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 proposals 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 CyperShake computational platform. The first year of effort (2007) began with a field tour of many of the PBR sites selected by collaborators in 2006 as critical to the validation of PetaSHA and with good potential for dating. We developed a methodology for cosmogenic nuclide 10Be sampling of the PBRs. The "age" of PBRs depends on when the balanced rock reaches precarious dimensions, or when the balance point is exhumed, whichever is later. Soil ages by Kendrick will also define the minimum age of balance point exhumation. The 10Be sampling was also designed to constrain inheritance (cosmogenic nuclide ingrowth prior to exhumation of the PBR) and post-exhumation erosion and shape evolution. We sampled 4 rocks for initial testing of these methods. The cosmogenic nuclide sample preparation is proceeding at my lab and 10Be data will be available in late summer to guide more extensive sampling in September.

Significance of PBRs for CyberShake, SHA, and TerraShake

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 thus stability, have not changed significantly over the last 10,000 years. If true, the locations of PBRs constrain the ground motion over the Holocene, with important implications for general SHA methodologies. This finding must be investigated further by constraining age in key PBRs that can validate CyberShake results and constrain National Seismic Hazard Maps.

Progress from 2007 Funds:

Development of Sampling Methodology

PBRs have complex histories, with shape evolution of the balanced rock pre- and likely post-exhumation. The exhumation of the pivot point between the balanced rock and base is also required for the rock to become precarious. For testing datability with cosmogenic nuclides, we needed to constrain five variables: inherited cosmogenic nuclides prior to exhumation, chemical erosion rates, time the balanced rock became precariously shaped, shape evolution of the balanced rock post-exhumation, and time of exhumation of the pivot point. We selected the best case PBR and three worst cases to examine the importance of these factors. The best case will help determine whether 10Be dating is possible, and the worst cases will highlight which of these factors are important and need to be constrained in non-ideal dating situations. We expect that best-case PBRs can be dated with 2-3 10Be samples, while those with more complex histories will require between 4 and 6 samples.

The sampling plan was designed to use multiple checks on each of the five factors. The basic sampling strategy was one sample on top, three on the sides of the balanced rock, and one on the base. Some PBRs where sampled in the center of the balanced rock after toppling, and/or a nearby soil sample for landscape lowering rate. Two cosmogenic 14C samples were also collected. Toppled rocks were oversampled, with large sample amounts, to provide an archive for outside confirmation of measured 10Be values if requested, and for future dating advances.

Explanation of Sampling Methodology

• Inheritance – 10Be ingrowth prior to sampling

1. Measuring cosmogenic 10Be and 14C pair in the center of a larger PBR. Excess 10Be, which decays more slowly, determines inheritance.
2. The 10Be sample profile of the PBR should decrease from top to bottom, due to angle of the incoming cosmic rays. A systematic offset of measured 10Be in the profile is due to inheritance, and can be subtracted from the measured samples.
3. The most important target for dating in 2008 is a quarry profile in the UC Mott Reserve, near the three worst-case PBRs in Perris. The shape of the profile and lower shielded samples should define the inherited concentration in the Perris area. There is also the possibility of constraining the age of the Perris peneplain.

• Erosion / Shape Evolution.
1. Measuring cosmogenic 10Be and 14C pair in the center pivot point of a larger PBR. A deficit in 10Be, which means the rock was originally wider at the pivot point, indicates erosion and shape evolution that makes the rock more precarious though time.
2. Direct constraint of maximum chemical erosion rate – cosmogenic 14C sample from the PBR displaying the fastest chemical erosion. 14C is sensitive enough to measure rates of 2mm/yr or greater.
3. 10Be concentrations that do not systematically decrease down the measured profile due to lower cosmic ray energy indicate erosion.
4. 10Be deficits in the samples on the balanced rock indicate shape evolution. Deficits near the pivot point or below the current center of mass equate to the rock becoming more precarious; deficits above the center of mass and on the top means it has become less precarious.
5. Investigation of the "turtle shell cracks" (Fig 1). These are found mainly on PBRs, and are generally hard plates about 30x30 cm, with cracks of 5-6 cm with no undercutting. These might indicate areas of no chemical erosion, which would make them excellent targets for dating. These plates fall off as a unit, generally from the sides / bottom of the balanced rock, which could indicate an increase in precariousness that could be easily quantified. See below for further work on "turtle shell cracks."

• Age of Balanced Rock
1. Measurement of 10Be profile on top and sides of balanced rock indicate when rock became precarious (and post-exhumation shape evolution).
2. If "turtle shell cracks" form rapidly after exhumation (or a quantifiable time after exhumation) and do not erode, targeting these at the top of the PBR will provide a maximum constraint on balanced rock age.

• Age of Pivot Point Exhumation
1. The age of pivot point exhumation is bracketed by the 10Be sample just above the pivot point on the balanced rock, and the 10Be sample on the base.
2. Systematic increase in 10Be concentrations from the top to bottom of the 10Be profile indicate slow exhumation.
3. 10Be measurements in soil will determine the maximum lowering rate over the Holocene and Late Pleistocene. (Soil – bedrock pairs would better measure the rate of soil development, and soil height would determine loss rate, if this becomes important).
4. Soil age determinations by Kendrick will provide a minimum age of pivot point exhumation. The smaller the basal rock, the better the age.

PBR Selection and Sampling Strategy

The PBR selection strategy for 2007 was to measure the best and three different worst-case 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., 2007a; Perg et al., 2007b; Grant Ludwig et al., 2007). These PBRs all constrain ground motions from along the San Jacinto and Elsinore faults (Brune et al., 2006). The best-case PBR is the Benton Road Rock (Fig. 2), and the worst-case rocks are in the Perris area (Fig. 3-5). If the best-case rock has a simple history, then sampling would require 1-3 samples (top; likely balanced rock pivot point; perhaps another on the balanced rock or on the base). If the worst-case rocks also have a simple history, we could confidently use 1-3 samples on all PBRs; otherwise, PBRs with a more complex history would require 4 or more to constrain the age.

Best Case – Benton Road Area (1 PBR)

• Benton Road Rock (Fig. 2)

This PBR is a pillar with datable soils. The granodiorite is extremely competent, with Schmidt hammer values of 60, which is similar to fresh granodiorite. The area has high relief, which suggests rapid exhumation and thus low cosmogenic nuclide inheritance. The shape of the balanced rock suggests one event – removal of half of the balanced rock – to become precarious. The soil ages are relatively old, based on exposure of a thick Bk horizon in the stream, and Tom Rockwell's assessment of the soil age (pers. comm.). “Turtle shell cracks” are present on the top and upper sides of the rock, and pinches in only about 10-15 cm on the lower sides of the balanced rock, which could indicate little post-exhumation shape evolution through erosion. An additional target in this best-case scenario was determining whether the removal of half the balanced rock occurred pre- or post-exhumation. If this PBR displays a simple history, others like it could be dated with 1-2 samples.

Worst Cases – Perris Area (3 PBRs)
The granodiorite in this area is the least competent observed; some rocks display large spalls, and other rocks display moderate to severe chemical erosion (“chicken neck” blebs of mafic material standing up 5-10 cm, to grüssification to the extent that minerals can be scooped out by hand). These rocks are the most likely to have experienced post-exhumation shape modification. This is a very low relief area, near the Perris peneplain surface, and is most likely to have significant inheritance. The low gradient between the Perris Valley and young age of the soils (Kendrick's assessment of ~5,000 years) speaks to slow exhumation. All of the sampled rocks were tipped over and the pivot point interiors accessible. One was tipped over ~18 months ago by vandals (Fig 3b.) and the other two were toppled in conjunction with our sampling to measure the stability, in advance of development in the area (Purvance et al., 2007). The greatly complex history of these rocks makes them the most challenging possible to date.

• <u>Perris Vandalized Rock</u> (Fig. 3)

This is a pillar PBR, and the rock with the least complex history in the Perris area. The vandalized rock displays the least erosion, with most of the erosion concentrated on the top (field observations indicate total erosion on top is likely less than 20 cm). Although the outside granodiorite on the balanced rock displays some grüssification, the inside is still very competent, as is the base rock. Since erosion appears to be low, and any shape evolution would likely make the rock slightly less precarious, the complexity is reduced to determining the inheritance, age of the balanced rock, and exhumation age. The thicker pillar made this the best sample for the direct measurement of inheritance though the 10Be and 14C pair, the age of the balanced rock (and erosion from the top) will be determined by the balanced rock profile, and the exhumation age by bracketing the pivot on the balanced rock and basal rock, and from soil ages.

• <u>Perris Powerline Road</u> (Fig. 4)

This is classified as a pillar, although the top is more bulbous than most pillars. This PBR displays abundant spalling, with medium competency to the granodiorite. “Turtle shell cracks” are abundant on the top and sides of the balanced rock; these have spalled off on the underside of the balanced rock, raising the center of mass and making the PBR more precarious. There is also a spall on the base rock, although it does not affect the precariousness. The main concentration on this rock is determining the original age of the balanced rock, and the timing of erosional spalls and shape evolution. Due to spalling at the pivot and base, the inheritance and exhumation age will likely be best measured though the vandalized PBR, soil ages, and inheritance profile in the quarry. (A paired 10Be-14C sample was taken from the base of the balanced rock for the archive; this sample could directly measure inheritance.)

• <u>Perris Barking Dog</u> (Fig. 5)

This is an undercut PBR, classified as a mushroom. There looks to be a remnant few “turtle shell cracks” at the tip of the PBR, and the overall shape is typical of the small arched domes in the area, so the erosion on the top is likely low. There are large joints spalled off the back face of the base, and the underside of the mushroom and base are extremely grüssified (abundant minerals at base, can scoop out minerals from rock) and the granodiorite has low competency except near the top of the balanced rock. The maximum age of the balanced rock can likely be determined from the top of the balanced rock, and the profile samples constrain the almost certain shape evolution. A cosmogenic 14C sample on the base, in the most rapidly eroding area, will constrain maximum chemical erosion rates (sensitive to > 2mm/yr erosion). The inheritance and exhumation age will again likely be best constrained through the vandalized PBR, soil ages, and inheritance profile.

Development of Sampling and Dating Plan for Critical PBRs in 2008
Fieldwork and sampling will proceed in September 2008, to overlap with Eppes in the field, analyze 10Be measurements from 2007, and to combine airfare with the SCEC conference.

- Highest priority is to collect a sample profile from a quarry at UC Mott Reserve near Perris to provide a direct measure of likely inheritance. This will be combined with a trench by Kendrick for undisturbed soil ages.
- Collect further PBR samples, selecting PBR locations in southern California overlying the 2% PE in 50 year 2002 National Seismic Hazard Map for PGA (Frankel et al. 2002). Highest priority are Mocking Bird and Tooth (San Jacinto - Elsinore), Pacifico (Mojave-San Gabriel) and Pioneer Town (Southern San Andreas) due to validation

of PetaSHA.

- Number of PBRs dated in 2008 depends on complexity of history in the Benton Road Rock and Perris PBRs, and the field interpretation of the rocks targeted above. Best case is 1-3 samples per PBR, intermediate case is about ~4 samples per PBR, and complex case is 5+ samples per PBR. We expect a mix of further method developments and calibrations for complex PBRs, and use of 2007 year's results to extend number of PBRs dated by selecting those with less complex histories requiring fewer samples.

Modeling Cosmogenic Nuclide Ingrowth

To interpret the 10Be profiles, and the 10Be-14C pair for inheritance, it is first necessary to have a model for 10Be ingrowth in the PBRs. These are complex shapes, with cosmic rays penetrating through the rock from all directions. The energy of the cosmic rays changes non-linearly from vertical to the horizon, due to different atmospheric thicknesses (total mass). The UNR group has developed a method of determining 3D shape from photographing targets on the rock at different angles, and processing into 3D polygons (e.g. Purvance et al., 2007). Purvance and I are working on a model of cosmogenic nuclide ingrowth (and decay for 14C), which will volumetrically fill the 3D PBR shape. The model is currently envisioned as static, but could be modified if shape evolution is important. This type of modeling has not been done before, and will also be a general contribution to cosmogenic nuclide dating of boulders and more complex shapes.

Genesis and Degradation of "Turtle Shell Cracks"

I have started work with Martha ("Missy") Eppes, one of the foremost experts in rock cracking. She was independently examining the "turtle shell cracking" phenomenon in the Mojave and Peninsular Ranges; her hypothesis is that rocks heated to high temperatures in the summer and subjected to a sudden cold rain shower break into the 30x30cm plates with the ~5 cm deep straight cracks (Fig. 1). Several questions brought up specifically by the PBRs, and the strength of combining 10Be measurements with field and lab observations, have led to this collaboration. We mean to answer questions such as timing of cracking and the relationship with balanced rock formation; why cracks are found almost exclusively on PBRs and not younger rocks or surrounding rocks of similar height and exposure history; quantify the hardness of pristine "turtle shell plates" and implications for chemical erosion – our current hypothesis is that pristine shells are hardened to the point there is little or no chemical erosion; how, when and where plates are eroded / removed, and implications for shape evolution. Another question is the lack of varnish on the pristine "turtle shell plates," if they are as stable as we assume. Lack of varnish could be due to unsuitable conditions for varnish formation, Holocene cracking ages, or that the age of PBRs with "turtle shell cracks" are uniformly Holocene. I am in the midst of a literature search for evidence of varnish formation in the Peninsular Rages; the archeology petroglyph literature should be thorough enough to prove a negative result. 10Be profile measurements, and field observations, will help constrain any time gap between balanced rock formation and "turtle shell cracking." If the 10Be dated PBRs are all younger than Pleistocene, and if we eliminate the first two "turtle shell" and varnish hypotheses, it would strongly suggest that all PBRs with these "turtle shell cracks" are Holocene.

Initial Development of a Temporal Renewal Model for Exhumation of PBRs in So. California 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. Since most of the rocks were originally corestones that have been exposed by erosion of decomposed granite (grüss), it is important to understand the effect of landscape lowering 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 6. 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 both stream and hillslope erosion rates through cosmogenic nuclides, understanding this process can provide important information about seismic hazard and random background earthquakes. After identifying appropriate sites, we expect to measure 1-3 pilot 10Be derived stream erosion rates in 2008.

Figure 1: “Turtle Shell Cracks”

1a: Benton Road Rock – Pristine

1b: mushroom rock – Some Erosion

Figure 2: Benton Road Rock (Perg for scale)

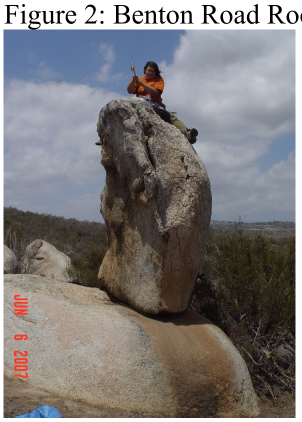
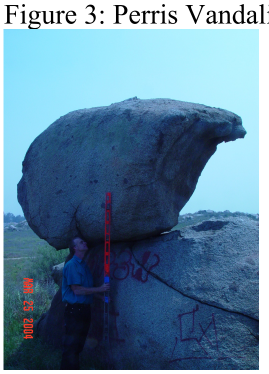


Figure 2a: Side

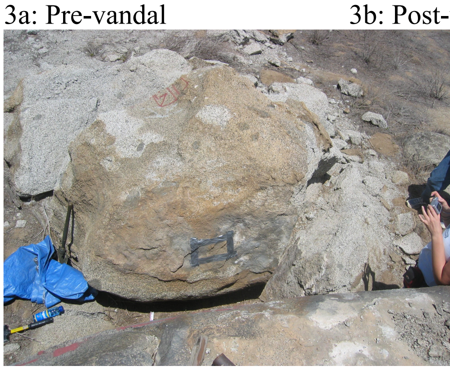
Figure 2b: Back (pristine “turtle shell cracks”)

Figure 3: Perris Vandalized Rock (person, sledgehammer for scale)



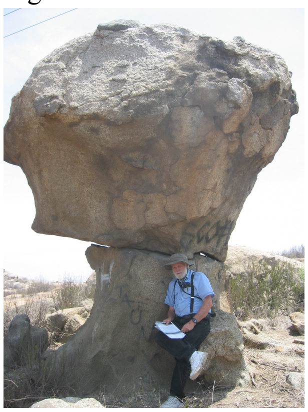
3a: Pre-vandal

3b: Post-vandal, side view



3c: Post-vandal, top view from pedestal. Duct tape is paired 10Be-14C cosmogenic nuclide sample.

Figure 4: Perris Powerline Road (Brune for scale)



4a: Pre-toppling

4b: Post-toppling (basal sample is archived paired 10Be-14C sample)

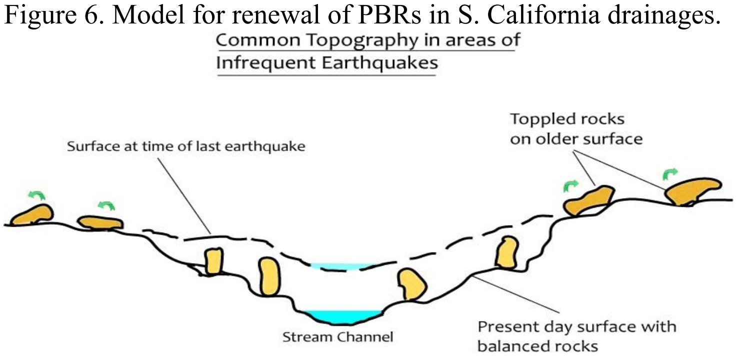
Figure 5: Perris Barking Dog (Anooshepoor for scale).

5a: Pre-toppling (line is vertical)

5b: While toppling

5c: Post-toppling

Figure 6. Model for renewal of PBRs in S. California drainages.



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