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Age Constraints for Precarious Rocks in a Humid-Temperate Environment

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Introduction

SCEC-funded work over the last year has been focussed on constraining the age of precariously-balanced rocks (PBRs) within the humid-temperate environment of New Zealand using in-situ cosmogenic isotopes and geomorphic interpretation. Previous PBR age-related studies have been almost exclusively restricted to arid environments in the western United States, making the present study important in terms of assessing PBR age and development in a different climatic environment. The other important potential benefits are in constraining seismic hazard estimates at a near fault site, and for validating the New Zealand seismic hazard model (e.g. Stirling et al. 2002).

Our work has been focussed specifically on reducing the large age uncertainties for schist PBRs reported in an earlier SCEC-funded study at the Clyde site in the central Otago province (Fig 1; Stirling & Anooshehpoor 2006). The pilot study made some preliminary comparisons of PBR fragilities (estimates of PGAs required to topple the PBRs) and limited PBR age data (i.e. only two ^{10}Be cosmogenic exposure ages obtained) to seismic hazard curves (i.e. estimates of expected earthquake ground motion strength as a function of return period). The seismic hazard curves were derived from the New Zealand seismic hazard model (Stirling et al. 2002) for the Clyde site (Fig. 1). The Dunstan Fault is less than 5km from the site (Fig. 1), and the southwestern section of the fault has been assigned a recurrence interval of 8kyr for magnitude (M)7 earthquakes in the national seismic hazard model. The Stirling & Anooshehpoor (2006) study suggested a major discrepancy between the seismic hazard estimates and presence of the PBRs, but asserted that the large age uncertainties in the PBRs (10-70kyrs) needed reducing before any firm conclusions could be made from the findings. Such age uncertainties allow for the PBRs to have experienced anything from nil to many Dunstan Fault earthquakes.

This annual report is a brief précis of a paper that has been prepared for submission to an international journal. We therefore recommend the full paper be consulted for a satisfactory explanation of the study, rather than relying solely on the information provided in this brief report.

Cosmogenic ^{10}Be Data

We here briefly describe cosmogenic in-situ ^{10}Be data obtained for 11 rock samples taken from the Clyde site (Table 1). Eight of these come from the top and side of the Clyde-6 PBR (Stirling & Anooshehpoor, 2006), two are from a neighbouring tor, and one is from a large silicified sarson stone nearby (Fig. 2). In an attempt to determine when the PBR became precarious, three of these eight samples were taken from the pedestal of the PBR (samples 6-8). A vertical transect of two samples were taken from the top of the tor to obtain information about the evolution of shielding of cosmic rays due to attenuation by surrounding rock. The sample results are shown in Table 1, and the location of samples are shown on Figure 2.

Table 1. Sample results: ^{10}Be concentration in quartz, attenuation, zero-erosion exposure age, and steady-state erosion rate. Zero attenuation equates to an attenuation correction factor of 1. Exposure age and erosion rate values are quoted with two types of 1-sigma errors, separated by a backslash: the 1st is without the uncertainty in the production rate, while the 2nd one includes it. Attenuation and production rate modeling are discussed in the text.

ID#	^{10}Be conc. [10^3 g_{qtz}^{-1}]	depth interval [cm]	attenuation correction [ ]	zero-erosion exposure age [ka]	steady-state erosion rate [mm ka^{-1}]
1	623±7	0 – 3	0.975±0.002	74±1\4	7.92±0.10\0.5
2	369±5		0.58±0.21	73±27\27	8±3\3
3	337±8		0.53±0.24	73±33\33	8±4\4
4	331±7		0.52±0.24	73±34\34	8±4\4
5	232±7		0.36±0.32	74±66\66	8±8\8
6	338±5		0.53±0.24	73±33\33	8±4\4
7	382±8		0.60±0.20	73±25\25	8±3\3
8	392±7		0.61±0.20	74±24\24	8±3\3
9	1037±15	0 - 2	0.983±0.002	123±1.8\7	4.69±0.08\0.3
10	952±13	4 - 7	0.911±0.009	122±2.0\7	4.74±0.09\0.3
11	6756±47	0 - 2	0.983±0.002	965±7\57	0.488±0.009\0.07

The ages in Table 1 (Column 5) reflect the period of cosmic-ray exposure to the present, calculated with the assumption that no material between the sampled surface and the atmosphere was removed during that interval (zero erosion). The other end-member use of the data is for estimation of bedrock erosion rates (Column 6 in Table 1). This interpretation requires assumption of erosional steady-state (i.e. the rate by which ^{10}Be is produced, at a certain depth below the eroding surface, equals its disappearance due to erosion and radioactive decay). Utility of the steady-state assumption is in providing a maximum allowable value for the rate of erosion, albeit at the expense of information about the true exposure age. Based on our analyses and close compatability of our data to previous cosmogenic exposure dating studies in the central Otago region (Bennett et al, 2006), we conclude that the assumption of erosional steady-state is the more valid approach for interpreting our data.

Focussing on samples 1, 9 and 10 (i.e. PBR/outcrop top samples, which allow model parameters to be easily determined), erosion rates are of the order 0.5cm/kyr. These rates are similar to rates derived from an ensemble of environments and methods in previous studies (e.g. Rapp, 1960; Bishop et al. 1984, Bennett et al. 2006), including from within central Otago. For instance, Bishop et al. (1984) showed that similar rates of catchment denudation are presently occurring in the nearby Falls Dam catchment area, based on sediment volumes accumulated since the dam was constructed. The results of the Falls Dam study supports the conclusion that the erosion rates derived from the ^{10}Be data are realistic estimates of true schist erosion rates at the Clyde site.

Schist erosion rates of the order 0.5cm/kyr are perhaps further supported by independent evidence from soils buried by schist slabs shed from the Clyde-6 PBR. Calibrated radiocarbon dates from bulk soil samples show dates of 5400 $\pm$ 40 years BP near the base of the 50cm soil profile (GNS Science NIC lab pers comm.; Fig. 3). This is consistent with the PBR being a Holocene feature, based on the assumption that the soils reflect the present geomorphic processes. It is acknowledged, however, that radiocarbon dates obtained for bulk soil samples are often fraught with uncertainty due to the unknown amount of carbon cycling that has taken place in the soil-atmosphere system. Accordingly, major pre-treatment was carried out on the soil samples prior to radiocarbon dating, so these uncertainties have been minimized as much as possible.

Evolution of PBRs in the Context of Near-field Dunstan Fault Earthquakes

Having obtained estimates of the exposure age and vertical erosion rates of the Clyde-6 PBR and nearby tor, and having modeled how schist erosion rates might have varied through time, we now have an idea as to how rapidly unstable schist landforms might develop in the temperate New Zealand environment. The PBR erosion rate average is 0.5cm/kyr and from this we infer that at the start of the Holocene, the PBR would have been ~5 cm larger on all sides (Fig. 4). Given the added stability this extra rockmass would have given to the PBR it is likely that the Clyde-6 PBR only developed the present precariousness in the Holocene. In the context of the location of the Clyde site near the Dunstan Fault, it is possible that few or no Dunstan Fault earthquakes ($M \geq 7$ and recurrence interval of 8kyrs) have shaken the PBR in the present form. Analyses by Stirling and Anooshehpoor (2006) show that the PBR is expected to be shaken down by a PGA of less than 0.2g, which from quick examination of relevant attenuation models appears to be less than one-half to one-third of the median PGA expected from large Dunstan Fault earthquakes. PBRs at the Clyde site possibly form in the time between major earthquakes and are either shaken down by the major earthquake and/or become eroded to such an extent that they become unstable and topple without the assistance of earthquake shaking. For the rest of central Otago, the importance of earthquake-induced PBR destruction would depend on location, as PBRs located away from active faults would be mainly destroyed by erosion, whereas near-fault PBRs would be destroyed by both strong shaking and erosion. The PBRs may therefore be in a time-independent state of creation and destruction in the former areas, but destruction in the latter areas could also be punctuated by periodic strong shaking.

Comparison with western United States PBR studies

The wider implications of the Clyde PBR results are that the PBRs are much younger than counterparts in arid environments of the western United States (e.g. Bell et al. 1998). The humid-temperate environment and schist geology of the central Otago region has apparently led to bedrock erosion rates of the order 0.5cm/kyr, rates that will have led to the present PBRs being formed within the Holocene. Our results could be relevant to metamorphic terranes in humid-temperate environments in the western United States (e.g. parts of Central California and Pacific Northwest) and elsewhere, where PBR dating has not yet been undertaken. The extrapolation of our New Zealand-based results to these regions may be more appropriate than extrapolations from nearby arid environments.

Conclusions

We have constrained the rate of development of PBRs within a metamorphic terrane and humid-temperate environment in New Zealand using in-situ cosmogenic isotopes and geomorphic interpretation. Cosmogenic in-situ ^{10}Be concentrations from 11 samples of schist and silcrete from the Clyde PBR site in the central Otago region imply rock surface erosion rates of the order 0.5cm/kyr, consistent with rates of landform evolution and catchment denundation determined elsewhere in the region. The PBRs may have reached their precarious state less than 10kyr ago, and may not have experienced any earthquakes on the nearby Dunstan Fault in the present states of precariousness, given the long recurrence interval of the fault. PBRs from metamorphic terranes in humid-temperate environments similar to that of central Otago (e.g. parts of central California and Pacific Northwest) may therefore be considerably younger than counterparts in the arid western United States. PBRs in temperate environments may therefore evolve more rapidly than in desert environments, at least for areas of similar lithology to that of central Otago.

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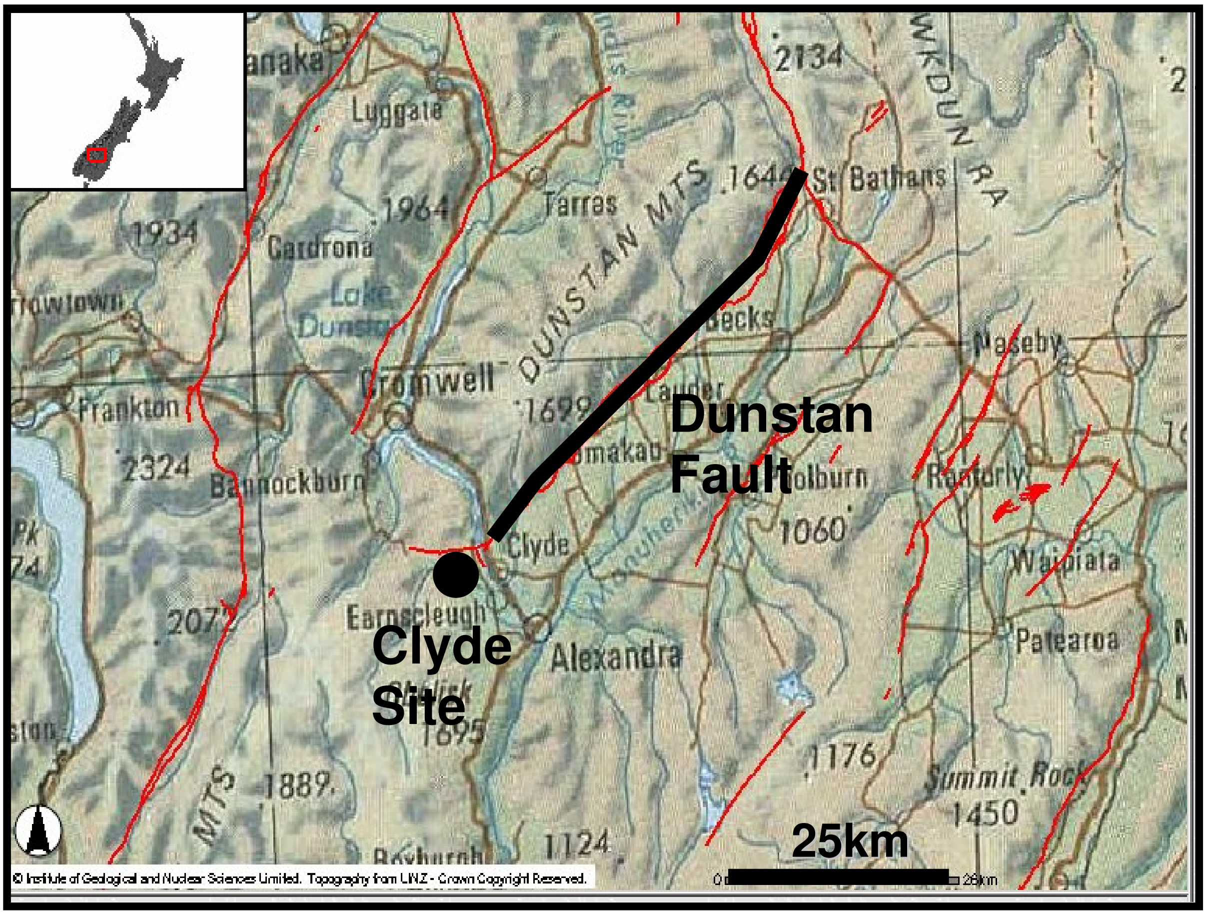

Figure 1: Location of the Clyde PBR site in central Otago, New Zealand. Numerous PBR and semi PBRs are present in the approximately 3x3km area of the site (see images in Stirling & Anooshehpoor, 2006).

Figure 2: Clyde-6 PBR (right) and neighbouring tor (left) showing sample locations and numbers.

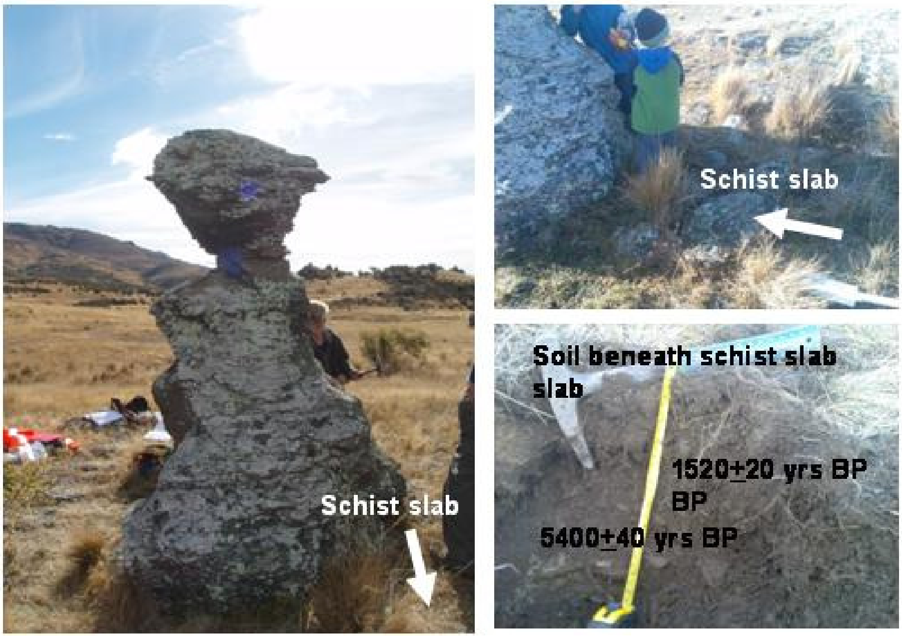

Figure 3: Calibrated radiocarbon dates for soils buried beneath a schist slab derived from Clyde-6. The length of the tape measure shown in the image is 50cm.

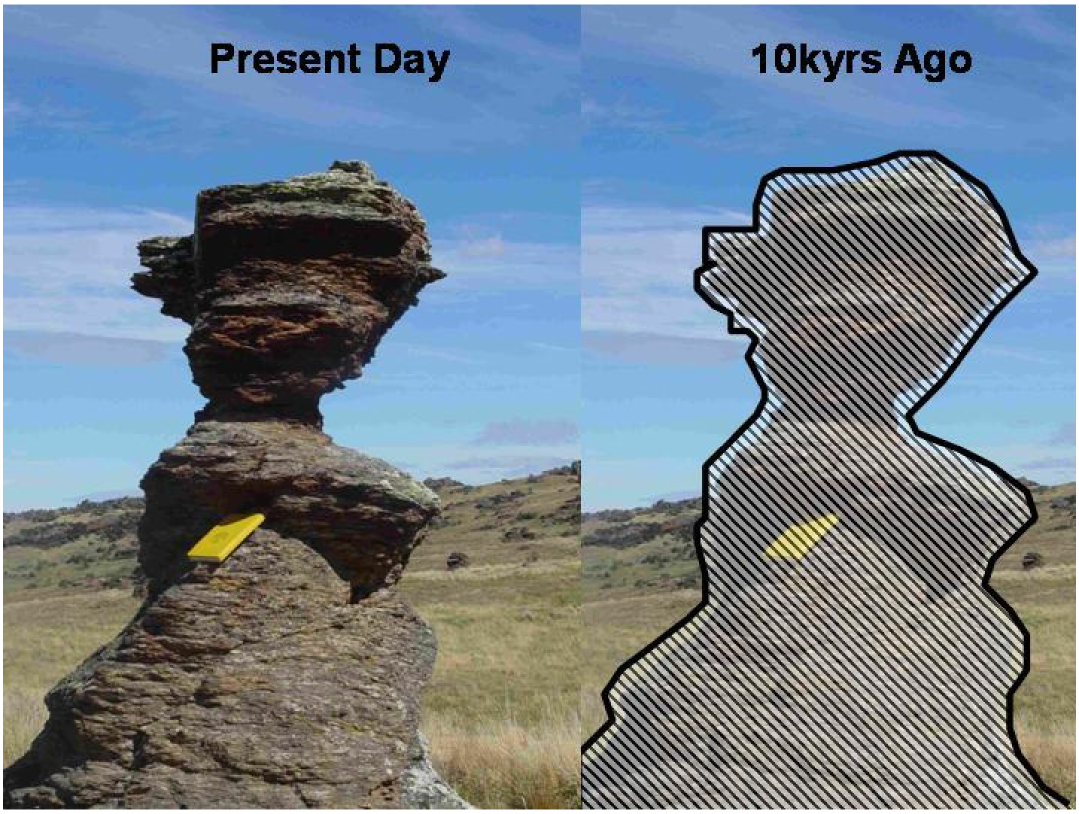

Figure 4: Hypothetical 10kyr profile for Clyde-6 assuming that an erosion rate of about 0.5cm/kyr has been in operation over the Holocene. The profile does not consider additional modification due to slabs falling off the PBR, such as that shown in Figure 3.