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### **Obtaining Age Control on Select Precariously Balanced Rocks in the Mojave via the Varnish Microlamination (VML) Method**

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#### **Introduction**

The methodology to constrain ground motion estimates via precariously balanced rocks (PBRs) has improved substantially over the past few years. These improvements include physics-based fragility estimates derived from overturning simulations using earthquake ground motions, refined field testing methods to account for rough basal contacts (Purvance et al. 2008a), and accurate PBR shape determination to assist in field testing and numerical modeling (Anooshehpour et al. 2007, Purvance et al. 2008b). Purvance et al. (2008b) further established quantitative methods to determine whether or not seismic hazard estimates are consistent or inconsistent with PBR fragilities. Thus the unexceeded ground motion constraints provided by PBRs can be used to directly test seismic hazard estimates. Purvance et al. (2008b) demonstrated that such efforts rely heavily on the PBR residence times (e.g., the time intervals over which the PBRs have been in their fragile configurations). Previously Bell et al. (1998) found that a number of PBRs in Southern Nevada and California have resided in their current positions for greater than 10,000 years via both varnish microlamination (VML) and terrestrial cosmogenic isotope age estimation methods. Rood et al. (2008) utilized  $^{10}\text{Be}$  to estimate residence times of a Mojave PBR in Southern California corroborating the Bell et al. (1998) findings. In order to further refine PBR residence time estimates for crucial PBRs, we proposed to focus VML studies on Mojave PBRs that provide strong unexceeded ground motion constraints due to their locations and fragile configurations. In late December, 2008, we collected > 30 VML at or adjacent to PBRs in the vicinity of the Mojave section of the San Andreas Fault. These samples are currently being processed with minimum surface exposure age dates expected prior to the 2009 Annual SCEC Meeting.

#### **VML Background**

Rock varnish is a slowly accumulating, (e.g., tens of microns per thousand years, Liu and Broecker 2000) surficial deposit composed primarily of manganese and iron oxides in combination with clay minerals. As reported in Fleisher et al. (1999), the abundance of anthropogenically produced isotopes ( $^{137}\text{Cs}$  and  $^{210}\text{Pb}$ ) found in varnish samples suggests that atmospheric dust contributes fundamentally to its creation. Perry and Adams (1978) first recognized that alternating layers of material (varnish microlaminations or VML) in ultrathin sections of varnish could be correlated with paleoclimatic events, providing a unique constraint on the subaerial exposure ages of the geomorphic features on which the varnish has been collecting. Broecker and Liu (2001)

report similarities in varnish microstratigraphies across the drylands of the western US, suggesting that indeed these layers correspond to large scale climate variations. Liu (2003) further refined the chronological sequence of varnish microstratigraphy in the western drylands through sequence reconstructions based on samples obtained from radiometrically dated features such as paleoshorelines, paleolandslides, fault scarps, alluvial-fan surfaces, and lava flows. Utilizing his new microstratigraphy map, Lui (2003) undertook a blind test and compared VML ages of lava flows with the  $^{36}\text{Cl}$  cosmogenic age dates obtained by Phillips (2003). The results of these completely blind tests demonstrated without a shadow of a doubt that exposure ages obtained via the VML method are nearly identical to cosmogenic  $^{36}\text{Cl}$  ages. In an editorial in *Geomorphology*, the editor Richard Marston states “Results of the blind test provide convincing evidence that varnish microstratigraphy is a valid dating tool to estimate surface exposure ages.” (Marston 2003). Lui and Broecker (2007a, 2007b, 2008a, and 2008b) continue to refine this methodology for more age resolution during the Holocene and developed further age correlated varnish microstratigraphic layering sequences into the late Quaternary.

It is important to understand that VML surface exposure estimates truly represent minimum exposure ages. For instance, a small amount of weathering may act to remove all traces of rock varnish, effectively resetting the VML clock. Thus the surface exposure ages provided by the VML methodology may be significantly less than surface exposure ages obtained from cosmogenic isotope analysis, for instance. Though this may be the case, such minimum exposure information may still be useful and utilized when comparing with seismic hazard estimates.

### **Sample Collection**

Figure 1 documents the locations where surface samples were collected for VML analysis. All of these sites lie within 35 km of the Mojave section of the San Andreas Fault. These represent hard rock sites composed of similar granitic outcrop with some variation in rock friability, composition, and competence. During this field excursion in December, 2008, numerous granitic PBRs and their pedestals in the region were examined for the presence of datable surficial varnish accumulation. Rock varnish is considered useful for surface exposure age dating when it produces pronounced stratigraphy in microbasins when viewed in ultrathin section. We found varnish with high probability of being useful for surface exposure age dating in perhaps up to 30-40% of PBRs in the region. “Dirty” varnish was present on the majority of PBRs investigated; this material is unfortunately not useful for surface exposure age dating due to the lack of varnish layering in the microbasins. Such varnish is readily identifiable from visual inspection with a hand lens as containing significant dirt and grime. According to Tanzhuo Liu, the VML expert, such dirty varnish indicates that the surface has been stable for greater than a few hundred years and perhaps up to a few thousand years but cannot be utilized for refined or defensible surface exposure age estimates. The field investigations also pointed out the fact that one must be very careful not to utilize varnish that may have been formed inside a crack. For instance, crack varnish may have developed in an environment that may be significantly wetter than an exposed surface, leading to systematic variations in varnish layering. Crack varnish is generally identifiable based on the local surface topography.

In order to constrain the surface exposure ages of PBRs where no useful varnish has been observed, we searched for datable material on adjacent rock surfaces in the vicinity below the bottom of the nearby PBR. Such samples place a constraint on the PBR surface exposure ages due to their close proximity and inferior positions.



Figure 1. Locations where samples have been obtained for VML analysis. All of these sites are within 35 km of the Mojave section of the San Andreas Fault. Samples were obtained on PBR pedestals or on adjacent rock surfaces that are below the PBR bases.

### Conclusions

In late December, 2008, numerous PBR sites have been visited and > 30 VML samples have been obtained for analysis. The results of these analyses will be available for documentation at the 2009 Annual SCEC Meeting.

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