Chapter F

A 3.7-Million-Year Offset Rate on the Windy Wash Fault at the South End of Yucca Mountain, Nevada

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Abstract

The Windy Wash fault is situated in Crater Flat, Nye County, Nevada, about 3.5 kilometers west of the potential high-level radioactive-waste repository at Yucca Mountain. Near the south end of the mountain, the Windy Wash fault offsets a 3.7-million-year old basalt flow. Three shallow seismic refraction profiles were completed to determine the thickness of alluvium over the offset basalt and to determine whether or not fault offset contains a lateral component of slip.

The maximum burial depth of the basalt along the 823-meter-long profile is 56 meters. The top of the exposed offset basalt flow on the footwall is 40.5 meters above the adjacent land surface on the hanging wall. A seismic refraction profile at the north end of the exposed basalt indicates that a

maximum of 18 meters of left-lateral slip is associated with 96 meters of vertical slip on the Windy Wash fault. If 2 meters of surface erosion has occurred on the exposed basalt, and the ratio of vertical to left-lateral slip on the fault is 5:1, then a net offset of about 101 meters has occurred during the past 3.7 million years. The long-term slip rate since the middle Pliocene is about 0.027 millimeters per year. This slip rate is about equal with the sum of Quaternary slip rates on the Solitario Canyon, Fatigue Wash, and central Windy Wash faults, all of which intersect the southern Windy Wash fault. The similarity between late Quaternary and Pliocene slip rates indicates that the deformation of Yucca Mountain has been nearly constant for the last 3.7 million years.

Introduction

Yucca Mountain consists of a series of subparallel ridges that were formed by the breakup of a large sheet of Miocene ashflow tuffs into blocks bounded by north-trending normal faults (fig. 1). Extension during the last 13 m.y. has resulted in gently eastward dipping blocks that are partly buried by adjacent alluvial, colluvial, and eolian deposits. The largest of these blocks, Yucca Ridge, is being considered as a potential geologic repository for high-level radioactive waste. An important aspect of geologic characterization of this site is the assessment of seismic hazards. Information derived from surface and subsurface exposures of each bounding fault can be used to assess fault length, style of faulting, fault dip, slip rate, and recurrence interval of paleoseismic surface ruptures. It is also important to know whether rates of fault activity have increased, decreased, or remained the same during the last several million years as a basis for predicting future activity.

This report presents the results of an investigation to define the long-term rate of slip on the Windy Wash fault. A shallow seismic refraction technique was used to determine the amount of alluvium that overlies an offset Tertiary basalt flow on the downthrown block adjacent to the Windy Wash fault. By comparing the offset on the faulted Tertiary basalt with offset of

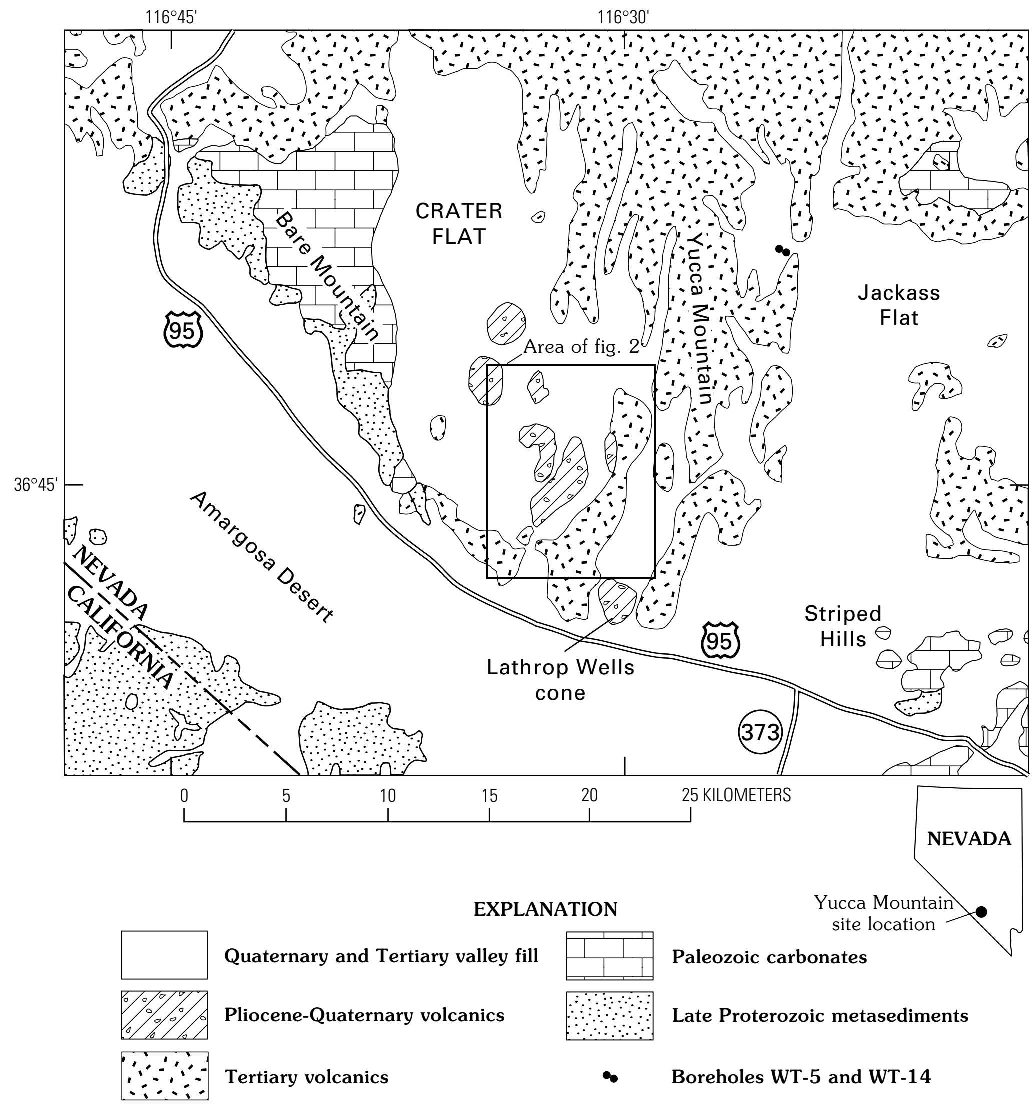

Figure 1. Generalized geology of the Yucca Mountain region, southern Nevada (modified from Faulds and others, 1994).

dated Quaternary deposits, the long-term slip rate on the Windy Wash fault can be compared with Quaternary slip rates on other Yucca Mountain faults that have been determined from trench studies.

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Windy Wash Fault

The Windy Wash fault, located 3.5 km west of Yucca Ridge, is one of six north-trending and block-bounding faults at Yucca Mountain that contain evidence of Quaternary faulting. The fault can be traced nearly continuously for about 25 km from the south rim of the Claim Canyon caldera to the southeast edge of Crater Flat (Faulds and others, 1994; Simonds and others, 1995). A fault-line scarp defines the northern portion of the fault (Harrington and others, this volume). A southeast splay of this fault crosses the fault block and appears to merge with the Fatigue Wash fault. Less than 12 km south of this junction, the Fatigue Wash fault intersects the Windy Wash fault at the north end of the southwest ridge of Yucca Mountain. This middle segment of the Windy Wash fault crosses eastern Crater Flat and displays both east- and west-facing scarps in alluvial deposits. The southern segment of the fault forms a fault-line scarp along the west side of the southwest ridge of Yucca Mountain. Another splay of the Windy Wash fault splits southeastward and strikes toward the west edge of the Lathrop Wells cinder cone. The average dip on the Windy Wash fault is 63° W.; sense of slip on slickensides ranges from dip-slip to high-angle left oblique slip (Simonds and others, 1995). The left oblique component is also demonstrated by en echelon, left-stepping fault scarps and rhomboid-shaped pull-apart grabens (O Neill and others, 1992).

About 2 km south of the north end of the southwest ridge of Yucca Mountain, the Windy Wash fault offsets a basalt flow that abuts the ridge. Near the middle of the flow, a southwestern splay of the southern Solitario Canyon fault intersects the Windy Wash fault. The basalt flow is part of an eroded complex of Pliocene vents and flows that erupted in southeastern Crater Flat 3.7 Ma (Vaniman and others, 1982).

Seismic Refraction Survey

Location of Seismic Profiles

The seismic refraction survey was conducted during June 1993 in the southeastern part of Crater Flat and consisted of three profiles which totaled 1,700 m (fig. 2). Profiles A and B trend generally north and are positioned adjacent to the north end and the central section of the Pliocene basalt flow exposed along the east side of Windy Wash. These profiles were also positioned parallel to the trace of the Windy Wash fault and are used to determine the thickness of the alluvium overlying the hanging wall of the fault. Profile A was also used to estimate the lateral-slip component along the fault at the north end of the flow. Profile C was positioned at the shortest perpendicular distance between the basalt flow exposed to the east, which is downfaulted by the Windy Wash fault, and another exposed basalt flow to the west. This profile, which is about 825 m long, depicts depth estimates to marker units in the hanging wall beneath Windy Wash and determines whether or not the flows exposed on opposite sides of Windy Wash were connected and therefore originated as one flow.

The north-trending A and B profiles are generally parallel to the exposed basalt flow that forms a topographic bench above and west of Windy Wash. There was a concern that, during seismic profiling, geophones along these profiles might detect waves refracted laterally from this bench on the footwall, and that arrivals from these waves could be confused with arrivals from the buried units. Profiles A and B are located 125 m and 170 m west of the surface trace of the Windy Wash fault, respectively. All of the first-arrivals below profiles A and B were derived from refraction surfaces at depths less than the distance to the potential side-wall refractor; thus they can safely be assumed to be from refractors vertically under the geophone spread.

Description of Equipment, Data Collection, and Technique

An EG&G Geometrics model ES-2415F, 24-channel signal-enhancement seismograph was used to collect the seismic refraction data. The seismograph is housed in a portable, weatherproof aluminum case and operates from a 12-volt direct-current power supply. Incoming seismic signals are automatically digitized and stored in an internal memory. The seismic-wave traces are displayed on a cathode-ray tube screen and adjusted by the operator for optimal resolution of the first-arrival energy before they are printed out as a permanent record on electrosensitive paper. A two-component explosive, buried a few feet below land surface, was used as the energy source. The size of the shot ranged between 2 and 5 pounds (0.9–2.25 kg), which provided excellent first-arrival energy. Initiation of the charge and seismograph was accomplished using a seismic-source synchronizer system operated by radio signals. This system provides accurate, reliable timing between source and seismograph at long distances.

The seismic profiles are made up of one or more 335-m geophone spreads that were shot end-to-end to provide continuous coverage of subsurface interfaces beneath each profile. The spreads consisted of 12 vertical geophones with a natural frequency of 14 hertz that were spaced either 15 or 30 m apart. Each spread was reversed (that is, shots were obtained in both directions) and center shots were made for several spreads.

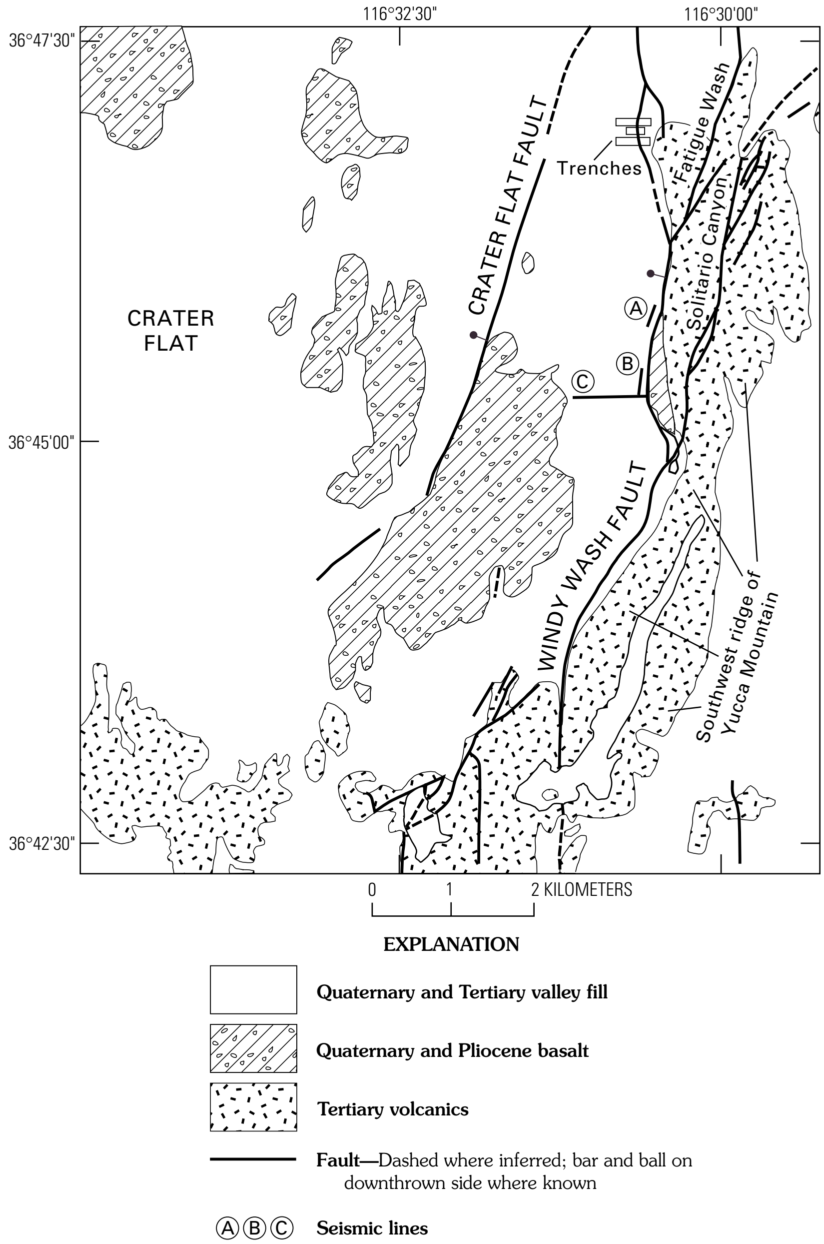

Figure 2. Simplified geology of southern Yucca Mountain and Crater Flat.

Source offset distances were equal to one geophone interval and were in-line with each geophone spread.

The seismic refraction data were initially interpreted in the field from time-distance curves using the intercept-time formula of Dobrin (1976). Subsequent interpretation was done using a computer modeling procedure based on a delay-time technique developed by Barthelmes (1946), modified by Pakiser and Black (1957), and further developed by Scott and others (1972) and by Scott (1973, 1977a, 1977b, and 1993). The program creates an initial two-dimensional depth model using the delay-time method. The depth model is then refined by a series of ray-tracing iterations to minimize discrepancies between the measured travel times and the corresponding times traced through the depth model. In addition to the basic principles and limitations inherent in the seismic refraction technique, the computer model requires that the seismic refractors are continuous beneath the profiles and that each layer beneath a profile has constant horizontal and vertical velocities, which may not necessarily be equal. Because of the requirement that refractors must be continuous beneath the spread in order to use the computer model, the two seismic spreads for profile A were interpreted individually, as discussed in the following section.

Analysis of Seismic Profiles

To measure seismic-velocity of near-surface materials, an experimental geophone spread was set up near the south end of the basalt flow. This spread used a 15-m phone spacing and was 200 m long, which allowed detection of a 15- to 18-m-thick unconsolidated gravelly layer. By reversing the shots along the line of geophones, direct-wave velocities from this layer were measured that ranged from 2,200 ft/s to 3,500 ft/s[1] and averaged about 3,000 ft/s. Results from the center shot indicate the presence of a slower velocity layer (about 1,700 ft/s) at depths of less than 1.5 m below land surface. This thin near-surface layer was not considered in subsequent interpretations.

A three-layer velocity model was chosen to represent the subsurface geology beneath the three profiles. A fixed velocity (V1) of 3,000 ft/s was used to represent layer 1, which is unconsolidated alluvium. Measured seismic refraction velocities (V2) for layer 2 ranged from 4,000 ft/s to 4,400 ft/s. Layer 2 is interpreted to represent unconsolidated to semiconsolidated alluvium that probably contains calcareous soils. Seismic velocities for layer 3 (V3) are interpreted to have refracted in the Pliocene basalt flow and range from 9,500 ft/s to 15,000 ft/s. The lower velocities probably represent the thin edge of the buried basalt that is highly fractured and perhaps discontinuous, whereas the higher velocities reflect more competent and thicker sections of basalt. This interpretation is consistent with observations of the exposed flow.

Profile A

The center section of profile A is positioned about 140 m west of the north end of the exposed basalt flow on the footwall of the Windy Wash fault (fig. 2). The time-distance curve and the velocity-depth cross section interpreted beneath profile A are shown in figure 3. Profile A was shot in two spreads that overlap at seven geophone locations along the profile (150–335 m). Most of spread 1, to the south, is opposite the exposed basalt body, whereas most of spread 2, to the north, is not (fig. 2).

Spread 1 (south spread) was interpreted using the computer model because both the forward and reversed shots produced refracted first arrivals from the top of the basalt, which indicates that the basalt is continuous beneath spread 1. Spread 2 (north spread) was interpreted by applying the intercept-time formula to the forward and reverse shots.

The general appearance of the combined traveltime curves indicates that the Pliocene basalt flow is not continuous beneath this profile, but rather that it terminates at the 185-m marker beneath the north end of spread 1, about 18 m south of the end of the exposed basalt. Because the buried basalt flow probably thins and ends in a train of basalt boulders, 18 m is the apparent maximum amount of left-lateral slip on the 3.7 Ma basalt. Although the shape of the traveltime curve generated by spread 2 is ambiguous, it may indicate lateral changes in velocities caused by a decrease in the thickness of competent basalt toward the north. A similar traveltime curve which shows no inflection in one direction and a single abrupt break in the opposite direction is presented by Ackermann and others (1986, fig. 8). The computed velocity for the basalt beneath profile A is lower than that expected and indicates that the basalt flow thins and is fractured to the north, as is observed at the north end of the exposed flow. The calculated thickness of the alluvium overlying the basalt beneath spread 1 ranges from 61 m to about 40 m.

Profile B

Profile B is located opposite the center section of the basalt flow that abuts the southwest ridge of Yucca Mountain, approximately 670 m south of profile A (fig. 2). The south end of profile B connects at nearly right angles with profile C. Forward (north), reverse (south), and center shots were made along this profile, and the resulting traveltime curves are presented in figure 4. The seismic refraction velocity of the basalt (layer 3) was measured at 13,000 ft/s, which indicates that the basalt flow beneath this profile is more competent than that under profile A. The thickness of alluvium above the basalt varies from 37 to 67 m; the median depth is about 52 m. The variation in depth can be partly explained by the fact that this seismic line crossed an alluvial fan.

Profile C

Profile C is nearly perpendicular to the Windy Wash fault and the west edge of the exposed basalt (fig. 2); it is made up of several geophone spreads that overlap to provide a continuous subsurface profile about 825 m long. Profile B intersects this profile at the 700-m marker. Measured seismic refraction velocities of the basalt flow beneath this profile ranged from 11,000 ft/s to 15,000 ft/s and averaged about 13,600 ft/s. The traveltime curves shown in figure 5 clearly show that the buried basalt (layer 3) steadily increases in depth eastward toward the Windy Wash fault, which indicates that the offset basalt flow was originally continuous between the two exposed flows. Maximum alluvial cover over the basalt is 56 m at the closest approach to the Windy Wash fault. The profile could not be extended closer to the exposed fault, because of the potential problem of side-wall reflection from the hillslope adjacent to the exposed flow.

The south end of profile B terminates against profile C about 120 m west of the east end of profile C. A difference of about 4.5 m to the top of the basalt at this intersection of the two profiles probably is due to the different measured velocities used to compute depth to layers 2 and 3. On profiles B and C, layer 2 velocities were measured at 4,200 ft/s and 4,400 ft/s; and on layer 3 (the basalt), they were measured at 13,000 ft/s and 13,600 ft/s. At a depth of about 75 m below the surface, there appears to be about a 6 percent error between the calculated depths to the top of the basalt below profiles B and C.

Long-Term Slip Rate on the Windy Wash Fault

The maximum depth of the basalt below the surface at the east end of profile C is about 56 m. The topographic relief between the end of profile C, which was located on alluvium in the wide streambed that drains Crater Flat, to the highest point

[1]Velocities are given in feet per second (ft/s), which is an accepted standard for reporting seismic profile data.

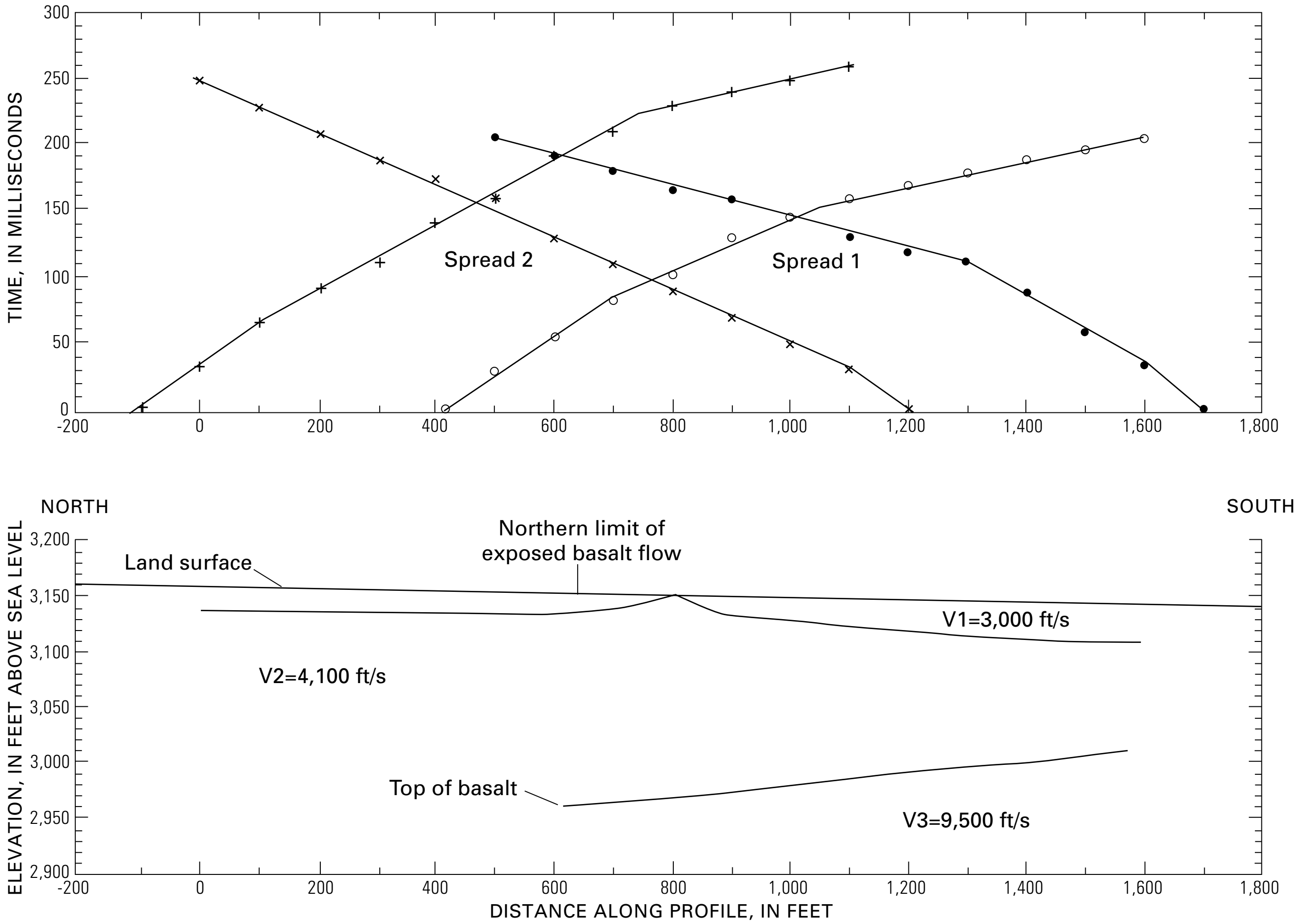

Figure 3. Time-distance curve and velocity-depth cross section of profile A, Windy Wash. (Note that distances and velocities are given in feet and feet per second rather than in metric units, which is an accepted standard for displaying seismic profile data.)

on the upthrown basalt is about 41 m. The apparent vertical offset of the basalt flow is about 97 m.

Seismic line B was located perpendicular to and extended northward from near the east end of line C. It is nearly parallel to the Windy Wash fault. The north end of the line is closer to the fault than is the east end of profile C, and the calculated depth to the basalt surface was 10.6 m deeper at 67 m. However, the topographic relief from the surface at the north end of profile B to the top of the basalt is about 30 m, nearly 11 m less than the relief at the end of profile C, because seismic line B was situated on an alluvial fan. Thus, both the perpendicular and parallel refraction lines agree on an apparent vertical offset of about 97 m on the Tertiary basalt flow.

Harrington and Whitney (1991) calculated that hillslope erosion rates in the Yucca Mountain area were low, about 1.2 mm/k.y. However, this rate was determined from hillslope colluvium, not bedrock. Because the rate of surface erosion on the exposed basalt appears to be about half the hillslope rate, or about 2 m of total surface erosion during the last 3.7 k.y., this amount is added to the vertical offset. On the basis of the maximum apparent lateral slip (about 19 m) measured from profile A, the net dip-slip has a 5:1 ratio of vertical to left-lateral movement. The total net slip, then, is about 100 m, and the average annual slip rate since the basalt was deposited 3.7 Ma is about 0.027 mm/yr.

Comparison of Miocene and Quaternary Slip Rates at Yucca Mountain

A long-term average slip rate can be calculated for the Paintbrush Canyon fault, which lies east of Yucca Mountain, for the last 13 m.y. Based on subsurface borehole data, the Topopah Spring Tuff of the Paintbrush Group is offset about 360 m along this fault (Dickerson and Spengler, 1994). The long-term offset rate is slightly less than 0.03 mm/year, nearly the same rate (0.027 mm/yr) calculated for the southern Windy Wash fault in this study for the last 3.7 m.y. The fact that similar slip rates can be calculated on rocks of substantially

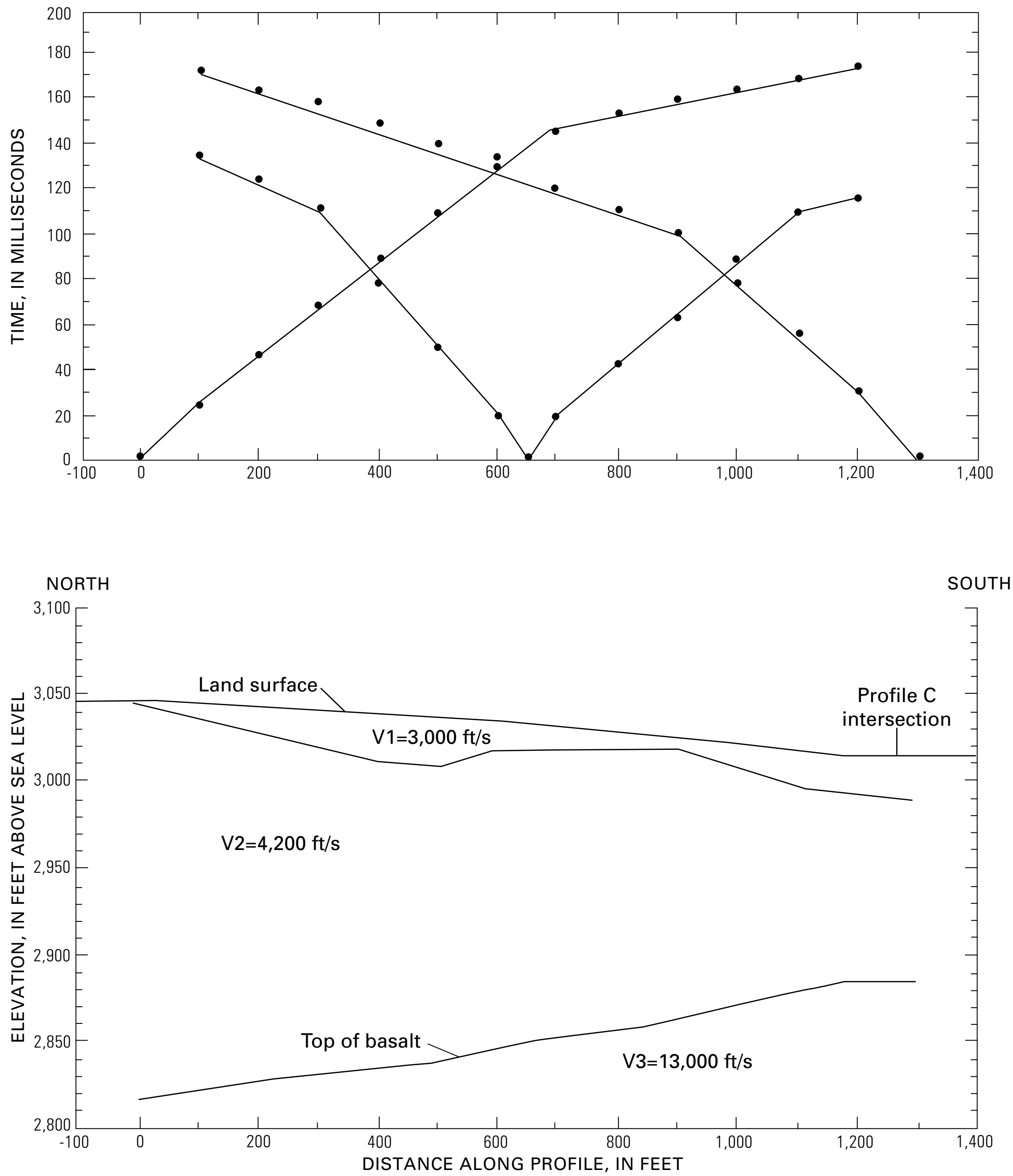

Figure 4. Time-distance curve and velocity-depth cross section of profile B, Windy Wash. (Note that distances and velocities are given in feet and feet per second rather than in metric units, which is an accepted standard for displaying seismic profile data.)

different ages may suggest that deformation has proceeded at nearly constant rates from 13 Ma to the present. However, earlier investigators (Scott, 1990; Carr, 1984) concluded that middle Miocene slip rates were likely an order of magnitude (0.01–0.05 mm/yr) higher than Quaternary rates. If a substantial amount of the total deformation took place during the middle Miocene, then a significant reduction in activity may have taken place during the late Miocene. Fox and Carr (1989) suggested that renewed extension began when the 3.7 Ma basalts were extruded in Crater Flat. This renewed extension was evidently at a much lower rate than during the time of maximum extension in this region.

Two trenches are located across the Windy Wash fault north of the fault's intersections with the Solitario Canyon and Fatigue Wash faults (fig. 2). Offset alluvial units and colluvial wedges in these trenches indicate several episodes of Quaternary surface faulting, the most recent of which occurred during the last 5 k.y. (Whitney and others, 1986). About 1.2 m of offset are recorded by the last four surface ruptures. The original dating of the offset sediments by the uranium-trend method (Swadley and others, 1984) indicates that these four faulting episodes occurred during the last 250–300 k.y., which translates to an annual slip rate of about 0.008 mm/yr. Recent uranium-series dating in these trenches by Peterson and others (1995) indicates that the

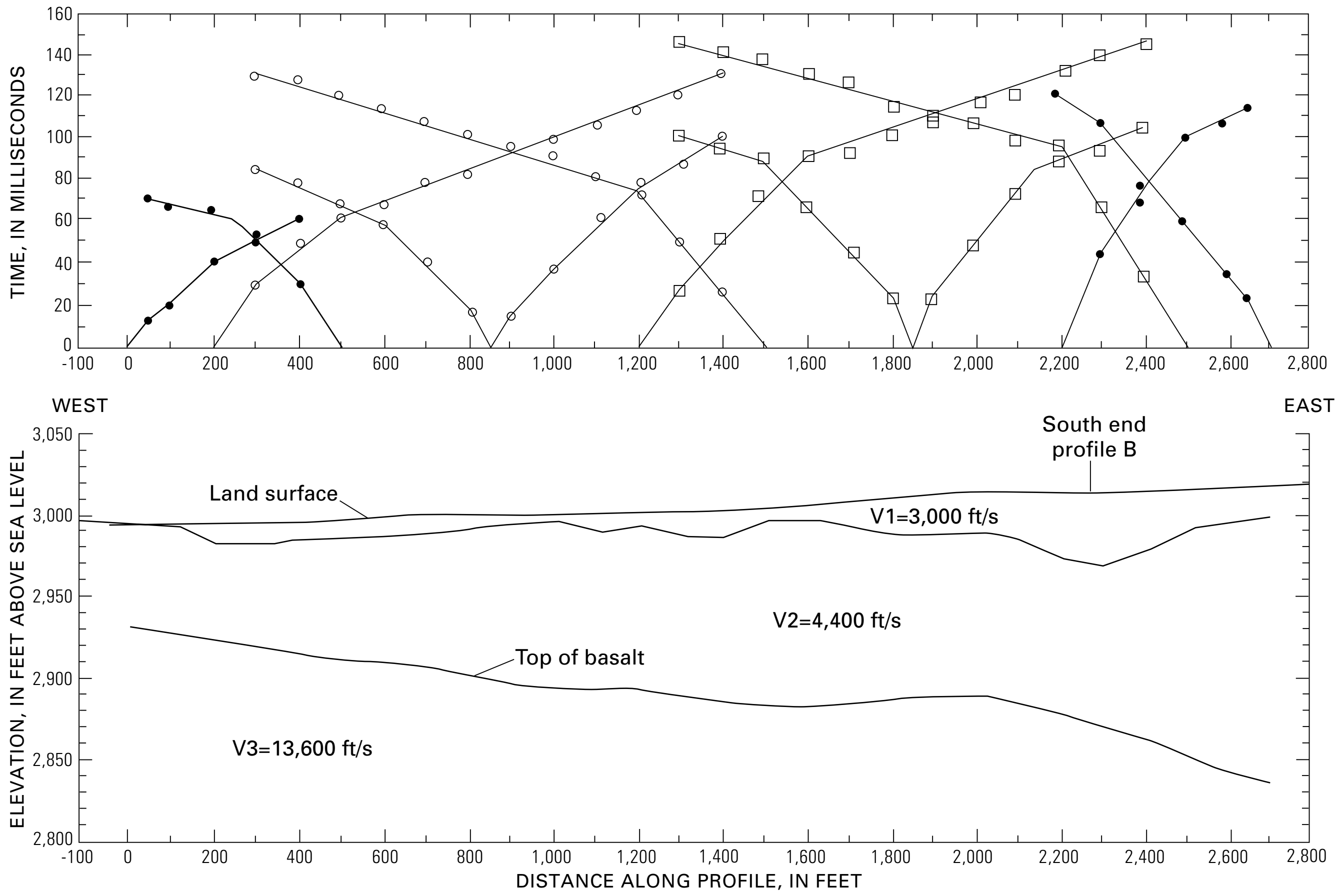

Figure 5. Time-distance curve and velocity-depth cross section of profile C, Windy Wash. (Note that distances and velocities are given in feet and feet per second rather than in metric units, which is an accepted standard for displaying seismic profile data.)

age of the soil carbonate on the youngest faulted gravel unit is 82.4 ± 9.4 ka. Assuming that the age of the lower part of the faulted gravel is about 100 ka instead of 250 ka, the Quaternary slip rate of the Windy Wash fault would be about 0.012 mm/yr. Recent uranium-series dating of several siliceous rinds on cobbles collected from the base of one trench indicates that about 2.6 m of apparent vertical slip occurred during about 270 ka (K.R. Ludwig, written commun., 1995). This relationship also indicates a Quaternary slip rate of about 0.01 mm/yr. By comparison, slip rates calculated for other major faults at Yucca Mountain that display evidence of Quaternary offset include: Bow Ridge fault, 0.002–0.007 mm/yr; Paintbrush Canyon fault, 0.001–0.03 mm/yr; and Stagecoach Road fault 0.02–0.07 mm/yr (C.M. Menges, written commun., 1999).

The long-term slip rate of 0.027 mm/yr on the southern Windy Wash fault appears to be more than twice the rate of the revised late Quaternary rate of 0.012 mm/yr. This contrast in rates may be deceiving, because the long-term rate has been calculated south of the intersection of the Windy Wash fault with the Fatigue Wash fault and a strand of the Solitario Canyon fault. If the total slip on the southern Windy Wash fault is distributed northward across all three faults (Ramelli and others, 1988), there may not be any significant difference between the late Quaternary and 3.7-m.y. slip rates on the Windy Wash fault. This possibility can be demonstrated by adding contributions of 0.01 mm/yr slip from the Solitario Canyon fault (A.R. Ramelli, Nevada Bureau of Mines and Geology, written commun., 1995) and 0.004 mm/yr slip from the Fatigue Wash fault (J.A. Coe, written commun., 1995) to the 0.012 mm/yr on the central Windy Wash fault segment. Considering the different dating methods used to study Quaternary offset on each fault, the 3.7 m.y. slip rate is essentially equal to the combined late Quaternary slip rate. Though slip rates may have increased during episodes of temporal clustering of earthquakes, the overall results indicate that deformation at Yucca Mountain has been nearly constant since the Pliocene.

Summary

Three seismic refraction lines were constructed parallel and perpendicular to the southern Windy Wash fault at Yucca Mountain, Nev., in order to measure the thickness of alluvium above an offset basalt flow and to determine if the offset contains a lateral component of slip. Both parallel and perpendicular profiles revealed about the same maximum elevation for the offset basalt. Apparent vertical offset on the 3.7 Ma basalt is 97 m, but we suggest a net slip closer to 100 m, in order to account for surface erosion of the exposed basalt on the upthrown block and an assumed small component of left-lateral slip. The presence of the exposed basalt flow near the projected position of the buried basalt indicates that the lateral slip component is small.

The 3.7 m.y. slip rate on the Windy Wash fault is 0.027 mm/yr, which is essentially equal to slip rates calculated for faults cutting the 13 Ma tuffs on Yucca Mountain. Assuming that slip rates were higher between 14 Ma and 11 Ma when Miocene extension was at its peak in the Yucca Mountain area, we suggest that a hiatus in extension took place until the time of the extrusion of the 3.7 Ma Crater Flat basalts. Quaternary slip rates on the Windy Wash fault (0.012 mm/yr), Fatigue Wash fault (0.004 mm/yr), and Solitario Canyon fault (0.01 mm/yr) appear to be less than the long-term slip rate; however, the Windy Wash and Fatigue Wash faults, and a strand of the Solitario Canyon fault, all merge near the basalt flow. The sum of Quaternary slip rates on these faults is nearly equal to the rate of slip since the middle Pliocene. This similarity in slip rates indicates that except for occasional episodes of temporal clustering, deformation at Yucca Mountain has been virtually constant for the last 3.7 m.y.

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