GROUNDWORK FOR USING PRECARIOUSLY BALANCED ROCKS TO CONSTRAIN SEISMIC HAZARD MODELS IN NEW ZEALAND

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ABSTRACT :
We have undertaken a detailed cosmogenic dating study of precariously-balanced rocks (PBRs) in the central Otago province, New Zealand to understand the age and genesis of PBRs to an unprecedented level of detail within the temperate-humid New Zealand environment. Previous PBR studies have been restricted to desert environments. At face value our ^{10}Be dates indicate that the numerous PBRs in the Clyde area of central Otago have been unstable for around 40ka, although previous central Otago-based studies raise the possibility that the ages are apparent and the PBRs are much younger (≤10ka). Consideration of these age uncertainties raises the question as to whether the PBRs have experienced multiple large near-field earthquakes on the Dunstan Fault, or no such earthquakes, considering the long recurrence interval of the fault. Resolution of this issue might therefore have significant implications for near-fault motions for the Dunstan Fault. The dating of buried soils at the base of the PBR to resolve the issue is the goal of current efforts.

KEYWORDS:
Seismic hazard, precarious rocks

1. INTRODUCTION

This paper provides a précis of recent work being undertaken to develop ground motion constraints at near-fault sites from precariously-balanced rocks (PBRs) in New Zealand. The study has the objective of applying the wholly North American-based PBR methodology in a different environment to determine whether PBRs have a wider applicability, and for the obvious potential benefits of constraining seismic hazard estimates in New Zealand. Recent efforts have been focussed on gaining a greater understanding of the ages and genesis of PBRs within the New Zealand environment. The North American studies have focussed on developing sophisticated methods for estimating fragility functions for the PBRs (e.g. Purvance et al., 2008), and also on addressing PBR age determination within desert environments (e.g. Bell et al. 1998).

Our recent work has focussed specifically on reducing the large age uncertainties for schist PBRs reported in a pilot study at a near-fault site in the central Otago province (Fig. 1; Stirling & Anooshehpoor 2006). The pilot study made some preliminary comparisons of limited PBR age data (i.e. only two cosmogenic dates obtained) to seismic hazard curves derived from the New Zealand seismic hazard model (Stirling et al. 2002) at a near-fault site in the central Otago province (Cairnmuir Flats; Fig. 1). The Dunstan Fault is less than 5km from the site (Fig. 1), and the southwestern section of the fault is currently assigned a recurrence interval of 8ka for M7 earthquakes in the national seismic hazard model (Stirling et al. 2002). In the last year we have obtained considerably more cosmogenic age control than in the pilot study. The presentation and discussion of these new results, and ongoing work form the basis of this paper.

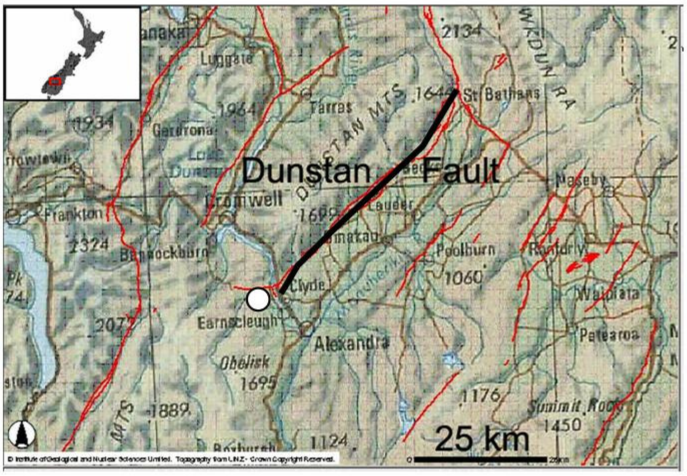

Figure 1: Location of the Clyde precariously-balanced rock (PBR) site (white circle) in the central Otago region, and in relationship to the active Dunstan Fault (black) and other active faults (red).

2. COSMOGENIC DATING OF PBRS

We obtained a total of 8 cosmogenic (^{10}Be) dates across the surface of a single PBR (the Clyde-6 BPR of Stirling & Anooshehpoor; Fig. 2). The PBR is one of many such features identified in the immediate vicinity (see Appendix of Stirling & Anooshehpoor, 2006). Four of these samples were obtained from the pedestal, or in other words the surface upon which the PBR is balanced (directly below the narrowest part of the PBR showing sample numbers 3, 6, 7, and 8 in Fig. 2). Pedestal dates presumably give an estimate of the time that the rock became precarious. The purpose of the dating was to establish, to an unprecedented level of detail (both in New Zealand and North America), the surface age distribution of a PBR. Such age control would hopefully allow a detailed understanding of the geomorphic development of a PBR, and assessment of the time since the rock became precarious. Thus far, age control for PBRs has mostly been obtained from desert granite lithologies in North America (e.g. Bell et al. 1998), and models for PBR development have been largely based on geomorphology textbooks (e.g. Twidale & Romani, 2005).

Figure 2: The Clyde 6 PBR (at right), showing the location of schist samples and the associated ^{10}Be cosmogenic dates (in units of thousands of years). The pedestal area of the PBR is marked by sample numbers 3, 6, 7 and 8.

3. RESULTS

The new dating control for the "Clyde 6" PBR (Stirling and Anooshehpoor, 2006; Fig. 2) shows minimum exposure ages for the top of the rock to be 76ka, the base to be 28ka, and the pedestal to be around 40ka. At face value, the PBR therefore appears to have been exposed over the period 76ka to 28ka, and the pedestal to have developed around 40ka. The latter would therefore indicate that the PBR has been in the present unstable state for the last 40ka. In terms of the neotectonic setting of the PBR, the 40ka age implies that the rock has been exposed to around five M7 near-field earthquakes on the nearby Dunstan Fault (Stirling et al. 2002), for which our preliminary analyses of toppling fragilities (using the methodology of Purvance et al., 2008) indicates a potentially serious discrepancy between predicted ground motions and PBR presence (Fig. 3). However, interpretations of ^{10}Be data from schist surfaces elsewhere in central Otago (Bennett et al., 2006) suggest that the dates are only apparent due to the schist being in a condition of steady-state between erosion and ^{10}Be accumulation. If such is the case then the exposure ages (above) are meaningless, and the issue of the age of the PBRs remains unresolved. In such situations, the maximum erosion rates (derived from the apparent exposure age but based on the assumption that the system is in steady-state) are more informative, and can be used to do a reconstruction of the shape of the PBR through time. Since we estimate erosion rates of around 10mm/ka for the ^{10}Be data for the Clyde 6 PBR with the assumption of steady state, the rock could possibly have been in a much more stable state as recently as 10-20ka ago (e.g. there could have been a 200-400mm wider contact between the PBR and the pedestal; Fig. 4). Since this erosional steady-state viewpoint is not shared by all cosmogenic dating experts, the question of whether the exposure ages or erosion rates are most valid for the PBR remains unresolved. As things stand, the PBR could be tens of thousands of years old, or considerably younger, an unacceptably large epistemic uncertainty given that the recurrence interval for the Dunstan Fault is estimated to be around 8ka (Stirling et al. 2002). Simply put, the PBR may have experienced as many as five near-field M7 earthquakes if the former is the case, or perhaps no such earthquakes if it has only become unstable within the Holocene. If it has experienced multiple Dunstan Fault earthquakes, then there are significant implications for near-field ground motions at the site. Indeed similar issues may well face the companion PBR studies being undertaken in the United States unless PBR surfaces in desert settings are clearly shown to be eroding extremely slowly. Strong supporting evidence for desert PBRs being greater-than-10ka comes from recent varnish lamination dating studies in southern California, in addition to the older study of Bell et al. (1998).

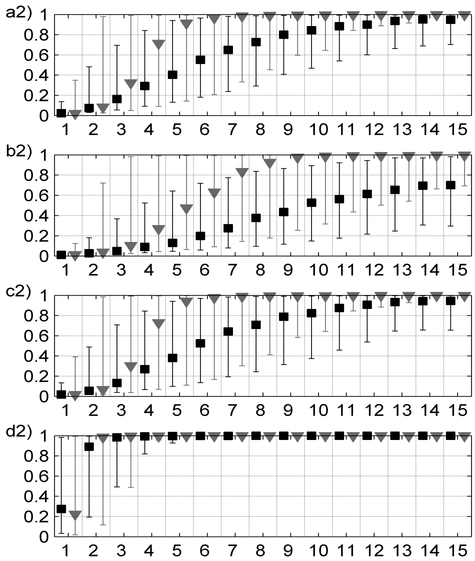

Figure 3: Comparison of PBR overturning probability (y-axis) as a function of the number of M7 Dunstan Fault earthquakes (x-axis) when exposed to median random ground motions taken from attenuation relations where PGA – Sa(1) are uncorrelated (black squares) and completely correlated (gray triangles). Bars correspond to the 20th and 80th percentiles. The graphs are ordered vertically according to the attenuation model used, as follows: McVerry et al. (2006), Boore & Atkinson (2006), Chiou & Youngs (2006), and Abrahamson & Silva (1997). An assumed PBR age of c. 40ka would correspond to c. five Dunstan Fault earthquakes (5 on the x-axis).

Figure 4. The Clyde 6 PBR (from Fig. 2) shown with reconstructed 20ka profile (red) based on assumption of erosion rates of the order 10mm/ka. See the text for further explanation.

4. FORWARD PATH

Independent data are now being acquired in order to interpret the ^{10}Be data in the context of erosion rates versus exposure ages. Our data will be AMS radiocarbon dates obtained from bulk soil samples buried beneath boulders shed from the Clyde-6 PBR at some point in the past. The soil dates will provide a maximum age of the boulder-fall event, and therefore a maximum estimate of the time that the PBR was last modified in a significant way. Soil dates of greater than 20ka would favour interpretation of the ^{10}Be data as exposure ages (and therefore the PBRs as truly ancient features), whereas soil dates less than 10ka would favour the use of the ^{10}Be data to estimate erosion rates (and the PBRs being relatively young features).

5. SUMMARY AND CONCLUSIONS

We have undertaken a detailed cosmogenic dating study of a PBR in the central Otago province, New Zealand to understand the age and genesis of PBRs to an unprecedented level of detail within the temperate-humid New Zealand environment. At face value the ^{10}Be dates indicate that the numerous PBRs in the area have been unstable for around 40ka, although previous central Otago-based studies raise the possibility that the ages are apparent and the PBRs are much younger ($\leq$10ka). Consideration of these age uncertainties raises the question as to whether the PBRs have experienced multiple large near-field earthquakes on the Dunstan Fault, or no such earthquakes. Resolution of this issue might therefore have significant implications for near-fault motions for the Dunstan Fault. The dating of buried soils at the base of the PBR to resolve the issue is forming the basis for current efforts.

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