2007 PROGRESS REPORT
Age Of Precariously Balanced Rocks (PBRs) For Validation Of A Petascale Cyberfacility For Physics-Based Seismic Hazard Analysis

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Overview
This is one of several collaborative efforts to further develop, refine, and implement the use of precariously balanced rocks (PBRs) to validate PetaSHA type outputs provided by the SCEC / Community Modeling Environment (CME) collaborative CyberShake computational platform. In the first year of effort (2006), a preliminary selection of PBR sites judged to be critical to this initiative was compiled (Fig. 1-2 and Table 1). These rocks were selected due to their potential for dating and their significance for validation of PetaSHA. In the second year of effort (2007), we developed a methodology for dating a suite of PBRs across So. California and sampled 4 rocks (red type in Table 1) for initial testing of our developed methods. Three of those rocks have been extensively sampled due to tipping and shattering by vandals or construction activities. Preparation of the samples for cosmogenic radionuclide (CRN) dating is pending in Perg's lab at UMN. Results of the CRN dates are expected in time to guide our efforts for more extensive sampling in the summer of 2008.

Significance of PBRs for CyberShake, SHA, and TeraShake
CyberShake is a high profile computational platform of the Community Modeling Environment (CME) for SCEC3. The CME collaboration proposes to transform seismic hazard analysis (SHA) into a physics-based science by deploying a cyber-facility that can execute SHA computational pathways – PetaSHA – and manage data volumes using the nation's petascale computing resources. Once deployed, validation of these physics-based SHA estimates will be accomplished using seismic and paleoseismic data in Southern California. Paleoseismic data, in the form of PBRs, provide validation of ground motions on the time scale necessary to test complete earthquake rupture forecasts and SHA estimates. The preliminary investigation of Bell et al. (1998) suggests that PBR shapes (and therefore stability) have not changed significantly over the last 10,000 years. If true, the locations of PBRs constrain the level of ground motions during the Holocene, with important implications for general SHA methodologies. This finding needs to be investigated further by dating key PBRs that can validate CyberShake results and constrain National Seismic Hazard Maps such as the example shown in Figure 1.

Progress from 2007 funds: Sample collection and dating plan
In 2006, SCEC provided seed funds for a feasibility study and development of research collaboration. Working relationships were established with collaborators listed on this report, and Brune was appointed Visiting Professor at UC Irvine to work closely with Grant's research group on the next phase. We identified the most promising PBR sites and rocks for dating (see Figures 1, 2).

In 2007, our goal was to develop a dating methodology, and identify and sample PBRs with the simplest history, greatest significance for validating ground motion, and greatest chance of yielding interpretable age results. Photos of PBRs in Figure 2 show that they can be roughly divided into two main types: "mushrooms" which appear to be undercut, and "pillars", which have relatively straight sides. Another category can be developed based on the presence and potential for dating either the pedestal or soil/sediment, as indicated in Table 1. We are especially interested in PBRs Benton, Perris and Mocking Bird (bold, Table 1) because of the potential for obtaining both soil and cosmogenic dates. For future work, we are interested in Tooth, Pacifico and Pioneer Town because of their significance for validation of PetaSHA(bold, Table 1).

In summer 2007, we sampled 4 different PBRs to develop constraints on the length of time they have been precariously balanced, and to increase our understanding of how they became precarious (Perg et al., 2007; Grant Ludwig et al., 2007). We sampled three rocks near Perris and one rock near Benton Road (red type, Table 1). These rocks constrain ground motions from earthquakes on the San Jacinto and Elsinore faults (Brune et al., 2006). Two of the Perris rocks were toppled in conjunction with our sampling to measure their stability (Purvance et al., 2007). A third Perris rock was previously tipped by vandals. All three Perris rocks were extensively sampled. Our sampling strategy was to collect 5-6 samples per PBR: 1 on top, 3 on the sides, 1 on the pedestal, and 1 on the ground surface. We also collected from the interior of the rocks that shattered.

After sample preparation in Perg's lab (pending) they will be analyzed for cosmogenic 10Be. We will develop a model of their temporal evolution within the context of landscape exhumation and erosion, lateral erosion, and ground motion. Interpretation of dates will be complex. The initial suite of 4 sampled rocks will provide a comparison of "best case" and "worst case" scenarios from the Benton Road and Perris Rocks respectively. The Benton Road PBR has very little chemical erosion, with Schmidt hammer results similar to fresh granodiorite. It is from a high relief area, and is therefore likely to have a low inheritance problem, with relatively fast exhumation. Its shape suggests the hypothesis that this PBR became precarious through one event (removal of half the balanced rock), and therefore we expect it will be relatively easy to quantify the age/time of precariousness. In contrast, the Perris Rocks may have problems with inheritance because they are relatively near the surface of the Perris peneplain. There is a low gradient between the peneplain and Perris valley bottom, suggesting that the exhumation rate has been low. Field investigations of the Perris PBRs show the highest observed chemical weathering rates and small scale physical erosion. Thus, these rocks have likely experienced post-exhumation shape modification.

Soils were described in a small open basin below one of the Perris PBRs. The degree of soil development was very minimal, suggesting young deposition (less than ~ 5 ka). This site is an open basin, and therefore not ideal to evaluate soil age, but the implication is that erosion of the outcrops has been ongoing at this site. This is in stark contrast to the Benton Road site where Tom Rockwell (personal comm.) assessed soil conditions which are consistent with much older ages. Soils will be described on the broad surface west of Perris PBR sites to provide minimum ages for the duration of the stability of this surface, and establish timing of initial erosion and exhumation of the PBRs.

Development of Sampling and Dating Plan for Critical and/or vulnerable PBRs

After obtaining dates from samples collected in 2007, we plan a more ambitious sampling and dating program, guided by initial results.

- Highest priority is to collect a sample profile from a quarry at Mott Reserve near Perris to provide a direct measure of likely inheritance.
- Collect further PBR samples, depending on results of analysis of 2007 samples. If PBRs have a complex history and/or need further method development: sample ~4 additional PBRs with 5-6 samples per PBR. If rocks have a moderately complex history, 3-4 samples per PBR, ~6 additional PBRs. For rocks with very simple history, 2-3 samples per PBR.
- We expect a mix of further method developments and calibration for more complex PBRs, and use of 2007 year's results to select PBRs with less complex history to increase total number measured.

Initial development of a temporal renewal model for exhumation of PBR in So. Calif. drainages

The correlation of precariously balanced rocks with slope, and presumably erosion rate, has not been documented in Southern California. Most of the obvious examples to date have been found in Nevada and Eastern California, where the repeat times for large earthquakes are much greater than in Southern California. We posit that such a correlation exists in Southern California.

Numerous papers describe enigmatic pedestal rocks, tors, balanced rocks, perched rocks etc, and address questions about the mechanism of their formation and ages relative to other elements of the landscape and rates of soil formation. (Selected examples include: Leigh, 1970;Twidale and Campbell, 1992; Heimsath et al., 2000). Reconnaissance surveys have located hundreds of precariously balanced rocks in Southern California in the last decade, and currently a number of studies are using them to place constraints on seismic hazard estimates (e.g., Brune et al. 2007, Purvance et al 2007). To make full use of the rocks we need to determine the timescale and mechanisms for creating and exposing – i.e. renewing - these rocks, along with the nature of earthquake ground motions which could topple them. Since most of the rocks were originally corestones that have been exposed by erosion of decomposed granite (grus), it is important to understand the effect of erosion rate on the distribution of such rocks. A correlation that has been suggested by reconnaissance surveys in Nevada and Eastern California is that in many areas where there are zones with numerous precarious rocks next to zones where rocks have obviously been knocked down, and that the precarious rocks tend to appear on the steeper slopes where the erosion rate is presumably faster. This suggests that the rocks on older surfaces may have been knocked down by one or more early large earthquakes, and that the remaining precarious rocks have been exposed after the last earthquake by a more rapid erosion rate. A typical situation is illustrated in Figure 3. Rapid erosion rate on the steep slope at the edge of a stream channel has exposed precarious rocks, whereas on the gentler slope away from the stream channel the rocks appear to have been shaken down. If true, accurate knowledge of the erosion rate adjacent to the stream channel could be used to constrain time since the last strong earthquake. Since we now have methods of dating erosion rates through CRN, understanding this process can provide important information for about seismic hazard and random background earthquakes.

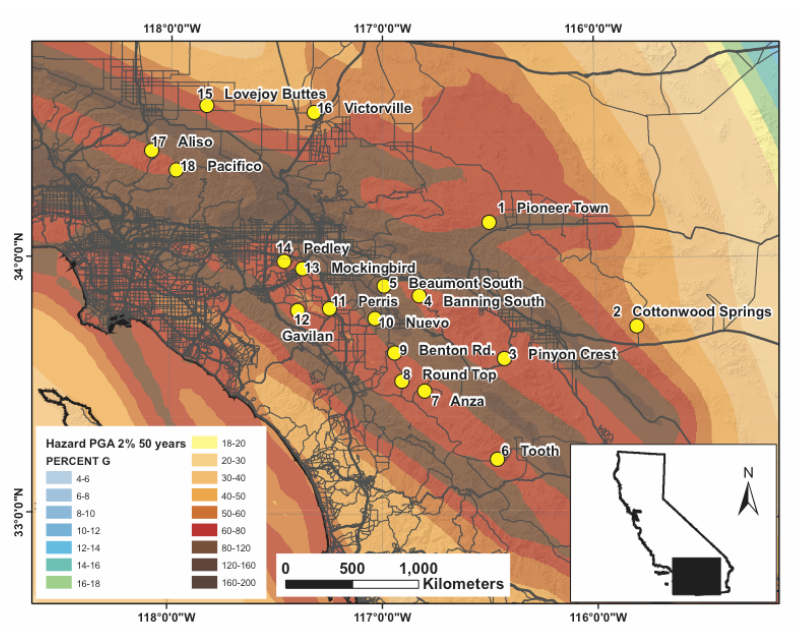

Figure 1. Select PBR locations in southern California overlying the 2% PE in 50 year 2002 National Seismic Hazard Map for PGA (Frankel et al. 2002).

TABLE 1	**2002 Hazard, 2% in 50 years (%g)**	**Cosmogenic Pedestal Datable / Sampled**	**Soil-Age Datable**
Southern San Andreas (Also Constraint for Terashake)			
Pioneer Town	80	✓	?
Cottonwood Springs	55	?	?
Pinyon Crest	70	✓	?
Banning South	80	✓	✓
Beaumont South	100	✓	?
Riverside-Borrego Line (Elsinore & San Jacinto Faults)			
Tooth	70	✓	?
Anza	70	✓	✓
Round Top	70	✓	?
Benton Road	80	**Sampled, 2007**	✓
Nuevo-1	100	✓	✓
Perris -1, 2, 3	60	Tipped & sampled, 2007	✓
Gavilan	75	✓	?
Mocking Bird	60	x	✓
Pedley	75	x	?
Mojave-San Gabriel			
Lovejoy Buttes	70	✓	?
Victorville	55	✓	?
Aliso Canyon	80	?	?
Pacifico	75	✓	?

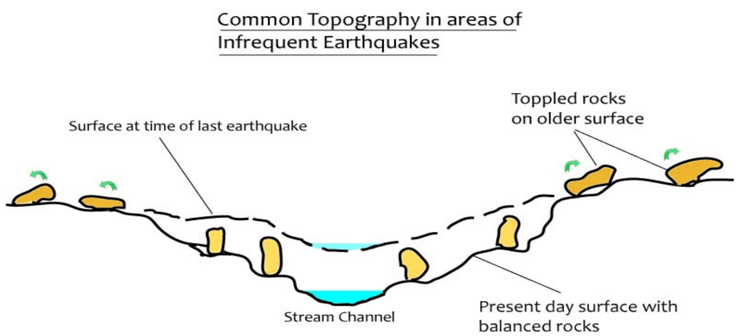

Figure 3 Model for renewal of PBRs in S. California drainages.

Figure 2. PBRs selected for testing with numbers corresponding to the site numbers given in Fig. 1.

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