Chapter M

Precarious Rocks and Seismic Shaking at Yucca Mountain, Nevada

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Contents

Figures

Table

[For table of abbreviations and conversions, click here]

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Abstract

This report describes a methodology for using the distribution of precariously balanced rocks to study seismic hazard and applies the methodology to provide information about the seismic hazard at Yucca Mountain, Nevada, the site of a potential geologic repository for high-level radioactive waste. Zones of precariously balanced rocks are not found near rupture zones of historic large earthquakes. The distribution of such precarious rocks in southern California correlates very well with areas at a distance from known active faults. Numerous precarious rocks exist in Solitario Canyon, Nevada, near the potential repository. Estimates of toppling accelerations using computer models, physical models, and field tests indicate that these rocks would be toppled or removed by ground acceleration of a few tenths of the acceleration of gravity. These estimates indicate that at Yucca Mountain ground accelerations have not exceeded 0.3 gravitational acceleration for the last several tens of thousands of years. This observation has been supported by paleoseismic studies of the Solitario Canyon fault that demonstrate that the last significant surface offset took place 75,000 to 80,000 years ago, and by geomorphic studies in Solitario Canyon that show no down-slope boulders lying on alluvial deposits with ages less than about 30,000 years. Precarious rocks are effective strong-motion seismoscopes at Yucca Mountain.

Introduction

Seismic hazards are being carefully investigated at Yucca Mountain, Nevada, the site of a potential high-level radioactive-waste repository. As a result of the discovery of numerous precariously balanced rocks in the vicinity of Yucca Mountain (Brune and Whitney, 1992), a methodology was developed to use these rocks as constraints on the probable ground motion to be expected at the potential repository. The precarious rock methodology gives a direct indication of the intensity of the last significant ground shaking at a site, in contrast to the indirect inference provided by trenching studies, which cannot specify the actual characteristics of fault slip.

In many types of terrain in California and Nevada, groups of precariously balanced rocks have evolved naturally by erosion. The common presence of rock varnish on such rocks indicates that they have been in their current unstable positions for at least thousands of years. Therefore, groups of precariously balanced rocks are, in effect, low-resolution strong-motion seismoscopes that have been operating on solid rock outcrops for thousands of years. As such, they provide important information about seismic risk. We have established the mechanical basis for rough estimates of the horizontal accelerations necessary to topple precarious rocks, using field observations and numerical and physical modeling. The distribution of precarious rocks relative to known active faults and intensity zones produced by historical earthquakes confirms their usefulness in outlining areas that have or have not undergone recent strong ground shaking (Brune, 1993a, 1993b, 1994).

A goal of Yucca Mountain precarious rock studies is to develop a methodology whereby precariously balanced rocks can be used to estimate both the minimum accelerations necessary to topple precariously balanced rocks and the time that has elapsed since strong ground motion has occurred near known faults where such rocks are found. The development of the precarious rock methodology has involved three tasks:

1. Documentation of the distribution of precarious rocks, both locally in the vicinity of Yucca Mountain and regionally in California and other parts of Nevada (Brune and Whitney, 1992; Brune, 1993a, 1993b, 1994).
2. Development of computer models, physical models, and field tests to quantitatively estimate the ground acceleration required to topple observed rocks (Shi and others, 1996; Shi and others, 1993).
3. Development of surface age-dating techniques to estimate the time various rocks have been in their observed positions.

In this report we document a number of precariously balanced rocks near Yucca Mountain and discuss their implications in the context of the paleoseismic histories of the Solitario Canyon fault and other nearby Quaternary faults.

Precarious Rocks Near Yucca Mountain

Description of Rocks

Near Yucca Mountain there are many spectacular precariously perched or balanced boulders, covered with dark rock varnish. These rocks appear to be so unstable that relatively weak motion from earthquakes—accelerations of about 0.1–0.3 *g*—would dislodge or topple them. Thus, they give an upper bound on the level of ground motion that has occurred during the time that they have been in precarious positions (Brune and Whitney, 1992). The darkness of the rock varnish[2] on many of these boulders suggests that they have been in these positions for more than 10 k.y. and perhaps several tens of thousands of years.

Figure 1 shows the locations of several spectacular examples of precarious rocks, and figure 2 is a series of photographs of such rocks. Nearly all are located on the western slope of the main ridge at Yucca Mountain. Table 1 lists the reference number and approximate dimension of each rock. Approximately 100 precarious rocks have been found in the vicinity of Yucca Mountain (from east to west, Fortymile Wash to Buck Springs, west of Beatty; and from north to south from Yucca Wash to several kilometers south of the mouth of Solitario Canyon (figs. 3 and 4)).

Distribution of Rocks

Most of the welded tuff outcrops extending from the northernmost end of Solitario Canyon to approximately 5 km

[2] Rock varnish is a subaerially deposited coating of manganese and iron oxides, clay minerals, and inclusions of organic matter.

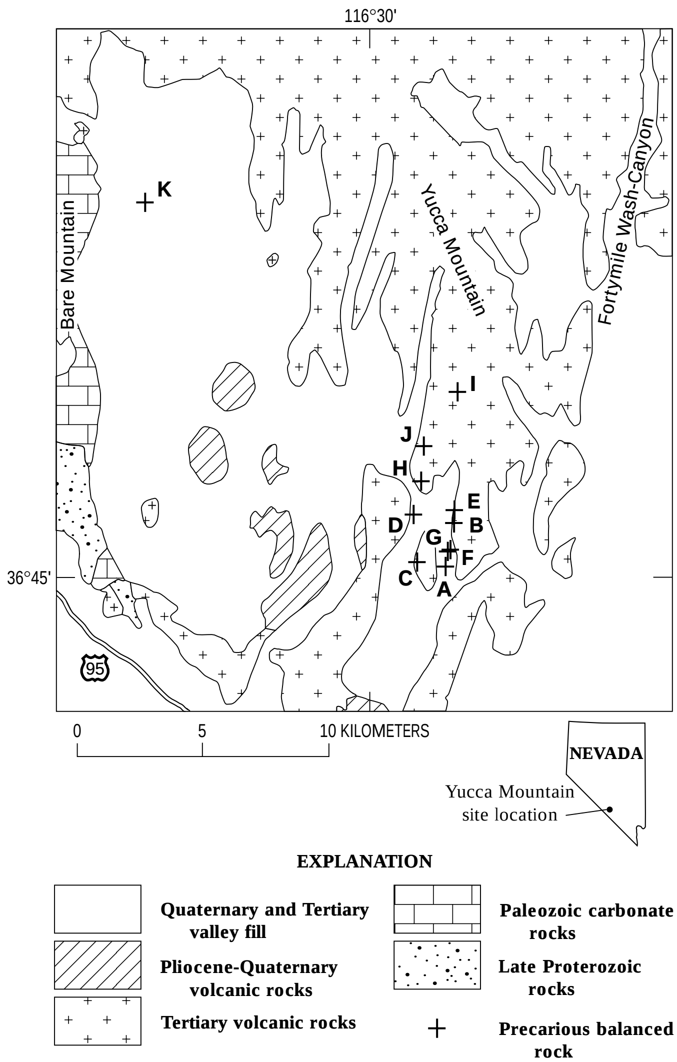

Figure 1. Simplified geologic map of Yucca Mountain area showing locations of precariously balanced rocks.

Table 1. List of precarious rocks shown in figure 2, with approximate dimensions.

Location[1]	Approximate height (meters)	Reference Number
A	1.0	92 JB LS AR
B	4.0	93 RC SC 72
C	1.4	93 RC YC 01
D	1.4	93 RC SC 65
E	2.0	93 RC SC 59
F	1.0	93 RC SC 82
G	0.6	93 RC SC 83
H	1.5	93 JB AC NW
I	0.8	93 JB NC 00
J	0.6	93 JB NC 07
K	2.2	93 JB CF N1
L	1.2	93 JB BSS 01

[1] Locations of A-K shown in figure 1; locale of L shown in figure 4.

south of the mouth of the canyon were examined. Precarious rocks are found along this whole distance, but their number diminishes southward, possibly owing to decreased distance to sources of shaking as well as to changes in geomorphic conditions. The locations of approximately 90 precarious rocks in Solitario Canyon have been accurately located on a 1:3,000-scale aerial photograph. Individual rocks are documented in archives by notes, photographs, and a written description.

Several somewhat precarious rocks were found during a reconnaissance investigation of the west face of Jet Ridge (fig. 3). Such rocks appear to be fewer at that locality than in Solitario Canyon. Farther west, on West Ridge and in northern Crater Flat, precarious rocks were not found during a reconnaissance inspection. A small number were observed in Fortymile Wash and a few in Yucca Wash, but weathering and erosion of most of the volcanic outcrops on the north side of Yucca Wash do not appear to produce precarious rocks.

The old basalt flows and cones in southern Crater Flat between Solitario Canyon and Lathrop Wells show a number of precarious rocks. Bare Mountain is composed primarily of formations (Paleozoic and Precambrian sedimentary and metasedimentary rocks) that do not appear to form precarious rocks, except for some that formed in basalt dikes at the mouth of Tarantula Wash. There are a number of precarious rocks in Fluorspar Canyon at the north end of Bare Mountain, in nonwelded tuff just north of Crater Flat (fig. 2*K*), and in Beatty Wash and Fortymile Wash.

West of Beatty, several precarious rocks occur near Rhyolite and Buck Springs (fig. 2*L*), but no detailed survey of this region has been made. No obvious precarious rocks were observed along the highway from Beatty to Death Valley (through Daylight Pass), and in Death Valley precarious rocks do not seem to be found either on solid rock foundations or at high elevations. However, a number of rocks are supported on soft erosional remnant pillars (hoodoos), such as those in Wildrose Canyon going west out of Death Valley, and on Highway 190 just east of Furnace Creek. J.C. Yount (written commun., 1994) has also observed a number of these in Golden Canyon on the east side of Death Valley near Furnace Creek. These occurrences suggest that no strong ground shaking has taken place in Death Valley in at least the last few hundred years, as hoodoos can develop relatively rapidly in the soft material on which they form.

A 1993 survey of the region around Little Skull Mountain, site of a magnitude 5.6 earthquake on June 29, 1992 (Anderson and others, 1993; Smith, Brune, and others, this volume) revealed numerous fresh rockfalls on the prominent cliffs along the crest of the mountain, but no precariously balanced rocks were found. Different degrees of rock varnish were observed along the cliff face, which suggests that Little Skull Mountain has experienced similar shaking at other times during the Holocene, perhaps from earthquakes related to the Rock Valley fault zone.

Busted Butte, about 12 km from the epicenter of the Little Skull Mountain earthquake, is the site of a number of small, fresh rockfalls; yet a number of relatively precarious rocks remain in place.

Figure 2. Photographs of precariously balanced rocks (*A–L*, above and following pages). Scales vary. *A*, *C*, Note plumb bob, 6 in. long. *G*, Book 8 in x 5 in. *H*, Person for scale.

Origin and Antiquity of Precarious Rocks at Yucca Mountain

Precarious rocks at Yucca Mountain can be classified into two descriptive groups: large, individual balanced boulders and stacks of balanced boulders. Nearly all the precarious rocks in this study eroded from jointed, densely welded tuff, which weathers very slowly in the dry semidesert of the southern Great Basin. Unlike granite, welded tuff does not weather into small fragments, but typically breaks up into large boulders that maintain rectilinear shapes inherited from original jointing.

Boulders may become precariously balanced by root activity, freezing and thawing, jostling by rocks saltating downslope, occasional low levels of ground motion from distant earthquakes, and possibly other geomorphic and weathering processes. Wedging by root activity and freezing leads to opening of cracks and filling with fine material moving downslope from above. Erosion may then proceed to the point that blocks of rock become nearly unconfined: the fine material is washed out, leaving the rocks in isolated precarious positions (fig. 5). Precarious boulders of figures 2*C* and 2*I* are clear examples of the end result of this process. The boulders appear to have been pushed away from their original positions adjacent to bedrock, and cobbles remain between boulder and outcrop.

Precarious rocks 2*G*, 2*J*, and 2*L* (fig. 2) are good examples of boulders that may have become isolated and "balanced" owing to weathering of the base of the boulder and (or) the

surface on which the boulder sits. Precarious rock structure 2*K* is an example of grain weathering in a nonwelded tuff; surface hardening of the tuff allowed weathering to attack the more porous interior of the tuff along fractures and joints, which has resulted in a delicate arch.

One possible cause for the occasional shifting of large angular boulders into precarious positions is the ground motion that may have originated from any one of several nearby faults that are capable of generating high-frequency low-level ground motion at Yucca Mountain. During a search in Rock Valley for a possible surface rupture associated with the 1993 M 3.8 Rock Valley earthquake, a column of free-standing alluvium was observed separated about 15–25 cm from a vertical wall in a 2-m-deep trench. The column was apparently formed by low-intensity ground shaking during the earthquake, because it formed in unconsolidated alluvium, and delicate structures with

balanced cobbles and pebbles were present. The column was not present a year earlier, when a similar search for surface ruptures was undertaken, and the column collapsed less than 3 months after it was found. Because a relatively high level of shaking is required to initiate even a small amount of motion, and ground shaking only a little higher than this would topple the rocks, seismic shaking as a major contributor to the formation of precarious rocks is unlikely. The evidence at hand thus indicates that precarious rocks are not significantly affected by low-frequency, low-amplitude ground motion that many Quaternary faults in the region around Yucca Mountain are capable of generating.

Estimating when a given precarious rock attained its present position is difficult. As previously stated, many of the balanced rocks in this study area are partially or completely coated with rock varnish. Some of the darkest rock varnish

analyzed from surface boulders on Yucca Mountain hillslopes indicate that surface-exposure ages can exceed 100 ka (Whitney and Harrington, 1993). The darkness of the rock varnish on many of the boulders in this study suggests that they have been in these positions for more than 10 k.y., and probably several tens of thousands of years. The high slope stability, as evidenced by the preservation of middle Pleistocene deposits on Yucca Mountain hillslopes, is consistent with the relatively long term stability of precarious rocks.

The distribution of large boulders on Solitario Canyon hillslopes is useful to demonstrate the minimum passage of time since a large volume of boulders has been shaken down from

cliffs and ridges during the last coseismic surface rupture on the Solitario Canyon fault. The upper hillslope consists of bedrock outcrops, where many precarious rocks are located, and pediments cut on bedrock. Many of these pediments extend to the middle slope, where they are adjacent to colluvial deposits of middle and early Quaternary (>130 ka) age. The toes of the hillslopes generally contain colluvial deposits of late Quaternary age; most of these deposits are underlain by soils that are sufficiently developed to suggest that the colluvium was deposited primarily before the last Wisconsin glacial/pluvial episode (>30–>17 ka) (Peterson and others, 1995; S.C. Lundstrom, written commun., 1995). Large boulders are common on the rock pediments and middle Quaternary deposits on the middle slopes; however, they are rare or absent on the surfaces of deposits believed to be less than 30 ka. The lack of free-standing boulders on late Quaternary surfaces suggests that no significant ground shaking has taken place since these colluvial sediments were deposited.

Quaternary Faulting on the Solitario Canyon Fault

The main ridge at Yucca Mountain is bounded on the west by the Solitario Canyon fault. A prominent scarp is associated

with this fault, the appearance of which suggests that it was formed during the late Quaternary or Holocene. Recent cosmogenic dating of the scarp, however, indicates that it has been exposed for more than 20 k.y. (Harrington and others, this volume), and therefore no significant surface offset has occurred during this time. Several trenches expose the fault and demonstrate that multiple surface ruptures have occurred on this fault during the Quaternary (Alan Ramelli, University of Nevada-Reno, written commun., 1994).

The last significant surface rupture of the Solitario Canyon fault appears to be associated with a basaltic ash eruption from the Lathrop Wells volcanic center, because fissures exposed in trenches are filled with relatively pure basaltic ash. The ash itself produced a chlorine-36 date of 80 ka (Zreda and others, 1993), which is corroborated by an $^{40}Ar/^{39}Ar$ date of 77±6 ka reported by Heizler and others (1999). The cemented basaltic fissure fill has been fractured, but no demonstrated offset is associated with the fractures. If the fractures are related to an earthquake on the Solitario Canyon fault, then either the event took place between 20 and 40 ka (based on U-series dating of secondary carbonate in the fissure-fill; Alan Ramelli, Univ. of Nevada-Reno, written commun., 1994), or, if younger, the

ground motion was insufficient to disturb nearby precarious rocks. The fracturing may have resulted from low levels of ground motion on some nearby fault. All known faults within 10 km of Yucca Mountain are characterized by low rates of fault activity, generally small offsets, and long recurrence intervals. (For example, see Menges and others, 1994.)

Thus, the large number of relatively old precarious rocks situated on hillslopes above the Solitario Canyon fault corresponds well with radiometric evidence for timing of the last significant (>0.3 *g*) ground motion on that fault. The last significant surface offset took place more than 40 ka and perhaps as early as 80 ka. Cosmogenic radiocarbon dates confirm that relief of the main bedrock scarp has not been increased by offset within at least the past 20 k.y. (Harrington and others, this volume).

Verification of Lack of Precarious Rocks Near Historical Large Earthquakes

Reconnaissance searches for precarious rocks were made by the authors near epicenters of the following earthquakes:

Fort Tejon, Calif., 1857; Olinghouse, Nev., 1869; Owens Valley, Calif., 1872; Kern County, Calif., 1952; Fallon-Stillwater, Nev., 1954; Fairview Peak–Dixie Valley, Nev., 1954; Baja California, 1954, 1956; Borrego Mountain, Calif., 1968; Landers, Calif., 1992 (fig. 6). In none of these regions were zones of precariously balanced rocks found, in spite of the existence of numerous granite boulder fields or welded tuff cliffs of the same type as those where precarious rocks are typically found near Yucca Mountain and at other sites in Nevada and California. In most of these regions, slopes below steep cliffs had a shaken-down appearance, with many boulders at the foot of the slopes, and a skyline appearance quite different than the rugged angular appearance of the skyline and cliffs in zones of precarious rocks. On the basis of these reconnaissance searches, we concluded that no precarious rock zones are found within 20 km of zones of high-energy release of large historical large earthquakes (for normal faults and thrust faults, the center of energy release is probably displaced about 5 km in the dip direction from the surface trace of the fault). The lack of precarious rocks near large historical earthquakes implies that in areas where precarious rocks are found, such as Yucca Mountain, no strong ground shaking has recently occurred.

Precarious Rock Methodology

Validation of Precarious Rock Methodology in Southern California

In California, major faults have been mapped, their slip rates determined, and predicted probabilistic ground motion maps constructed. These data, when compared with the distribution of known precarious rock zones in California, can validate the precarious rock methodology presented here.

To document the occurrence of precarious rocks in southern California, we carried out surveys along major roads. Four zones containing relatively large numbers of precarious rocks and five zones containing somewhat fewer precarious rocks have been documented. Published probabilistic ground motion maps for southern California were compared with the maps of zones of precarious rocks. All the ground motion maps show some general features that correlate with the occurrence of precarious rocks. Zones containing relatively large numbers of precarious rocks correlate with areas of low probability of significant ground motion in the central Sierra Nevada and the central Peninsular Ranges. Zones containing fewer precarious rocks correlate with areas of somewhat higher probabilities in the Mojave Desert, and zones containing no precarious rocks are found near known active faults. However, ground motion maps that assume relatively large, randomly occurring earthquakes or large earthquakes not associated with known active faults clearly contain discrepancies when calculations are extended to periods on the order of a thousand years, indicating that for some areas the assumption of large random earthquakes is incorrect. The generally good agreement with ground motion maps that do not

assume large random earthquakes provides a validation of the precarious rock methodology, and indicates that strong ground shaking, of the intensity which occurs near large earthquakes, has not occurred at Yucca Mountain.

Estimation of Toppling Accelerations

Techniques for estimating toppling accelerations of precarious rocks were developed using computer models,

physical models, field tests, and measurements from photographs. In this report, the term “toppling accelerations” refers to the approximate peak acceleration of one component of ground motion in a typical strong-motion record such as that from El Centro or Taft (Ishiyama,1982). This definition ignores sharp, high-frequency spikes in the ground motion. These spikes may be considerably higher and not topple larger rocks (Weichert, 1994), but they are usually not critical in seismic design considerations. Any one component of motion will, of course, occur in the presence of similar accelerations in the other two component directions (horizontal and vertical).

Studies of numerical computer models and physical models made out of styrofoam blocks were compared. Two-dimensional computer simulation results (using a code similar to that of Weichert, 1994) agree very well with results from physical models. Direct tests were also made on a number of rocks in the field to determine the steady-state toppling accelerations. Rocks were pulled with a flexible cord or chain such that the horizontal force vector passed through the center of mass. Results of these tests, which confirm the ability to make rough estimates of steady-state toppling accelerations, indicate that most of the rocks described in this study would be toppled by accelerations of about 0.20–0.30 *g* (in some cases less). Three precarious rocks in Solitario Canyon were tested and were toppled by steady-state accelerations of less than 0.2 *g*.

Keefer (1984) studied rockfalls from numerous earthquakes and found that rockfalls are common on steep slopes

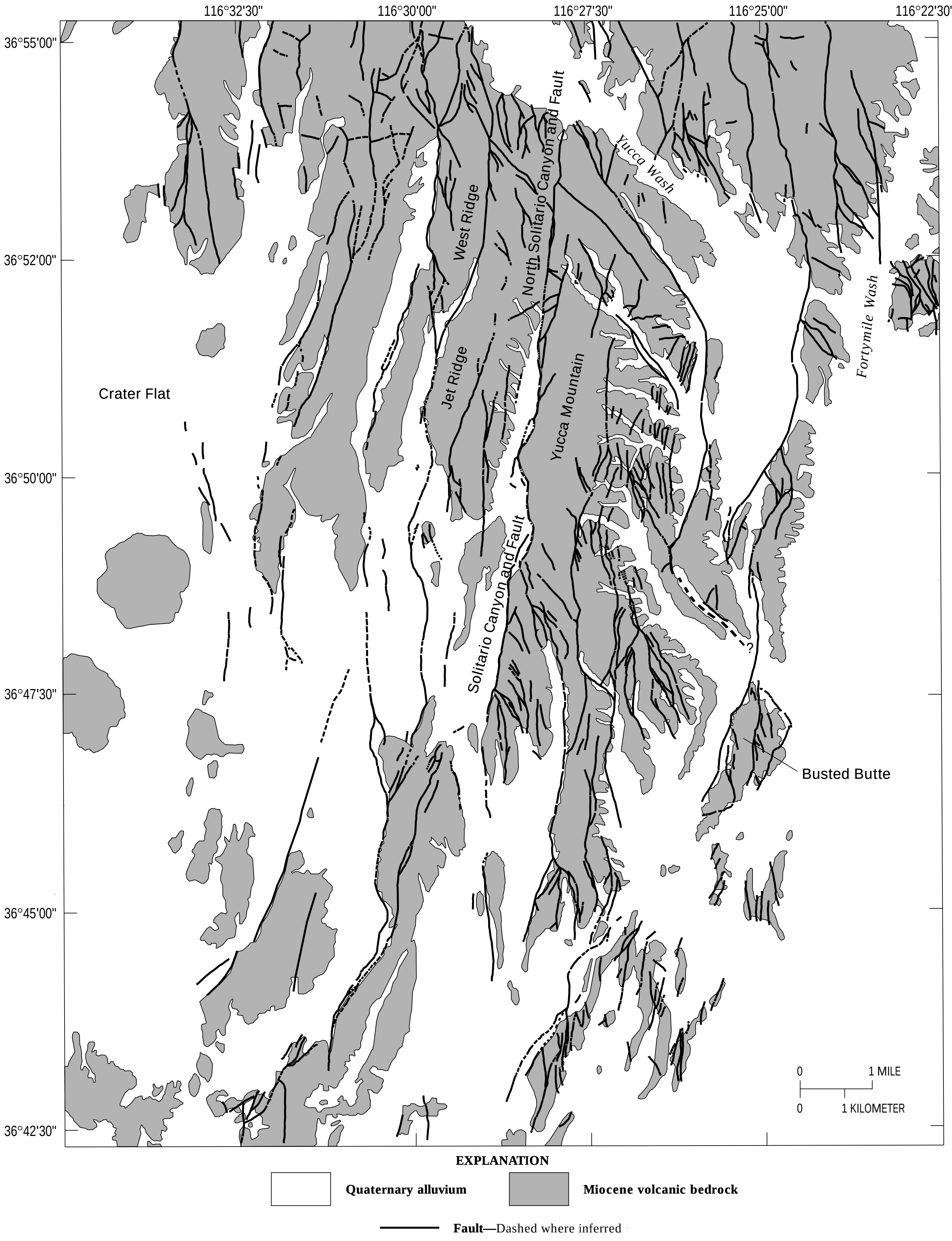

Figure 3. Location of geographic features and faults at and near Yucca Mountain.

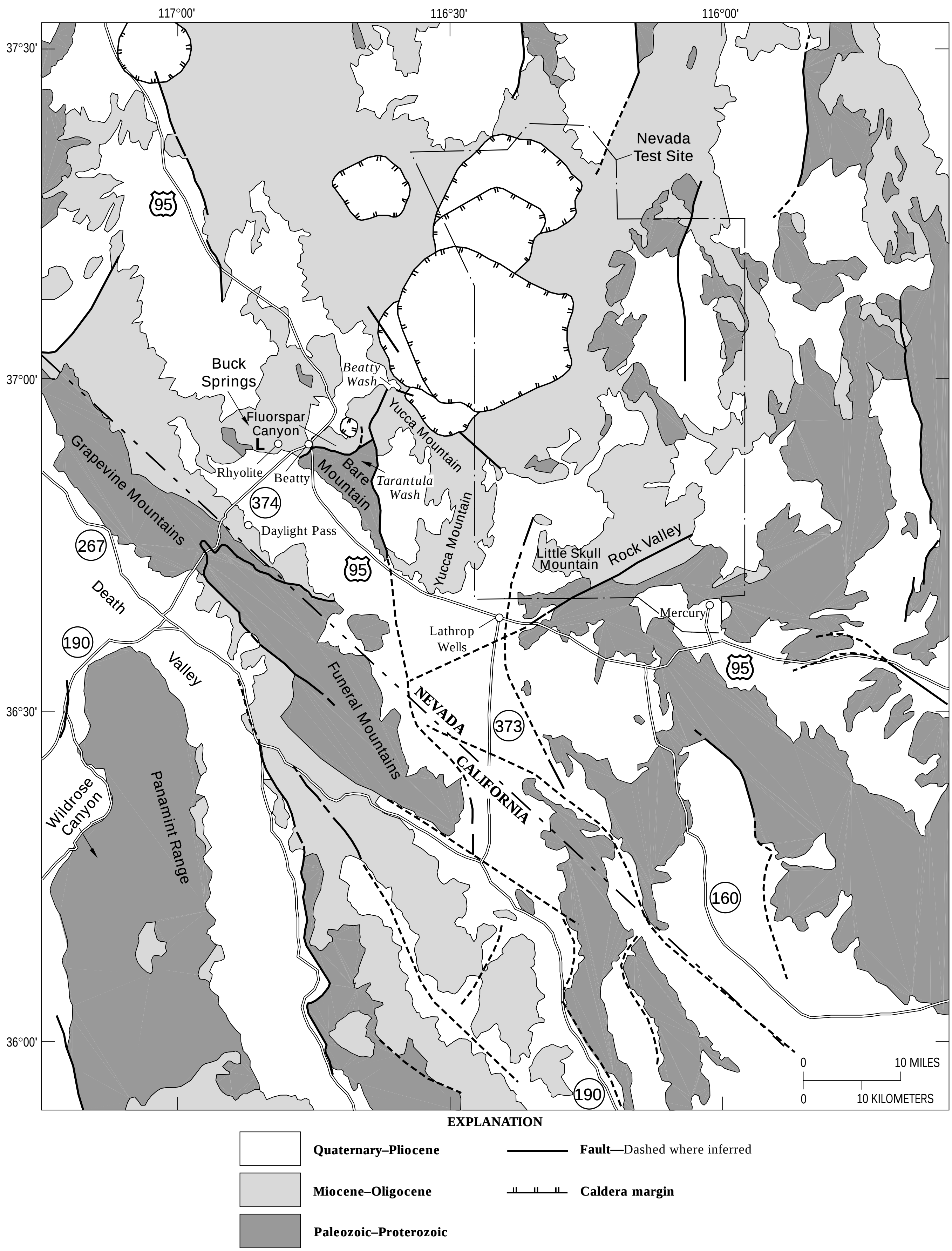

Figure 4. Location of major geographic and geologic features and the general distribution of principal stratigraphic units in Yucca Mountain region. **L**, location of precarious rock shown in figure 2*L*.

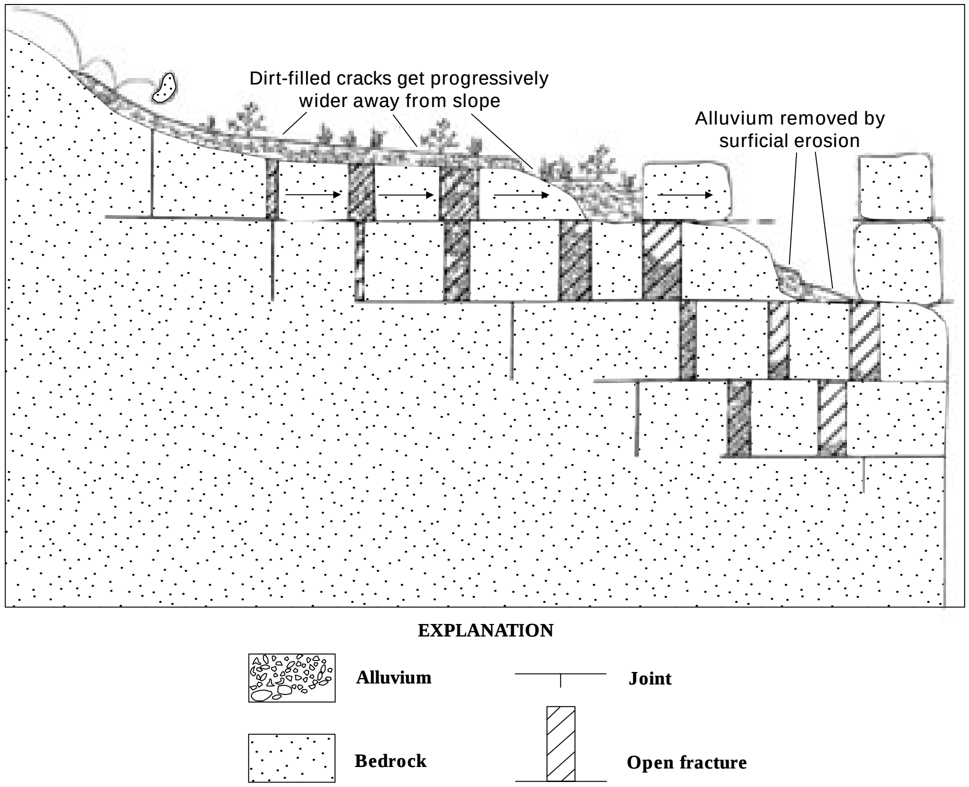

Figure 5. Schematic cross section showing development of a precariously balanced rock.

subject to intensities of about VII or greater (modified Mercalli scale), corresponding to accelerations of about 0.10 to 0.15 *g* (Bolt, 1988). Comparison of the locations of precarious rocks with respect to intensity maps of historic earthquakes in California and Nevada indicates that few zones of precarious rocks have been exposed to Intensity VII, and none are known to have been exposed to Intensity VIII. The Intensity VII survived by some precarious rocks resulted from more distant, larger earthquakes, which have lower accelerations for a given intensity (by as much as a factor of 2) than is the case for closer earthquakes (Murphy and O'Brien, 1977). Thus, these observations are in agreement with Keefer's (1984) interpretation that intensities of about VII (near-source, 0.10 to 0.15 *g*) are sufficient to cause rockfalls. We infer from the foregoing that (1) if an earthquake with Intensity VII (near-source) had occurred in or near the area of the present study during at least the last 20–40 k.y., it would probably have toppled most of the precarious rocks we have described; and (2) if an event with Intensity VIII (near-source accelerations of about 0.25–0.35 *g*) would have occurred, all would have toppled.

Conclusions

The numerous precarious rocks at Yucca Mountain are considered to be strong-motion seismoscopes that have been in operation for thousands of years, and to therefore provide direct constraints on the magnitude of ground shaking that has occurred in the area in the past. Preliminary results from the modeling and testing of rocks at Yucca Mountain, supplemented by paleoseismic evidence from the Solitario Canyon fault, indicate that many of the rocks could be toppled or dislodged by ground accelerations of less than 0.3 *g*. These results strongly suggest that the Yucca Mountain region has not been subjected to ground accelerations of this level during the last 75–80 k.y.

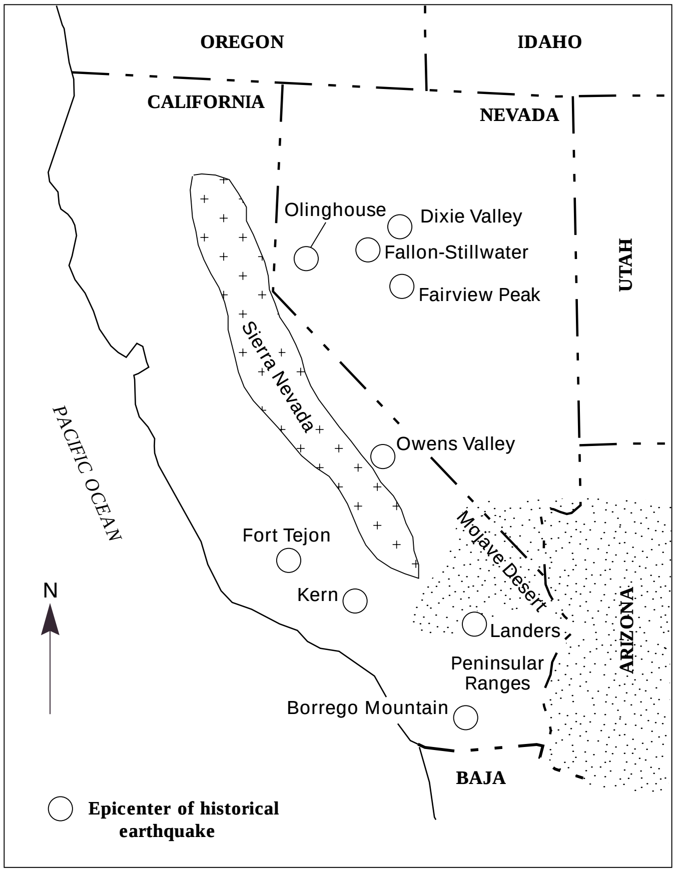

Figure 6. Location of large historical earthquakes in Nevada and California.

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