Chapter E

Perspectives on Basin and Range Structure and Basaltic Volcanism—Bare Mountain–Crater Flat Area, Nye County, Nevada

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Abstract

A comparison of the structural geology, stress state, and record of basaltic volcanism in the Bare Mountain–Crater Flat area with those facets of other Basin and Range structures is helpful in drawing testable inferences. For example, earthquakes on seismically active faults provide information that is not obtainable on the Bare Mountain fault, and seismic reflection data in other basins may provide information that clarifies structural complexities in Crater Flat. Similarly, an observation-based theory of the interactions of stress, earthquakes, and the injection of basaltic dikes indicates a potential for similar interactions in the Yucca Mountain area. Such comparisons indicate that the Bare Mountain fault zone may consist of multiple high-angle step faults and that the basin fill in Crater Flat might contain alluvial fans and landslide debris near the fault zone. Either or both conditions can explain the gravity data and can be tested by seismic imaging techniques that have been effective in other basins. Stress relations, observed strain rate, and the scarcity of seismic activity in and around Crater Flat are consistent with

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extension by normal faulting and injection of basalt dikes at depth. The stress relations also indicate that horizontal sheet intrusions beneath Crater Flat are a possibility.

Introduction

Yucca Mountain, in Nye County, Nev., is being characterized as a potential high-level radioactive-waste repository. Bare Mountain and Crater Flat, which lie immediately west of Yucca Mountain, are separated by the Bare Mountain fault (fig. 1). This feature is an east-facing range-front fault that has been the focus of geologic and geophysical studies. Because the surface manifestations of the Bare Mountain fault and the adjacent Crater Flat basin are similar to those of better exposed Basin and Range faults elsewhere, the latter are useful for comparisons. One extensively explored basin is Dixie Valley, east of Fallon in west-central Nevada (fig. 1). A large earthquake there in 1954, accompanied by surface faulting, prompted several geophysical studies that included seismic refraction, gravity, and magnetics (Thompson and Burke, 1973, 1974). Later, interest in the geothermal resources led to seismic reflection profiling (Okaya and Thompson, 1985). Stress/strain studies were possible because of earthquake and geodetic data, extensive exposures of fault surfaces, and offsets of a 12-ka lake shoreline and an older basalt. Dixie Valley is similar to Crater Flat in that each is asymmetrical and bounded by a large, sinuous normal fault with horizontal components of slip.

Similarly, the regional tectonic stress and its relation to basaltic volcanism significantly influence geologic processes in the Yucca Mountain region. A large body of information on stress directions, which are notably consistent over large regions of the Basin and Range province, is available (Zoback, 1989). This report draws analogies with other Basin and Range faults to infer the subsurface structure and stress conditions around the Bare Mountain fault.

Bare Mountain Fault

Evidence from gravity and seismic refraction studies (Snyder and Carr, 1984; Oliver and Fox, 1993; Mooney and Schapper, 1994) clearly demonstrates large structural relief—at least 3 km—across the fault boundary between Bare Mountain and Crater Flat. However, existing geophysical data do not have enough resolution for unequivocal support of any one model for the boundary. Alternatives include the following: a low-angle fault, a zone of stepped high-angle normal faults, a high-angle normal fault with thick alluvial fan and landslide deposits producing a lateral gradation in density and seismic velocity, a caldera wall, or some combination of these features.

Comparisons to the Dixie Valley Fault

For comparative purposes, the Dixie Valley fault in west-central Nevada near Fallon (fig. 1) is perhaps the best example (Page, 1965; Thompson and Burke, 1973). Like the Bare Mountain fault, the Dixie Valley fault is sinuous in strike and, where exposed, dips 45°–75°. Seismic reflection data (fig. 2) demonstrate that the fault is approximately planar downdip and dips 50° to a depth of 3 km (Okaya and Thompson, 1985). The fault is active and produced a large earthquake pair (Dixie Valley–Fairview Peak, 4 minutes apart) in 1954. At a hypocentral depth of 15 km, the focal mechanism of the Fairview Peak earthquake indicates a fault dip of 62° (Romney, 1957; Okaya and Thompson, 1985; Doser and Smith, 1989). This observation of moderate to steep dip (>40°) can be generalized: active earthquake-producing normal faults in the Basin and Range province generally dip moderately to steeply through the entire seismogenic crust (Jackson, 1987). Exceptions to the steep dip (Johnson and Loy, 1992) may arise from aseismic creep, as in landslides; from fault-plane tilting; or from ductile shear, as in metamorphic core complexes. These and possibly other exceptions aside, we would expect the Bare Mountain fault to dip moderately to steeply. Are the gravity data consistent with this inference?

Bouguer gravity data across the Dixie Valley fault indicate a gradient that is not steep enough to result from basin fill of uniform density bounded by the seismically determined high-angle fault (Okaya and Thompson, 1985). Instead, the basin fill grades laterally from low-density clastic sediments (lake and stream) in the center of the basin to a denser stack of alluvial fan deposits near the Stillwater Range. The facies change is seen clearly in the seismic reflection section (fig. 2) and is confirmed by gravity models. Elsewhere along the Dixie Valley fault zone, down-to-the east movement on multiple concealed faults produced a step effect (fig. 3; Herring, 1967). This pattern was imaged by multiple seismic refraction lines parallel and perpendicular to the strike of the fault. Thus, the Dixie Valley gravity data are consistent with the seismic data when facies changes and multiple fault steps are recognized.

Similarly, the gravity anomaly associated with the Bare Mountain fault shows too small a gradient to represent a single high-angle fault without facies changes in the basin fill of Crater Flat (Snyder and Carr, 1984). Langenheim (this volume) has simulated alternatives that include a high-angle fault with dense slide-block debris in the basin fill near the mountain front. Slide debris has been mapped at the surface and identified in a drill hole (Carr and Parrish, 1985). Seismic reflection data or drilling in Crater Flat should be capable of defining and verifying this structure.

Slip Vectors and Stress

Throughout much of the Basin and Range province, including the Dixie Valley region in west-central Nevada and the Yucca Mountain region in southern Nevada, stress directions are simple and uniform despite the geologic complexity of the two areas (Zoback, 1989). This fact is well illustrated by the Dixie Valley fault, which varies more than 90° in strike but maintains a comparatively uniform slip direction of WNW.-ESE. (Thompson and Burke, 1973). As the mountain and basin blocks moved apart along the sinuous normal fault,

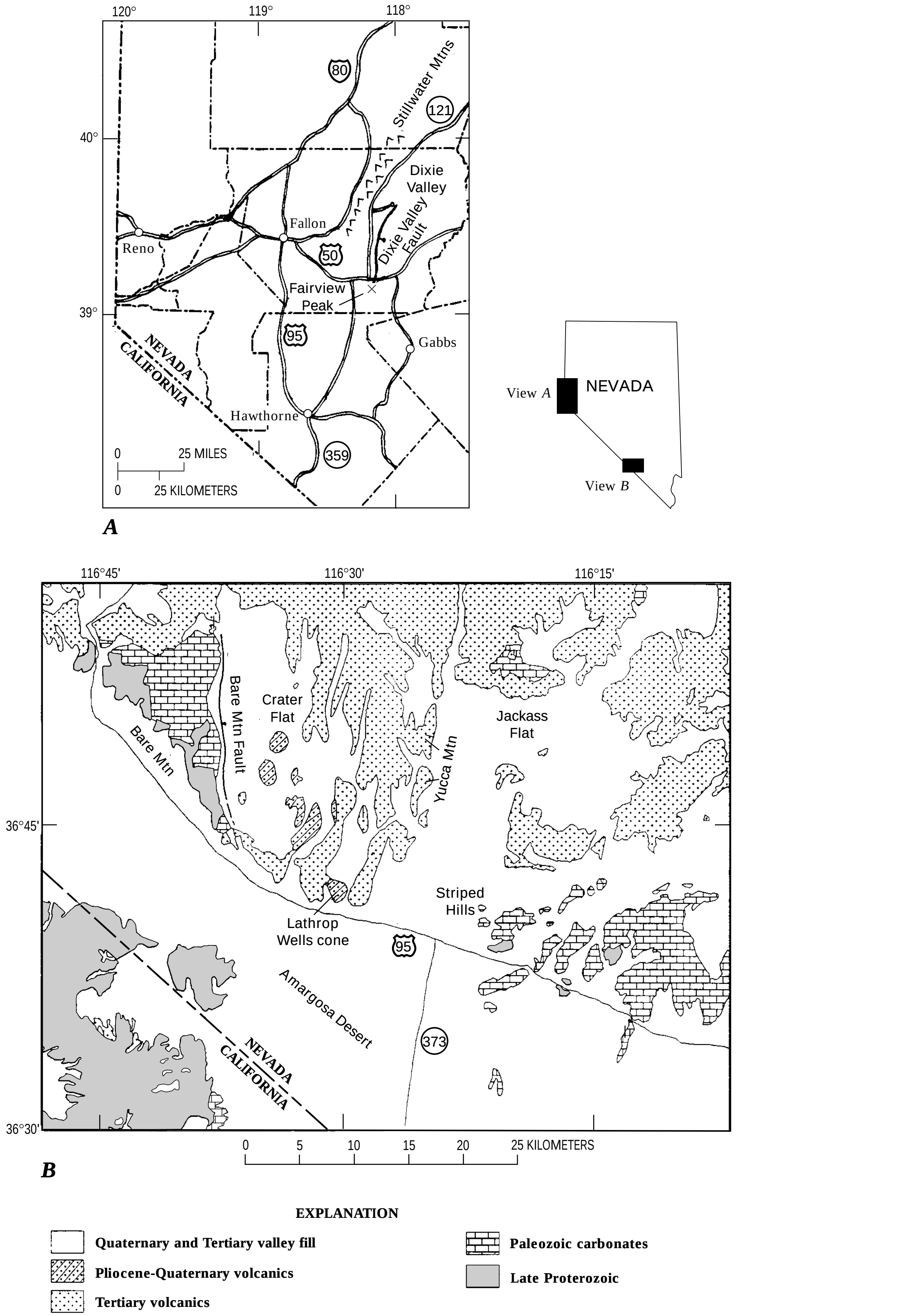

Figure 1. Index maps of *A*, Dixie Valley, and *B*, Yucca Mountain regions. Faults shown with bar and ball on downthrown side.

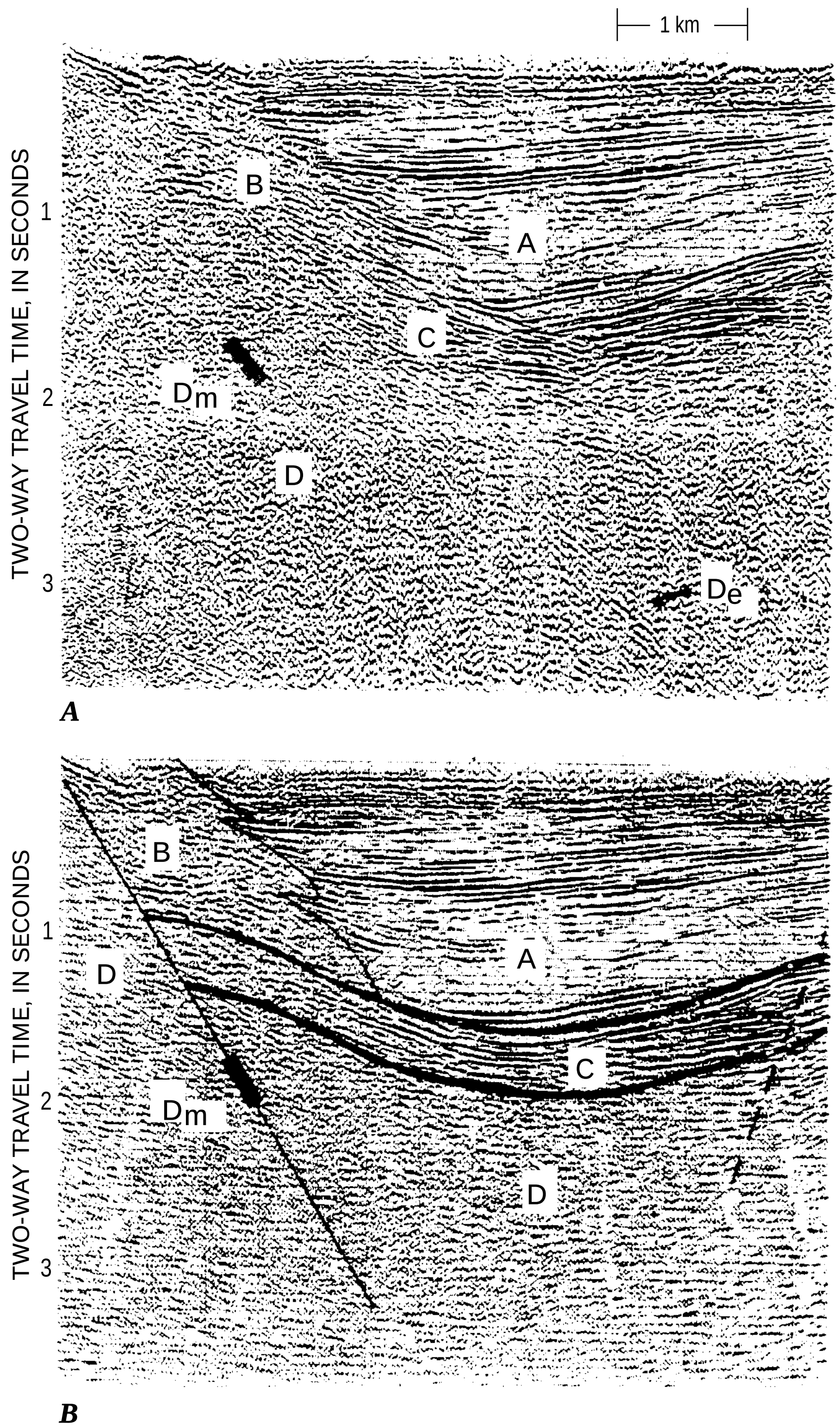

Figure 2. Seismic reflection section of Dixie Valley fault at Boyer Ranch; vertical exaggeration is approximately 1:1 at 3 km/s. *A*, stacked data; *B*, finite-difference time migration. A, lacustrine and stream deposits; B, alluvial fan deposits; C, Tertiary volcaniclastic deposits; D, Mesozoic basement; D_e, steeply dipping fault-plane reflections; D_m, hand migration of event D_e. Modified from Okaya and Thompson (1985).

some parts of the fault would be expected to have left-lateral and some right-lateral components of slip; grooved fault surfaces support that expectation.

In Dixie Valley, the WNW.-ESE. least principal stress (direction of extension) applies to the last 8–10 m.y., the age of the basin. Focal mechanisms of historical earthquakes, which

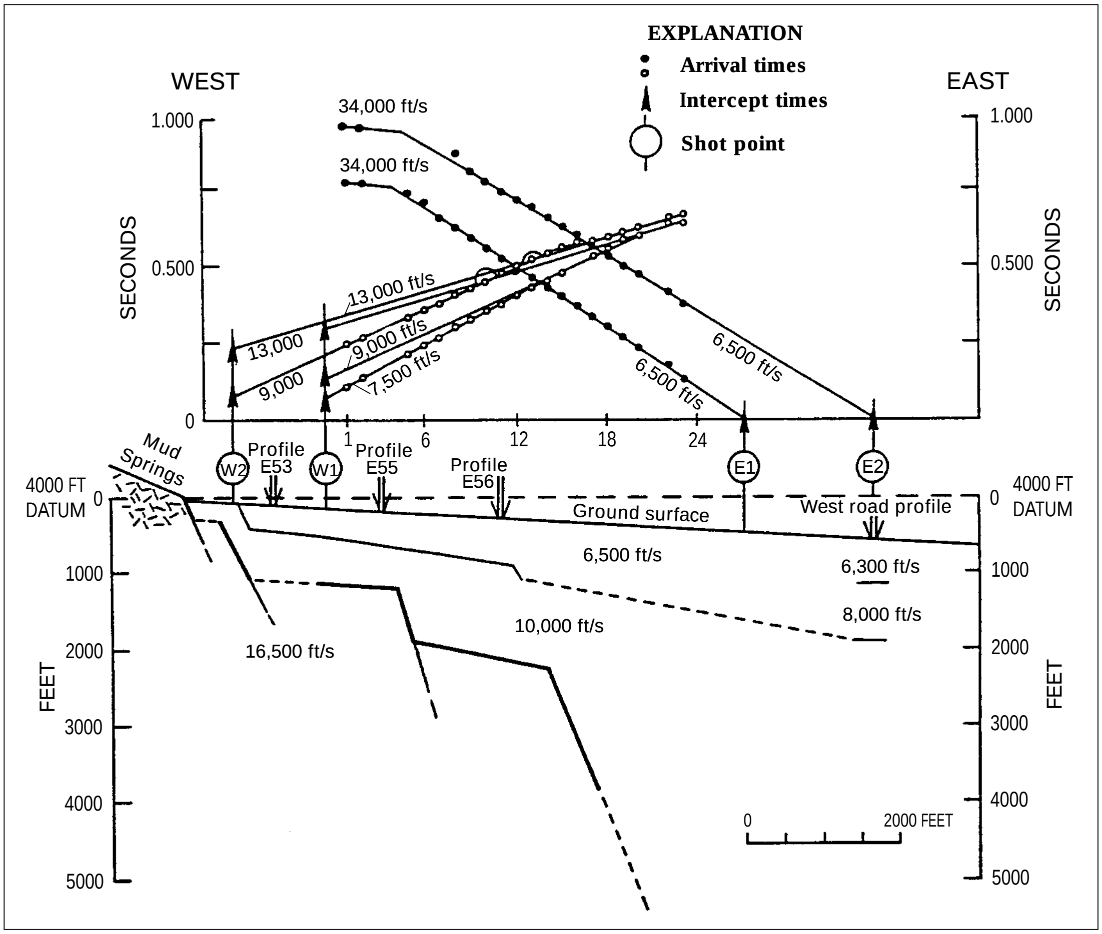

Figure 3. Seismic refraction section of stepped Dixie Valley fault zone at Mud Springs. Modified from Herring (1967).

are used to sample the fault at depth, indicate approximately the same direction. The entire Basin and Range province exhibits remarkable agreement among stress indicators within the ages to which they apply: (1) slip vectors on faults, (2) earthquake focal mechanisms, (3) hydrofracture measurements in boreholes, (4) well-bore breakouts, and (5) volcanic vent alignments and dikes, which are analogous to hydrofractures (Zoback and Zoback, 1989).

Prior to approximately 10 Ma the least principal stress in Nevada was WSW.-ENE., as indicated by the great dike swarms of 17–14 Ma that are associated with the northern Nevada rift (Zoback and Thompson, 1978; Zoback and others, 1994). Subsequently the extension direction rotated clockwise to its present WNW.-ESE. direction, and some of the earlier rift-related normal faults acquired an oblique slip.

Evidence in the Yucca Mountain region indicates that its stress history follows this general pattern: (1) hydrofracture measurements in boreholes indicate that the present direction of least principal stress is WNW.-ESE. (Stock and others, 1985); (2) earthquake focal mechanisms, including that of the Little Skull Mountain earthquake of 1992, confirm the direction at a greater depth (Rogers and others, 1987; Gomberg, 1991; K.D. Smith, University of Nevada, Reno, written commun., 1994); and (3) the alignment of 1 Ma cinder cones in Crater Flat (Cornwall and Kleinhampl, 1961) indicates the same alignment at an earlier time. Prior to about 3.7 Ma, however, the least principal stress direction was different, and, as in the broader region just discussed, it rotated clockwise to its present orientation. The older direction is indicated by 3.7 Ma basalt vents aligned north-south (Bruce Crowe, Los Alamos National Laboratories, written commun., 1994) and by latite dikes in Bare Mountain dated at 14 Ma; these dikes parallel the average north-south trend of the Bare Mountain fault (Monsen and others, 1992). These relations indicate that the least principal stress direction was approximately east-west when the vents and dikes were emplaced and during the early history of the Bare Mountain fault. After rotation of the least stress to its present WNW.-ESE. orientation, existing faults of north-south orientation, such as the Bare Mountain fault, would tend to develop a right-lateral component of slip; this inference is confirmed for depths of 10–15 km by earthquake focal mechanisms (Rogers and others, 1987; Gomberg, 1991). In some cases, moreover, a complementary new set of normal faults may develop such that slip on the old and new sets, integrated over multiple earthquake displacements, accommodates WNW.-ESE. extension. Faults parallel and approximately perpendicular to the northern Nevada rift manifest this complementary relation following rotation of the stress field (Zoback and Zoback, 1980).

Stress Modification by Dikes and Effect On Earthquakes

Although both hydrofractures and dikes fracture rocks perpendicular to the least principal stress, they differ in one fundamental way. Whereas hydrofractures leak rapidly and tend to open only a millimeter or so, basalt dikes chill and seal against their walls and commonly inflate to widths of centimeters or meters. This inflation, against the direction of least principal stress, increases the least stress and decreases the stress difference (fig. 4). In the case shown in figure 4*A*, the stress difference is large enough for the Mohr circle to touch the failure envelope, and normal faulting ensues. In figure 4*B*, dikes are shown to intrude on vertical planes, exploiting the weak tensile strength of rocks. As the dikes intrude, they press against their walls in the direction of extension and opposite the least principal stress. The net effect is an increase in the least principal stress, which in turn decreases the size of the Mohr circle and prevents faulting. Continued dike injection (fig. 4*C*) increases the stress in the X direction such that it is no longer the least principal stress, and the intermediate stress also increases by a factor of Poisson's ratio. Given a sufficient magma supply and pressure, the vertical stress can then become the least principal stress, and horizontal intrusions are favored (Parsons and Thompson, 1991; Parsons and others, 1992). The vertical stress is fixed by the overburden weight. Injection of a dike thus relieves accumulated tectonic stress in much the same way as a normal-fault earthquake does, but without the topographic step produced by normal faulting. This complementary behavior of dikes and normal faults is observed worldwide (Parsons and Thompson, 1991).

The scarcity of earthquakes in the Crater Flat area (Gomberg, 1991) is attributable to sporadic subsurface dike injection that maintains the stress difference at a level low enough to preclude large earthquakes. Emplacement of a 1-m dike in the last 100 k.y., roughly the age of the last basaltic events at the surface, would be sufficient to take up all of the estimated 0.01 mm/yr of extension (J.W. Whitney, oral commun., 1994) across the Crater Flat area. Moreover, the southward decrease of normal-fault topographic relief toward the basalt centers in Crater Flat would indicate that suppression of faulting and earthquakes by dike injection has been going on for millions of years.

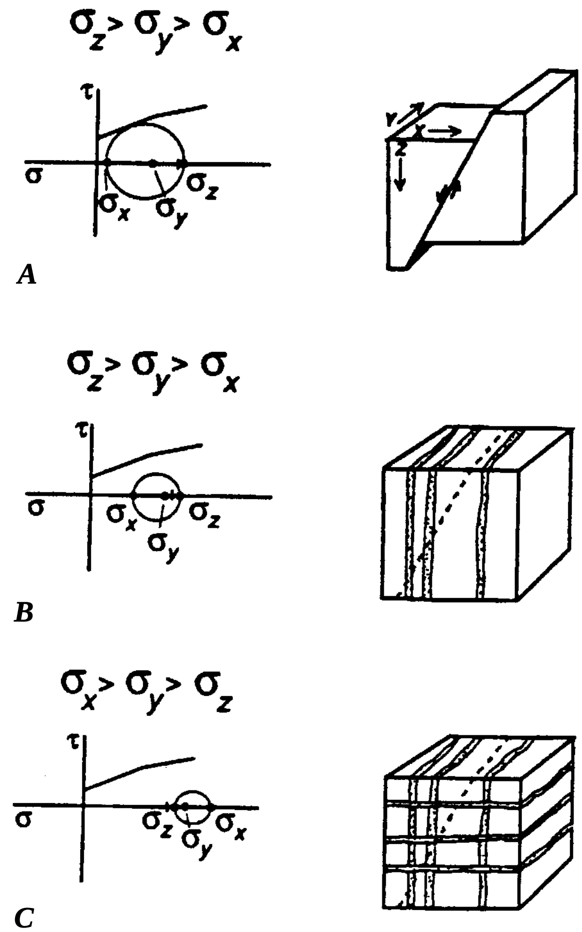

Figure 4. Mohr-Coulomb representation of the stress field in relation to *A*, normal faulting, and *B*, *C*, dike injection. Horizontal axis, compressional stress; vertical axis, shear stress; diameter of circle represents stress difference; line divides zone of stability below it from zone of failure above. Modified from Parsons and Thompson (1991).

Conclusions

These comparisons and analyses indicate that the Bare Mountain fault dips moderately to steeply and that the low gravity gradient is caused either by denser basin fill such as landslide debris or by concealed fault steps. In the present stress field, the Bare Mountain fault and similar parallel faults would be expected to have a right-lateral component of Quaternary slip. An exception to this expectation would require clockwise rotation of blocks, and this possibility is considered because of paleomagnetic evidence of clockwise rotation of southern Yucca Mountain.

The observed suppression of earthquakes and of topographic relief around the area of Quaternary basaltic volcanism indicates stress conditions favorable for the intrusion of horizontal sheets or sills in the Crater Flat area. If it becomes necessary to understand magma flow paths better, reflection seismology can be used to search for intrusive sheets, heat-flow measurements may detect the sheets' thermal output, and stress measurements can test the local stress field for compatibility with horizontal intrusions.

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