Chapter G

Cosmogenic Dating and Analysis of Scarps Along the Solitario Canyon and Windy Wash Faults, Yucca Mountain, Nevada

By Charles D. Harrington,[1] John W. Whitney,[2] A.J.T. Jull,[3] *and* William Phillips[3]

Contents

Figures

Table

[For table of abbreviations and conversions, click here]

[1]Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, N. Mex.
[2]U.S. Geological Survey, Denver, Colo.
[3]University of Arizona AMS Facility, Tucson, Ariz.

Abstract

Sharp, topographically prominent bedrock scarps bound several fault blocks at Yucca Mountain, Nevada. Historical and Holocene coseismic scarps in central and northern Nevada possess similar height, morphology, and appearance on aerial photos. The similarity of all these scarps suggests that late Holocene movement occurred on several Yucca Mountain faults. Determining the historical activity of faults near Yucca Mountain is a major focus of site characterization studies at the potential repository for high-level radioactive waste. Accordingly, this study sought to determine, by use of geomorphic analysis and a relatively new dating technique—in situ ^{14}C exposure (cosmogenic) dating—whether the scarps were initially formed as late as Holocene time, or are pre-Holocene in age.

Geomorphic field studies along the Solitario Canyon and Windy Wash scarps demonstrate that differential hillslope erosion is the primary process responsible for the topographic prominence of the Yucca Mountain scarps. Erosionally resistant siliceous Tertiary fault breccias were exhumed by erosion of poorly consolidated colluvium and nonwelded volcanic tuff away from the base of the scarps; the erosion was caused by activation of debris flows on the downthrown (downslope) side of the scarp. The bedrock scarps are shown to be older than Holocene by two important lines of evidence. First, the scarps are markedly incised at some smaller hillslope channels and are completely eroded away by larger hillslope streams. Second, most in situ ^{14}C exposure samples collected from three different sites on each bedrock scarp yield saturated (secular equilibrium between in situ production and radiogenic decay) values. These values indicate that the scarp face on both faults has been exposed for more than 20,000 years.

We believe that scarp relief has not been appreciably increased by coseismic surface rupture during at least the last 20,000 years. Thus, the striking fault-line bedrock scarps on Yucca Mountain are significantly older than the topographically similar historical and Holocene fault scarps in colluvium that are found in other parts of the Basin and Range province.

Introduction

Prominent bedrock scarps on the west side of Yucca Mountain, Nev., may be interpreted to have been formed by surface ruptures during the Holocene, or possibly during historical time, because they have steep faces that are about 1.5 m high. Understanding how these scarps evolved will help investigators evaluate the magnitude and recency of surface ruptures and lengths of fault segments. It will also provide valuable data for the analysis of potential seismic hazard in the vicinity of Yucca Mountain.

This study of scarp evolution was undertaken to determine the following: (1) the role of erosional processes in the evolution of morphology on bedrock scarps along faults that appear to have low to very low slip rates (0.1–0.001 mm/yr), (2) the usefulness of using cosmogenic dating techniques on these scarps by direct dating of the bedrock scarp face, and (3) on the basis of these dates, whether the prominent bedrock scarps on the Windy Wash and Solitario Canyon faults (fig. 1) were formed tectonically during the Holocene.

Nearly a dozen historical surface ruptures have resulted from earthquakes in the Great Basin since 1872, most of which occurred in the north-northeast-trending central Nevada–eastern California seismic belt. Maximum surface displacements range from 20 cm to 5.8 m on earthquakes varying from M_L 5.6 to M_S 7.6 (dePolo and others, 1991). Scarps of historical and Holocene ages are prominent topographic features in the Great Basin, and the relative steepness of the scarps is generally related to scarp age, and, in some cases, the age of the last surface rupture (Wallace, 1977; Mayer, 1984).

Prominent bedrock scarps bound the west side of several fault blocks in the Yucca Mountain area. In Crater Flat, for example, segments of the Solitario Canyon (fig. 2) and Windy Wash faults (fig. 3) are characterized by steep to nearly vertical bedrock scarp faces (Harrington and others, 1994). On the basis of low sun-angle photography and the prominence of the scarps, the suggestion is that several faults experienced Holocene surface ruptures (Ramelli and others, 1988).

Low sun-angle photography is a useful tool for identifying Quaternary fault activity because the low sun-angle light highlights linear features such as low fault scarps that may not be readily seen on vertical aerial photographs with minimal

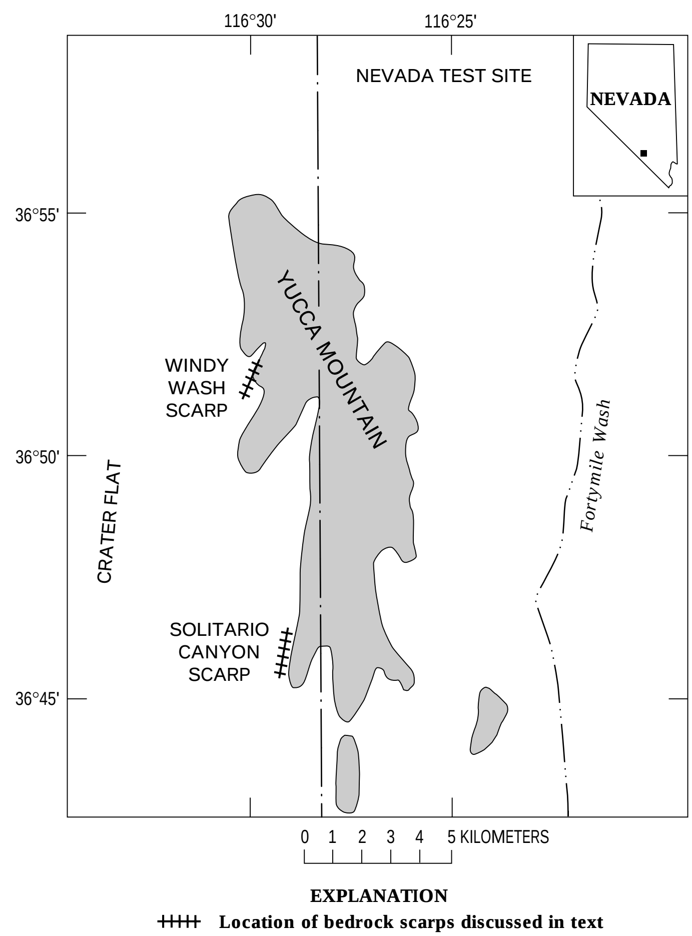

Figure 1. Index map of Yucca Mountain area showing location of bedrock scarps on Solitario Canyon and Windy Wash faults.

Figure 2. View looking east at western slope of Yucca Mountain (total relief 300 m), showing bedrock scarp along a strand of Solitario Canyon fault. Arrows bound segment of scarp that was studied.

shadows. Identifying faults that are active using low sun-angle aerial photography has become a common practice in Quaternary tectonic and seismic hazard analysis (Bell and Slemmons, 1979; Ramelli and others, 1988; Reheis, 1992; Dohrenwend and others, 1992). Where faults are located in remote regions or in areas of difficult ground access, the identification of Quaternary activity on a potential seismic source may rely entirely on interpretations from aerial photography. At Yucca Mountain both low sun-angle and vertical aerial photographs were used by U.S. Geological Survey and State of Nevada investigators to identify and map faults with suspected Quaternary activity (Swadley and others, 1984; O'Neill and others, 1992; Ramelli and others, 1988; Faulds and others, 1994). Subsequently, a strip map of each fault was made on the basis of field examinations of all fault exposures. These strip maps were compiled into a map that shows all known faults in the Yucca Mountain site area and distinguishes fault segments with known Quaternary movement from bedrock faults and fault segments with only suspected Quaternary movement (Simonds and others, 1995). The results of the present study on the age and evolution of Yucca Mountain scarps are pertinent to the interpretation of Quaternary fault activity and to the definition of fault segments, when compared to an interpretation that relies solely on low sun-angle photography.

Acknowledgments

We thank Chris Menges, Alan Ramelli, and John Oswald for assistance in the field and helpful discussions; and Jamie Gardner and John Gosse for helpful reviews. Anthony Garcia prepared the illustrations.

Methodology

Geomorphic Analysis of Scarps

A map showing the location and characteristics of scarps that occur between bedrock and surficial deposits along the traces of the Solitario Canyon and Windy Wash faults was prepared by Simonds and others (1995). During the present study, special emphasis was placed on obtaining additional and more detailed information with which to interpret the processes responsible for scarp evolution and exposure, including data on (1) the nature of the land forms and alluvial and colluvial materials associated with the scarps, (2) the character and development of hillslope drainage channels across the scarps, and (3) conditions of erosion above and below the scarps. Also, the

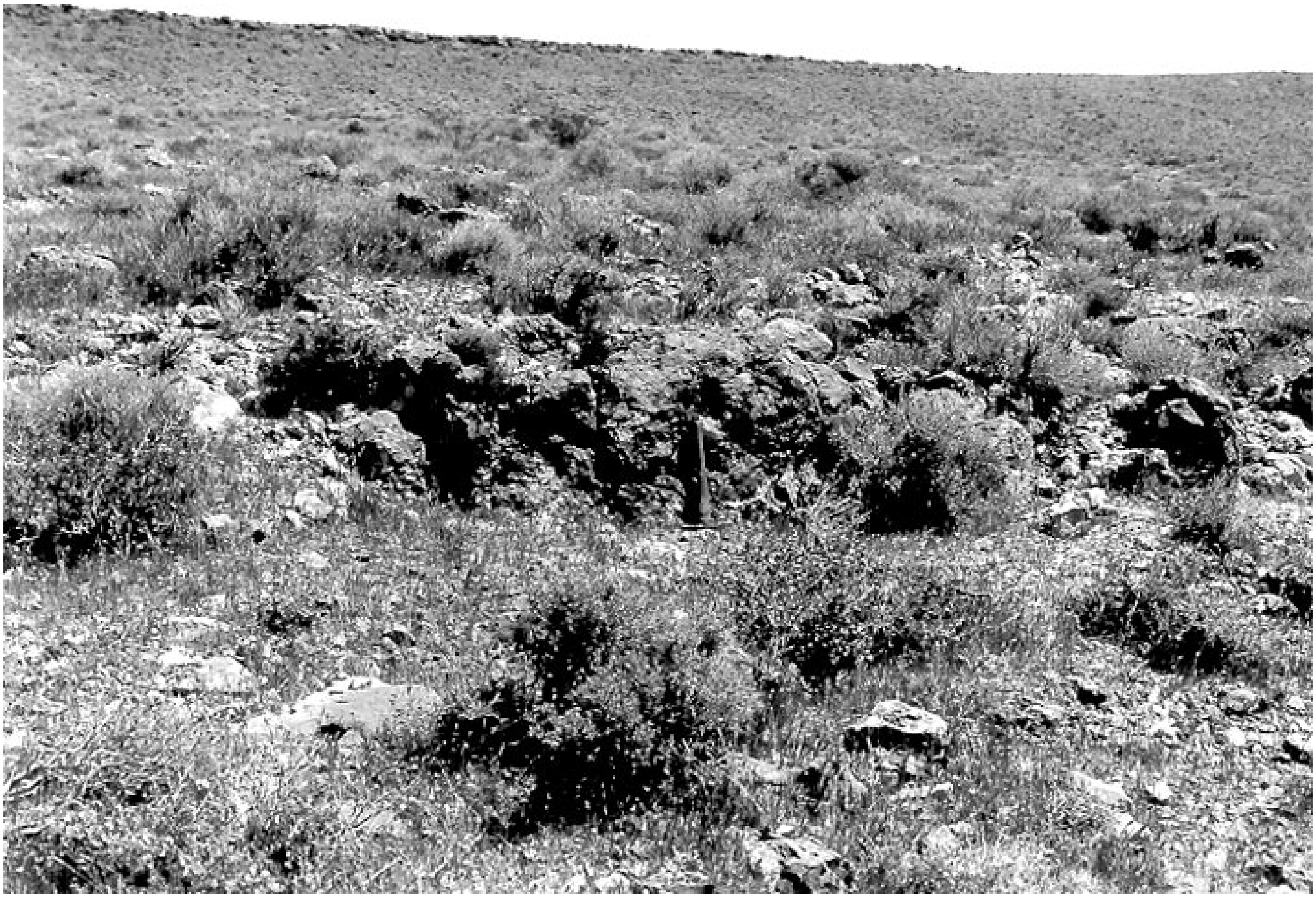

Figure 3. View of scarp formed on welded tuff along Windy Wash fault at sample site WWF-2. Hammer against scarp is 35 cm long.

positions of the most recent surface ruptures were traced where they did not coincide with the bedrock scarps.

In Situ ^{14}C Exposure Dating of Bedrock Scarps

In situ carbon-14 (^{14}C) exposure dating technique is a relatively new surface-exposure dating technique with potential for dating features formed during Holocene or historical time. An objective of the present study is to assess the applicability of surface-exposure dating for bedrock scarps by directly dating the scarp face using this technique. The scarps are formed in quartz-rich materials that are well suited to in situ ^{14}C because of its short half life (5,730 years). The technique can be used to date relatively young features (a few thousand to about 20 ka), and requires relatively small sample sizes (less than 30 g).

Sixteen samples were collected from bedrock scarps at three sites along both the Solitario Canyon and the Windy Wash fault traces. Samples were collected using a rock drill with a 1-in.-diameter core barrel, so that sample sites would not be limited to locations where samples could be easily extracted from the scarp faces. Two samples, each as long as 5 cm and containing as much as 30 g of rock, were taken from each scarp face. One sample was collected near the top and one near the base of the scarp-front slope. At localities where the scarp height was greater than 1 m, a third sample was collected from the middle of the scarp face.

The following steps were followed in the laboratory analysis of in situ produced ^{14}C:

1. Rock samples weighing 10–30 g crushed in a steel mortar and pestle.
2. Rock powder treated with 3N hydrochloric acid until no further action observed, then rinsed with distilled water and dried.
3. Samples treated with a succession of solutions (nitric acid, sodium metaborate, sulfuric acid) to remove any contaminants.
4. Samples again washed with distilled water and dried.
5. As much as 30 g of the cleaned rock powder placed in a crucible fabricated from 0.0039-inch-thick molybdenum foil.
6. Crucible loaded into a vacuum system, and suspended inside a quartz tub surrounded by a radio frequency (RF) induction coil.
7. System evacuated and a flow of helium and oxygen added.
8. Sample and crucible preheated to an estimated 500°–600° C for 30 minutes.
9. Gases collected after heating and a new gas flow of helium and oxygen added to system.

10. Recirculating pump used to assure that all evolved gases were forced through cold traps.
11. Crucible heated to white heat, ≈> 1,500°C, some using a resistance furnace rather than RF.
12. Evolved gases pumped through a manganese oxide trap to remove sulfur compounds and through a platinum/copper oxide trap at 450°C to convert all carbon compounds to carbon dioxide (CO_2).
13. CO_2 gas collected along with water and liquid nitrogen in a –196°C trap.
14. After cooling, oxygen pumped away and CO_2 separated from the water by warming the trap to –70°C (in a dry ice and alcohol mixture).
15. CO_2 collected and its volume measured, using a capacitance manometer.
16. Gas reduced to graphite in a small reaction system (Donahue and Jull, 1993); in this process the CO_2 was reduced to carbon monoxide (CO) over zinc at 450°C, which then reacted further with iron at 625°C to produce graphite.
17. Radioactive ^{14}C content of graphite measured; the graphite powder then pressed into an accelerator mass spectrometer target holder (see Donahue and Jull, 1993) and backed with a 1 mm aluminum plug.
18. Graphite sample loaded into the accelerator ion source with other samples and some standards. (Donahue, Jull, and Linick, 1990, and Donahue, Linick, and Jull, 1990, have described the accelerator mass spectrometer measurement procedures in detail.)

In situ ^{14}C analyses yield estimated ages with an uncertainty of about 10 to 20 percent, based on the present knowledge of production rates. These rates have been determined from independently dated late Pleistocene features with well-constrained ages at Tabernacle Hill, Utah, and within the Zuni-Bandera volcanic field in west-central New Mexico (Lifton and others, 1994). The production rate of in situ cosmogenic ^{14}C used to interpret the dates in the present study is 60 at/g/yr (atoms per gram per year) at an elevation of 1,160 m (3,800 ft) and at lat 36.8° N. (The bedrock scarps along both faults lie near lat 36.8° N. The elevation of the Solitario Canyon scarp is 1,160 m; the Windy Wash scarp is 43 m higher.) The production rate used was corrected for the difference in elevation of the two scarps. The additional 43 m of elevation of the Windy Wash scarp samples lessens the calculated age for these samples by about 5 percent. The production rate was also corrected for the angle between the scarp face and the horizontal (measurements are included in table 1) and by a shielding factor, using the angle from the sample location to the ridge crest that lies up slope just to the east of the scarps along both the Windy Wash and Solitario Canyon faults (in table 1). No other shielding affected any of the samples. The shielding correction to the production rate was calculated assuming an inverse cosine dependence.

Geomorphic Characterization of Scarps

The two bedrock scarps examined in this study are located along the trace of the Solitario Canyon fault on the lower west

Table 1. In situ cosmogenic ^{14}C data, Solitario Canyon and Windy Wash bedrock scarps.

Sample No.	Location	Scarp slope (degrees)	Ridge shielding (degrees)	^{14}C concentration $\times 10^5$ (at/g)	^{14}C concentration saturation $\times 10^5$ (at/g)	Exposure age (k.y.)	Scarp height (m)
Windy Wash scarp							
WWF 1-1	Top scarp	75	35	Saturated	4.75	>29	1.0
WWF 1-2	Base scarp	80	35	Saturated	4.00	>20	
WWF 2-1	Top scarp	55	10	Saturated	4.50	>20	1.5
WWF 2-2	Mid scarp	75	10	1.96	2.75	10.3	
WWF 2-3	Base scarp	60	10	Saturated	4.16	>20	
WWF 3-1	Top boulder	0	25	0.83	2.50	3.3	na[1]
WWF 3-2	Front boulder	90	25	1.5	5.00	2.9	
WWF 4-2	Top scarp	70	25	Saturated	2.93	>20	2.0
WWF 4-3	Base scarp	80	25	0.0	2.61	0.0	
Solitario Canyon scarp							
SCF 1-2	Mid scarp	50	40	Saturated	3.90	>20	1.0
SCF 1-3	Base channel	50	40	1.5	3.90	4.0	
SCF 2-1	Top scarp	65	25	Saturated	3.20	>20	1.3
SCF 2-2	Base scarp	65	25	Saturated	3.20	>20	
SCF 2-3	Back of scarp	0	25	1.12	5.00	2.1	
SCF 4-3	Top scarp	70	20	1.49	2.93	5.7	2.1
SCF 4-1	Base scarp	70	20	0.85	2.93	3.1	

[1] Not applicable.

slope of the main ridge of Yucca Mountain (fig. 2), and along the trace of the Windy Wash fault (fig. 3) at the north end of Crater Flat. In these places, the exposed scarps range in height from 0.3 m to >1.5 m. The scarps are commonly formed on a silica-cemented fault breccia of welded tuff; however, in a few places they have formed on bedrock of welded tuff. The lower face of some scarp exposures is veneered with calcium carbonate. The scarps on silica-cemented fault breccia are sharp, unbroken faces, whereas scarps formed in bedrock are characterized by a stairstep appearance of the face of the scarp.

Several lines of evidence indicate that the prominent expression of these scarp segments did not result from Holocene surface ruptures. Most, if not all, of the presently visible bedrock scarps have instead developed from a combination of erosional exhumation of a resistant fault breccia and pre-Holocene coseismic surface offsets. The geomorphic evidence is as follows:

1. Scarp relief is not consistent along the length of the scarps; areas of exposure increase markedly where the scarps intersect small hillslope drainage channels. Maximum local relief of 1.5–2.0 m is developed at the axis of the channel, and the relief decreases away from the channel axis to a minimum, typically <0.3 m, near the interchannel divide areas on the hillslope. At several localities, thin colluvial aprons grade across sections of the scarp with no apparent displacement. This pattern of variations in scarp relief, where relief is directly related to the presence and size of the hillslope channels, is not characteristic of relatively young fault scarps.

2. Larger hillslope drainage channels notch bedrock scarps. Where the bedrock scarp intersects larger hillslope drainage channels, erosional power has generally been sufficient to cut through the scarp. The size of the notch is generally related to the size of the hillslope drainage area above the scarp (fig. 4). Scarp sections as long as 4 m have been completely removed across several of the largest hillslope drainage channels. Because hillslope erosion has been demonstrated to be very slow (0.2 cm/k.y.) on Yucca Mountain (Whitney and Harrington, 1993), it is unlikely that scarps formed in resistant bedrock could become so deeply incised only during the Holocene.

3. Smaller hillslope drainage channels erode sediment from the base of bedrock scarps. Where a bedrock scarp intersects small hillslope channels and the stream power is insufficient to carve a notch, erosion at the base of the scarp produces increased scarp relief. Unconsolidated sediment is removed from the downslope side of the scarp primarily by debris flows

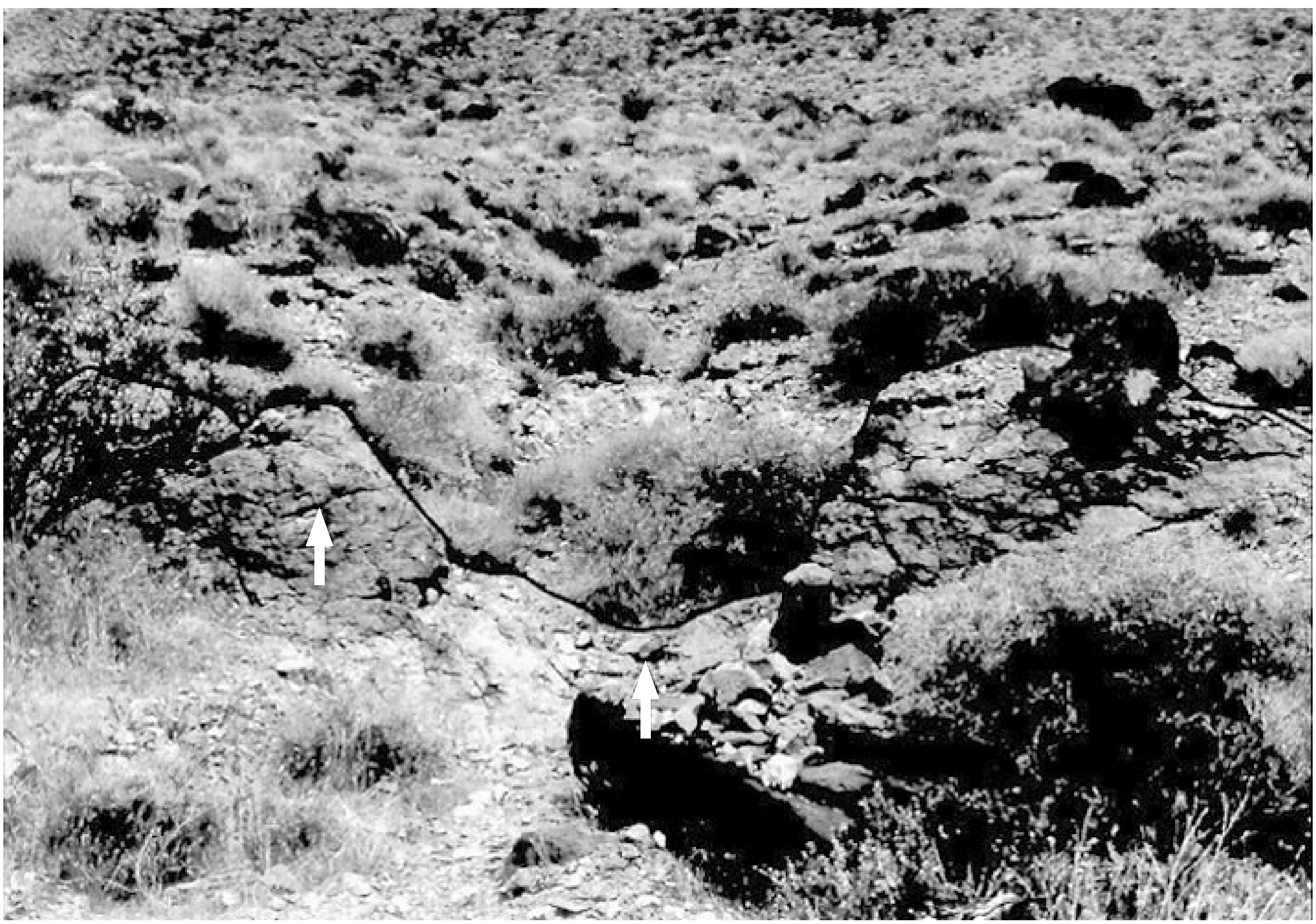

Figure 4. View of Solitario Canyon scarp, at a location where a hillslope channel has eroded away a section of the silica-cemented breccia scarp. Scarp is 1.25 m high at the V-shaped notch. Arrows point to base and side of channel.

that are activated at the scarp face by runoff across the scarp. Repeated erosion ultimately creates small triangular (in map view) basins with the scarp face as the headwall, sides that are formed of debris flow levees, and an apex that extends downslope 5–15 m (fig. 5).

4. Some scarp faces are coated with well-developed, dark rock varnish. The degree of varnish development varies little from the top to near the base of the scarp. At least several millennia are required for rock varnish to completely coat an exposed rock surface (Bull, 1991, p. 89), and the degree of rock varnish development observed along parts of these scarps probably requires an exposure time measured in tens of thousands of years. Because the dark rock varnish coating extends to the scarp base at many exposures, it is unlikely that late Holocene surface ruptures have occurred on these scarps. A young surface rupture would have exposed unvarnished bedrock surfaces at the base of the scarp.

5. The bedrock scarps do not consistently coincide with the most recently active fault trace. In places, thin (<2 m) wedges of colluvium of Quaternary age overlie nonwelded tuff of Miocene age on the downthrown side of the scarps (fig. 6). The lack of thick wedges of fault-derived colluvium indicates either that very low rates of Quaternary faulting took place along these scarps or that the topographically prominent bedrock scarps do not coincide with the presently active strand of the fault. These faults originated between 14 and 12 Ma during the Miocene pulse of extension that broke the original sequence of ash flow tuffs into fault-bounded blocks (Scott, 1991). Nonwelded tuffs were then deposited about 11.3 Ma in half grabens and against fault scarps that had formed earlier along both the Windy Wash and the Solitario Canyon faults. A combination of subsequent differential erosion and very low rates of faulting during the last 11 m.y. has partially exhumed these Miocene fault scarps.

At the south end of the Solitario Canyon scarp, the most recently active trace of the Solitario Canyon fault, which has experienced multiple surface ruptures during the Quaternary, is exposed about 35 m west of the topographically enhanced bedrock scarp (Ramelli and others, 1988). However, at the north end of the study area, the active trace of the fault coincides with the bedrock scarp. Without close examination in the field, an investigator might assume that the active fault trace also coincided with the most topographically prominent scarp along the southern section of the Solitario Canyon fault.

Figure 5. View of a topographically enhanced segment of Solitario Canyon bedrock scarp. Scarp forms head of a triangular basin with debris flow levees (L) forming basin sides. Scarp is about 2 m high at channel axis.

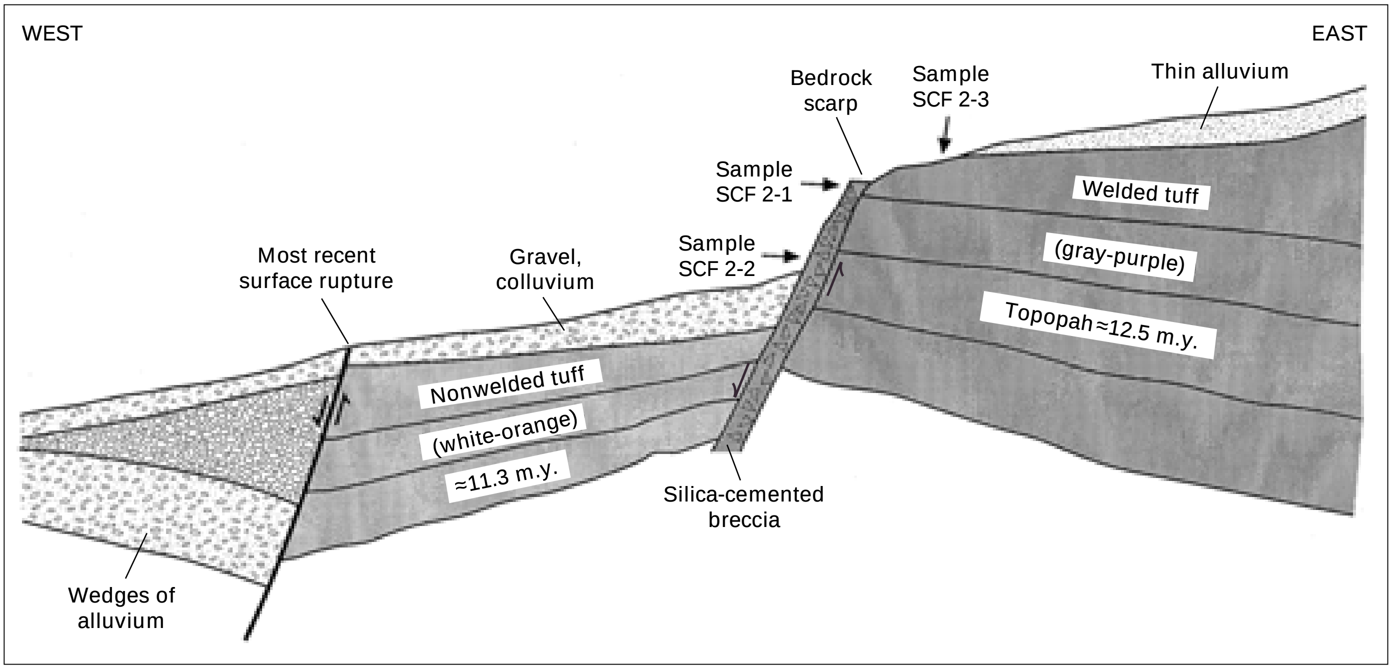

Figure 6. East-west schematic cross section of field relations at locality of Solitario Canyon bedrock scarp shown in figure 4. Fault barbs show direction of relative movement. Sample numbers refer to table 1.

Cosmogenic Geochronology

Three prominent scarp exposures were analyzed for in situ cosmogenic ^{14}C on both the northern Windy Wash fault and on the central trace of the Solitario Canyon fault. A large, unvarnished boulder (sample WWF-3), situated about 3 m upslope from the Windy Wash fault, was also sampled in order to compare its estimated age with well-varnished scarp exposures.

At sample sites WWF-1 and WWF-2 on the Windy Wash scarp and at site SCF-2 on the Solitario Canyon scarp, samples from both the top and bottom of the scarp face are saturated with respect to in situ cosmogenic ^{14}C (table 1). These saturated samples indicate that scarp faces at these three locations have surface-exposure ages greater than 20 ka. These well-varnished scarp locations therefore have not experienced increased vertical exposure by any process, tectonic or geomorphic, for at least the last 20 k.y. The unvarnished boulder (WWF-3), in contrast, was determined to be about 3 ka.

At sites WWF-4 and SCF-1, the top of the scarp face is saturated with in situ cosmogenic ^{14}C, whereas the base of each scarp site was found to be significantly younger: a middle Holocene date for SCF-1 and a modern date for WWF-4. Cosmogenic dates from site SCF-4 on the Solitario Canyon fault indicate the scarp face there was exposed during the middle Holocene. The dates of modern, 4.0 ka, and 3.1 ka at these sites indicate that exposure along the scarp base occurred at three different times, which is best explained by localized hillslope erosion at each site. This lack of concordant dates along with the dates of >20 ka at three other sample sites is strong evidence that neither fault has been appreciably enhanced by coseismic surface rupture during the Holocene.

A test was performed at site SCF-2 to examine the possibility of the scarp face being saturated, not by saturation of the exposed scarp face, but rather by vertical penetration of the ground surface above the scarp following removal of most of the overlying sediment. Sample SCF 2-3 was collected from the bedrock ground surface, 1 m back from the scarp face, and was found to be far below saturation with an exposure age of only 2.1 k.y. Thus, the saturated values of the scarp face are the result of exposure of the scarp face for a period greater than 20 k.y., and not the result of cosmogenic nuclide concentration from an earlier period of vertical cosmic ray penetration of the ground surface above the scarp. Additionally, if the scarp face was exposed during an earlier time and subsequently buried, the ^{14}C, a radioactive isotope, would begin to decay. Thus, reexposure of the scarp during the late Holocene could not result in saturated values.

Conclusions

Several geomorphic characteristics of the bedrock scarps along segments of the Solitario Canyon and Windy Wash faults indicate that hillslope erosion, rather than Holocene fault rupture, is the primary process responsible for the prominent topographic expression of these scarps. This general conclusion is based on several lines of evidence, as follows: (1) scarp height varies considerably along the length of the scarp; scarp exposure is greatest where the scarp is crossed by hillslope channels, and is least, or nonexistent, near interchannel divides on the hillslope; (2) small triangular erosion basins commonly form on the downthrown side of the scarp as poorly consolidated colluvium or tuff is carried away from bedrock scarp by runoff-induced debris flows; (3) the bedrock scarp does not consistently coincide with the most active fault trace; and (4) cosmogenic ^{14}C dating indicates that large segments of the bedrock scarp have been exposed for more than 20 k.y. The dates at the base of the scarp range from >20 ka through the middle Holocene to the present, which supports the interpretation that these scarps continue to be exposed primarily by erosion and not by coseismic surface offsets.

In this study, cosmogenic radiocarbon dates, combined with geomorphic observations, demonstrate that prominent scarps were not created by recent or Holocene coseismic surface ruptures, and point out the pitfalls of assuming the presence of Holocene surface ruptures solely on the basis of a topographically prominent scarp. These results also demonstrate that in situ cosmogenic ^{14}C dating has significant potential for dating tectonic landforms.

References Cited

Bell, E.J., and Slemmons, D.B., 1979, Recent crustal movements in the central Sierra Nevada-Walker Lane region of California-Nevada—Part II, The Pyramid Lake right-slip fault zone segment of the Walker Lane: Tectonophysics, v. 52, p. 571–583.

Bull, W.B., 1991, Geomorphic responses to climatic change: New York, Oxford University Press, 326 p.

dePolo, C.M., Clark, D.G., Slemmons, D.B., and Ramelli, A.R., 1991, Historical surface faulting in the Basin and Range province, western North America—Implications for fault segmentation: Journal of Structural Geology, v. 13, p. 123–136.

Dohrenwend, J.C., Schell, B.A., McKittrick, M.A., and Moring, B.C., 1992, Reconnaissance photogeologic map of young faults in the Goldfield $1° \times 2°$ quadrangle, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2183, scale 1:250,000.

Donahue, D.J., and Jull, A.J.T., 1993, Some applications of accelerator mass spectrometer measurements made at the University of Arizona, *in* International Conference on Accelerator Mass Spectrometry, Beijing, Proceedings: Long, World Scientific.

Donahue, D.J., Jull, A.J.T., and Linick, T.W., 1990, Some archaeological applications of accelerator radiocarbon analysis: Nuclear Instrumental Methods, B45, p. 561–564.

Donahue, D.J., Linick, T.W., and Jull, A.J.T., 1990, Isotope-ratio and background corrections for accelerator mass spectrometry radiocarbon measurements: Radiocarbon, v. 32, p. 135–142.

Faulds, J.E., Bell, J.W., Feurerbach, D.L., and Ramelli, A.R., 1994, Geologic map of part of Crater Flat, southern Nevada: Nevada Bureau of Mines and Geology Map 101, scale 1:24,000.

Harrington, C.D., Whitney, J.W., Jull, A.J.T., and Phillips, William, 1994, Implications of surface-exposure dating of scarps along the Solitario Canyon and Windy Wash faults, Yucca Mountain, Nevada, by in situ produced cosmogenic ^{14}C: Geological Society of America Abstracts with Programs, v. 25, p. A303.

Lifton, N.A., Phillips, William, Jull, A.J.T., and Quade, Jay, 1994, Integrated late Quaternary production ratios for in situ-produced cosmogenic ^{14}C from Lake Bonneville shoreline quartzites, using improved extraction techniques: Geological Society of America Abstracts with Programs, v. 26, p. A257.

Mayer, L.M., 1984, Dating Quaternary fault scarps formed in alluvium using morphologic parameters: Quaternary Research, v. 22, p. 300–313.

O'Neill, J.M., Whitney, J.W., and Hudson, M.R., 1992, Photogeologic and kinematic analysis of lineaments at Yucca Mountain, Nevada—Implications for strike-slip faulting and oroclinal bending: U.S. Geological Survey Open-File Report 91-623, 24 p.

Ramelli, A.R., Bell, J.W., and dePolo, C.M., 1988, Evidence for distributive faulting at Yucca Mountain, Nevada: Geological Society of America Abstracts with Programs, v. 20, p. A383.

Reheis, M.C., 1992, Aerial photographic interpretation of lineaments and faults in late Cenozoic deposits in the Cactus Flat and Pahute Mesa 1:100,000 quadrangles and the western parts of the Timpahute Range, Pahranagat Range, Indian Springs, and Las Vegas 1:100,000 quadrangles, Nevada: U.S. Geological Survey Open-File Report 92-193, 14 p., 3 pls.

Scott, R.B., 1991, Preliminary geologic map of the Vigo NW quadrangle, Lincoln County, Nevada: U.S. Geological Survey Open-File Report 91-389, scale 1:24,000, 47 p.

Simonds, F.W., Whitney, J.W., Fox, K.F., Ramelli, A.R., Yount, J.C., Carr, M.D., Menges, C.M., Dickerson, R.P., and Scott, R.B., 1995, Map showing fault activity in the Yucca Mountain area, Nye County, Nevada: U.S. Geological Survey Miscellaneous Investigations Map I-2520, scale 1:24,000.

Swadley, W C, Hoover, D.L., and Rosholt, J.N., 1984, Preliminary report on Late Cenozoic stratigraphy and faulting in the vicinity of Yucca Mountain, Nye County, Nevada: U.S. Geological Survey Open-File Report 84-788, 43 p.

Wallace, R.E., 1977, Profiles and ages of young fault scarps, north-central Nevada: Geological Society of America Bulletin, v. 88, p. 1267–1281.

Whitney, J.W., and Harrington, C.D., 1993, Relict colluvial boulder deposits as paleoclimatic indicators in the Yucca Mountain region, southern Nevada: Geological Society of America Bulletin, v. 105, p. 1008–1018.