Chapter 9

Quaternary Faulting on the Windy Wash Fault

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Contents

Abstract

The Windy Wash Fault is traceable as fault scarps in surficial deposits in eastern Crater Flat and as faultline scarps on tilted fault blocks of Miocene tuff. Three trenches that were excavated in Quaternary alluvium and colluvium across the northern segment of the Southern Windy Wash Fault, expose evidence of as many as eight surface-rupturing paleoearthquakes during the mid-Quaternary to late Quaternary, between 400 and 3 ka (preferred dates); the average recurrence interval is 40–45 k.y. for the most recent four faulting events and 50–57 k.y. for all faulting events. The most recent surface-rupturing paleoearthquake, which occurred during the late Holocene, appears to have been the youngest faulting event in the vicinity of Yucca Mountain.

Total net displacement of exposed surficial deposits on the Windy Wash Fault is 3.7 m, and the average slip rate during the Quaternary is estimated at 0.011 mm/yr. On the basis of a displacement of about 101 m on a 3.7-Ma basalt flow along the fault, the slip rate since Pliocene time is estimated at 0.027 mm/yr. Taking into consideration possible interconnections with the adjacent Solitario Canyon and Fatigue Wash Faults, which also record Quaternary movement, an adjusted late Quaternary slip rate for the northern segment of the Southern Windy Wash Fault is comparable, indicating that deformation has been nearly constant for the past 3.7 Ma.

Introduction

The Windy Wash Fault in eastern Crater Flat, about 4 km west of the proposed repository site for the storage of high-level radioactive waste at Yucca Mountain (fig. 1), consists of three segments: the Northern Windy Wash Fault, a central fault segment, and the Southern Windy Wash Fault (figs. 2, 4). The combined features (see discussion in chap. 3) are traceable as fault scarps and faultline scarps in both bedrock and surficial deposits for distances ranging from less than 1 to as much as 3 km (O’Neill and others, 1991; Simonds and others, 1995). Along several segments, the fault forms the bedrock-alluvium contact (fig. 2; Day and others, 1998a). The 25-km-long fault is also distinguished as a clearly recognizable aeromagnetic anomaly.

Two trenches, CF2 and CF3 (fig. 2), were excavated in 1981 at sites about 60 m apart that cross a prominent scarp along the northern segment of the Southern Windy Wash Fault (fig. 2). After initial logging in 1981, Swadley and others (1984) reported evidence for two surface ruptures in these trenches and, on the basis of U-trend analyses of alluvial units in trench CF3 (Rosholt and others, 1985), suggested that the most recent event occurred sometime between about 260 and 40 ka, with a preferred date of middle Pleistocene for the most recent surface rupture.

Additional logging of trenches CF2 and CF3 was conducted in 1985, and evidence of multiple Quaternary surface-rupturing paleoearthquakes along the Windy Wash Fault, including a late Holocene event, was reported by Whitney and others (1986). A third, but shorter, trench (CF2.5, fig. 2) was excavated between trenches CF2 and CF3, and small test pits were also dug within the larger trenches at the fault planes.

Table 27. Numerical ages of deposits exposed in trenches CF2, CF2.5, and CF3 across the Windy Wash Fault in the Yucca Mountain area, southwestern Nevada.

[See plates 12–16 and figures 1 and 2 for locations. Samples: HD (error limits, ±2σ), U-series analyses by J.B. Paces; TL–3 through TL–5, thermoluminescence analyses from Whitney and others (1986); TL–59 (error limit, ±2σ), thermoluminescence analysis by S.A. Mahan; CF 6 (error limit uncertain), U-trend analysis by Rosholt and others (1985); U1–U4, U-series analyses by Peterson and others (1995)]

Trench	Sample	Unit and material sampled	Estimated age (ka)
CF2 (pls. 12, 13)	HD 1617	M, clast rind	333±62
	HD 1618	J, opaline silica laminae	105±2, 153±13
	HD 1619	M, clast rind	91±2, 96±2, 159±7, 264±12, 277±22, 278±13, 331±33
	HD 1620	M, clast rind	214±22, 270±135, 287±13
	HD 1621	M, clast rind	267±14, 311±56
Trench CF2.5 (pl. 14)	TL–3 through TL–5	B, buried Av soil horizon	3–6.5
Trench CF3 (pls. 15, 16)	TL-59	C, sand	11±2
	HD 1615, HD 1820	E, clast rinds	52±4, 62±4, 78±5, 86±5
	HD 1821	E, rhizolith, opaline silica stringers	12±0.2, 13±1, 47±1
	CF 6	D, buried B soil horizon	190±5
	U1 through U4	F, soil carbonate, carbonate on clast rinds	17±3, 38±3, 39±3, 82±9

In 1994, the trench logs were further revised, and additional samples were collected for U-series and thermoluminescence analyses, the results of which are listed in table 27.

Cosmogenic dating of the exposed bedrock scarp on the Northern Windy Wash Fault (figs. 2, 4) by Harrington and others (2000) was done to determine whether this scarp formed during the past 20 k.y. The 3.7-Ma basalt flow that is offset along the Southern Windy Wash Fault was studied to calculate the net cumulative fault slip since Pliocene time (Whitney and Berger, 2000).

Trench Stratigraphy

Trenches CF2 (pls. 12, 13), CF2.5 (pl. 14), and CF3 (pls. 15, 16) were excavated across scarps in alluvial deposits along the northern segment of the Southern Windy Wash Fault; they were photogrammetrically mapped in detail according to the procedures of Fairer and others (1989). Trenches CF2.5 and CF3 were excavated primarily in upper Quaternary alluvium, and trench CF2 through older, well-cemented gravel and cobbles juxtaposed with gravelly fine-grained colluvium that washed downslope across the fault after infrequent surface ruptures. An unnamed ephemeral stream that flowed west-southwestward across the Windy Wash Fault south of the fault scarp where trench CF2 is located deposited younger alluvium across the fault. Thus, an unusually long alluvial record and fault-displacement history is exposed in and between trenches CF2 and CF3. Subsequently, the stream was headwardly captured and diverted southward by another ephemeral stream that flowed along the base of the south ridge of Yucca Mountain (fig. 1) parallel to the Southern Windy Wash Fault.

Stratigraphic Units in Trenches CF2.5 and CF3

Units A through D (pls. 12–16) are present in all trenches and are labeled alphabetically, generally in the order of increasing age. Units E through H are present in the lower parts of trenches CF2.5 (pl. 14) and CF3 (pls. 15, 16) but are absent in trench CF2 (pls. 12 , 13). Correlations of units E through H with the units exposed in trench CF2 are discussed primarily in the unit descriptions for trench CF2.

Unit A consists of eolian sand that contains scattered pebbles and is capped by the modern desert pavement. In trenches, the unit is discontinuous and generally 12 to 20 cm thick. This surficial deposit has been reworked by overland flow and occurs as a fissure fill that was deposited after the most recent surface rupture. In trench CF2.5 (pl. 14), the fill is about 75 cm thick. Just south of trench CF2 (pls. 12, 13), where the fault plane in unit B was exposed by a bulldozer, loose sand of unit A was revealed in a delicately preserved 8- to 15-cm-wide fissure in unit B (fig. 40). At present, unit A continues to aggrade from eolian deposition and is reworked by surface wash from infrequent rainstorms. The deposit is dated at late Holocene because it overlies unit B, which is dated at middle to late Holocene.

Unit B is a thin silty sand deposit that is typical of the eolian silt which has been accumulating on most basin surfaces in the Mojave Desert during the Holocene, owing to an increase in aridity that took place in the region at the end of the Pleistocene (McFadden and others, 1987). In Crater Flat, the unit is either unconformably overlain by thin, loose sand of unit A or capped by desert pavement where unit A is absent. Unit B is generally 20 to 30 cm thick and is easily recognizable by its vesicular texture. It contains the greatest component of silt and clay (35–55 volume percent) of all map units and commonly includes scattered pebbles.

Unit B is the youngest unit offset by the most recent surface rupture. Where the fissure produced by this faulting event is wide, as in trench CF2.5 (pl. 14), large intact chunks of sand fell into the fissure and were buried by unit A. In trenches CF2 (pls. 12, 13) and CF3 (pls. 15, 16), however, the fissure is narrow and appears to have been healed by constant wetting and drying of the vesicular A soil horizon over time. In trenches CF2 and CF3, unit B is preserved on the hanging wall but is mostly or completely stripped off the footwall. Thermoluminescence analyses of the fine-grained-silt fraction of samples from trench CF2.5 (samples TL–3 through TL–5, pl. 14; table 27) range from 3 to 6.5 ka, indicating that eolian deposition on Crater Flat surfaces became a dominant process as the climate became more arid during the early to middle Holocene (Spaulding and Graumlich, 1986).

Unit C consists of loose, gravelly and silty sand; the characteristically poor sorting indicates that it was most likely deposited by one or more debris flows. The unit lies unconformably on eroded unit D. The long erosional hiatus at the contact between these two units is shown in a large pit that is exposed between stations 4 and 8 m, near the west end of the north wall of trench CF3 (pl. 15). Our preferred interpretation is that this feature was partly created by a large mass of former tree roots and (or) by a large maze of tunnels created by burrowing animals. At present, burrowing rodents commonly choose fault zones in which to burrow, and the spoil from their tunnels is commonly seen along fault scarps in Crater Flat. An alternative explanation is that the pit was originally a channel eroded into older deposits and then filled with unit C material. Unit C is generally thin (10–20 cm thick), except where it fills the pit in trench CF3 and where it is a major component of the fissure fill in trench CF2.5 (pl. 14). The unit is discontinuous in trench CF2 (pls. 12, 13).

Figure 40. Surface rupture from a late Holocene coseismic event exposed in vesicular A soil horizon that underlies modern desert pavement on scarp just south of trench CF2 across the Windy Wash Fault in the Yucca Mountain area, southwestern Nevada (figs. 1, 2). Fissure is 8 to 15 cm wide; hand trowel is 21 cm long.

Unit C has little soil development, with a weak Bk horizon, and underlies unit B of Holocene age. A thermoluminescence analysis sample (TL–59, table 27) yielded an age of 11±2 ka, indicating that unit C was deposited at the end of the latest cool, pluvial episode in the southern Great Basin. Dating in trench CF3 (pls. 15, 16) by Peterson and others (1995) indicates that unit C may be a little older, but still late Pleistocene. A radiocarbon analysis of desert varnish on the surface adjacent to trench CF3 dates the desert pavement at about 29 ka (Peterson and others, 1995). Similar ages (19–30 ka on five samples) were obtained for desert pavements believed to have formed over the "Late Black Cone" unit in Crater Flat (see table 2). Because unit C was the last alluvial/colluvial deposit that formed on the surface before the eolian deposition of units B and A, it is the most likely source of the gravel that forms the modern desert pavement. Thus, unit C may range in age from about 13 to 30 ka.

Unit D is distinctive because of its unique soil profile, which is characterized by a Bt horizon and an oxidized color. The unit consists primarily of a gravelly-silty sand, containing about 15 volume percent clasts in trench CF2 (pls. 12, 13) and 40 volume percent clasts in trench CF3 (pls. 15, 16). The average clay content is not as high as the soil development might suggest; laboratory analyses yielded a clay content of only 5 to 8 volume percent in three samples but 31 volume percent in a fourth sample. The thickness of the unit varies because surface erosion has stripped some of it off the hanging wall of the fault and all of it from the footwall, as well as from steep parts of the scarp at trench CF2 (pls. 12, 13). We suggest that the lower clay contents resulted from stripping away of the original upper Bt soil horizons. At the west end of trench CF2 (pls. 12, 13), unit D thickens noticeably where the surface slope flattens, owing to redeposition of sediment eroded from farther upslope. The position of the unit as the first buried soil, in combination with its distinctive color, ped development, and clay coatings, makes this unit a good candidate for correlation with the units exposed in other fault trenches in the Crater Flat area (figs. 1, 2).

Unit D is clearly offset by a surface rupture that predates the most recent faulting event along the Southern Windy Wash Fault (figs. 2, 4), because the unit is preserved on the hanging wall against the main fault plane in trench CF3 (pl. 15) but is mostly stripped away on the footwall. Additionally, unit D is offset more than the overlying units. A U-trend analysis by Swadley and others (1984) on the deposit yielded an estimated age of 190±50 ka (sample CF6, table 27), which indicates that deposition occurred near the end of the middle Pleistocene—a date that seems too old because it would indicate that no subsequent deposition occurred on this alluvial surface for more than 100 k.y. The presence of reworked basaltic ash, which is correlated with the Lathrop Wells volcanic center to the south (fig. 1; F.V. Perry, written commun., 1996), in the matrix of unit D indicates that the Lathrop Wells basaltic cone had erupted before the unit was deposited. The main blanket of basaltic ash was erupted from the Lathrop Wells volcanic center at 77±6 ka (Heizler and others, 1999), providing a maximum age of about 80 ka for unit D.

Unit E consists of sandy-bouldery cobbles that were deposited by a stream only on the hanging wall and against the Southern Windy Wash Fault scarp (visible in trenches CF2.5 and CF3, pls. 14–16). Although the easternmost 4 to 5 m of the unit, against the fault plane, contains a large concentration of boulders, we refer to this deposit as an alluvial rather than a colluvial wedge, because the debris does not originate from, nor was it deposited across, a newly formed fault scarp. Before the underlying unit F was faulted, its surface was an active flood plain. After the coseismic surface rupture, the stream deposited a long, thin (max 50 cm thick) wedge of bouldery debris into the newly subsided segment of the flood plain. Rapid deposition is indicated by poor sorting of the clasts in unit E, in marked contrast to the good sorting of the underlying gravel in unit F. Not long after unit E was deposited, the ephemeral stream responsible for depositing units E and F and possibly older units, was diverted southward away from this site. The eolian sand of unit D was then deposited, followed by a long period of soil development.

Cobbles in the upper part of unit E are partly coated by rinds with $CaCO_3$ stage I morphology, and cobbles in the lower part of the unit have rinds with $CaCO_3$ stage II morphology. U-series analyses of two silica-rich stringers in the matrix, one carbonate rhizolith, and two silica-rich clast rinds from trench CF3 (pls. 15, 16) indicate that (1) silica deposition in the matrix occurred about 13–12 ka (sample HD 1821, table 27), (2) the rhizolith (a carbonate-filled root cast) is dated at about 47 ka, and (3) the clast rinds are dated at 78±5 ka to 86±5 ka (samples HD 1615, HD 1820), indicating that silica and carbonate deposition by soil processes continues over time in response to appropriate climatic conditions. Thus, the oldest ages most closely limit the minimum age of unit E and are stratigraphically correct because overlying unit D contains the 77±6-ka basaltic ash.

Unit F consists of well-sorted alluvial gravel with a sand matrix. The gravel clasts are imbricated, indicating streamflow from the east, are subangular to subrounded, and are commonly 2 to 4 cm in diameter. Larger clasts and a few thin discontinuous cobble lenses are also present. The good sorting and absence of debris-flow deposits indicate that the stream flowed for sustained periods of time during the year, and so the unit was probably deposited during pluvial climatic conditions. The gravel in unit F eroded into and was deposited across the underlying coarser cobble deposits of units G and H.

The base of unit F is offset more than its top, and the deposit is thicker on the hanging wall than on the footwall, indicating that coseismic surface ruptures occurred both during and after deposition of this unit. In trench CF3 (north wall, pl. 15), the angle of gravel imbrication increases at a depth of about 75 cm below the top of the unit on the hanging wall. This horizon was chosen as the position of the event horizon, although we recognize that the angle of imbrication may also have flattened, owing to changing alluvial conditions on the flood plain at that time. In trench CF2.5 (pl. 14), unit F is coarser in its lower part, and an internal disconformity indicates that deposition was interrupted and altered, possibly in response to a tectonic offset.

The time interval represented by unit F is unknown; however, the absence of any buried soils within it indicates a relatively constant rate of deposition. The good to very good sorting and absence of debris-flow deposits indicate that deposition may have taken place during a pluvial climate.

Four U-series analyses by Peterson and others (1995) on soil carbonate in unit F yielded ages ranging from 17±3 to 82±9 ka (samples U1–U4, table 27). As stated above, the variation in soil carbonate ages reflects times of climatically controlled secondary-carbonate deposition. The sample yielding the 17±3-ka age, for example, was deposited during the latest pluvial climate in the southern Great Basin. Thus, the oldest U-series age is the best minimum limiting age of the deposit. The maximum age of 82±9 ka agrees well with the U-series ages of 78±5 ka and 86±5 ka (samples HD 1615, HD 1820, table 27) for unit E, indicating that unit F was likely deposited during the late Pleistocene pluvial period of 105–90 ka.

Unit G is the lowest deposit exposed on the hanging wall of the Southern Windy Wash Fault (figs. 2, 4), adjacent to the main fault zone in trenches CF2.5 (pl. 14) and CF3 (north wall, pl. 15). The unit consists of a pebbly gravel with a sandy matrix; it contrasts with unit F by its strong cementation by secondary carbonate, and with unit H by its better sorting and its content of smaller clasts. The base of unit G is not exposed, and so its thickness is indeterminable. It appears to have been deposited only on the hanging wall against a paleoscarp after a surface-rupturing paleoearthquake (similar to unit E).

Unit H consists of a gravelly-sandy cobble deposit on the footwall that bears a strong physical resemblance to, and is correlated with, the coarse-grained gravel deposits on the footwall of trench CF2 (unit P, pls. 12, 13). Boulders as large as 30 cm in diameter are common. The deposit generally has a $CaCO_3$ stage III morphology; however, the upper part of the soil horizon on unit H was stripped away by erosion before unit F was deposited. Unit H was clearly offset during unit F time and later, but evidence of possible earlier faulting events is absent because so little of the unit is exposed at the base of trench CF3 (north wall, pl. 15). No age is available for unit H, except that it predates unit F.

Stratigraphic Units in Trench CF2

Trench CF2 (pls. 12, 13) was excavated across a 3-m-high scarp about 60 m north of trench CF3 (figs. 2, 4). Stratigraphic units A through D have textures and soil characteristics similar to those of the younger sequences exposed in trenches CF2.5 (pl. 14) and CF3 (pls. 15, 16), but are more discontinuous. The older units in trench CF2, however, differ markedly in texture from those in the other two trenches because they are primarily colluvial rather than alluvial, owing to the presence of the topographic high formed by the fault scarp. Because of the resulting lithologic differences, the lower units are designated E through

G (or H) in trenches CF2.5 and CF3, as described above, and I through P in trench CF2, as described below.

Units I through L in trench CF2 (pls. 12, 13) consist largely of gravelly sand composed of reworked eolian sand and colluvial gravel that were washed downslope over the Windy Wash Fault scarp. Some sand may also have been blown against the scarp. No sharp contacts exist between these hanging-wall colluvial deposits, and some depositional boundaries are obscured because of carbonate overprinting that has resulted from multiple episodes of soil development. In addition, several wedge-shaped deposits downslope appear to be gradational with adjacent units, whereas unit D tapers upslope and wedges out in the opposite direction because of surface erosion. Stonelines, carbonate stringers, and B soil horizons are primarily used to distinguish these fine-grained colluvial deposits, and some unit boundaries are identifiable.

In trench CF2 (pls. 12, 13), the colluvial deposits consist mainly of eolian sand and silt that accumulated against the Windy Wash Fault scarp on the hanging wall. These deposits bear little resemblance to the coarse cobbly-bouldery gravel on the footwall. The carbonate cementation on the surface of the footwall has a $CaCO_3$ stage II–III morphology, and surface erosion appears to have partly stripped away the original soil profile, including the K horizon. Because eolian deposition is common only during interpluvial climates, deposition on the hanging wall may not have occurred immediately after surface-rupturing paleoearthquakes; thus, the hiatus between faulting and hanging-wall deposition is difficult to determine in trench CF2.

Unit I consists of a colluvial wedge of primarily carbonate-cemented sand that contains some scattered gravel and cobbles. The unit appears to be a local subunit of unit J, proximal to the fault and distinguished by its wedge shape. Unit I underlies unit D in trench CF2 (pls. 12, 13) and is correlated stratigraphically with unit E in trenches CF2.5 (pl. 14) and CF3 (pls. 15, 16), which is also a wedge of sedimentary material against the fault, as described above. On the basis of this correlation, the minimum age of unit I is considered to be about 90 ka.

Unit J is primarily a slopewash deposit composed of gravelly silty sand. On the north wall of trench CF2 (pl. 12), a conspicuous sandy-cobbly gravel interbed terminates about halfway between the main fault zone and the west end of the trench. The deposit is cemented by carbonate with $CaCO_3$ stage II–III morphology that composes the K soil horizon in this unit. Thin stringers of discontinuous secondary carbonate are common. Unlike units I, K, and L, unit J does not thin downslope away from the fault zone, indicating that a long interval of hillslope erosion and redeposition took place after the coseismic surface ruptures that had created the space for units J, I, and D to be emplaced. After unit D was deposited on top of unit J, the landscape was stable long enough to form a reasonably mature soil profile characterized by a Bt horizon and a horizon with $CaCO_3$ stage II–III morphology.

Two U-series analyses of the silica matrix from two adjacent subhorizontal soil carbonate stringers in the lower part of the K horizon in unit J yielded ages of 105±2 and 153±13 ka (sample HD 1618, table 27) that are stratigraphically and sequentially consistent. If unit I correlates with unit E in trench CF3 (pls. 15, 16), then unit J correlates with the next-older unit (F) in trench CF3. Both units F and J are persistent in their respective trenches. The soil carbonate developed on unit E was dated at 78±5 to 86±5 ka (samples HD 1615, HD 1820, table 27), and we are confident that there was no depositional hiatus between units E and F. Thus, the age of unit J, as well as of unit F, ranges from 90 to about 180 ka.

Unit K consists of a wedge of colluvial silty sand that contains a few scattered clasts. On the north wall of trench CF2 (pl. 12), unit K disconformably overlies part of an older fissure fill in the main fault zone. This relation is also indicated on the south wall (pl. 13) but is not so clear cut. The absence of distinctive textural characteristics and abrupt contacts between units J, K, and L make these units difficult to differentiate.

Unit L is also a sandy colluvium that tapers downslope away from the main fault zone on the south wall of trench CF2 (pl. 13). This deposit appears to contain more scattered cobbles than unit K. On the north wall of the trench (pl. 12), unit L overlies a buried fault zone and a fissure fill that was created when unit M was deformed. Another wedge of colluvium is interpreted to be present against the main fissure; however, the stratigraphic correlation of this wedge is equivocal.

No direct dating was done on unit K or L; however, their ages can be interpolated between dated units J and M. Unit K is dated at older than 180 ka, younger than unit M. U-series analyses of silica from carbonate soils in unit M yielded ages ranging from about 91 to about 331 ka (sample HD 1619, table 27). Ages on the upper soils seem to cluster between 264 and 278 ka, indicating that both units K and L were deposited between about 300 and 180 ka (lower age limit of unit J). Because there are no well-developed B soil horizons on these two colluvial wedges, we suggest that both units may be closer in age to unit J than to unit M. Arbitrarily splitting the time interval between units K and L results in approximate ages of 180–220 ka for unit K and 220–260 ka for unit L.

Unit M dominates the lower walls in trench CF2 (pls. 12, 13) west of the main fault zone. Unlike the overlying fine-grained colluvial deposits, this unit consists primarily of alluvial gravelly sand with a $CaCO_3$ stage II+–III soil horizon developed on it. Its gravel content is about 80 volume percent at the west end of the trench and less than 15 volume percent near the fault; the gravel exhibits good sorting indicative of deposition by ephemeral streams rather than slopewash. Near the fault zone, the gravel interfingers with predominantly sandy material that appears to have been washed across a paleoscarp and deposited over a highly fractured, carbonate-cemented cobbly sand, which composes unit N. The sandy facies of unit M could be a coseismic wedge overlying the gravelly facies of unit M.

Unit M is the oldest stratigraphic unit dated in trench CF2 (pls. 12, 13). An experiment in U-series dating was conducted on opaline silica from secondary-carbonate rinds in the K soil horizon. Whole rinds were analyzed along with outer, intermediate, and inner rinds adjacent to clasts from the upper and lower parts of unit M. In all samples, the silica adjacent to the clast was older than the outer rind or the whole rind. Whole-rind analyses gave ages of 91±2 to 96±2 ka, whereas seven analyses of rinds adjacent to the clasts ranged from 277±22 to 333±62 ka (samples HD 1617, HD 1619, table 27). Three analyses (samples HD 1617, HD 1619, HD 1621, table 27) yielded ages of more than 300 ka, indicating that the deposit is dated at older than 300 ka, possibly as old as 350 ka.

Unit N, which is exposed below unit M on the hanging wall adjacent to the main fault zone, consists of cobbly sand that contains as much as 35 volume percent clasts, all of welded tuff. The unit is clearly distinguishable from the overlying unit M because the sand matrix is well cemented by secondary carbonate and has a distinctive closely spaced fracturing, sometimes referred to as a raveled appearance. No direct dating of unit N was attempted; it is dated at older than 350–380 ka on the basis of the oldest U-series ages of 300–333 ka on silica-rich, carbonate clast rinds from the overlying unit M.

Unit P is a gravelly-sandy cobble deposit that occupies nearly all of the footwall of both walls in trench CF2 (pls. 12, 13). The unit is primarily clast supported and exhibits very good sorting and good rounding. The average clast size is 5 to 6 cm (median diameter), and boulders as large as 25 cm in diameter are common. Minor channels and crossbedding are also present. No buried soils or clear depositional breaks can be distinguished within the unit.

The surface of unit P was eroded over a substantial time interval. The footwall, extending back (eastward) from the fault at least 60 m, has a gentle convex surface across a west-dipping slope of about 19°. The internal stratification of unit P is horizontal, not warped, indicating that the surface slope is erosional. Surface erosion has partly stripped and in some places, largely removed the soil developed on unit P. The remaining soil is cemented by secondary carbonate with $CaCO_3$ stage II+ morphology and silica-rich rinds on clasts; in places, remnants of a K horizon with $CaCO_3$ stage III morphology are present.

In general, a coarse-grained gravel that has undergone continual surface erosion over time is difficult to date. Because unit P was not exposed on the hanging wall, we assume that it is below the floor of the trench and so predates any of the dated units on the hanging wall in trench CF2 (pls. 12, 13). The three oldest U-series ages for the hanging wall on clast rinds from unit M, are 311±56, 331±33, and 333±62 ka (samples HD 1621, HD 1619, and HD 1617, respectively, table 27). Unit N underlies unit M and has a well-developed soil on it. We estimate unit N to be older than 380 ka and suggest an age of at least 400 ka for the top of unit P, probably more than 450 ka. Correlation of unit P with the oldest units (G, H) exposed in trenches CF2.5 (pl. 14) and CF3 (pls. 15, 16) is uncertain.

Structures and Deformation in Trenches Across the Windy Wash Fault

In trench CF2 (pls. 12, 13), the main Windy Wash Fault zone is about 1.2 m wide on the north wall (pl. 12) and splits into two splays on the south wall, with a combined width comparable to that on the north wall (pl. 13). The fault planes strike N. 4°–20° W. and dip 77°–90° W. At least five fissure fills of different ages can be identified in the fault zone on the basis of crosscutting relations, depth of burial, carbonate cementation, and the presence of basaltic ash. The fissures are primarily filled with sand, silt, gravel, and carbonate-cemented clasts. Units K and L overlie two of the older fissure fills that are strongly sheared, and much carbonate has precipitated in the lower part of the fault zone because of easy infiltration.

West of the main fault zone in trench CF2 (pls. 12, 13) are two narrow (5–15 cm wide) secondary faults that display only small offsets. On the north wall (pl. 12), these two secondary faults define a small graben. Fractures are present primarily on the hanging wall within 10 m of the main fault; however, fractures are observed but with decreasing density to the end of the trench. Some fractures are buried by subsequent hanging-wall deposits and can be used to help define faulting-event horizons.

In trench CF3 (pls. 15, 16), the Windy Wash Fault is present as two splays, 4 to 6 m apart. A pit was excavated against the north wall (stas. 16–20 m, pl. 15) to expose the deeper fault fissure and the oldest offset deposits. At the base of the pit, the fault fissure is 65 cm wide and narrows to 15 to 30 cm in the unconsolidated, younger deposits. A strong contrast in fault width is evident by comparing the western fault strands on both walls in trench CF3. On the north wall (pl. 15), the fissure is narrow (<10 cm at sta. 14 m) and is associated with minor stratigraphic displacements; however, on the south wall the same strand is 20 to 40 cm wide (stas. 14–15 m) and is associated with one of the largest individual displacements (for example, top of unit E) recorded in the trench. Fewer fractures are preserved in trench CF3 than in trench CF2 (pls. 12, 13). No backtilting, folding, or warping was observed in any of the trenches. The main fissure in trench CF2.5 (pl. 14) is unlike that in any of the other trenches, in that it widens considerably within 1 m of the surface, resembling an inverted cone, or what is sometimes referred to as a flower structure on seismic profiles.

Evidence and Interpretation of Past Surface Ruptures

Event Z

The most recent faulting event (Z) on the Windy Wash Fault affected all units except the youngest unit (A) that overlies the vesicular silty Av soil horizon. This event is best represented in trench CF2.5 (pl. 14), where the Av soil horizon was broken up by extension across the fault zone and large fragments became incorporated into the loose sand and silt of unit A that was deposited on top of the older fissure fill. On the north wall of trench CF2.5, the Av soil horizon remained intact and was downdropped about 10 cm at the west edge of the fissure. In trench CF2 (pls. 12, 13), this faulting was recorded primarily by a 4- to 8-cm-wide fissure in the Av soil horizon that is filled with loose sand. The surface rupture caused by event Z was also exposed at the ground surface just south of trench CF2 by scraping off the desert pavement and loose sand of unit A from the buried vesicular A soil horizon of sandy silt (unit B). As shown in figure 40, the surface rupture there clearly created a small (8–15 cm wide) fissure, now filled with sand, through the middle and upper Holocene eolian deposits. In trench CF3 (pls. 15, 16), event Z is recorded only on the western fault strand, where it is manifested primarily by cracking with but little fissure development. On the basis of the relations just described, event Z definitely ruptured the ground surface but is probably best described as a cracking or fracturing event with only minor (≤10 cm) local displacement.

Thermoluminescence analysis of Av soil horizons (Whitney and others, 1986) yielded ages ranging from about 3 ka (late Holocene) for the upper horizon to 6.5 ka for the lower horizon (samples TL–3 through TL–5, table 27). Because the upper part of the Av soil horizon is ruptured, event Z occurred during the past 3 k.y. We prefer a date of 3–2 ka because of the absence of a fresh scarp, the reforming of an Av soil horizon over some fault strands, and the undeformed appearance of the desert pavement above the fissure. Event Z on the Windy Wash Fault is the youngest documented surface rupture in the Yucca Mountain area (figs. 1, 2) and may correlate closely with Holocene faulting events on the nearby faults (see chap. 14).

Event Y

Event Y is represented at the top of unit D, the only unit with an oxidized Bt soil horizon. After the faulting event, the surface of this unit was modified by a relatively long period of erosion; the unit was stripped from some footwalls and is discontinuous on the hanging wall in trench CF2 (pls. 12, 13). Because of erosion, the base of unit D is the best reference horizon for measuring the fault offset caused by event Y. On the basis of exposures in the south wall of trench CF3 (stas. 14–15 m, pl. 16), which is the only place where this horizon is preserved on both the footwall and hanging wall directly adjacent to the fault zone, displacement ranges from 25 to 45 cm, depending on slope projections of the marker beds between the two fault blocks. Relations are not so clear in trench CF2.5 (pl. 14), although unit D is exposed on both the footwall and hanging wall, and even less so in trench CF2 (pls. 12, 13) where the unit is present only on the hanging wall. Considering all the measurements that were made or estimated in the three trenches, the average preferred displacement is 24 cm.

The maximum date of event Y is constrained by the presence of reworked basaltic ash, most likely originating from the eruption of the nearby Lathrop Wells volcanic center (fig. 1) at 77±6 ka (Heizler and others, 1999), in the matrix of unit D and by the U-series ages on clasts in unit E. The minimum date is constrained by the age of unit C, 13–30 ka. A long erosional period followed the formation of a Bt soil horizon on unit D, and the undulating surface of unit D is preserved on the hanging wall, indicating that much erosion of the unit had already occurred before event Y. Thus, we date event Y at about 75–30 ka (preferred value, ~40 ka).

Event X

Evidence for event X is related to the deposition of unit E, an alluvial deposit of coarse cobbles exposed on the hanging wall of the Windy Wash Fault in trenches CF2.5 (pl. 14) and CF3 (pls. 15, 16), and of unit I, a sandy colluvial wedge on the hanging wall in trench CF2 (pls. 12, 13). As discussed earlier, units E and I are considered to be correlative and were both deposited adjacent to a fault scarp.

The thickness of unit E reflects the approximate offset of unit F, as observed in trenches CF2.5 (pl. 14) and CF3 (pls. 15, 16), that was caused by event X. In trench CF3, slip occurred on two fault strands, with a total displacement ranging from 78 to 98 cm on the south wall (pl. 16) and from 71 to 96 cm on the north wall (pl. 15) (preferred value, 87 cm). In trench CF2.5, the displacement ranges from 33 to 54 cm on the one fault strand that is exposed. In trench CF2, the well-defined colluvial wedge (unit I) indicates an offset of 45 to 53 cm (preferred value, 50 cm).

The sandy matrix of unit E contains ash that is chemically similar to the basaltic ash from the Lathrop Wells volcanic center (fig. 1; F.V. Perry, written commun., 1996). The preferred age of the main Lathrop We t tlls ash sheet is 77±6 ka (Heizler and others, 1999). U-series analysis of silica from the inner carbonate rinds of clasts in unit E yielded ages of 78±5 and 86±5 ka (samples HD 1615, HD 1820, table 27). The ages of the rinds overlap with the age of the ash, indicating that event X was contemporaneous with, or occurred shortly after, deposition of the abundant basaltic ash and its reworking on the landscape.

Event W

Event W is the oldest faulting event for which reasonable age constraints can be assigned. The displacement from this event is best observed on the north wall of trench CF3 (pl. 15), where a pit was dug in the floor of the trench (between stas. 16 and 20 m) to expose the offset base of unit F, a fine-grained gravel characterized by very good sorting and imbrication. The base of unit F in trench CF3 is offset more than its upper surface, indicating that a coseismic surface rupture took place during the deposition of unit F. Event W is also evidenced by a fault that apparently offsets unit H in the footwall and terminates within unit F in trench CF2.5 (pl. 14). In trench CF2 (pls. 12, 13), unit J, which is correlated with unit F in trench CF3, was deposited on the hanging wall, probably in response to a surface rupture. Unlike the underlying colluvial wedges of units K and L, unit J persists and evens thickens downslope.

The displacement on the base of unit F ranges from 25 to 50 cm (preferred value, 35 cm) on one of the two fault strands. In trench CF2, displacement of unit J ranges from 18 to 25 cm on the north wall (pl. 12) and from 38 to 52 cm on the south wall (pl. 13). These offsets appear to be similar to those in trench CF3; the displacements may decrease slightly to the north.

Unit E and the underlying surface of unit F are dated at about 75–90 ka. The ages of clast rinds from near the base of unit J range from 105±2 to 153±13 ka (sample HD 1618, table 27). Assuming that the older age is closer to the maximum age of the base of the deposit, we date event W at 160–130 ka (preferred value, ~150 ka).

Event V

Event V is represented by a wedge of gravelly sand, mapped as unit K, on the hanging wall in trench CF2 (pls. 12, 13). Unit K clearly buries the west edge of the main fault zone (stas. 14.5–15.5 m, pl. 12). The unit is about 73 cm thick (range 70–83 cm) on the north wall and only 28 cm (range, 24–30 cm) thick on the south wall. The width of unit K on the south wall (pl. 13) is considered a minimum because the unit cannot be accurately traced back to the main fault zone, owing to the presence of an intervening zone of highly disturbed material. Also, the contact between units K and L is indistinct, primarily because no well-defined upper soil horizons were preserved on either unit; thus, the displacements represented by these wedges are only approximate, though well within the range of the described displacements. Event V is recorded in trenches CF2.5 (pl. 14) and CF3 (pls. 15, 16) by contrasting deposits (units G, H) across the main fault zone at the base of each trench. No thicknesses are available for either unit, and so no displacements are determinable in those trenches.

The date of event V is bracketed by the U-series ages of clast rinds in units J and M. The base of unit J is dated at about 160 ka, and younger soil ages on unit M cluster around 270 ka (sample HD 1619, table 27). No geologic or pedologic data are available to constrain the date of event V, and so we choose to arbitrarily place event V in the later half, and event U in the earlier half, of the interval between units J and M. On this basis, we date event V at about 220–180 ka, (preferred value, 200 ka).

Event U

In trench CF2 (pls. 12, 13), event U is represented by a small wedge of fine-grained deposits (unit L) that buried a fault fissure. On the north wall, two small wedges were mapped: the western wedge buried a fissure that subsequently remained dormant, and the eastern wedge is a poorly defined colluvial wedge against the main fault zone (pl. 12). On the south wall, unit L tapers downslope on the hanging wall over the distinctly gravelly unit M (pl. 13). The surface offset represented by unit L ranges from 15 to 24 cm on the south wall and from 30 to 60 cm on the north wall. If the eastern wedge on the north wall is not a deposit that resulted from event U, then the total offset on the north wall is only about 30 cm.

The date of event U is bracketed by U-series ages of clast rinds in units J and M. The base of unit J is dated at about 160 ka, and the ages of younger soils on unit M cluster around 270 ka. Deposition of unit L postdates the earlier of two surface-rupturing paleoearthquakes that occurred between these dates. We date event U at 260–220 ka (preferred value, ~240 ka).

Event T

Event T is represented by another surficial deposit, unit M, in trench CF2 (pls. 12, 13). Unlike the overlying younger units in this trench, however, most of unit M consist of alluvial cobbly-sandy gravel rather than colluvial sand that washed over the Windy Wash Fault scarp. The gravel content of the unit decreases near the fault, and unit M becomes a gravelly sand. The lateral textural contrast may indicate that the sandier part of the unit represents a colluvial sand that was deposited across the scarp shortly after event T and interfingered with the active-channel deposits.

The base of unit M is sharply defined because it unconformably overlies a highly fractured and sheared deposit of cobbly sand, unit N. The thickness of unit M ranges from 48 to 60 cm on the north wall (pl. 12) and from 55 to 65 cm on the south wall (pl. 13); the preferred surface displacement from event T is 50 to 60 cm.

Multiple ages were determined on clasts in unit M collected from the south wall (see samples HD 1617, HD 1620, HD 1621, table 27). U-series analyses of silica on the inner rinds of clasts yielded ages consistently older than those on whole rinds or on outer or intermediate rinds. Thus, the ages of the inner rinds best approximate the maximum age of the deposit. The three oldest ages are 311–333 ka, indicating that unit M is dated at about 280–380 ka, taking into account the 2σ error limits on these ages. Event T must have occurred during this time interval; we suggest a date of 370–300 ka (preferred value, 370–340 ka), constrained to precede the deposition of unit M.

Event S

The presence of unit N in trench CF2 (pls. 12, 13) provides the only evidence for event S. This cobbly-sand deposit bears no textural or sedimentologic similarities to the gravel and cobble deposits on the footwall, and so unit N is interpreted to have been deposited in response to a scarp-forming event before unit M was deposited. We date event S, on the basis of the age of the overlying unit M, at no later than 400–390 ka, probably earlier. The minimum displacement represented by unit N is approximately 0.5 m. Because unit N is strongly sheared and the overlying unit M is not, this shearing may represent another surface-rupturing paleoearthquake that occurred before event T, although the raveled appearance of unit N may, instead, be entirely related to event T.

Tectonic Interpretations

Recurrence Intervals

The paleoseismic record of the Windy Wash Fault is unusual in its detail in the Yucca Mountain area (figs. 1, 2) because several surface-rupturing paleoearthquakes are recorded by the various deposits exposed in the trenches. Five coseismic, scarp-forming events are recorded in trenches CF2.5 (pl. 14) and CF3 (pls. 15, 16) in alluvial and eolian deposits, and eight such events in trench CF2 (pls. 12, 13). Individual vertical offsets per event (preferred values) range from 4 to 88 cm and average about 36 cm.

Four events occurred after the deposition of unit J at the site of trench CF2 (pls. 12, 13) about 160 ka, indicating an average recurrence interval of 40 k.y. for surface-rupturing paleoearthquakes since the end of the middle Pleistocene. In the same trench, seven events occurred since unit N was faulted and unit M was deposited against a paleoscarp on the Windy Wash Fault about 400–350 ka; the average recurrence interval between all faulting events is 50–57 k.y. We suggest that this recurrence interval may be somewhat longer than that observed in trench CF3, because the fine-grained texture of the deposits and the poor definition of the contacts between some hanging-wall units in trench CF2 make detection of small events (such as events Z and Y) difficult. If two or three of the mapped hanging-wall units in trench CF2 represent more than one faulting event, then the long-term average recurrence interval may be closer to 40 k.y., as observed in trench CF3. Therefore, the recurrence interval for this segment of the Windy Wash Fault is estimated at 40–57 k.y. (preferred average, 40–45 k.y.).

Slip Rates

A long-term average vertical-slip rate can be calculated on the Windy Wash Fault from the displacement of the oldest exposed unit (N) below the original surface of the footwall, which must be reconstructed to account for surface erosion over time. The total apparent vertical offset of unit N is 3.7 m on the north wall of trench CF2 (pl. 12), about 0.35 m greater than that measured on the south wall. This offset includes 1.2 m of displacement that is reconstructed (owing to erosion) on the footwall. Ages of soil horizons from unit M indicate that the unit was deposited by at least 350 ka, possibly 400 ka. The long-term average vertical-slip rate therefore ranges from 0.0092 to 0.0105 mm/yr.

To calculate the net fault-slip rate, the dip and left-oblique motion of the fault must be taken into consideration. Dips of the main fault zone are nearly vertical. No slickenlines were observed on fault planes to indicate the rake of latest motion on the fault, and so we assume a left-oblique motion of as much as 25° from dip slip, or a southwestward plunge of 65°, on the basis of the field data of Simonds and others (1995). This oblique slip geometrically translates into a multiplier of 1.1 for total slip. Thus, the long-term net-slip rate on the Windy Wash Fault is 0.01 to 0.0116 mm/yr (preferred value, 0.011 mm/yr). A slip rate independently calculated for the four latest faulting events in trench CF3 is the same as that calculated for the past 350–400 k.y. in trench CF2.

Temporal-Spatial Variations

Over the past 400 k.y., seven or eight coseismic surface ruptures have occurred on the Windy Wash Fault. The most recent event (Z) ruptured a late Holocene vesicular silty-sand deposit (Av soil horizon) that underlies the modern desert pavement (fig. 40) along the southern fault segment. This event does not appear to have ruptured the Northern Windy Wash Fault. Harrington and others (2000) used cosmogenic radiocarbon dating of the exposed bedrock scarp in northern Crater Flat to demonstrate that this scarp has been exposed for more than 20 k.y. The late Holocene faulting event may also have ruptured the Southern Crater Flat Fault, as observed in trench CFF–T1A (see chap. 10). Such a young event has not been observed on faults on the east side of Yucca Mountain (see chaps. 5, 14; fig. 59).

The colluvial wedge of sediment deposited on the hanging wall in response to event X (unit E in trench CF3 and unit I in trench CF2) contains sand-size shards of basaltic ash in the matrix. Basaltic ash is also present in one of the vertical, carbonate-cemented fissure fills in trench CF2 (pls. 12, 13). Chemical analysis of this ash (F.V. Perry, written commun., 1996) indicates that it, as well as basaltic ash in the main fault fissures of the Fatigue Wash and Solitario Canyon Faults (see chaps. 7, 8), most likely originated from the nearby Lathrop Wells volcanic center (fig. 1). The presence of basaltic ash in fault-related deposits in three adjacent fault zones indicates that slip was probably distributed on at least three faults in eastern Crater Flat during a paleoearthquake that occurred either during or shortly after the main ash-producing eruption

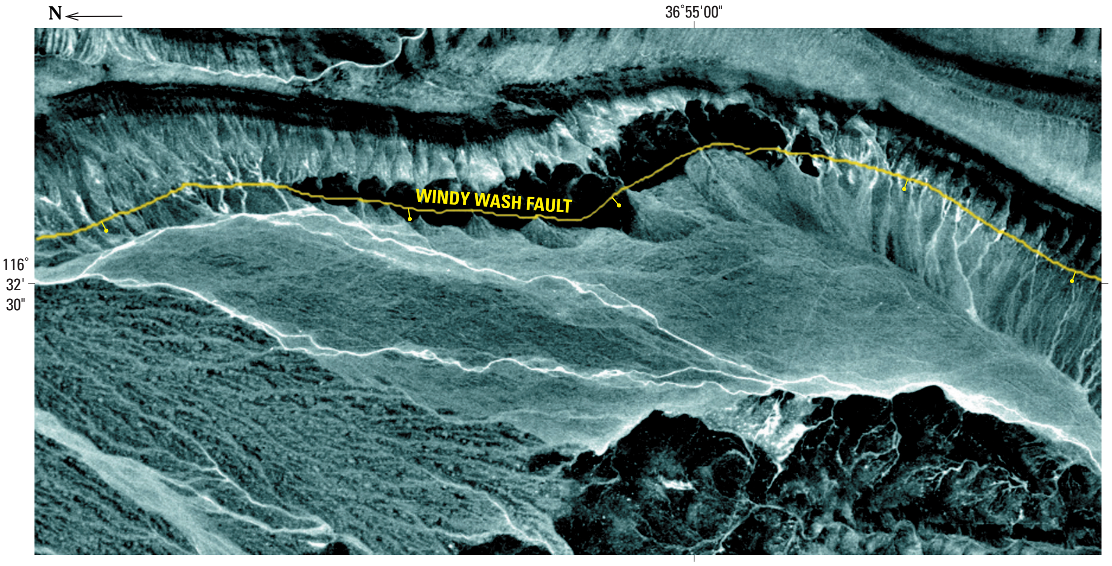

Figure 41. Southern Windy Wash area of Crater Flat in the Yucca Mountain area, southwestern Nevada (figs. 1, 2), showing Windy Wash Fault trace and offset 3.7-Ma basalt against south ridge of Yucca Mountain. Bar and ball on downthrown side of fault.

of the Lathrop Wells basaltic cone at 77±6 ka (Heizler and others, 1999; see chap. 14; fig. 59).

Unlike on the Stagecoach Road Fault and, possibly, the Solitario Canyon Fault (see chaps. 5, 7), no strong evidence of temporal clustering of seismicity was observed on the Windy Wash Fault. However, because surface ruptures with small displacements (<20 cm) are difficult to recognize in trenches across the Windy Wash Fault, we believe that one or two small paleoearthquakes may have occurred much closer in time to a larger faulting event than is indicated by the estimated average recurrence interval of 40–45 k.y. For example, the absence of strong soil development between colluvial-wedge units K and L may indicate that they were deposited nearly contemporaneously; however, surface erosion may have stripped away part of a deposit or its soil, such as in unit D. The relatively regular intervals between coseismic surface ruptures on the Windy Wash Fault are similar to the paleoseismic record on the Paintbrush Canyon Fault at Busted Butte (see chap. 5).

The slip rate and recurrence interval for the Southern Windy Wash Fault indicate that the fault is more active than the Fatigue Wash Fault (see chap. 8). The Fatique Wash Fault is a splay of the Windy Wash Fault, which defines the east edge of a small graben with a down-to-the-east segment of the Windy Wash Fault that begins about 200 m north of trench CF2. Clearly, the Southern Windy Wash Fault is more active than the central section and the Northern Windy Wash Fault. The long-term slip rate of the Windy Wash Fault is similar to those of the Bare Mountain, Solitario Canyon, and Paintbrush Canyon Faults.

Comparison of Late Tertiary and Quaternary Slip Rates

The Southern Windy Wash Fault cuts a 3.7–Ma basalt flow (fig. 41). An investigation by Whitney and Berger (2000), including shallow seismic-refraction surveys, was conducted to (1) determine the thickness of alluvium that overlies the offset basalt on the downthrown (west) block adjacent to the fault, (2) compare the offset of the Tertiary basalt with that of dated Quaternary deposits in the fault zone, and (3) determine the long-term slip rate on the Windy Wash Fault. The top of the exposed basalt flow on the footwall is 40.5 m above the adjacent land surface on the hanging wall, and the maximum depth of burial of the flow in the downthrown block is 56 m, as recorded by an 823-m-long seismic-refraction profile oriented perpendicular to the trend of the fault (Whitney and Berger, 2000). If 2 m of surface erosion, based on calculations of hillslope-erosion rates by Harrington and Whitney (1991) for the Yucca Mountain area (figs. 1, 2), is added, the total vertical offset of the basalt is about 98 m. Seismic profiling also recorded 18 m of apparent left-lateral slip. Factoring in that value at a ratio of 5:1 (vertical to lateral movement), the total net slip on the Windy Wash Fault is about 101 m, and the average slip rate for the past 3.7 m.y. is about 0.027 mm/yr.

The Quaternary slip rate on the Windy Wash Fault is about 0.011 mm/yr, as calculated from offset and dated carbonate soils. The long-term slip rate appears to be more than double the Quaternary slip rate, in which case tectonic activity would appear to have decreased since the Pliocene. However, if slip rates for Quaternary displacements on the Solitario Canyon Fault (0.01–0.02 mm/yr; see chap. 7) and the Fatigue Wash Fault (0.003–0.007 mm/yr; see chap. 8), which may be interconnected with the Southern Windy Wash Fault (see chap. 3), are added, the combined slip rate is comparable to the slip rate of 0.027 mm/yr since the Pliocene. If this interpretation is valid, then the Pliocene and late Quaternary fault-slip rates indicate that overall deformation has been nearly constant for the past 3.7 m.y.

Summary

The Windy Wash Fault is in the Crater Flat Basin, about 4 km west of the proposed repository site for the storage of high-level radioactive waste at Yucca Mountain. The fault is about 25 km long and can be divided into three segments: the Southern Windy Wash Fault, a central segment, and the Northern Windy Wash Fault. Three trenches (CF2, CF2.5, CF3) were excavated across the north end of the Southern Windy Wash Fault. Evidence for as many as eight coseismic surface ruptures was observed in trench CF2 and five ruptures in trenches CF2.5 and CF3. The timing of many of these faulting events was determined by dating soils in the faulted deposits by U-series analysis, volcanic ash correlation, or thermoluminescence analysis of fine silt. Individual displacements per event ranged from 4 to 87 cm (preferred values), mostly from 20 to 60 cm. The smallest offsets were detected for the two most recent surface ruptures, indicating that small surface ruptures may have occurred earlier but are now obscured because of long intervals of erosion and overprinting by strongly carbonate cemented soils.

Surface faulting occurred on the Windy Wash Fault about 3, 40, 75, 150, 200, 240, 340, and 400 ka (preferred values or midpoints of ranges of event timing). The recurrence interval for the last four faulting events is about 40–45 k.y. For the longer paleoseismic record in trench CF2, the average recurrence interval is 50–57 k.y. Assuming that two or three small-displacement events are obscured in middle Pleistocene deposits, we prefer a recurrence interval of 40 k.y. for the Windy Wash Fault. Total net displacement on the oldest hanging-wall deposit is 3.7 m, indicating a long-term average fault-slip rate of 0.01 to 0.0116 mm/yr.

An average slip rate of 0.027 mm/yr calculated for the Southern Windy Wash Fault over the past 3.7 m.y. was from a buried offset basalt flow, on the basis of seismic-refraction data. The Pliocene slip rate appears to exceed the Quaternary slip rate measured from trench studies. However, if the slip rates for the Fatigue Wash and Solitario Canyon Faults, which appear to be interconnected with the Southern Windy Wash Fault, are added, then the Pliocene and Quaternary slip rates are similar, indicating that overall deformation has been nearly constant over the past 3.7 m.y.