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SELECTION AND DOCUMENTATION OF PRECARIOUSLY BALANCED ROCKS IN THE VICINITY OF LOS ALAMOS NATIONAL LABORATORY FOR DYNAMIC TESTING BY THE UNIVERSITY OF TEXAS, FY14

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Introduction

Precariously balanced rocks (PBRs), also known as hoodoos, are boulders perched atop rock pedestals that appear to be unstable with respect to ground accelerations (Figure 1). A detailed analysis of these PBRs, including location, formation history, fragility, material properties, and age, may support the upcoming update to the Los Alamos National Laboratory (LANL) Probabilistic Seismic Hazards Assessment (PSHA) by providing geologic constraints for hazard evaluations. To be useful constraints, a complete characterization of PBRs located near the Pajarito fault system (PFS) will be required, including cosmogenic and radiocarbon age-dating to determine the location, formation age, and relative long-term stability of these features. Additionally, information about the surface and sub-surface geology as well as geophysical characteristics may be needed in order to determine specific seismic site effects.

This scope of work contains a summary of tasks that were completed during FY14, including a literature review, GIS mapping to locate PBRs, and vibroseis experiments performed in conjunction with the University of Texas.

Figure 1. Precarious rocks in Pueblo Canyon, photographed in 2013.

Literature Review

A thorough literature review and characterization of the geology is essential to understand how PBRs can possibly be used to constrain estimates of peak ground motion based on the paleoseismic history of the PFS. Much depends on the PFS's relationship to the formation, location, and viability of PBRs. Some of the pertinent references are summarized below in order of oldest to most recent and demonstrate an evolution of understanding of PBRs; see the appendix for additional references.

Brune (1996) performed some of the initial PBRs studies and their relationship to ground-motion in southern California. As suggested by this study, groups of PBRs evolve naturally unless shaken down by earthquakes, and these PBRs may provide a direct indication of past ground shaking. While the time scale of evolution is currently unknown, Brune hypothesized that PBRs form and stabilize within a few thousand years. The Victorville zone, a small area in southern California located approximately 30 km from the San Andreas Fault, contains numerous PBRs and is the primary study area. In this region, the presence of rock varnish suggests that the PBRs have been in their current (i.e. unstable) position for a minimum of thousands of years. Several of the PBRs in this area can be toppled with relatively small hand forces corresponding to ground accelerations of only 0.1*g*–0.3*g*, despite evidence for large events during the Holocene, i.e. events thought to be large enough to topple these PBRs.

Building off of Brune (1996), Brune et al. (1996) broadened the study area to central and southern California, extending from the California-Mexico border in the south to Fresno in the north, and found that PBRs are found only in relatively arid regions and predominantly on outcrops of hard, weather-resistant rocks such as granites, tuffs and other volcanics, and strong sandstones. Heavy rainfall most likely destroys PBRs in a relatively short geologic time. The authors noted that the time scale of evolution and stability is on the order of thousands of years, but cited the lack of precarious rocks in glaciated regions as evidence that the average formation time might be more than 10,000 years. Lastly, Brune et al. (1996) noted that a common situation is to find precarious rocks near the bottom of a canyon, but not on the higher ridges above, even though the outcrops are similar. Possible explanations for this are that rapid erosion near the canyon bottom has exposed precarious rocks since the last major ground-shaking event, or that strong ground motion in the bottom of canyons is either attenuated or much lower than that on ridges.

Bell et al. (1998) contains some of the first research efforts to date PBRs using ^{36}Cl cosmogenic dating and varnish microlamination (VML) dating as outlined by Dorn (1990); Liu (1994); Cremaschi (1996); and Liu and Dorn (1996). Dates were obtained for precarious rocks in hills and pediments near Victorville and Jacumba, CA, as well as volcanic tuff cliffs at Yucca Mountain, NV. VML dating correlates manganese-rich layers with episodes of humid climatic conditions and manganese-poor layers with episodes of arid climatic events; these results allow correlation with climatic events rather than distinct age-dating results. Microlamination dating results suggest that the varnish has undergone at least one wet climatic cycle, i.e. the Younger Dryas event, which represents a minimum age of 10.5 ka. VML dates for the California locations ranged from 10.5 to 21 ka; VML dates for the Nevada locations ranged from 10.5 to 14.5 ka, although some rocks may be slightly older (21 to 27 ka) based on the presence of an additional microlamination layering unit. Cosmogenic dates for the California locations ranged from 15 to 61 ka, assuming a negligible rate of erosion. The older cosmogenic dates are attributed to inherited ^{36}Cl, resulting in higher concentrations and therefore an older age.

After introducing the idea in Brune (1996a), Brune (2000) explored in further detail the link between PBRs and evidence for low ground shaking on the footwall of major normal faults. Work performed by Brune (1996), Shi et al. (1997), Ogelsby et al. (1998), Brune and Anooshehpoor (1999), and Shi (1999) showed that physical and numerical models of normal faults indicate that the footwall has relatively low ground motions compared to similar strike-slip ruptures; these ground motions were estimated at 1/5 to 1/10 of those for strike-slip faulting. In many places, particularly in California and Nevada, PBRs extend nearly to the fault trace on the footwall side, and oftentimes they are located close to faults that are known or believed to have had major earthquakes in the Holocene. The young dates of earthquakes in these two regions make it almost certain that the PBRs from this particular study survived ground motion during large earthquakes.

Additional studies regarding ground motion can be found in Seeber et al. (2000). This study recorded a M7.2 earthquake in a step-over basin near the Sea of Marmara, Turkey. A site only about 100m from a step-over normal fault had almost 2m of displacement, but the recorded ground acceleration was only about 0.1*g*. This study strongly supports the hypothesis that the footwall of normal faults can have very low ground accelerations.

In an attempt to further constrain the ages and formation history of PBRs, Stirling and Anooshehpoor (2006) studied PBRs in New Zealand and used ^{10}Be cosmogenic dating techniques to date the pedestal beneath PBRs as close as possible to the rocking point of the caprock. In this manner, the authors were able to predict a date that was as close as possible to the time that the PBR achieved its present geometry. Dates of 40 to 77 ka were obtained, within about 4 ka of certainty. The fault that is located closest to these PBRs has experienced at least four surface ruptures in the last 24 ka, a time span only about half that of the age of the PBRs; this suggests that topographic effects are poorly understood as they relate to potential stabilization of PBRs. Additional dating efforts were undertaken by Stirling et al. (2008). The authors cosmogenically dated surfaces across a single PBR as well as buried soils at the base of PBRs. Cosmogenic results showed that the top of the PBR was 76 ka, the pedestal is around 40 ka, and the base is 28 ka. Therefore, the PBR was formed over a 50,000 year period.

Some of the most recent dating efforts have been done by Balco et al. (2011) on PBRs located in Southern California. While cosmogenic dating was used in this study, it was noted that cosmogenic dating can be extremely complicated when applied to PBRs. This is due to the fact that nuclide production occurs throughout the exhumation of the PBR, so the apparent exposure age exceeds the time the rock has been actually been precariously balanced. In addition, if a PBR was exhumed or formed very slowly, many parts of its surface could have been exposed for a long time before the rock actually became fragile. Multiple equations are presented in order to determine the exposure age of PBRs, and estimated ages at 18,5 ka ± 2.0 ka, which is consistent with other estimates of PBR ages.

In summary, extensive work on PBRs has taken place in both California and Nevada. Many of these studies have estimated that PBRs could topple at ground accelerations as low as 0.1*g*–0.3*g*, suggesting that the presence of PBRs indicates that either (1) no strong ground motions have occurred in a particular zone since the time that the rocks have become precariously balanced (Brune et al., 1996), or (2) ground motion in the vicinity of PBRs is somehow attenuated (Brune, 1996). However, more recent work has demonstrated that the footwall of normal faults experiences significantly less ground motion when compared to similar strike-slip ruptures. These lower ground motion values might help explain the presence of PBRs so close to projections of mapped faults, as is the case in the Los Alamos Townsite;

alternatively, the PBRs have formed more recently than the last significantly large magnitude (M>6) earthquake that has occurred on the PFS and therefore have not experienced any significant ground motion. Additional data useful to resolve issues presented by examination of PBR literature could include:

- Information regarding ground motion through volcanic rocks, garnered from vibroseis or other seismic experiments
- Borehole and/or drilling information regarding the subsurface geology in the areas between faults and PBRs locations
- Where available, rock properties of each unit found in the subsurface

GIS Mapping

Potential "precarious geology" points were identified by LANL GIS analysts performing visual observation of high-resolution color orthophotographs (Figure 2). Photos flown in early 2011 are the primary identification source for these features, while photos flown in 2008 and 2005 were used for point verification where identification was in question. Since precarious formations tend to be fairly narrow vertical spires with little cross section, shadows that these features cast on the surrounding landscape were used for PBR identification. This is possible because aerial photography is typically flown early in the morning, resulting in long shadows of features being cast in a westerly direction.

In the vicinity of Los Alamos, precarious formations are known to exist in two geologic media: (1) softer units of Bandelier Tuff, dominantly the Otowi Member, and (2) the Puye Formation. In some locations, these precarious formations have caprock boulders of variable lithology balancing atop a pedestal. Under ideal circumstances, these caprock boulders can be seen in the shadows cast by the identified features. The most identified precarious formations exist outside of the graben formed by the east-dipping Pajarito fault and the west-dipping Rendija Canyon fault. Most of these features appear to be on the footwall of the Rendija Canyon fault, well outboard of the main Pajarito fault. PBRs that were tested by UT are also shown in Figure 2.

Vibroseis Truck Experiments

In late summer of 2014, UT arrived at LANL with two vibroseis trucks for a number of seismic experiments. During this time, three hoodoos were instrumented for a detailed analysis of ground motion response to various geologic units and a better understanding of approximate ground motion required to topple caprocks (Figure 2).

One hoodoo was instrumented in Rendija Canyon but was not subjected to vibroseis truck experiments due to infrastructure concerns (Figure 3). Rather, this location was analyzed using hand-held hammers for a seismic source. This hoodoo was formed in the Puye Formation. Two hoodoos were instrumented in Pueblo Canyon and were subjected to hammer and vibroseis truck excitations (Figures 4 and 5). Both of the hoodoos in Pueblo Canyon are made up of the Otowi Member of the Bandelier Tuff at the base, and a basaltic caprock of the Cerro Toledo member. Figure 5 also has almost 2m of alluvium between the base and caprock. Results of the vibroseis experiments will likely be made available during FY15.

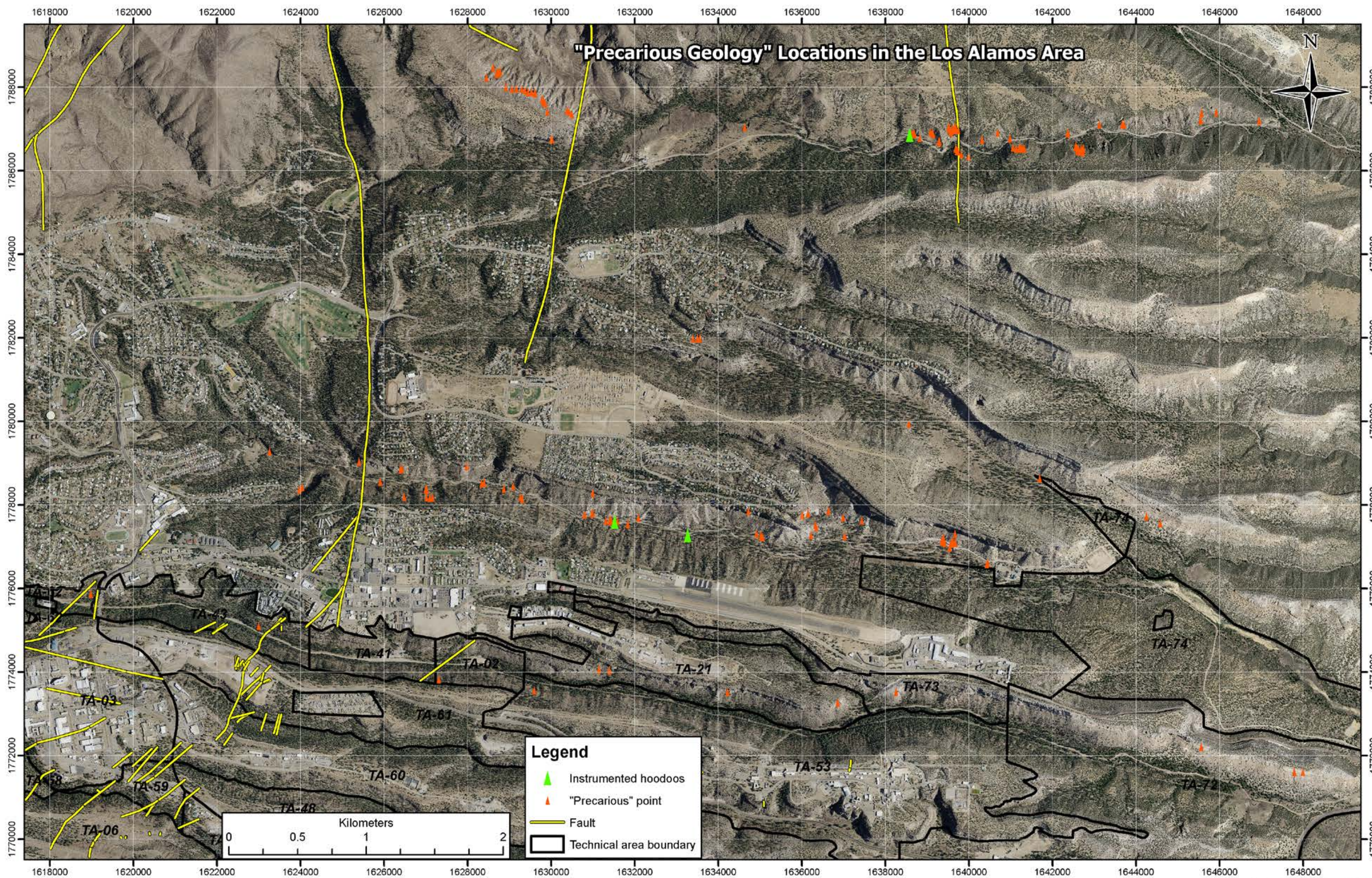

Figure 2. Precariously balanced rocks in the Los Alamos Area. Green triangles indicate the three hoodoos that were instrumented during the UT field campaign during FY14. Mapped faults of the Pajarito fault system shown in yellow.

Figure 3. Hoodoo in Rendija Canyon.

Figure 4. Hoodoo in Pueblo Canyon. The hoodoo that was instrumented is in the foreground.

Figure 5. Hoodoo in Pueblo Canyon. Note the nonconformable contact between the Otowi Member (whitish base) and the older alluvial package situated beneath the caprock.

Additional Field and Laboratory Tasks to Perform Further Geologic Investigations of the Hoodoos

The following tasks are proposed to be performed in future years according to the level of funding provided to answer critical questions regarding the age and properties of PBRs around Los Alamos.

[1] Geologic fault mapping to supplement the existing maps of the PFS to help assess the numerous localized hanging walls and footwalls of the fault system and the role that fault splays play in ground motion. Additional field mapping will be performed as needed to supplement the current knowledge of surficial and subsurface geology.

[2] Support PBR integrity modeling work, scheduled to be performed by E. MacFarlane, by providing data for models

[3] Choose up to 10 PBRs for expert evaluation and potential cosmogenic age and rock varnish dating sampling (if applicable). Up to an additional 4 sites will be identified where PBRs are believed to have fallen from their pedestal. Locations will include a range of PBRs, from very near to the fault to very far away.

Ideally, a suite of samples will be collected at each PBR: sample(s) from various heights on the pedestal rock (ground, middle, and top), and sample(s) from the cap rock (base and top). This will potentially allow for a reconstruction of the exhumation history. 3 samples should be collected from each pedestal rock that no longer contains a cap rock (base, top of rock, and top of pedestal sediment, if it still remains). Sampling the top of the pedestal and any remaining cementing sediment will provide an estimate of when the cap rock toppled. However, based on expert evaluation, fewer total samples may be required to make interpretations.

[4] Determine the best age-dating methods for the PBRs, which are typically dated using VML and cosmogenic ^{26}Al and ^{10}Be. PBRs will need to be assessed for the presence of rock varnish in order to determine if varnish microlamination dating is viable. In addition, pedestal and caprocks will be assessed for the presence of quartz and sanidine in order to allow for dating via ^{26}Al or ^{10}Be methods. Cost estimates of each dating method will also be obtained.

[5] Radiocarbon dating will be used to date soil samples and incised terraces. In cases where the cap rock has failed but the boulders are still lying near the pedestal rock, soil samples will be collected from beneath the boulders that have failed. These samples will be dated in order to provide a maximum estimate of time that the PBR was last modified in a significant way. Radiocarbon dating will also be used to constrain the age of incised terraces in the canyons in order to calculate the approximate pedestal height at the time of the most recent event on the PFS, and in turn infer the time-constrained stability of the PBRs.

Following extensive data collection and age-date analyses, the following items will be integrated into a comprehensive final report:

[1] Assessment of when and how the PBRs formed, using age dates, weathering and erosional history, and other pertinent information

[2] Results of modeling work regarding relatively instability of PBRs

[3] Refinement of a map of the PBR locations throughout LANL and Los Alamos Townsite and their proximity to the PFS

[4] Probabilistic and deterministic ground motion prediction estimates of ground motion at PBR sites, in order to estimate the ground motions that the PBRs near the PFS have experienced

[5] Incorporation of information gained from the UT seismic experiments on PBRs in Pueblo Canyon, and engineering estimates of PBR fragilities to assess ground motion hazard constraints and their uncertainties.

References

Anderson, J.G. and Brune, J.N., 1999, Methodology for using precarious rocks in Nevada to test seismic hazard models, Bulletin of Seismological Society of America, v. 89, no. 2, pp. 456-467.

Balco, G., Purvance, M.D., and Rood, D.H., 2011, Exposure dating of precariously balanced rocks, Quaternary Geochronology, v. 6, pp. 295-303.

Bell, J.W., Brune, J.N., Liu, T., Zreda, M., and Yount, J.C., 1998, Dating precariously balanced rocks in seismically active parts of California and Nevada, Geology, v. 26, pp. 495-498.

Brune, J.N., 1996, Precariously balanced rocks and ground-motion maps for Southern California, Bulletin of the Seismological Society of America, v. 86, no. 1A, pp. 43-54.

Brune, J.N., Bell, J.W., and Anooshehpoor, A., 1996, Precariously balanced rocks and seismic risk, Endeavour, v. 20, no. 4, pp. 168-172.

Brune, J.N., 2000, Precarious rock evidence for low ground shaking on the footwall of major normal faults, Bulletin of the Seismological Society of America, v. 90, no. 4, pp. 1107-1112.

Cremaschi, M., 1196, The rock varnish in Messak Settafet (Fezzan, Libyan Sahara), age, archaeological context, and paleoenvironmental implication, Geoarchaeology, v. 11, pp. 393-421.

Dorn, R.I., 1990, Quaternary alkalinity fluctuations recorded in rock varnish microlaminations, Paleogeography, Paleoclimatology, and Paleoecology, v. 76, pp. 291-310.

Haddad, D.E., 2009, Estimating the geometrical parameters of precariously balanced rocks from unconstrained digital photographs, Model *PBR_slenderness_DH_v1_0*.

Liu, T., 1994, Visual microlaminations in rock varnish: A new paleoenvironmental and geomorphic tool in drylands, Ph.D. thesis, Tempe, Arizona State University, 173 pp.

Liu, T., and Dorn, R.I., 1996, Understanding the spatial variability of environmental change in drylands with rock varnish microlaminations, Association of American Geographers Annals, v. 86, pp. 187-212.

Seeber, L., Armbruster, J.G., Ozer, N., Aktar, M., Baris, S., Okaya, D., Ben-Zion, Y., and Field, N., 2000, The 1999 earthquake sequence along the North Anatolian transform at the juncture between two main fault ruptures, The 1999 Izmit and Duzce Earthquakes: Preliminary Results, pp. 209-223.

Stirling, M.W. and Anooshehpoor, R., 2006, Constraints on Probabilistic Seismic-Hazard Models from Unstable Landform Features in New Zealand, Bulletin of the Seismological Society of America, v. 96, no. 2, pp. 404-414.

Additional References on Geologic Investigations of Precarious Rocks

Anderson, J.G. and Brune, J.N., 1999, Methodology for Using Precarious Rocks in Nevada to Test Seismic Hazard Models, Bulletin of the Seismological Society of America, v. 89, no. 2, pp. 456-467.

Anooshehpoor, A., Brune, J.N., and Von Seggern, D.H., 2002, Constraints on Ground Motion at Yucca Mountain Provided by Precarious Rocks, DOE Final Technical Report.

Anooshehpoor, A., Brune, J.N., and Zeng, Y., 2004, Methodology for Obtaining Constraints on Ground Motion from Precariously Balanced Rocks, Bulletin of the Seismological Society of America, v. 94, no. 1, pp. 285-303.

Brune, J.N., 2003, Precarious rock evidence for low near-source accelerations for trans-tensional strike-slip earthquakes, Physics of the Earth and Planetary Interiors, v. 137, pp. 229-239.

Brune, J.N., Anooshehpoor, A., Shi, B., and Zeng, Y., 2004, Precarious Rock and Overturned Transformer Evidence for Ground Shaking in the M_s 7.7 Kern County Earthquake: An Analog for Disastrous Shaking from a Major Thrust Fault in the Los Angeles Basin, Bulletin of the Seismological Society of America, v. 94, no. 6, pp. 1993-2003.

Haddad, D.E., 2009, Estimating the Geometrical Parameters of Precariously Balanced Rocks from Unconstrained Digital Photographs, Technical Report.

Haddad, D.E. and Arrowsmith, J.R., Geologic and Geomorphic Characterization of Precariously Balanced Rocks, Arizona Geological Society Contributed Report.

Purvance, M.D., Brune, J.N., Abrahamson, N.A., and Anderson, J.G., 2008a, Consistency of Precariously Balanced Rocks with Probabilistic Seismic Hazard Estimates in Southern California, Bulletin of the Seismological Society of America, v. 98, no. 6, pp. 2629-2640.

Purvance, M.D., Anooshehpoor, A., and Brune, J.N., 2008b, Freestanding block overturning fragilities: Numerical simulation and experimental validation, Earthquake Engineering and Structural Dynamics, v. 37, pp. 791-808.

Rood, D., Balco, G., Purvance, M., Anooshehpoor, A., Brune, J., Grant-Ludwig, L., and Kendrick, K., How do we date a PBR?: A robust method using ^{10}Be surface exposure dating with numerical models, AGU abstract.

Shi, B., Anooshehpoor, A., Zeng, Y., and Brune, J.N., 1996, Rocking and Overturning of Precariously Balanced Rocks by Earthquakes, Bulletin of the Seismological Society of America, v. 86, no. 5, pp. 1364-1371.

Stirling, M., Ledgerwood, J., Liu, T., and Apted, M., 2010, Age of Unstable Bedrock Landforms Southwest of Yucca Mountain, Nevada, and Implications for Past Ground Motions, Bulletin of the Seismological Society of America, v. 100, no. 1, pp. 74-86.