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Age of Unstable Bedrock Landforms Southwest of Yucca Mountain, Nevada, and Implications for Past Ground Motions

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Abstract We determine minimum exposure ages for unstable outcrops at three sites in Amargosa Desert, southwestern Nevada, including a site at the southern end of Yucca Mountain. Varnish microlamination dating techniques provide minimum exposure ages of 12.5–36 k.y. for the unstable outcrops of welded tuff, including a 24 k.y. age for the south Yucca Mountain site. The youngest exposure age (12.5 k.y.) is found at the site located only 10 km from the Death Valley–Furnace Creek fault, suggesting outcrops may be more frequently modified when close to major active earthquake sources. A simplistic stability assessment of the south Yucca Mountain outcrops suggests peak ground accelerations (PGAs) may not have exceeded about $1g$ (uncertainty bounds 0.5–$2g$) in at least 24 k.y. A PGA of $1g$ is consistent with the predicted 24 k.y. return period PGAs from the near decade-old Yucca Mountain probabilistic seismic hazard (PSH) model, except for the ninety-fifth percentile and above. We gain confidence in our interpretations by additionally observing: (1) minimal damage to the south Yucca Mountain outcrops from a recent moderate earthquake that is estimated to have produced a PGA of less than $0.1g$ there (i.e., motions less than $0.5g$ do not significantly damage the outcrops); and (2) severe damage to similar volcanic outcrops associated with PGAs of the order 0.5–$1g$ near a nuclear blast site from the 1960s. These observations support our suggestion that PGAs greater than 0.5–$1g$ have not occurred at the south Yucca Mountain site for a time period of at least 24 k.y. Significant seismic events that substantially modify the outcrops and produce associated rubble fields may therefore occur on longer time scales.

Introduction

Over the past two decades there have been considerable efforts focused on developing methods to validate probabilistic seismic hazard (PSH) models for long return periods (i.e., of the order 10^4–10^6 yrs). Efforts initiated by Brune and Whitney (1992), and furthered by Brune (1996), Bell *et al.* (1998), and others, have sought to use fragile geomorphic features such as unstable cliff faces and precariously balanced rocks (PBRs) to place constraints on ground motions for long return periods. While PSH models constructed to provide ground-motion estimates for shorter return periods (e.g., 10^0–10^2 yrs) are able to be compared to historical earthquake records (e.g., Stirling and Petersen, 2006; Schorlemmer and Gerstenberger, 2007), no testing criteria are available for longer return periods. The most significant body of research focused on validating PSH models for long return periods is centered on the proposed Yucca Mountain high-level nuclear waste repository, where the mean estimates of peak ground acceleration (PGA) and peak ground velocity (PGV) are about $3g$ (g is the acceleration or force of gravity; 9.8 m/sec^2) and 300 cm/sec respectively, for the 10^6 yr return period (Stepp *et al.*, 2001). There is lack of confidence in the seismological community as to whether these ground-motion levels could be exceeded in the normal faulting environment of Yucca Mountain. Research funded by the U.S. Department of Energy has been focused on studying unstable ancient landforms such as PBRs and steep unstable cliff faces in an effort to provide validation criteria for the Yucca Mountain ground-motion estimates (e.g., Brune *et al.*, 2008; Purvance and Brune, 2008; Purvance *et al.*, 2008; Whitney *et al.*, 2008). In desert environments these landform features can be dated by cosmogenic techniques, and minimum surface exposure ages can be obtained from varnish microlamination (VML) techniques (the VML techniques provide an estimate of the surface age since the last surface spallation of rock from an outcrop surface; e.g., Liu and Broecker, 2007, 2008). There have also been some efforts to estimate the fragility of the landforms to strong ground motions at Yucca Mountain (e.g., Purvance *et al.*, 2008).

In this article we undertake the follow-up of the earlier studies of unstable outcrops in the vicinity of the proposed Yucca Mountain repository. Our study area is within Amargosa Desert, immediately southwest of the proposed

Yucca Mountain repository (Fig. 1), in which we seek to determine the age of unstable outcrops in the area and also consider their potential constraints on ground motions for long return periods. Our choice of sites is based on the presence of unstable outcrops of welded tuff similar to those of Yucca Mountain (Fig. 1), the close proximity to Yucca Mountain, and the easy access outside of the Nevada Test Site (NTS). Minimum surface exposure ages are estimated from VML dating, and first-order estimates of ground motions for major modification (destruction) of the outcrops are made from geotechnical relationships that correlate ground-motion levels to slope instability for a wide range of site geology and topography (e.g., Newmark, 1965; Jibson, 2007). We then compare these age and ground-motion constraints for the outcrops to the ground motions predicted from the original Stepp *et al.* (2001) Yucca Mountain model for return periods equivalent to the ages of the outcrops (methodology of Anderson and Brune, 1999). Lastly, historical analogues of outcrop damage associated with moderate versus strong ground motions are, respectively, obtained from (1) observations of outcrop damage associated with the 1992 *M* 5.6 Little Skull Mountain earthquake to the east of the study area and (2) outcrop damage at close distances to nuclear blasts. These efforts represent a follow-up to earlier studies conducted by Brune *et al.* (2003, 2005).

Methodology

We seek to determine the age and upper bounds on ground motions implied by the presence of unstable outcrops of welded volcanic tuff at our three sites. We define unstable outcrops as irregular cliffs with numerous open joints and teetering slabs and columns of rock (Fig. 2). If the age of unstable outcrop features are known for a site, and the threshold ground-motion level for major outcrop damage (i.e., destruction of all unstable features of the outcrop, rather than failure of just a few of them) is also known, then these data can be used to estimate ground-motion levels that have not been exceeded in the time span since the unstable outcrop formed.

Our work comprises selecting and sampling key sites to obtain minimum exposure age estimates for the outcrops from VML methods, followed by a first-order assessment of the fragility of the outcrops (i.e., the strength of shaking required for failure of the outcrops), and then comparison of these data and estimates to the predicted ground motions from the Stepp *et al.* (2001) Yucca Mountain PSH model. We follow the methodology of Anderson and Brune (1999) in making the comparison between outcrop data and PSH model in that the relevant ground motion from the PSH model has a return period equal to the age of the outcrops.

Study Sites and Sampling Strategy

Three sites were chosen for the study and are shown in Figure 1. The sites are all underlain by Miocene welded tuffs (e.g., Stuart and Carlson, 1977), as is the case at the proposed Yucca Mountain repository site. The morphology of the outcrops is similar to that of the area of the proposed repository site (an example of outcrop morphology is shown in

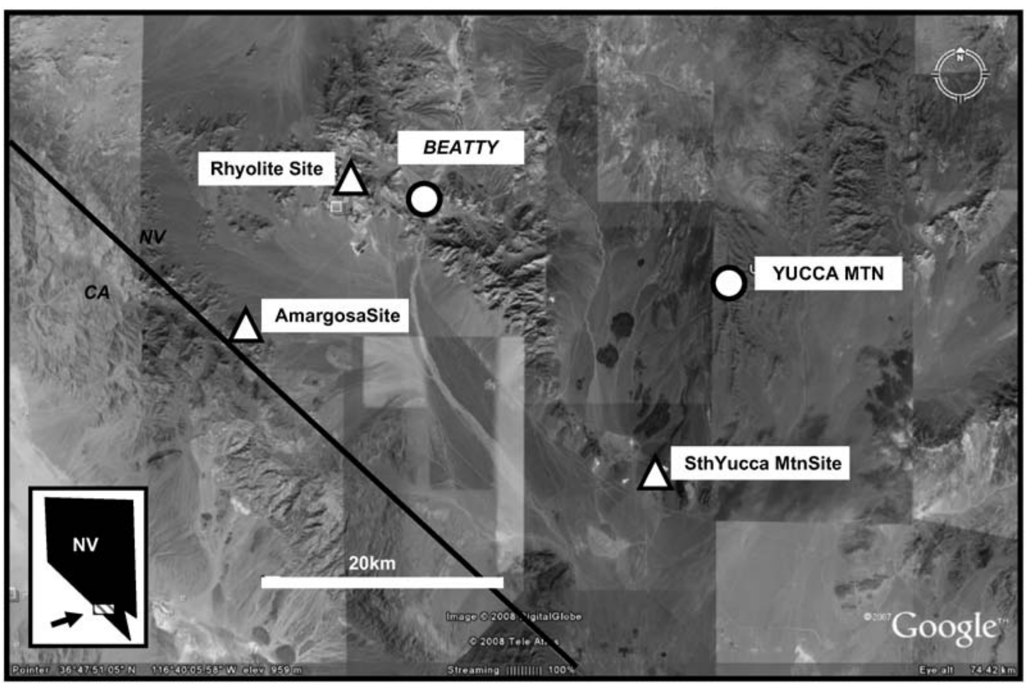

Figure 1. Google Earth image of the study area. Our study sites are marked with white triangles, along with the town of Beatty and the proposed Yucca Mountain repository site as white circles.

Figure 2. Typical unstable outcrop; this particular example being at the south end of Yucca Mountain and composed of vesicular welded tuff of Tertiary age. (The case for all of our sample sites.) A compass is in the center of the image for scale.

Fig. 2), especially the outcrops present on the steep west-facing side of Yucca Mountain. We wish to constrain an estimate of the time span that the outcrops have been in their present unstable morphology, or in other words, the time span of minimal modification. VML techniques provide minimum estimates of outcrop exposure age, given that previous studies have shown cosmogenic exposure ages to be greater than the VML ages for a given outcrop (e.g., Bell *et al.*, 1998). Spallation of the outcrop surfaces results in complete removal of the accumulated varnish, whereas cosmogenic exposure ages are not so sensitive to spallation. Our sampling strategy for dating of the outcrops is to obtain rock varnish samples that are representative of the outcrop as a whole (i.e., similar overall color, intensity of varnish development). A similar strategy is applied to samples taken from the tops of the boulders in the talus slopes below the outcrops. VML dates therefore provide minimum exposure age constraints for the outcrops and boulder fields as a whole, rather than for restricted areas of lighter colored surfaces that have experienced more recent spallation of Surficial rock. While cold Pleistocene climates would have resulted in much stronger weathering and changes to outcrop morphology, our sampling and dating strategy gives an estimate of the time span over which modification has been minimal.

The site descriptions are as follows:

1. South Yucca Mountain site: 36°41.1′/116°32.2′; located at the south end of the west-facing Yucca Mountain escarpment and in similar lithology to that of the proposed repository site (Fig. 3a). Lithophysal welded tuff is exposed as generally open jointed stable to unstable rock outcrops over much of the upper slopes and crest of the site. We plot the joint dips and dip directions and average outcrop slope and azimuth on a lower-hemisphere stereogram in Figure 3b. The joint orientations are such that the outcrop has readily developed an irregular morphology of unstable prismatic blocks that is typical of volcanic rocks in the Yucca Mountain area. The steep joint sets control the lateral extent of the prismatic blocks, and the subhorizontal joint set controls the vertical extent of the blocks. The latter joint set dips across, rather than into, the outcrop slope. Bouldery colluvial slopes are widespread beneath the slopes (Fig. 3a). The similarity of lithology to the actual proposed Yucca Mountain repository site is apparent on geological maps (the length of Yucca Mountain is underlain by Miocene welded tuffs of the Paintbrush and Crater Flat Groups; Potter *et al.*, 2002) and also from field inspection of the repository site by the lead author in 2006 and 2008 (photography was not permitted on the NTS). We therefore consider our south Yucca Mountain site to represent a close geological and geomorphic analogue to the proposed Yucca Mountain repository but conveniently located just outside of the NTS. A total of five VML samples were taken from unstable outcrops and also from boulders resting on the colluvial slopes beneath.
2. Rhyolite Ghost Town site: 36°54.6′/116°49.6′; hill immediately north of Rhyolite Ghost Town, and a few kilometers east of Beatty (Fig. 3c). The hill was chosen for its proximity to the proposed Yucca Mountain repository site (about 20 km to the north) and because of its reasonable similarity of geology and topography to that of the proposed repository site (Miocene welded tuff and same prismatic outcrop morphology as the south Yucca Mountain site). A total of three VML samples were taken from unstable outcrops of welded tuff and from boulders resting on the colluvial slopes below.
3. Amargosa Valley area site: 36°47.7′/116°55.5′; located in the hill country to the west of Amargosa Valley and east of Death Valley (Fig. 3d). This location was chosen as a comparative site to (1) and (2) to determine whether a close proximity to an active seismic source has any influence on outcrop surface age (the Death Valley–Furnace Creek fault [DVFCF] is only 10 km southwest of the site). The DVFCF contributes significantly to the PGV hazard at the 10^6 yr return period at the proposed Yucca Mountain repository in the Stepp *et al.* (2001) PSH model and represents the most active source in the region in terms of

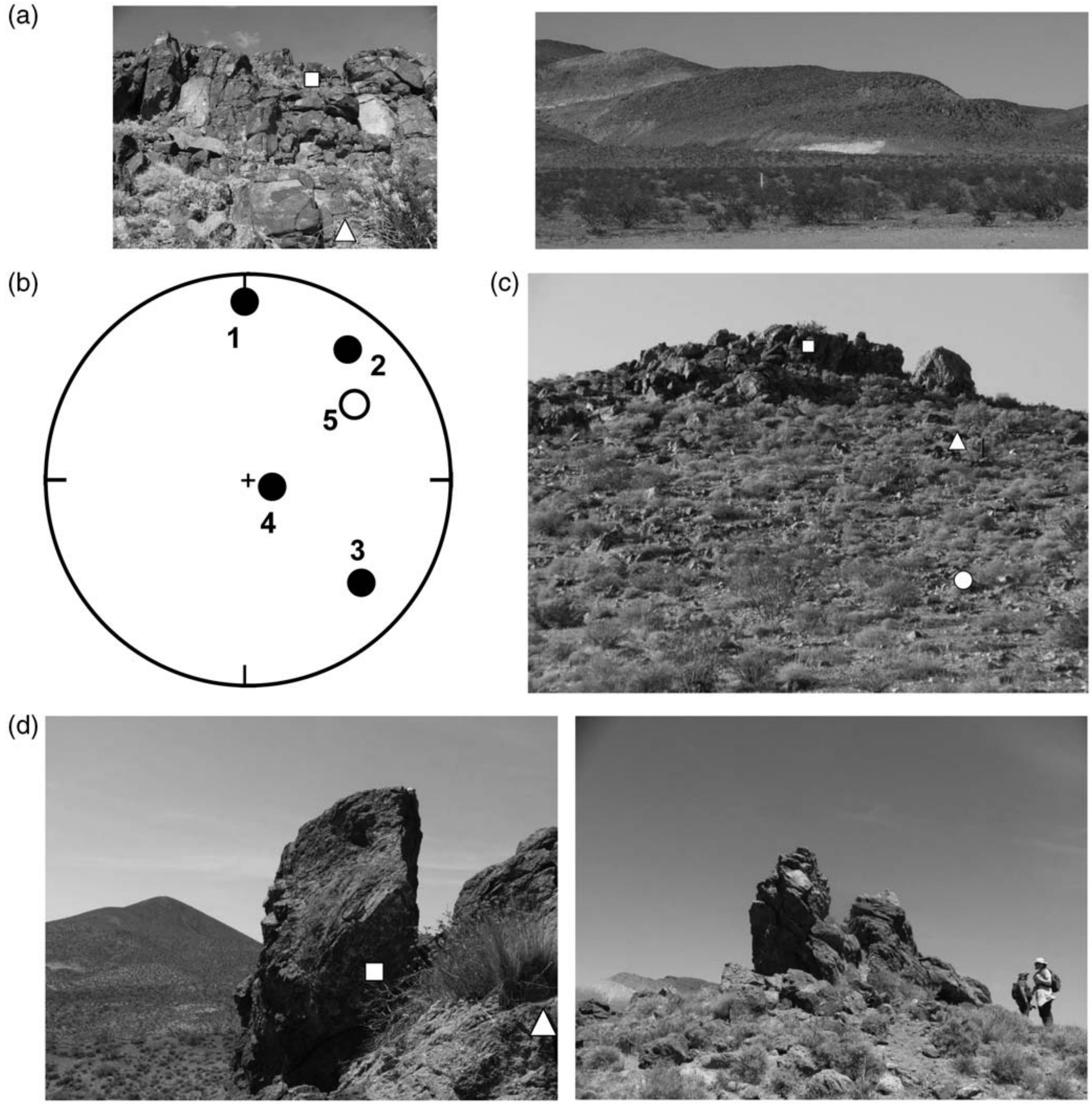

Figure 3. (a) Rock varnish sample locations at the south Yucca Mountain sample site. The topography and lithology (Topopah Springs tuff) are both similar to that observed in the vicinity of the Yucca Mountain proposed repository about 20 km to the north. VML dates of 24 k.y. have been gained for the outcrop faces (see the square on the image) and 24–39 k.y. for the boulders resting on the slopes immediately beneath the outcrops (triangle). The sample site is located above and to the right of the white slope in the lower image. (b) Lower-hemisphere, equal area stereogram showing the poles to the planes of the major open joint surfaces (solid circles) and average slope (open circle) of the south Yucca Mountain site. The three steeper joints (1–3), and one shallowly dipping joint (4; dip direction is slightly oblique to the outcrop face, 5), would allow the outcrop to readily fail in prismatic blocks if failure were to occur. Joint spacings are (1) 0.4–2 m, (2) 0.5–1 m, (3) 0.5–1.5 m, and (4) 1–2 m. (c) Rock varnish samples at the Rhyolite Ghost Town sample site. VML dates of 39 k.y. have been gained for the outcrop faces (square) and from 46 (triangle) to 60 k.y. (circle) for the boulders resting on the slopes beneath the outcrops (oldest VML dates near the base of the slope; see circle). (d) Rock varnish samples from the Amargosa sample site. VML dates of from 12.5 (square) to 24 k.y. (triangle) have been gained for the outcrop faces and 24 k.y. for the boulders resting on the slopes immediately beneath the outcrops.

magnitude and frequency of earthquakes. A total of two VML samples were taken from unstable outcrops and one from a boulder resting on the colluvial slopes beneath. Three samples of a pack rat midden built against the backwall of an overhang developed in coarse-grained, highly weathered tuff were also taken for radiocarbon dating. This particular midden showed that around 15 cm of bedrock spallation had occurred in the backwall and roof of the overhang since the midden was deposited (see the VML Results section). Dating the midden would allow a rate of bedrock erosion to be calculated, although recognizing that the soft, weathered, and coarsely crystalline nature of the rocks would prevent extrapolation of the erosion rate to (1), (2), and the rest of (3). No rock varnish was observed on the soft weathered rock surfaces.

VML Dating

Rock varnish is a slowly accreting (a few micrometers per thousand years; Liu and Broecker, 2000) dark coating on subaerially exposed rock surfaces in arid to semiarid deserts of the world. It consists of alternating Mn-rich and Mn-poor microlaminations that record paleoclimatic fluctuations (Dorn, 1990; Cremaschi, 1996; Broecker and Liu, 2001; Lee and Bland, 2003). Mn-rich layers, which appear black in varnish ultrathin sections under a microscope with transmitted light, are formed in a relatively wet climate; Mn-poor orange/yellow layers are deposited in a relatively dry climate (Cremaschi, 1996; Liu and Dorn, 1996; Broecker and Liu, 2001; Lee and Bland, 2003). Because climatic signals recorded in varnish are regionally contemporaneous (Liu and Dorn, 1996; Liu *et al.*, 2000), VMLs once radiometrically calibrated have the potential use as a dendrochronologylike correlative dating tool. A rigorous blind test of this method has been conducted on late Quaternary lava flows in Mojave Desert, California (Liu, 2003; Phillips, 2003). The test results demonstrate that VML is a valid dating tool to provide surface exposure age for late Pleistocene Surficial geomorphic features in the drylands of the western United States (Marston, 2003) (Fig. 4). New radiometric age calibration and climatic correlation of varnish microstratigraphy with the SPECMAP record (Martinson *et al.*, 1987) have extended the utility of the VML method to Surficial geomorphic features of late Quaternary (Liu and Broecker, 2007, 2008).

VML Results

Minimum exposure ages from VML data for the three samples are shown in Table 1. The dates show that most of the unstable outcrops and boulders on the slopes beneath them have surface ages of at least 24–40 k.y. The south Yucca Mountain site yields ages of around 24 k.y. for outcrops (Yucca Mountain samples 5c–5e are all outcrop samples), 39 k.y. for the Rhyolite site (Rhyolite sample 3b is an outcrop sample), and 12.5 k.y. for the Amargosa site (Amargosa 4c is an outcrop sample). Boulders resting on the colluvial slopes beneath the outcrops yield ages generally similar to those of the outcrops, indicating consistency in timing of the last outcrop-erosional and slope-depositional event or phase at each site. The one exception is the 60 k.y. age for the boulders found near the base of the hill slope at the Rhyolite site, an age much older than that of the outcrops and possibly reflecting an earlier phase of outcrop erosion and slope deposition. The concavity of this slope at this site (Fig. 3c) is probably indicative of incomplete burial of older (60 k.y.) deposits near the base of the slope by younger deposits further up the slope.

Samples taken from the base and top of the pack rat midden from the Amargosa site (Fig. 5) yield calibrated radiocarbon ages of 12.9–13.1 and 22.8–23.7 k.y., respectively. Therefore, 15 cm of spallation of the backwall and roof of the overhang has occurred in 12.9–13.1 k.y., yielding a spallation rate of about 1.1–1.2 cm/k.y. This is comparable to bedrock erosion rates that have been determined for an ensemble of arctic to temperate environments (e.g., Rapp, 1960; Bishop *et al.*, 1984). However, we assume that this erosion rate will be much faster than erosion rates on the other rock outcrops observed in our study, given that the spalling rock is more coarse grained and weathered than the other outcrops observed in our study and that the rock is absent of rock varnish.

The 12.5 k.y. age of some of the outcrops at the Amargosa site is the youngest of VML ages determined for outcrops at our three sites, which is consistent with the potentially higher levels of seismic disturbance at this site relative to the other sites. The site is only 10 km from the DVFCF, the most active fault source in the region.

Constraints on Past Ground Motions

The greatest potential application of our unstable outcrop age data is to constrain seismic hazard estimates in the vicinity of the Yucca Mountain proposed repository site. To do so requires estimates of the fragility of the outcrops to earthquake motions, which involves either (1) estimating the strongest ground motions that the outcrops could sustain without significant damage or (2) estimating the minimum motions that would be required to destroy the outcrops. The latter motions cannot have occurred because the outcrops reached their present fragility; so they potentially provide a constraint on seismic hazard. Specifically, we would compare these limiting ground motions to the ground motions predicted from the Yucca Mountain PSH model (Stepp *et al.*, 2001) for a return period equivalent to the minimum exposure age of the outcrops from the VML data.

Estimating the threshold ground motions for major damage of the outcrops would normally involve detailed geotechnical modeling and analysis of the outcrops and application of well-established methods such as that of Newmark (Newmark, 1965; Jibson, 2007). Because this detailed work is beyond the scope of our study we instead use some simplistic approaches to obtain a first-order estimate of the upper limits of ground motions at the south Yucca Mountain site for a time period equal to the minimum exposure age of

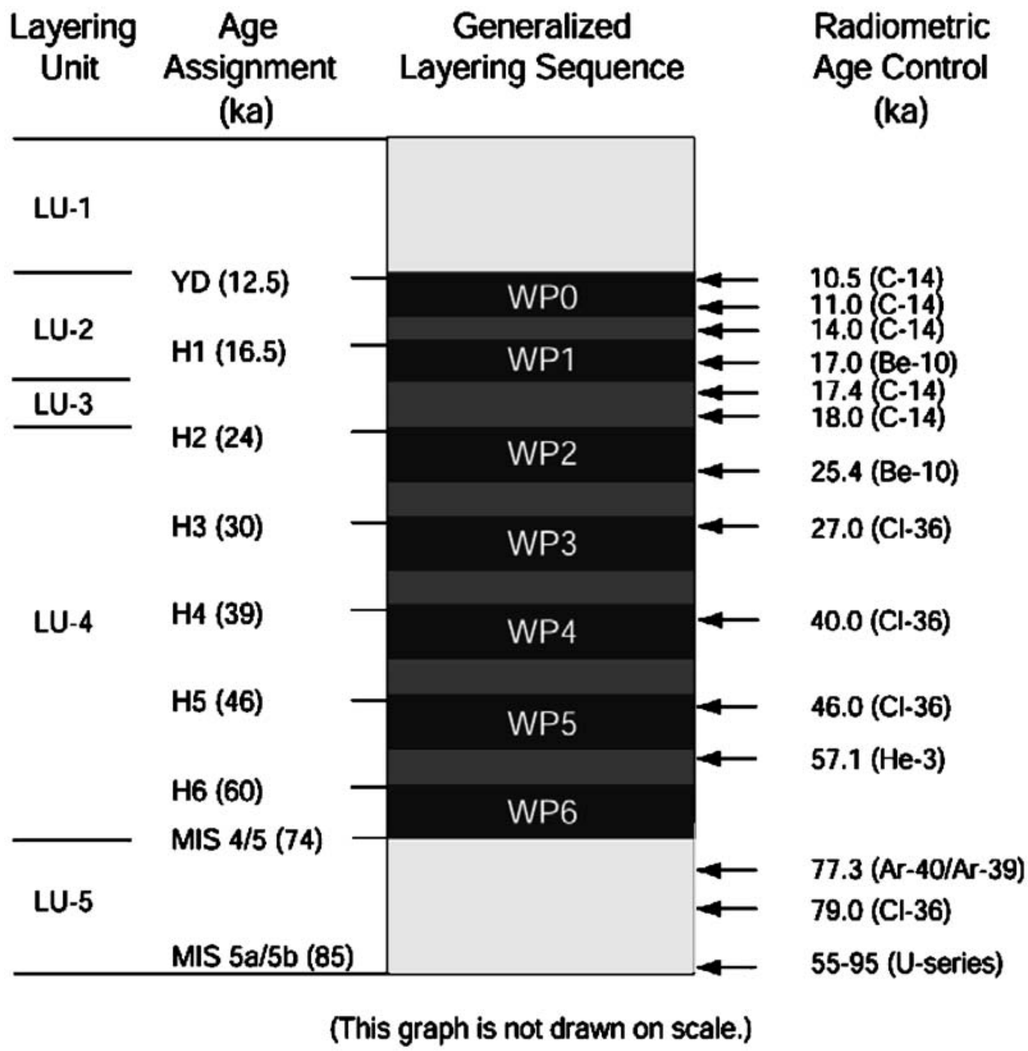

Figure 4. Generalized varnish layering sequence of the western U.S. drylands and the corresponding radiometric age calibration. The age assignments of the dark layers are based on climatic correlation of the regional wet events recorded as dark layers in the varnish layering sequence and the North Atlantic cold Heinrich events. LU, layering unit; WH, wet event in Holocene; WP, wet event in Pleistocene; YD, Younger Dryas; H, Heinrich event; MIS, Marine isotope stage. See Liu (2003) for detailed discussion on VML dating terminology and radiometric age calibration of varnish microstratigraphy.

the outcrops (24 k.y.). Such approaches have been applied to regional landslide susceptibility studies, with reliance placed on remote sensing techniques to estimate slope stability parameters (e.g., Godt *et al.*, 2008). Our ground-motion estimate is then compared to the ground motions predicted for the Yucca Mountain proposed repository (Stepp *et al.*, 2001) for a return period equivalent to the VML age of the south Yucca Mountain outcrops. Attention is limited to our south Yucca Mountain site due to the proximity to the Yucca Mountain proposed repository site where the PSH model was developed and similarity of geology and geomorphology. The two other VML outcrop sites are further away from Yucca Mountain, and our attention is therefore limited to obtaining outcrop stability estimates at the south Yucca Mountain site.

A Newmark analysis provides a critical PGA for initiation of block motion down a slope for a wide range of slope geology and geomorphology. The applicable equation is

$$\mathrm{Ac} = (\mathrm{FS} - 1)\sin(\alpha), \tag{1}$$

in which Ac is the critical acceleration for failure (PGA in units of g), FS is the static factor of safety, and α is the slope angle in degrees (Newmark, 1965; Jibson, 2007). The factor of safety is the ratio of resisting forces to sliding forces and is most simply defined for dry rock conditions (i.e., the conditions of our outcrops) by the following equation:

$$\mathrm{FS} = \tan(\phi)/\tan(\alpha), \tag{2}$$

in which ϕ is the angle of internal friction and α is the slope angle (Bell, 1993). A factor of safety of less than one represents a situation of instability without the requirement of any external influences (earthquake motions represent external influences in the context of our study), whereas a factor of safety greater than one would require earthquake motions

Table 1
VML Minimum Exposure Ages from the Three Sites

Rock Varnish Sample	Number of Ultrathin Sections	Layering Patterns and Number Observed	Oldest Layering Pattern	VML Age Estimate* (in cal ka)
Rhyolite-3A	5	LU-1/LU-2/LU-3/LU-4 (WP6) (4) LU-1/LU-2/LU-3/LU-4 (WP5) (5)	LU-1/LU-2/LU-3/LU-4 (WP6)	60
Rhyolite-3B	2	LU-1/LU-2/LU-3/LU-4 (WP4) (3)	LU-1/LU-2/LU-3/LU-4 (WP4)	39
Rhyolite-3C	3	LU-1/LU-2/LU-3/LU-4 (WP5) (5)	LU-1/LU-2/LU-3/LU-4 (WP5)	46
Amargosa-4A	2	LU-1/LU-2/LU-3/LU-4 (WP2) (1) LU-1/LU-2/LU-3 (WP1+) (1)	LU-1/LU-2/LU-3/LU-4 (WP2)	24
Amargosa-4C	2	LU-1/LU-2 (WP0) (2)	LU-1/LU-2 (WP0)	12.5
Amargosa-4D	3	LU-1/LU-2/LU-3/LU-4 (WP2) (2)	LU-1/LU-2/LU-3/LU-4 (WP2)	24
Yucca Mtn-5A	4	LU-1/LU-2/LU-3/LU-4 (WP2) (2) LU-1/LU-2 (WP0) (2)	LU-1/LU-2/LU-3/LU-4 (WP2)	24
Yucca Mtn-5B	4	LU-1/LU-2/LU-3/LU-4 (WP3+) (1) LU-1/LU-2/LU-3/LU-4 (WP3) (4) LU-1/LU-2/LU-3/LU-4 (WP2) (4)	LU-1/LU-2/LU-3/LU-4 (WP3+)	30–39
Yucca Mtn-5C	3	LU-1/LU-2/LU-3/LU-4 (WP2) (7)	LU-1/LU-2/LU-3/LU-4 (WP2)	24
Yucca Mtn-5D	2	LU-1/LU-2/LU-3/LU-4 (WP2) (2)	LU-1/LU-2/LU-3/LU-4 (WP2)	24
Yucca Mtn-5E	3	LU-1/LU-2/LU-3/LU-4 (WP2) (5)	LU-1/LU-2/LU-3/LU-4 (WP2)	24

*The VML age estimates are based on the age scale of the generalized late Quaternary varnish layering sequence for the western U.S. drylands (Liu and Broecker, 2008).

to initiate failure. Examination of the generally fragile nature of the outcrops at the south Yucca Mountain site (Figs. 2 and 3a) is consistent with a factor of safety of close to, but obviously greater than, one. The open joints on three main orientations (Fig. 3b) have resulted in the development of an irregular unstable blocky outcrop face, and our impression is that a large proportion of the face would become unstable under earthquake loading. A useful visualization would be these rock outcrops perched immediately above a highway. Major rockfalls onto the highway during strong earthquake

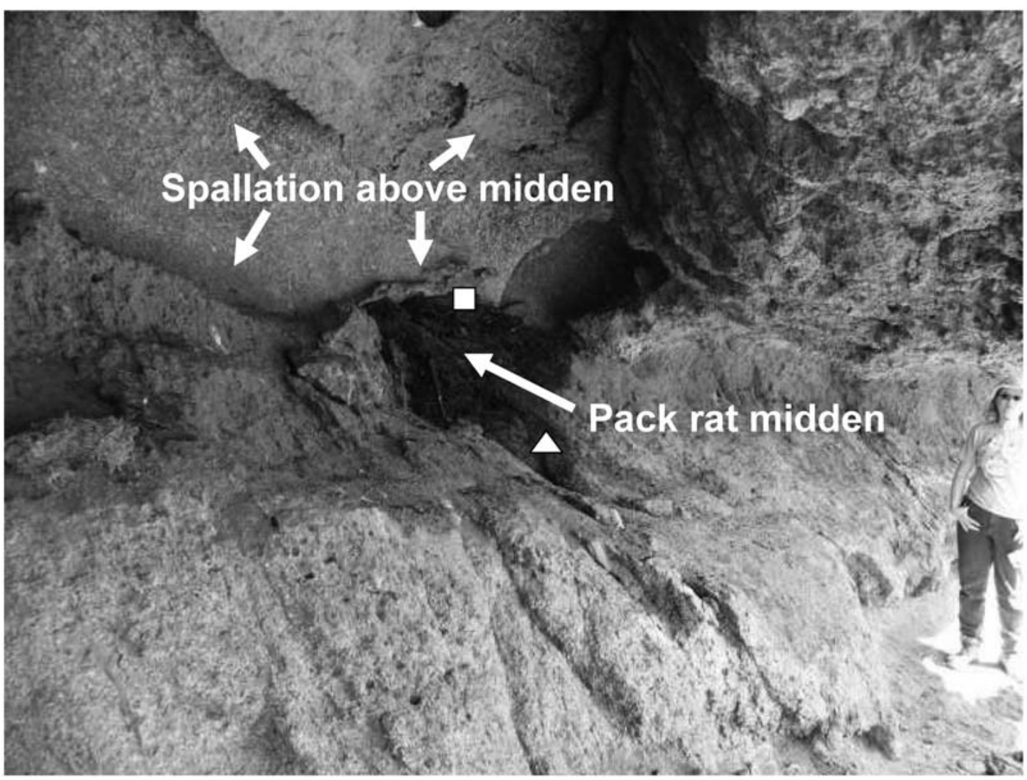

Figure 5. Spallation of the coarsely crystalline tuffaceous wall and roof of the overhang around the pack rat midden (dark deposit at center of the figure) at the Amargosa site. Radiocarbon dates for the pack rat midden are 12.9–13.1 (square) and 22.8–23.7 k.y. (triangle) at the top and base, respectively.

shaking is easily imaginable in this scenario. In the context of a Newmark model, block sliding would be expected to occur along the joint set subparallel to the slope (joint set dip of about 75° with joint spacing of 0.5–1.5 m, and outcrop slope of about 60°; Fig. 3b). If ϕ (equation 2) is simplistically assumed to be approximated by the dip of the joint set (75°), then a factor of safety of around 2 and Ac of around $1g$ are implied (equations 1 and 2). There is obviously large uncertainty associated with this value of Ac derived from equations (1) and (2) given that we have not conducted a detailed field geotechnical study at the site. To illustrate, a $75° \pm 5°$ uncertainty range placed on ϕ would result in Ac of 0.5–$2g$ (i.e., $1g$ $-0.5g/+1g$). Therefore, the Ac estimate of $1g$ is only suggestive of the levels of ground motion that have not been exceeded since the outcrops have been in the present unstable form and requires additional analyses for verification.

An estimate of $1g$ for Ac for the south Yucca Mountain outcrops (24 k.y.) for the Stepp *et al.* (2001) PSH model reveals that $1g$ is equal to the eighty-fourth percentile of PGA (Fig. 6). In contrast, the ninety-fifth percentile PGA of the PSH model ($1.4g$) is greater than Ac, so it is inconsistent with the age and stability of the outcrops unless uncertainties in ϕ (previously) are taken into account.

An additional study that potentially provides low-resolution constraints on the upper limits of ground motions

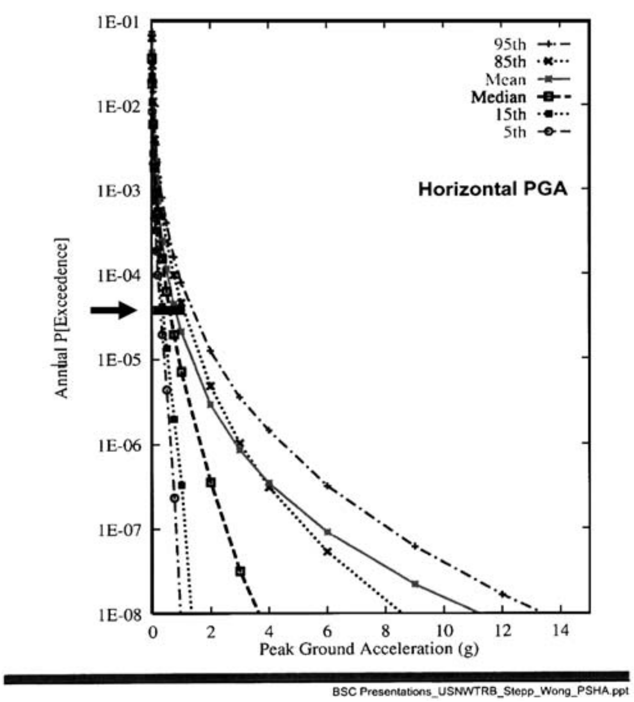

Figure 6. Hazard curve for PGA derived from the Stepp *et al.* (2001) PSH model for the proposed Yucca Mountain repository site. The allowable range of PGA from our first-order stability analysis of the south Yucca Mountain site is shown as the small horizontal black line on the graph (0–$1g$). The y axis is equal to $1/24$ k.y. See the text for further explanation. The hazard curve has been reproduced with the permission of Ivan Wong.

is the worldwide dataset of earthquake induced landslides of Keefer (1984a,b). Keefer studied landslide occurrence in relation to earthquake magnitudes and intensities across a worldwide ensemble of physiographic and geologic environments and showed that earthquake induced landsliding occurs for Modified Mercalli Intensity (MMI) of 5 or greater. Utilizing the newly developed MMI-to-PGA and MMI-to-PGV relationships of M. C. Gerstenberger. C. B. Worden, D. A. Rhoades, and D. J. Wald (unpublished manuscript, 2009), such intensities are equivalent to a huge (and uninformative) range of PGA (0.01–$2g$), and PGV (0.6–200 cm/sec). These large ground-motion uncertainties accommodate both the range of MMIs that have produced landslides and the large uncertainties in converting from MMI to PGA and PGV (M. C. Gerstenberger. C. B. Worden, D. A. Rhoades, and D. J. Wald, unpublished manuscript, 2009). If we limit our consideration to the upper bounds of those PGA and PGV distributions, the presence of unstable outcrops that have not been destroyed by earthquake induced landsliding would imply that ground-motions levels have not exceeded about $2g$ and 200 cm/sec since the unstable outcrops formed. However, in light of the huge uncertainties in the threshold PGA and PGV (discussed previously), we do not consider these to represent realistic constraints on the maximum ground motions at the south Yucca Mountain site. Furthermore, the unknown applicability of the geologic environments embodied within the Keefer landslide dataset to the south Yucca Mountain site greatly limits the application of this work to our study.

Discussion

Our study contributes to a growing body of literature that investigates the utility of ancient, unstable geomorphic features for providing constraints on prehistoric ground motions. At present unstable landforms appear to be the only limiting criteria available for testing PSH models at return periods longer than those of historical records. The VML dating method is proving to be a readily applicable and cost-effective tool for providing minimum exposure ages for desert landforms, as we have found in our study. A first-order interpretation of our VML data in the context of earthquake hazard is that the youngest surface exposure age inversely correlates with proximity to a major active earthquake source. Specifically, the Amargosa site (VML age is 12.5 k.y., the youngest of the three sites) is close to the DVFCF, the most active earthquake source in the region. Frequent strong ground motion from DVFCF earthquakes may therefore be responsible for the relatively young VML age by way of shaking-induced damage.

While the estimates of damaging ground motions for our unstable outcrops are very crude, they imply that PGAs of the order $1g$ have not been exceeded at the south Yucca Mountain site in at least the last 24 k.y. The implication of the south Yucca Mountain outcrop data is that the Stepp *et al.* (2001) PSH model is consistent with the outcrop data, except perhaps for the most upper-bound (ninety-fifth percentile and above) motions predicted for the 24 k.y. return period ($\geq 1.4g$). The treatment of epistemic uncertainty in the Stepp *et al.* model may therefore produce discrepancies with the outcrop data at the ninety-fifth percentile level. This interpretation is limited to the 24 k.y. return period and should not necessarily be considered relevant to longer return periods.

A further set of observations of relevance to our study is the damages to outcrops where we can constrain the maximum strength of earthquake shaking from a recent local earthquake. While the south Yucca Mountain site has not experienced PGAs that would severely damage the outcrops at the site for 24 k.y. (Ac of the order $1g$), it is likely that the site actually experienced slight damage during motions of less than $0.1g$ during the 1992 *M* 5.6 Little Skull Mountain earthquake. The earthquake occurred about 12 km east of the south Yucca Mountain site, and ground motion modeling by Brune *et al.* (2005) indicates that rock PGA was less than $0.1g$ at that distance. A strong ground motion instrument located on deep alluvium at the Lathrop Wells volcano (only 1 km from our south Yucca Mountain site) recorded $0.21g$ during the earthquake, suggesting amplification of PGA relative to rock (Brune *et al.*, 2005). While the irregular, fragile south Yucca Mountain outcrops are almost exclusively darkish due to a uniform cover of desert varnish (more than 80% covered with 24 k.y. vanish), two outcrop surfaces of a whitish shade can be observed in Figure 7 (see arrows), along with a whitish boulder immediately beneath one of them. These whitish surfaces are due to the presence of caliche and are indicative of a freshly exposed surface (caliche is removed in just hundreds of years of exposure; Brune *et al.*, 2005). We therefore consider it likely that the Little Skull Mountain earthquake PGA of less than $0.1g$ caused these relatively minor failures. Had stronger motions occurred during the Little Skull Mountain earthquake we would expect there to be a much larger proportion of the caliche faces exposed and a lighter appearance of the overall outcrop (see the outcrop damage at the crest of Little Skull Mountain in fig. 2 of Brune *et al.* [2005]). The general uniformity of dark 24 k.y. varnish on the vast majority of the outcrop surfaces (Figs. 2 and 7) indicates that PGAs of the strength produced by the Little Skull Mountain earthquake do not significantly alter the outcrop face. If they did then the outcrop would have heterogeneous varnish cover due to a heterogeneous exposure history. Much stronger motions would be required to majorly alter the outcrops surfaces, consistent with our Ac of $1g$.

Another useful set of observations of damage associated with recent strong ground motions is at outcrops close to nuclear blasts. Observations by Brune *et al.* (2003) of severely damaged cliff faces near NTS nuclear blasts clearly show that strong ground motions and outcrop failures are strongly linked. We have undertaken a survey of damage produced by two nuclear blasts outside of the NTS to obtain first-order observations of shaking-induced damage to outcrops

Figure 7. Freshly exposed rock faces at the south Yucca Mountain site (the two white areas at center left and center right of the image; see arrows), possibly exposed by shaking associated with the nearby 1992 *M* 5.6 Little Skull Mountain earthquake. See the text for further explanation.

similar to those of our three sites. We visited the immediate vicinities of the 1963 SHOAL and 1968 FAULTLESS nuclear tests, which had yields of 12 kt and approximately 1 Mt, respectively. For the FAULTLESS test site, we were able to document recent (presumably blast-induced) damage to Tertiary welded tuff outcrops very similar in lithology and joint orientation/spacing to those of our study sites (e.g., see the Data and Resources section). In Figure 8 we show six sites near the FAULTLESS test site that reveal varying degrees of damage to outcrops and also list the predicted PGA as a function of distance to ground zero for each in Table 2 (attenuation relationships given by Murphy and Lahoud [1969] and Vortmann [1980]). Our assessment of the degree of recent outcrop disturbance is based on the approximate percentage of freshly exposed (i.e., whitish caliche/nonvarnished) outcrop surface (Table 2). In this context damage within 5–8 km of the FAULTLESS ground zero appears to have been most severe (percentage of fresh rock exposed typically about 50%) relative to damage at greater distances (30% or less fresh rock exposure). The attenuation relationships (Brune *et al.*, 2003) indicate PGAs of 0.5–1g for the 5–8 km distance range (Table 2) and less pronounced at around 15 km (PGA 0.1–0.2g). Assuming outcrop damage is due to the nuclear tests, the unstable outcrops have been severely damaged by ground motions with a predicted strength of about 0.5–1g near the FAULTLESS test site. The absence of similar damage at our south Yucca Mountain site is suggestive that ground motions of 0.5–1g or more have not occurred at the site over at least the last 24 k.y., consistent with the 1g Ac (and lower bound Ac of 0.5g) obtained from our simplistic Newmark analysis (equations 1 and 2). We fully acknowledge that the predicted PGAs for the nuclear blasts come from very different source mechanisms than those of natural earthquakes, and the attenuation relationships used to predict the nuclear blast-induced PGAs are also very generalized with respect to the great variability of damage that may occur over short distances due to unknown local effects. In this respect the three sites studied at Petroglyph mesa (0.5 km from the FAULTLESS blast; Fig. 8b–d; F1, F5, and F6 in Table 2) show damage to outcrops at the crest of the mesa and walls of the main valley (Fig. 8b,d) but little discernible damage to the walls of the tributary canyon walls (Fig. 8c). Well-preserved Native American petroglyphs on these tributary canyon outcrops clearly attest to the fact that blast-induced ground motions did not significantly damage the outcrops (Fig. 8c). The contrasting damage within a short distance may be due to contrasting lithological characteristics (the tributary canyon wall rock appears more widely jointed and massive than the other sites) and topographic effects on ground motions, in which ground motions at the crest of the mesa and along the main valley wall are amplified relative to those of the tributary canyon walls. Furthermore, because our research indicates that the petroglyphs were most likely produced by the Fremont people (700–1300 A.D.) these tributary canyon walls appear to have survived 700–1300 yrs of fluvial and natural seismic activity, in addition to the FAULTLESS blast. For the much smaller yield SHOAL test site, we observed major fracturing of granitic outcrops and localized rockfalls about 0.6 km from ground zero (Fig. 8h) that were presumably due to the strong ground motions produced by the blast. The attenuation relationships of Murphy and Lahoud (1969) and Vortmann (1980) indicate a PGA of 1.8–6.3g for the fractured outcrops and rockfalls at this close distance to ground zero (Table 2). The granitic geology of the SHOAL test site is not relevant to our study sites in terms of mineralogy and composition but will be reasonably relevant in terms of engineering properties (density, fracture pattern/spacing, etc.). In other words, rock types observed at the two sites can both be considered as engineering rock.

Though an implication of our analysis is that the Stepp *et al.* PSH model would pass a test based on our VML data (except for the ninety-fifth percentile and above), we emphasize that the test would only be relevant for the 24 k.y. return period and irrelevant for longer return periods.

Conclusions

We have determined minimum exposure ages for unstable outcrops at three sites in Amargosa Desert, including a site at the southern end of Yucca Mountain. VML dating techniques provide minimum exposure ages of 12.5–36 k.y. for the unstable outcrops of welded tuff, including a 24 k.y. outcrop age for the south Yucca Mountain site. The youngest exposure age (12.5 k.y.) is found at the site located only 10 km from the DVFCF, suggesting outcrops may be more frequently modified when close to major active earthquake sources. A simplistic stability assessment of the south Yucca Mountain outcrops suggests PGAs may not have exceeded about 1g (uncertainty bounds 0.5–2g) in at least 24 k.y. A PGA of 1g is consistent with the predicted 24 k.y. return period PGAs from the near decade-old Yucca Mountain PSH model, except for the ninety-fifth percentile and above. We gain confidence in our interpretations by additionally observing (1) minimal damage to the south Yucca Mountain outcrops from a recent moderate earthquake that is estimated to have produced a PGA of less than about 0.1g there (i.e., motions of less than 0.5g do not significantly damage the outcrops) and (2) considerable damage to similar volcanic outcrops associated with PGAs of the order 0.5–1g near a nuclear blast site from the 1960s. These observations support our suggestion that PGAs greater than about 0.5–1g have not occurred at the south Yucca Mountain site for a time period of at least 24 k.y. Significant seismic events that substantially modify the outcrops and produce associated rubble fields must therefore occur on longer time scales.

Data and Resources

VML thin section photographs and layer-age assignments are freely available from the corresponding author. Outcrop field data and digital photographs are held by the

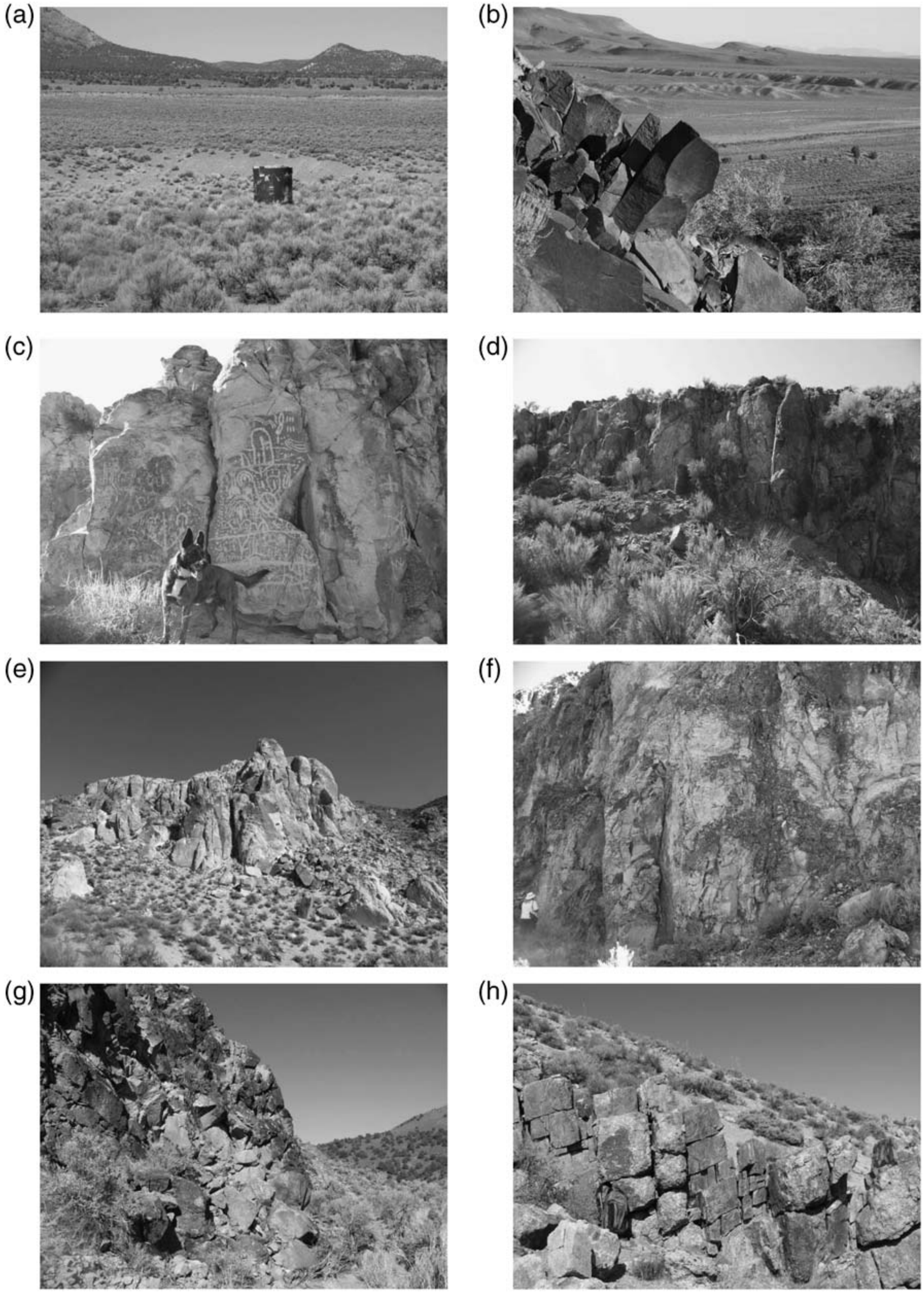

Figure 8. (a) Ground zero for the FAULTLESS nuclear test site, marked by the large-diameter drill casing in the center of the image, and subsidence scarps in the distance. Outcrops of welded tuff located at distances of 5–15.6 km from nuclear tests are shown as follows: (b) 5.0, (c) 5.4, (d) 5.8, (e) 6.5, (f) 7.6, and (g) 15.6 km from the FAULTLESS ground zero, and (h) 0.6 km from the SHOAL ground zero. See Table 2 and the text for further explanation.

Table 2
PGAs as a Function of Distance to Ground Zero for the FAULTLESS and SHOAL Nuclear Test Sites

Site	Site Latitude	Site Longitude	Distance (km)	PGA (g) Equation (1)	PGA (g) Equation (2)	Fresh Rock (%)
F1	38.67	−116.18	5.8	0.76	0.76	~50%
F2	38.69	−116.18	6.5	0.62	0.63	~50%
F3	38.70	−116.18	7.6	0.47	0.48	~50%
F4	38.77	−116.19	15.6	0.14	0.15	~20%
F5	38.67	−116.18	5.0	0.85	0.85	~70%
F6	38.68	−116.18	5.4	0.98	0.97	~30%
S1	39.20	−118.39	0.6	6.33	1.76	~50%

Coordinates of observations made in the vicinity of the FAULTLESS (F1–F6) and SHOAL (S1) nuclear test sites, distance of the sites to ground zero, predicted blast-induced PGAs based on the attenuation relationships of Murphy and Lahoud (1969) and Vortmann (1980), and percentage of the outcrop surface comprising newly exposed fresh rock. Not surprisingly, the most significant evidence of damage to outcrop features (generally 50% fresh rock exposure) is observed in the vicinity of 5–8 km from ground zero where PGAs of 0.5–0.8g are predicted. At the FAULTLESS site no outcrops closer than 5 km were able to be observed. FAULTLESS (F) ground zero is 38.634° latitude and −116.216° longitude. SHOAL (S) ground zero is 39.200° latitude and −118.384° longitude.

first author and freely available. The locations and directions to the nuclear test sites are given in many Web sites, for example, http://www.nbmg.unr.edu/earthcache/ProjectFaultless.pdf (last accessed May 2009); http://ludb.clui.org/ex/i/NV3134/ (last accessed May 2009); http://ndep.nv.gov/shoal/SHOAL1.HTM (last accessed May 2009).

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