Chapter 3

Distribution of Quaternary Faults at Yucca Mountain

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Abstract

Information on the extent, characteristics, and timing of Quaternary faulting is essential to evaluations of earthquake-recurrence intervals, event magnitudes, and potential seismic hazards, as well as to the development of tectonic models, for the proposed repository site for the storage of high-level radioactive wastes at Yucca Mountain. As a part of the site-characterization program, all major faults that cut through the area were mapped in detail and extensively studied in trench excavations to determine whether, and to what degree, associated Quaternary surficial units were involved in the faulting. The investigations resulted in the recognition that displaced or disturbed alluvial and colluvial deposits record late Quaternary faulting along eight faults, including (from east to west) the Paintbrush Canyon, Bow Ridge, Stagecoach Road, Solitario Canyon (including Iron Ridge), Fatigue Wash, Windy Wash, and Northern and Southern Crater Flat Faults. Nearly all of these features are north-trending normal faults with steep westward dips and down-to-the-west displacements. Neither the Ghost Dance and Sundance normal faults that are closest to the planned repository block, nor the northwest-trending strike-slip faults in Drill Hole, Pagany, and Sever Washes, show evidence of Quaternary activity.

Most of the Quaternary faults within the proposed repository-site area are major block-bounding features that form the structural boundaries of large east-dipping fault blocks with several hundred meters of bedrock displacement. Cumulative Quaternary fault movements along these faults range from less than 1 to as much as 8 m, and multiple surface ruptures are recorded on several of them. Bedrock scarps, subtle scarps and lineaments in alluvium, and short but abrupt bedrock-alluvium contacts commonly provide evidence of Quaternary fault activity and also serve as a basis for siting trench excavations that display fresh exposures of Quaternary stratigraphic sequences and fault relations.

In addition to faults within the immediate repository-site area, two other faults displaying Quaternary activity—the Bare Mountain and Rock Valley Faults, 14 km to the west and 25 km to the southeast, respectively—were studied as a part of paleoseismic investigations in the vicinity of Yucca Mountain.

Introduction

Information on the extent, characteristics, and timing of Quaternary faulting is essential to evaluations of earthquake-recurrence intervals, event magnitudes, and potential seismic hazards, as well to the development of tectonic models, for the proposed repository site for the storage of high-level radioactive wastes at Yucca Mountain (fig. 1).

Principal sources of the geologic mapping used in this report include the maps by Scott and Bonk (1984), Simonds and others (1995), and Day and others (1998a, b). The 1:12,000-scale mapping by Scott and Bonk (1984), which showed the complex fault patterns in the Yucca Mountain area in considerably greater detail than did earlier mapping (for example, Christiansen and Lipman, 1965; Lipman and McKay, 1965), served as a valuable guide for the planning of subsequent site investigations. The 1:24,000-scale map

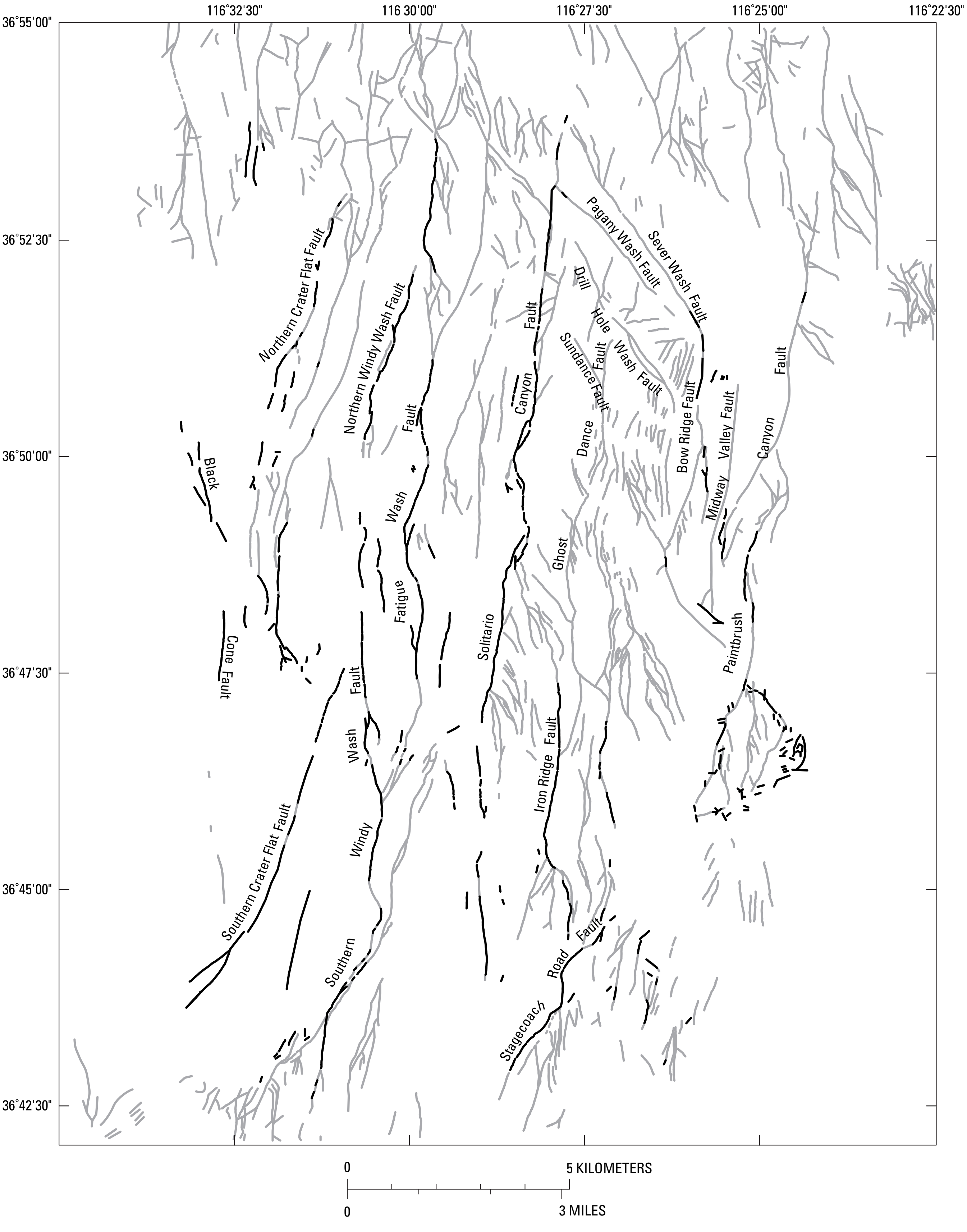

Figure 4. Faults in the Yucca Mountain area, southwestern Nevada (figs. 1, 2), simplified from map by Simonds and others (1995). Dark lines, faults with Quaternary or suspected Quaternary activity.

by Simonds and others (1995)—a compilation of all available data on Quaternary fault activity that had been collected through 1993—resulted in the recognition that displaced or disturbed alluvial and colluvial deposits record late Quaternary faulting along at least seven to nine major faults at Yucca Mountain. Such findings assisted in the selection of new trench sites and the location of key natural exposures for additional paleoseismic investigations. A more recent geologic-mapping program, begun in 1995, resulted in publication of two detailed geologic maps: (1) a 1:24,000-scale map of the Yucca Mountain area (Day and others, 1998a); and (2) a 1:6,000-scale map of the central-block area, centered over the proposed repository block itself (Day and others, 1998b). These two mapping efforts focused primarily on the distribution of the thick Miocene volcanic sequence, as defined and subdivided according to the presently accepted stratigraphic framework for the area (for example, Buesch and others, 1996), and on the geologic structures within bedrock units, resulting in further refinement of the fault patterns at Yucca Mountain and providing new data, especially on possible extensions and interconnections of major individual faults as their traces are projected beneath alluvial cover.

A simplified fault map of the Yucca Mountain area, based primarily on data from the 1:24,000-scale map of Simonds and others (1995), is shown in figure 4. Simonds and others' map is especially useful for showing the general extent of known or suspected Quaternary activity along individual faults or fault systems and includes notations describing the evidence for such activity as observed during field investigations or interpreted from aerial photographs along the mapped or projected fault traces.

The geologic maps by Day and others (1998a, b) do not extend far enough to show the location and extent of the Bare Mountain and Rock Valley Faults. The Bare Mountain Fault zone was mapped in detail at a scale of 1:24,000 by Monsen and others (1992), and the Rock Valley Fault system is shown on the 1:100,000-scale geologic-map compilation by Frizzell and Shulters (1990).

For the purposes of this report, faults with known late Quaternary displacement are categorized as traceable faults or fractures and scarps in alluvial material. Fractured or disturbed soil horizons and carbonate-cemented fault breccias that show fracturing or shearing in surficial materials are considered to be evidence for Quaternary fault activity. Places where late Quaternary displacement is suspected but unequivocal proof is absent include (1) traceable faults, suspected fault contacts, or fault traces along the projection of a fault that in some places has known or suspected Quaternary displacement; (2) possible fault-controlled lineaments, such as linear stream channels, aligned vegetation or burrows, stonelines, and photolineaments in Quaternary deposits; and (3) faultline scarps along bedrock-alluvium contacts where differential erosion has produced prominent linear scarps on the bedrock footwall. Faultline scarps are suspected to be of Quaternary age because local evidence typically exists for displacement of hanging-wall alluvial and colluvial deposits.

Major Faults

The drainage pattern at Yucca Mountain is controlled largely by faults, and so most of the main faults are named for the drainages in which they are mapped; other faults are named for nearby geographic features (figs. 2, 4). The major faults form the boundaries of large east-dipping structural fault blocks (Day and others, 1998 a, b), and most of them also define the bedrock-alluvium contact at the base of west-facing scarps in bedrock for at least part of their lengths.

The following sections provide general descriptions of the surface characteristics of the major faults, the locations of and evidence for Quaternary activity, the amounts and sense of displacement of both bedrock and Quaternary deposits, fault lengths, and, where applicable, evidence for geometric segmentation of a fault. The term "geometric segmentation" refers to subdivision of a fault into segments based on variations in its geometry or structure. Criteria used to define geometric-segment boundaries include abrupt changes in fault pattern marked by (1) zones of overlap between two strands of the fault zone, (2) bifurcation into large fault splays, (3) large gaps in the fault trace, (4) sharp deflections in the strike of the fault, and (or) (5) reversals in dip direction or sense of displacement along the fault. Fault characteristics are summarized in table 5. Results of the detailed mapping of trenches excavated across faults, which are sites where the geologic relations along faults and evidence for Quaternary activity are best exposed, as well as information on the timing, slip rates, and recurrence intervals of faulting events, are discussed in other chapters of this report.

Paintbrush Canyon Fault

The Paintbrush Canyon Fault (figs. 2, 4) is a major block-bounding fault on the east side of Midway Valley (fig. 1; Day and others, 1998a). The fault is exposed for a distance of 5 km in bedrock forming the highlands north of Yucca Wash, where it is shown as a west-dipping (56°–76°) normal fault with down-to-the-west displacement of 210 m (Dickerson and Drake, 1998). Along that section of the fault, the trace is marked by a discontinuous, west-dipping fault scarp, 0.3 to 4.0 m high. To the south, the fault extends beneath alluvial cover for 5 km before strands are exposed for about 1 km in bedrock along the west side of Fran Ridge (Day and others, 1998a); it may then continue southward for another 8 km to a possible intersection with the southwest-striking Stagecoach Road Fault.

Estimates of the amount of bedrock displacement on the Paintbrush Canyon Fault range from 210 m in the northern segment to as much as 500 m along other segments (Scott and Bonk, 1984; Day and others, 1998a). Evidence for Quaternary fault activity is observed in trenches and in natural exposures in sand ramps along the west side of Busted Butte, as discussed in chapter 5. Maximum observed displacements of surficial deposits range from 5.5 to 8.0 m.

Table 5. Summary of characteristics of major faults in the Yucca Mountain area, southwestern Nevada.

[See figures 1 and 2 for locations]

Fault (fig. 4)	Surface characteristics	Evidence of Quaternary activity	Average dip of fault	Sense of displacement	Amount of displacement (bedrock)	Amount of displacement (Quaternary)	Fault length
Crater Flat Fault zone (Northern and Southern).	Bedrock faults, bedrock scarps, subtle scarps and lineaments in alluvium, and bedrock-alluvium fault contacts.	Lineaments in alluvium; subtle scarps and fractures in alluvium.	70° W.	Oblique, left lateral	Unknown, down to the west.	1.2 m, late Quaternary	Min 1 km, max 20 km
Windy Wash Fault.	Prominent faultline scarp, east-facing scarps in alluvium, and bedrock- alluvium fault contacts. Merges with the Fatigue Wash Fault.	Three trenches show multiple events, fractures and scarps in alluvium, and basaltic ash in fault plane.	63° W.	Dip slip	Increases southward to ~500 m down to the west	3.7 m, late Quaternary	Min <3 km, max 25 km
Fatigue Wash Fault.	Bedrock fault, faultline scarp, scarps and lineament in alluvium, and bedrock scarps. Merges with the Windy Wash Fault.	One trench shows multiple events, fractures and scarps in alluvium, and basaltic ash in fault plane.	70° W.	Oblique, left lateral	100–400 m down to the west	1.3–2.8 m, late Quaternary	Min 9 km, max 17 km
Solitario Canyon Fault.	Prominent faultline scarp, discontinuous traces, and subtle scarps in alluvium. Iron Ridge Fault splay forms prominent faultline scarp. Merges (?) with the Stagecoach Road Fault.	12 trenches, 9 of which show multiple events, fractures in alluvium, and basaltic ash in fault plane.	72° W. (main trace), 68° W. (Iron Ridge Fault)	Oblique, left lateral	Increases southward from 50 m down to the east to 500 m down to the west	1.7–2.5 m, late Quaternary	Min 12.5 km, max >21 km
Stagecoach Road Fault.	Prominent scarp and traceable faults in alluvium. Merges with the Solitario Canyon and (or) Paintbrush Canyon Fault.	3 trenches, 2 of which show multiple events, fractures and scarps in alluvium, and basaltic ash in faulted alluvium.	73° W.	Dip slip	400–600 m, down to the west	1.0–3.1 m, late Quaternary	Min 4 km, max 7 km
Ghost Dance Fault.	Bedrock fault in a zone of subparallel minor faults and breccia zones.	None	Near vertical	Dip slip	Increases southward from 0 to 27 m down to the west	None	Min 2.5 km, max 7 km
Bow Ridge Fault.	Faultline scarp along bedrock-alluvium contact, subtle lineaments. May merge with the Paintbrush Canyon Fault.	6 trenches, 5 of which show multiple events, fractures in alluvium, and basaltic ash in fault plane.	75°–80° W.	Oblique, left lateral	125 m down to the west	0.5–1.22 m, late Quaternary	Min 4 km, max 11.5 km
Midway Valley Fault.	Bedrock faults at north and south ends; detected by geophysical surveys in covered areas.	None	Unknown; west(?)	Unknown, dip slip(?)	Several tens of meters down to the west	None	Min 1 km, max 13 km
Paintbrush Canyon Fault.	Bedrock faults, bedrock scarps, lineaments, bedrock-alluvium fault contacts, and faults in alluvium. May merge with the Stagecoach Road Fault.	4 trenches and natural exposures at Busted Butte show multiple events, fractures in alluvium, and basaltic ash in fault plane (locally).	71° W.	Dip slip to oblique, left lateral	210–500 m down to the west	5.5–8.0 m at Busted Butte, late Quaternary	Min 11 km, max 19 km
Northwest-trending faults.	Bedrock faults with local small bedrock scarps; some faults located on the basis of geophysical or drillhole evidence.	None, except for 1 trench located on the Pagany Wash Fault that shows possible Quaternary activity.	>70° S. to vertical	Strike slip, right lateral	5–10 m vertical, ~40 m right lateral	None	4 km
Bare Mountain Fault.	Faultline marked in places by bedrock-alluvium contact; offset of pre-Tertiary rocks evidenced by seismic-reflection data.	Surficial deposits displaced; scarps formed in alluvial fans.	50°–70° E.	Dip slip to oblique slip	3.5 km down to the east	Max 4–5 m	20 km
Rock Valley Fault.	Composed of multiple east-northeast-striking faults that form distinct scarps and lineaments in surficial deposits; bedrock offsets indicated by seismic data.	Scarps and lineaments in surficial deposits.	Varying to near vertical	Strike slip (left lateral) to oblique slip	≤4 km, left lateral	Min 5 cm, max 17 m	Min 19 km, max 65 km

Midway Valley Fault

The Midway Valley Fault (figs. 2, 4) is shown by Day and others (1998a) to extend northward from a 1-km-long exposure in bedrock (Tiva Canyon Tuff) at the southeast end of Bow Ridge for a distance of about 9 km beneath the surficial deposits flooring Midway Valley, and then to continue northward for at least another 3 km as a west-dipping normal fault that displaces bedrock about 120 m down to the west in the upper part of the Paintbrush Group (Dickerson and Drake, 1998). Displacements of buried bedrock within the valley are interpreted from gravity and magnetic surveys to be 40 to 60 m (Ponce and Langenheim, 1994), and the cross sections by Scott and Bonk (1984) show about 70 m of down-to-the-west displacement on a fault that dips 70° W. The Midway Valley Fault does not displace Quaternary alluvial deposits, as discussed in chapter 4.

Bow Ridge Fault

The Bow Ridge Fault (figs. 2, 4) has been studied in detail on the west side of Exile Hill, where it is well exposed in a 200-m-long segment marked by a low faultline bedrock escarpment. Trenches T14 and T14A through T14D (figs. 2, 8), which were excavated across projections of the fault beneath surficial deposits, revealed small-displacement Pleistocene faulting events (see chap. 5). Trench A/BR–3, excavated across a northward projection of the fault marked by a vegetation-change lineament, however, revealed no disturbance of the exposed surficial deposits.

Bedrock is displaced about 125 m down to the west along the Bow Ridge Fault on the west side of Exile Hill (Scott and Bonk, 1984). The fault dips 75°–80° W. (Simonds and others, 1995), and net displacement is left oblique. Upper Quaternary colluvial deposits are vertically displaced 0.5 m, but left-lateral striations on carbonate laminae in the fault plane indicate that cumulative net slip may be as much as 1.22 m (table 5).

Although the northward extent of the Bow Ridge Fault is uncertain, Day and others (1998a) showed it to extend beneath surficial deposits north of Exile Hill to the north side of Yucca Wash, a distance of about 4.5 km, and Dickerson and Drake (1998) mapped it cutting bedrock in the upper part of the Paintbrush Group for another 1 to 2 km to the north. From a point opposite the mouth of Yucca Wash, the fault is shown to have down-to-the-east displacement. About 4 km south of Exile Hill, at the south end of Midway Valley, displaced bedrock marks the fault trace along the west side of Bow Ridge. The fault is then shown to bend to the southeast beneath alluvium for a distance of another 2.5 km, where it may connect with the Paintbrush Canyon Fault (Day and others, 1998a). The total length of the Bow Ridge Fault may be as much as 11.5 km.

Stagecoach Road Fault

The Stagecoach Road Fault (figs. 2, 4), a northeast-trending structure south of Stagecoach Road, is traceable for 4 to 5 km as northeast-striking fractures and truncated alluvial surfaces in Quaternary alluvium (Simonds and others, 1995). A distinct west-facing topographic fault scarp, as much as 1.0 m high, is present along most of the fault trace, particularly where the fault exposes resistant well-developed carbonate soil in the footwall. The scarp is at the west edge of a 0.5-km-wide alluvium-mantled bedrock pediment formed to the west of a low bedrock ridge.

Upper Quaternary alluvial deposits are displaced along the entire trace of the Stagecoach Road Fault. Trenches SCR–T1 and SCR–T3 (fig. 2), which were excavated across the fault, contain evidence of multiple faulting events (see chap. 5). Trench SCR–T2 was excavated across a photolineament east of the Stagecoach Road Fault but did not expose a fault.

The amount of bedrock displacement on the fault is estimated at 400 to 600 m down to the west (Scott, 1990). Upper Quaternary alluvium is displaced 1.0 to 3.1 m. The fault has an average dip of 73° W.; slickenside measurements indicate that Quaternary movement is predominantly dip slip.

The Stagecoach Road Fault is traceable as a topographic fault scarp for nearly 4 km before disappearing under uppermost Quaternary materials. Continuation of surface rupture along the fault to the southwest or northeast of the main fault trace, if present, could consist only of minor fracturing or small displacements that have not persisted as fault scarps because of erosion or burial. Northeast-striking fractures at the north end of the Stagecoach Road Fault indicate a possible connection with the Paintbrush Canyon Fault south of Busted Butte, and northeastward structural continuation of the fault is supported by anomalies in shallow geophysical (aeromagnetic) surveys as well (V.E. Langenheim, written commun., 1995). However, no fault scarps or other surface expressions of faulting in alluvial fans were observed between the two faults. Its simple trace and the short length of the main fault zone indicate that the fault consists of only a single geometric segment.

Ghost Dance and Sundance Faults

The Ghost Dance Fault (figs. 2, 4) is the main structural feature in a diffuse zone of minor bedrock faults and fractures east of the crest of Yucca Mountain (Day and others, 1998b). Though not one of the major block-bounding faults at Yucca Mountain (it is classed as an “intrablock” fault), the fault is important because it extends across the proposed repository-site area (Day and others, 1998b). The Sundance Fault is a nearby subsidiary feature that also traverses the proposed repository site area.

The Ghost Dance Fault trends generally north to north-northeast, with subvertical to steep (>65°) westward dips; the main fault zone extends from Wren Wash near the southern margin of Drill Hole Wash southward to Broken Limb Ridge, a distance of about 2.5 km (Day and others, 1998b). Farther south, the fault zone bifurcates, striking southwest into the Abandoned Wash Fault of Scott and Bonk (1984) and southeast toward, but not into, the Dune Wash Fault.

As mapped and described in detail by Day and others (1998b), the Ghost Dance Fault zone can be divided into three sections on the basis of the amount of offset and brecciation within units of the Miocene Tiva Canyon Tuff:

1. The northern section, which lies north of Split Wash, is represented by a relatively narrow (2–4 m wide) damaged-rock zone with as much as 6 m of down-to-the-west displacement (see fig. 21 for location)
2. The central section, which extends from Split Wash to Broken Limb Ridge, displays 13 to 27 m of cumulative down-to-the-west displacement across two or more splays, distributed over a 55- to 150-m-wide zone.
3. The southern section, south of Broken Limb Ridge to where it merges with the Abandoned Ridge Fault, is represented by numerous splays that parallel the main north-striking zone. Here, the displacement (3–17 m) and width of brecciation (2–15 m) are considerably less than in the central section.

The Ghost Dance Fault is difficult to trace continuously across hillslopes either by surface mapping or by interpretation of aerial photographs, because only small segments are associated with linear gullies or with topographic steps or scarps that would give rise to noticeable lineaments marking the fault trace. The absence of strong geomorphic expression, in combination with the apparent absence of deformation of surficial deposits observed in several trenches excavated across the Ghost Dance Fault (see chap. 6), indicates that faulting events did not occur as late as Quaternary time.

The Sundance Fault is mapped as a 750-m-long zone extending from Dead Yucca Ridge southeastward to Live Yucca Ridge and is shown to have a maximum cumulative down-to-the-northeast displacement in bedrock of 6 to 11 m (Day and others, 1998b; Potter and others, 1999). In places, as many as four splays within a 70-m-wide brecciated fault zone are distinguishable. The Sundance Fault zone, as mapped by Potter and others (1999), terminates west of the Ghost Dance Fault, contrary to an earlier interpretation by Spengler and others (1994); the Ghost Dance Fault is shown to extend across Split Wash beneath surficial deposits, with no apparent offset by a younger fault (Day and others, 1998b). Like the Ghost Dance Fault, the Sundance Fault shows no evidence of Quaternary activity.

Solitario Canyon Fault

The longest continuously exposed fault trace at Yucca Mountain is associated with the Solitario Canyon Fault, the main trace of which extends from northernmost Yucca Mountain at the south margin of Yucca Wash to Stagecoach Road (including the section labeled "Iron Ridge Fault" in figs. 2 and 4; Day and others, 1998a). The fault is well expressed along the east side of Solitario Canyon, where, for much of its length, it forms a prominent faultline scarp along the bedrock-alluvium contact at the base of a large topographic bedrock escarpment. Scarp height ranges from 0.3 m (east facing) at the north end of the fault to as much as 5.0 m (west facing) at the south end. The fault bifurcates into several splays at its south end. The central splay consists of discontinuous fault traces and subtle scarps in alluvium that continue as far southward as Stagecoach Road. A discontinuous series of bedrock scarps has formed along the western splay, which trends south-southwest and may merge with the Southern Windy Wash Fault. Bedrock fault splays split off the central section of the main Solitario Canyon Fault trace and connect with a prominent west-facing faultline scarp, as much as 15 m high, at the base of a prominent bedrock escarpment. This eastern section of the Solitario Canyon Fault was called the Iron Ridge Fault by Scott (1992), a usage retained here even though it is now considered to be a splay of the Solitario Canyon Fault. To the south, the Iron Ridge Fault also strikes toward, and may connect with, the Stagecoach Road Fault (Simonds and others, 1995).

Naturally exposed evidence of Quaternary displacement is limited to sheared carbonate-cemented fault breccia at the bases of faultline scarps and to a few fractures in alluvium in the hanging wall of the Solitario Canyon Fault. A total of 11 trenches and 1 natural cleared exposure have been excavated across or near the Solitario Canyon and Iron Ridge Faults (fig. 2). Three of the older trenches—T13, T10A, and T10B—did not cross the main trace of the fault, and the others—GA1A, GA1B, Ammo Ridge, SCF–T4, SCF–T8, SCF–T3, SCF–T1, SCF–T2, and SCF–E1—contain evidence of multiple mid-Quaternary to late Quaternary faulting events (see chap. 7). Bedrock displacements on the Solitario Canyon Fault range from about 50 m down to the east at the north end to as much as 500 m down to the west near the mouth of Solitario Canyon to the south (Day and others, 1998a). Thus, the fault zone displays a scissors geometry that contains a null point with essentially no displacement where movement is reversed. Dips on the Solitario Canyon Fault range from 60° to 80° W. south of the null point; slickenside measurements indicate that the net slip is left oblique. The Iron Ridge Fault dips an average of 68° W. and displays left-oblique slip. Preliminary examination of four trenches on the Solitario Canyon Fault indicates that Quaternary deposits are displaced 1.7 to 2.5 m down to the west (table 5).

The Solitario Canyon Fault is exposed continuously for a distance of 12.5 km. If the fault extends as far southward as Stagecoach Road, its overall length is at least 18 km. If the fault is connected with the Iron Ridge Fault and also with the Stagecoach Road Fault, the total length may exceed 21 km. No evidence was observed for geometric segmentation of the central and southern sections of the fault where its trace is continuous. The part of the northern section with east-side-down displacement may represent a separate geometric segment, although the reversal in offset may reflect continuous scissoring movement of the hanging-wall or footwall blocks, with no relation to fault-rupture segmentation. The Iron Ridge Fault is a large splay that is considered to be a distinct geometric fault segment; the small central and western splays at the south end of the Solitario Canyon Fault may also represent distinct short fault segments.

Fatigue Wash Fault

The Fatigue Wash Fault (figs. 2, 4) is a poorly exposed bedrock fault in Fatigue Wash, about 2.25 km west of the Solitario Canyon Fault. From a point where it merges with bedrock splays from the Northern Windy Wash Fault (fig. 4) that cross the south end of West Ridge, the Fatigue Wash Fault forms a nearly continuous, 9-km-long sinuous trace toward the south. The fault trace consists of a faultline scarp at the base of a bedrock escarpment near the mouth of Fatigue Wash, and of traceable faults, piedmont fault scarps, and lineaments in alluvial and colluvial deposits near the mouth of Solitario Canyon. The south end of the Fatigue Wash Fault consists of bedrock faults and bedrock scarps that appear to merge with the Southern Windy Wash Fault, indicating that the two faults are interconnected (Simonds and others, 1995).

Quaternary alluvial-fan and colluvial deposits are displaced where the fault cuts across the mouth of Solitario Canyon. Trench CF–1 (fig. 2), which was excavated across a scarp in Quaternary alluvium, shows evidence of several Quaternary faulting events (see chap. 8). Several scarps in Quaternary alluvium lie between the Fatigue Wash and Windy Wash Faults to the west; the east-facing scarps may be antithetic to the Fatigue Wash Fault.

The down-to-the-west displacement of bedrock along the northern section of the Fatigue Wash Fault is about 100 m, but south of the mouth of Fatigue Wash, displacement is nearly 400 m (Day and others, 1998a). The average dip of the fault plane is about 70° W.; slickenside lineations on the fault plane have a moderate component of left slip that indicates net left-oblique displacement. The Quaternary displacement is about 2.2 m (table 5).

Although the Fatigue Wash Fault is well exposed for a distance of 9 km, the overall length of the fault may be as much as 17 km if its poorly exposed north end extends to Yucca Wash. However, little evidence was observed for Quaternary displacements on the fault north of its intersection with the northern section of the Windy Wash Fault at West Ridge. Thus, the central and, possibly, southern sections of the Fatigue Wash Fault south of that intersection appear to represent a geometric segment of the fault that exhibits the best evidence for Quaternary activity.

Windy Wash Fault

The Windy Wash Fault (figs. 2, 4), named for a prominent faultline scarp on the east side of Windy Wash, is traceable nearly continuously from the south rim of Claim Canyon Caldera (one of the eruptive centers in the southwestern Nevada volcanic field; Christiansen and Lipman, 1965) to the southeast edge of Crater Flat (Swadley and Carr, 1987; Frizzell and Shulters, 1990). The fault can be subdivided into three sections on the basis of contrasts in geomorphic expression and changes in dip direction. (1) The Northern Windy Wash Fault is marked by a west-dipping faultline scarp at the base of a bedrock escarpment that is continuous for 7 km, except for a 600-m-long interval where a bedrock fault splays to the east and appears to connect with the Fatigue Wash Fault (Simonds and others, 1995; Day and others, 1998a). (2) The central section of the fault is characterized by a 4- to 5-km-long discontinuous zone of east-facing scarps in the alluvial fan at the mouth of Solitario Canyon. (3) The geomorphic expression of the 9-km-long Southern Windy Wash Fault consists of a short (1 km long) series of west-facing fault scarps at the southernmost edge of the Solitario Canyon alluvial fan that continues southward into a prominent west-dipping faultline scarp at the base of a bedrock ridge. This scarp can be traced discontinuously for 5.5 km as the bedrock-alluvium contact along the southeast edge of Crater Flat. Near Stagecoach Road, the Southern Windy Wash Fault bends to the west. That southwest-trending segment of the fault consists of two parallel strands that merge to the south to form a 75-m-wide breccia zone. The fault appears to continue southward, except for a 500-m-wide gap where the faultline scarp bends to the south.

Evidence for Quaternary displacement along the Northern and most of the Southern Windy Wash Faults is limited to subtle scarps in Quaternary alluvium and fractures in the hanging walls of faultline scarps. Limits on the age of Quaternary displacements on the Northern Windy Wash Fault are provided by (1) several undisturbed mid-Quaternary to upper Quaternary talus fans that overlie the fault trace, and (2) results of exposure dating that show the exhumed fault surface to be no younger than late Pleistocene. Quaternary activity is indicated by fault scarps in alluvium along the central section of the fault. Trenches CF–2 and CF–3 (fig. 2), which were excavated across scarps in alluvium along the north end of the Southern Windy Wash Fault, contain evidence of multiple late Quaternary surface ruptures totaling about 3.7 m of offset, including a faulted upper Holocene deposit (see chap. 9; Whitney and others, 1986).

The bedrock displacement on the Windy Wash fault is uncertain; down-to-the-west displacement is interpreted to increase southward but is probably less than 500 m (Scott, 1990). Average dip is 63° W. on the Northern and Southern Windy Wash Faults, but east-facing fault scarps indicate eastward dips along the central section of the fault (Simonds and others, 1995). Slickenside measurements indicate mostly dip-slip displacement; slight components of both right and left slip were observed in some outcrops. Quaternary displacement is small, as indicated by subtle scarps in alluvium.

Individual exposures of the fault traces generally are less than 3 km long, and alluvial scarps are 1 to 2 km long. Connecting the fault traces, including east-facing scarps in alluvium, yields a total fault length of about 25 km for the Windy Wash Fault system (Simonds and others, 1995).

Northern and Southern Crater Flat Faults

Several bedrock faults and suspected Quaternary faults lie west of Windy Wash along the northeast edge of Crater Flat; these previously unnamed faults are here referred to collectively as the Northern Crater Flat Fault (fig. 4). The fault zone contains two subparallel, north-northeast-trending faults, 300 to 600 m apart, that are marked by small discontinuous bedrock scarps, subtle scarps and lineaments in alluvium, and short bedrock-alluvium contacts. The faults are best exposed in northeastern Crater Flat and are poorly exposed east and south of Black Cone (fig. 2). The section of the fault east of Black Cone has been referred to as the Black Cone Fault (fig. 4).

Though lacking surface expression directly south of Black Cone, the Crater Flat Fault zone originally was postulated by Simonds and others (1995) to continue southward and to connect with a suspected Quaternary fault in southeastern Crater Flat. However, abrupt changes in orientation, differences in geomorphic expression, and contrasts in paleoseismic history revealed in trenches indicate that the two faults are probably separate structures (see chaps. 10, 11). The southernmost fault, referred to as the Southern Crater Flat Fault (fig. 4), is marked by a northeast-striking linear basalt-alluvium contact, fractured carbonate-cemented alluvium, subtle scarps in alluvium, and a linear stream channel. Other down-to-the-west structures may be present in the subsurface 1 to 2 km west of the Crater Flat Fault zone, on the basis of a northerly alignment of basaltic dikes and fissure vents and north-northwest-trending, 0.3- to 0.7-m-high, east-facing scarps in alluvium near Black Cone.

Four trenches were excavated on the Northern and Southern Crater Flat Faults (fig. 2): trenches CFF–T1 and CFF–T1A across scarps north of the basalt flows along the Southern Crater Flat Fault, and trenches CFF–T2 and CFF–T2A across a lineament and a fault scarp along the Northern Crater Flat Fault. Three of these trenches expose fault zones that disrupt alluvium, thus providing clear evidence for multiple Quaternary displacements on both faults that supplements the surface expressions of Quaternary activity. No trenches were excavated across the postulated faults to the west, although topographic scarps indicate that at least some of these structures may have had Quaternary activity.

The down-to-the-west normal faults displace bedrock by an unknown amount. One slickenside measurement indicates a moderate left-lateral component of slip on a 70°-dipping fault plane. Trench exposures, in combination with subtle scarps and lineaments in alluvium, indicate that late Quaternary displacement is small—less than 1 m (table 5).

Individual exposures of the fault traces generally are less than 1 km long, but several traces are as much as 2 km. Connecting the exposed traces of the Northern Crater Flat Fault in northeastern Crater Flat yields a total length of about 10 km. The Southern Crater Flat Fault ranges from 4 to 7 km in length, depending on the extent of stream and basalt-alluvium contact lineaments included in the measurement. If the two faults are connected, the total length could be as much as 20 km. No evidence for geometric segmentation was observed in either the Northern or Southern Crater Flat Fault.

Northwest-Trending Faults

Sever, Pagany, and Drill Hole Washes are conspicuous northwest-trending drainages that appear to be controlled by northwest-striking faults, as identified on the basis of geophysical investigations, bedrock mapping, and examination of drill cores from Drill Hole Wash (Scott and others, 1984). A similar fault also was inferred to project beneath the Quaternary alluvial deposits of Yucca Wash, but more extensive geologic and geophysical investigations have been unable to confirm the existence of this structure (Langenheim and Ponce, 1994; Dickerson and Drake, 1998; Day and others, 1998a). The Sever Wash and Pagany Wash Faults are exposed in bedrock and locally are expressed as small bedrock scarps. The Drill Hole Wash Fault is largely concealed by Quaternary alluvium, but examination of drill cores from the wash confirms the presence of several separate but interconnected faults (Rousseau and others, 1999). Quaternary alluvial terraces on the floors of the washes do not appear to be displaced by the northwest-trending faults. Trench T12 (fig. 2), which was excavated across the Pagany Wash Fault, exposes faulted bedrock on the trench floor, but the overlying bedrock regolith and colluvium are not displaced.

The northwest-trending faults are believed to be strike-slip faults because they dip steeply (>70°), fault-plane surfaces locally contain slickenside lineations that are nearly horizontal, and vertical displacements generally are less than 5 to 10 m (Scott and others, 1984). The Sever Wash and Pagany Wash Faults show slickenside orientations and Riedel shears that indicate right-lateral slip. The amount of right-lateral slip on each fault was estimated at about 40 m (Scott and others, 1984). O'Neill and others (1991) concluded that the northwest-trending faults are extensional structures related to the left-oblique component of displacement along the north-trending faults.

The Sever Wash and Pagany Wash Faults are each about 4 km long. Both faults appear to terminate against the Solitario Canyon Fault to the west and, though concealed, are postulated to merge with a western strand of the Bow Ridge Fault to the east (Day and others, 1998b). The Drill Hole Wash Fault, which also is about 4 km long, appears to merge with a strand of the Bow Ridge Fault.

Bare Mountain Fault

The Bare Mountain Fault is a generally north striking, east-dipping (50°–70°), normal- to oblique-slip fault that forms the structural boundary between Bare Mountain to the west and Crater Flat Basin on the east (fig. 1; Reheis, 1988; Monson and others, 1992). The fault is approximately 20 km long and for part of its length is traceable as the bedrock-alluvium contact. Although no direct surface evidence was observed as to the amount of down-to-the-east displacement of bedrock (Paleozoic and Precambrian sedimentary strata), seismic-reflection data have been interpreted to indicate that the total offset of pre-Tertiary rocks is about 3.5 km (Brocher and others, 1998). Quaternary deposits are displaced along the Bare Mountain Fault, and young scarps are developed in alluvial fans (see chap. 12).

Rock Valley Fault

The Rock Valley Fault system includes several east-northeast-striking left-lateral faults and numerous other complex interconnecting faults within Rock Valley (fig. 1). A transverse seismic profile across the valley indicates that the fault zone is characterized by a series of narrow blocks cut by faults that dip steeply north and do not change in dip within the upper few thousand feet of bedrock (Tertiary volcanic rocks underlain by Paleozoic strata; Hinrichs, 1968). The result is a subdued half-graben in which the Tertiary strata are horizontal or dip slightly (≤20°) north. Various lengths have been shown for the fault system. If only faults in central Rock Valley are included, a minimum length of 19 km is indicated (Yount and others, 1987). However, if these faults are continuous with those to the northeast in Frenchman Flat, the minimum length would be 32 km, and a maximum length of 65 km is possible if they also connect southwestward to faults in Amargosa Valley (see Piety, 1994). O'Leary (2000) showed a length of 50 km, not extending the fault system into Amargosa Valley.

The Rock Valley Fault zone has been episodically active since late Oligocene time, with a total left-lateral displacement of less than 4 km (O'Leary, 2000). Although no large vertical displacement has occurred during the past 10 m.y., clear evidence was observed that Holocene deposits are displaced (see chap. 13). Quaternary fault scarps are preserved in many places, particularly in the central section of the fault zone, where scarps range in height from less than 1.0 to 2.5 m. Relations exposed in western Rock Valley show the formation of a 3-km-wide graben with a scarp relief of nearly 2 m. A trench across one of the bounding graben faults reveals a faulting event with 10 to 32 cm of vertical displacement during the past 38 k.y. (Yount and others, 1987). Evidence was also observed of earlier Quaternary faulting events, as well as an event possibly later than 2.5 ka. Repeated small earthquakes within Rock Valley and vicinity indicate that faults within the zone remain active—for example, the Little Skull Mountain M=5.6 earthquake of June 29, 1992 (Harmsen, 1994) and M=3.5 earthquake of September 7, 1995 (Smith and others, 2000).