2008 Progress Report
CONSTRAINING THE AGE, LOCATION, AND RENEWAL RATES OF PRECARIOUSLY BALANCED ROCKS (PBRs) IN SOUTHERN CALIFORNIA

Submitted by Lisa Grant Ludwig, University of California, Irvine

Collaborators: Dylan Rood (LLNL), James Brune (UCI and UNR), Matt Purvance (UNR), Rasool Anooshepoor (UNR), Katherine Kendrick (USGS), Sinan Akciz (UCI), Greg Balco (Berkeley Geochronology Center)

Student: Tyanna Schlom, SCEC Summer Undergraduate Research Experience Intern

Overview

We are engaged in collaborative research to develop, refine, and implement the use of precariously balanced rocks (PBRs) for validation of ground motion studies and seismic hazard analysis, including PetaSHA type outputs provided by the SCEC / Community Modeling Environment (CME) and CyberShake computational platforms. Our work focuses on constraining the age and exhumation or "renewal" rates of PBRs. In previous years we formed multi-disciplinary teams for effective research, and identified PBRs with good potential for dating at sites that are important for PetaSHA validation. In 2007 and 2008, we collected samples from 9 rocks at 6 sites for ^{10}Be analysis, and obtained preliminary, model-dependent exposure ages of four PBRs near the southern San Andreas fault. In early 2009, we collected additional samples to refine model dependent exposure ages of rocks at these sites, and to investigate activity of the Cleghorn fault at the critical Grass Valley site so that we can interpret results relative to ground motions from San Andreas and/or San Jacinto earthquakes.

2007- 2008 Pilot Study - Exposure Ages and Model Development

Cosmogenic radionuclide (CRN) exposure dating can be applied to constrain the age of formation of precariously balanced rocks (PBRs) (Perg et al., 2007; Grant Ludwig et al., 2007), but to interpret nuclide abundance requires knowledge of the geomorphic history of the rock. Cosmogenic ^{10}Be concentrations are complicated by (1) soil erosion/exhumation events, (2) inheritance (subsurface production), and (3) erosion of the rock/pedestal surface itself. Without, *a priori* knowledge of these variables, a single surface concentration will not yield a true exposure age. Since the geomorphic history and exhumation rate of the rock is also relevant to determining the length of time that the rock has been precariously balanced, the challenge in dating PBRs is similar to the "Chicken and Egg" provenance problem.

In our pilot study (Rood et al., 2008; Schlom et al., 2008; Anooshepoor et al., 2008), we have addressed this problem through targeted sampling of the pedestal and base on selected rocks at selected sites and development of a suite of models for calculation of preliminary ages. In our proposed work, we will collect samples of rocks and pedestals at multiple heights, measure the cosmogenic ^{10}Be, and develop a numerical model that predicts ^{10}Be profiles for a given different (1) exhumation rate and (2) exposure time. By comparing the forward model and observed concentrations, we can find the best fit, evaluate the geomorphic formation model, and interpret an exposure age with greater confidence.

Figure 1 – Selected PBR locations and sites in southern California overlaid on the 2% PE in 50 years 2008 National Seismic Hazard Map for PGA. In our 2007 Pilot Study we sampled rocks at Beaumont South, Grass Valley, Lovejoy Buttes and Pacifico for constraining hazard along the southern San Andreas (SA) and northern San Jacinto (SJ) faults. The Grass Valley site is U<U 1 km from the Cleghorn fault. The Cleghorn causes a notable "blip" in the hazard near the SA – SJ

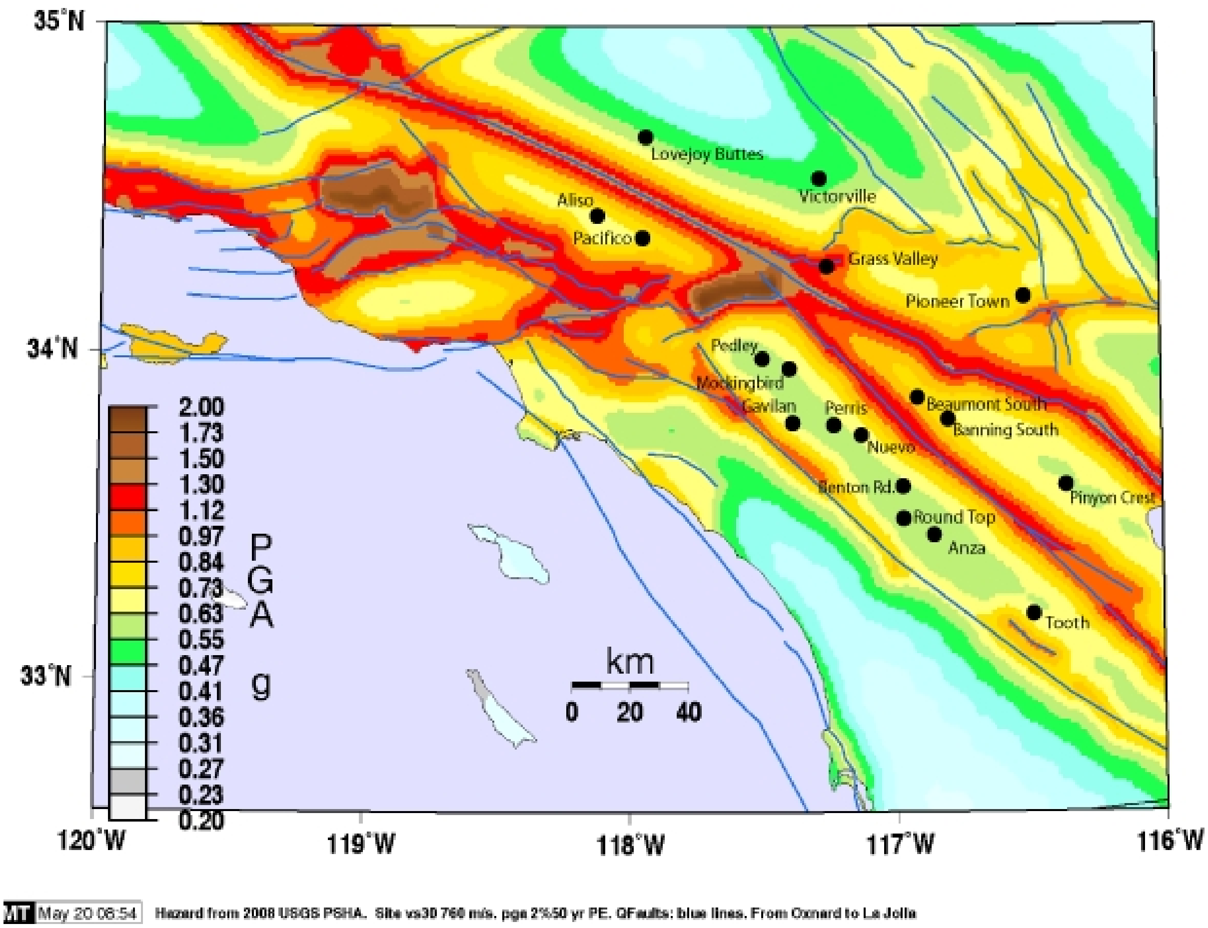


Figure 2 – (left to right) Rocks sampled at Lovejoy Buttes, Pacifico, Grass Valley and Beaumont South for 2007-2008 pilot study (Rood et al., 2008).

Our pilot dataset includes results from 10 samples from 6 PBRs at four sites (see Figures 1 and 2) spanning 110-km of the San Andreas Fault (SAF) in southern California. Apparent exposure ages range from ~50 ky to ~10 ky (model ages from individual samples calculated with zero erosion, no inheritance, and corrected for shielding). Pedestal samples consistently yielded younger apparent ages than the associated PBR, which confirms that exhumation history is important.

To better understand this exhumation history, we (Dylan Rood) developed a numerical model that uses known production equations (Gosse and Phillips, 2001; Balco et al., in press) to solve for ^{10}Be concentration as a function of depth, N(Z), where E_B is the exhumation rate before top of rock emerges (i.e. soil erosion rate), E_A is the exhumation rate after top of rock emerges, and T_{EXP} is the exposure time. Our model results show that different E_B/E_A yield different N(Z), the sign (positive, negative, or zero) of the profile's curvature value gives important information about the geomorphic exposure scenario (Fig. 3), and a minimum of three samples are necessary to define the curvature. For example, if $E_A > E_B$ (i.e. the PBR is exhumed rapidly relative to the previous soil erosion rate), then samples taken at various heights/depths on the PBR should fit an exponential function with a positive curvature (Scenario 1, Fig. 3). Also, model results show that the curvature of the ^{10}Be profile should provide predictions of the soil erosion rates, which span several orders of magnitude (Fig. 3). Thus, our modeling shows that by collecting samples that (1) define detailed ^{10}Be profiles on a PBR (2) estimate soil erosion rates, we can test different geomorphic exposure models and refine the exposure age.

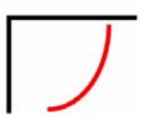
Scenario	E_A (m/Myr)	E_B (m/Myr)	T_{EXP} (yr)
1 FAST EXHUMATION ($E_A > E_B$)  Curvature = max +	2000	32	22000
2 EQUAL EXHUMATION RATES ($E_A = E_B$)  Curvature = 0	50	50	31000
3 SLOW EXHUMATION ($E_A < E_B$)  Curvature = max -	15	500	46000

Fig. 3 *(left). Model ^{10}Be profiles for different exposure scenarios, erosion rates, and exposure times. In profiles (red), x-axes are ^{10}Be concentration (N) and y-axes are depth/height (Z). Note curvature and magnitude of erosion rate differences that can be used to test geomorphic models and refine exposure times.*

If the PBR is exhumed quickly (e.g. E_A = 2000 m/Myr, Scenario 1, Fig. 3), then:

$$N(Z) = N_{EXP} + N_{INH}\, e^{-Z/L}$$

Here N_{EXP} is the nuclides produced since exhumation, N_{INH} is the nuclides inherited from subsurface production, Z is the depth/height, and L is the attenuation length. This equation is a constant plus an exponential; thus, with two samples we have two equations and two unknowns and can solve directly for N_{EXP}, which we can interpret as a true exposure age.

Interestingly, a parallel study of varnish microlamination (VML) development near Lovejoy Buttes suggests that E_A ~ 1000 m/Myr for one Lovejoy PBR. If we assume this rate of exposure, we can use the above equation to solve for N_{EXP} and can calculate exposure times on the 4 PBRs for which we have a profile with two samples. This calculation yields model ages that are 23-16 ka (Table 1), which are consistent with the available VML dates (minimum ages > 11-23 ka).

Table 1. Model ages for PBRs using rapid exhumation model.

PRECARIOUSLY BALANCED ROCKS ALONG THE SAN ANDREAS FAULT (FAST EXHUMATION MODEL)

Sample location**	Exposure Age (kyr)***	Internal Uncertainty (kyr)
BS1	23	1.2
GV2	16	0.8
LJ1	16	0.8
PC1	19	1

** Sites: BS=Beaumont south; GV=Grass Valley; LJ=Lovejoy Buttes; PC=Pacifico Summit.
*** Be-10 model ages calculated with zero rock erosion and corrected for shielding.

The results of our pilot study yield exposure ages that correspond with marine isotope stage (MIS) 2 (Fig. 4). We hypothesize that these results imply a causal relationship between climate cycles and PBR formation. For example, the Last Glacial Maximum (LGM) may have increased soil erosion rates, which rapidly exhumed these PBRs. This may be consistent with paleoclimate records from the Mojave Desert and Death Valley, which indicate a LGM climate with greater moisture availability and maximum lake high stands (Spaulding & Graumlich, 1986; Li et al., 1996; Anderson & Wells, 2003; Enzel et al., 2003; Yang et al., 2005). *We suggest that this indicates a climatic control on PBR exhumation, which we would like to test with future work.*

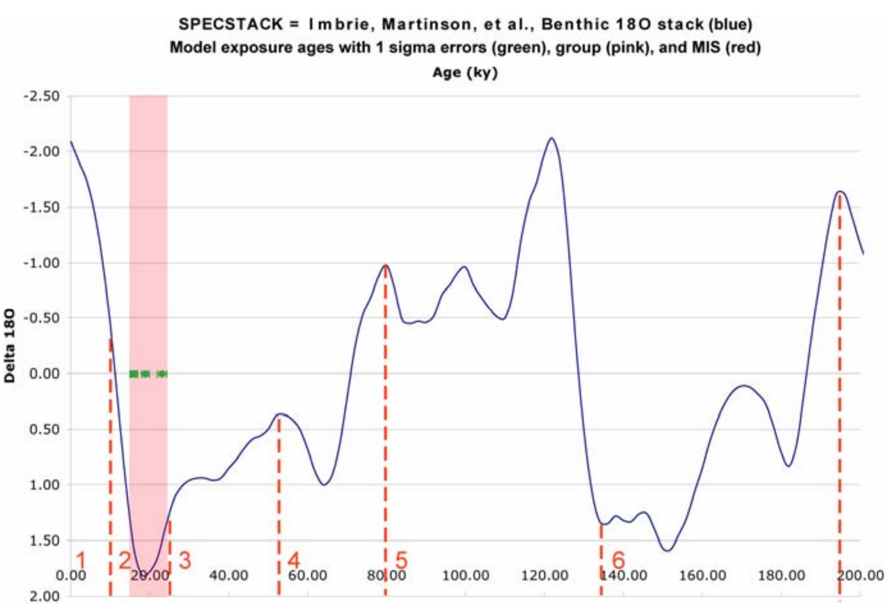


Fig. 4 (left). Marine delta P^{18P}O curve labeled with marine isotope stages 1 through 6. Note model exposure ages cluster within MIS 2 during the Last Glacial Maximum, possibly indicating a climatic control on PBR exhumation.

References (funded by**

this project)

Anderson, D.E., Wells, S.G., 2003. Latest Pleistocene lake highstands in Death Valley, California. Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts. Geological Society of America, Boulder, CO, pp. 115–128.

Anooshepoor, R., Purvance, M. D. and Brune, J. N. (2008). Field-testing precariously balanced rocks in the vicinity of San Bernardino, California: Seismic hazard ramifications, Southern California Earthquake Center 2008 Annual Meeting, Proceedings and Abstracts, v. XVIII, p. 100.

Balco, G., Stone, J., Lifton, N. and T. Dunai, 2007, in press. A simple, internally consistent, and easily accessible means of calculating surface exposure ages and erosion rates from Be-10 and Al-26 measurements. Quaternary Geochronology.

Bierman, P.R., and Steig, E., 1996, Estimating rates of denudation and sediment transport using cosmogenic isotope abundances in sediment: Earth Surface Processes and Landforms, v. 21, p. 125-139.

Brown, E.T., Stallard, R.F., Larsen, M.C., Raisbeck, G.M., and Yiou, F., 1995, Denudation rates determined from the accumulation of in situ-produced ^{10}Be in the Luquillo Experimental Forest, Puerto Rico: Earth and Planetary Science Letters, v. 129, p. 193-202.

Enzel, Y., Wells, S.G., Lancaster, N. (Eds.), 2003. Late Pleistocene Lakes along the Mojave River, Southeast California. Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts. Geological Society of America, Boulder, CO, pp. 61–77.

Frankel, A., M.D. Petersen, C.S. Mueller, K.M. Haller, R.L. Wheeler, E.V. Leyendecker, R.L. Wesson, S.C. Harmsen, C.H. Cramer, D.M. Perkins, and K.S. Rukstales (2002). Seismic hazard maps for the conterminous United States, Map C - Horizontal Peak Acceleration with 2% probability of exceedence in 50 years, *U.S. Geol. Surv. Open-File Rep.* 02-420-C (http://eqhazmaps.usgs.gov/).

Gosse, J.C., and Phillips, F.M., 2001, Terrestrial in situ cosmogenic nuclides; theory and application: Quaternary Science Reviews, v. 20, p. 1475-1560.

Granger, D.E., Kirchner, J.W., and Finkel, R., 1996, Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediments: Journal of Geology, v. 104, p. 249-257.

**Grant Ludwig, L., K. Kendrick, L. Perg, J.N. Brune, M.D. Purvance, A. Anooshehpoor, S. Akciz, and D.Weiser (2007). Preliminary Sample Collection and Methodology for Constraining Age of Precariously Balanced Rocks (PBR), Proceedings 2007 SCEC Conference, Palm Springs, Ca, Sept. 9-12.

Heimsath, A.M., Chappell, J.M.A., Dietrich, W.E., Nishiizumi, K. and Finkel, R.C., 2001. Late Quaternary erosion in southeastern Australia: a field example using cosmogenic nuclides. Quaternary International, 83-85:169-185.

Li, J., Lowenstein, T.K., Brown, C.B., Ku, T.-L., Luo, S., 1996. A 100 ka record of water tables and paleoclimates from salt cores Death Valley, California. Palaeogeography, Palaeoclimatology, Palaeoecology 123, 179–203.

**Perg, L., L. Grant Ludwig, K. Kendrick, J.N. Brune, M.D. Purvance, R. Anooshehpoor, S. Akciz and D. Weiser. Precariously Balanced Rocks (PBR) Surface Exposure History, Constrained by In-Situ Terrestrial Cosmogenic Nuclides (TCNs), Proceedings 2007 SCEC Conference, Palm Springs, Ca, Sept. 9-12.

Riebe, C.S., Kirchner, J.W., and Granger, D.E., 2001, Quantifying quartz enrichment and its consequences for cosmogenic measurements of erosion rates from alluvial sediment and regolith: Geomorphology, v. 40, p. 15-19.

**Rood, D., Brune, J., Kendrick, K., Purvance, M., Anooshepoor, R., Grant Ludwig, L. and Balco, G. (2008). “How do we date a PBR?: Testing geomorphic models using surface exposure dating and numerical methods”, presentation at the Southern California Earthquake Center 2008 Annual Meeting Extreme Ground Motion Workshop, Sept. 7, 2008.

**Schlom, T. M., Grant Ludwig, L. B., Kendrick, K. J., Brune, J. N., Purvance, M. D., Rood, D. H. and Anooshepoor, R. (2008).An initial study of precariously-balanced rocks at the Grass Valley site, and their relevance to Quaternary faults in an near the San Bernardino Mountains, CA, Southern California Earthquake Center 2008 Annual Meeting, Proceedings and Abstracts, v. XVIII, p. 103.

Spaulding, W.G., Graumlich, L.J., 1986. The last pluvial climatic episodes in the deserts of southwestern North America. Nature 320 (6061), 441–444.

Yang, W., Lowenstein, T.K., Krouse, H.R., Spencer, R.J., Ku, T.-L., 2005. A 200,000-year d18O record of closed-basin lacustrine calcite, Death Valley, California. Chemical Geology 216, 99–111.