ABSTRACT

Groundwater flow at Yucca Mountain, Nevada, must be understood to determine transport and dilution of contaminants released from the proposed high-level waste repository. The nature of such flow in a complexly faulted and fractured tuff aquifer is not easily characterized. Conceptual models of regional groundwater flow often assume isotropic transmissivity, resulting in flow being interpreted as parallel to the gradient of the potentiometric surface. However, fractured aquifers are typically anisotropic, their transmissivity controlled by the conductive properties of faults and fractures, which are partially controlled by the in situ stress field. Faults at Yucca Mountain predominantly strike approximately north (azimuth ~005). Slip and dilation tendency analysis of the region indicates that those faults and fractures ideally oriented for slip in the current stress field strike north-northeast (azimuth ~025–030) and dip moderately to steeply, whereas those ideally oriented for dilation strike north-northeast (azimuth ~025–030) and are vertical. Faults with favorable orientations for slip or dilation present potential fluid flow pathways. These observations imply anisotropic transmissivity at Yucca Mountain with an azimuthal direction of maximum transmissivity between 005 (based on dominant fault trend) and 030 (based on slip- and dilation-tendency constraints). Reinterpretation of data from a long-term aquifer pumping test on the eastern flank of Yucca Mountain indicates anisotropic transmissivity with a maximum principal transmissivity direction of approximately 030. This is consistent with anisotropic transmissivity controlled by faults and fractures active in the present-day stress field.

INTRODUCTION

Yucca Mountain, a faulted east-dipping cuesta of Miocene tuffs in southwestern Nevada, is being evaluated as the potential site for the nation’s first permanent repository for high-level radioactive waste (Fig. 1). The U.S. Department of Energy has prepared a viability assessment, which provides a characterization of the proposed repository, including descriptions of geologic setting, design, and long-term (10,000 year) performance (U.S. Department of Energy, 1998a, 1998b). The Department of Energy is expected to submit a license application in 2002. If the site is licensed by the U.S. Nuclear Regulatory Commission, high-level waste could be emplaced as early as 2010. Original consideration of Yucca Mountain as the candidate repository site was due in part to the >500-m-thick unsaturated zone beneath the mountain and the dry climate. These environmental characteristics were expected to inhibit release and transport of contaminants to the accessible environment via groundwater flow. Permeability in the Miocene welded tuffs and the underlying Paleozoic and Precambrian carbonate and clastic strata at Yucca Mountain and surrounding area is primarily controlled by faults and fractures (Waddele, 1982; Winograd and Thordarson, 1975; Fridrich et al., 1994). On the basis of alignment of springs (e.g., Ash...
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Meadows fault—Winograd and Thordarson, 1975; Dudley and Larson, 1976), and elevated groundwater temperatures along faults (e.g., Midway Valley and Solitario Canyon faults—Sass et al., 1995), studies have concluded that faults control groundwater flow locally and are paths for upward flow in the saturated zone at Yucca Mountain (Fridrich et al., 1994; Bredehoeft, 1997).

Anisotropic permeability in fractured aquifers arises from the abundance and distribution of faults and fractures and permeability of associated damage zones (e.g., breccia) (Fig. 2). Although it is known that faulted and fractured aquifers commonly have anisotropic transmissivity (National Research Council, 1996), maps depicting regional-scale groundwater flow usually assume flow parallel to the gradi-

Figure 2. Conceptual illustration of effects of faults with high slip tendency or high dilation tendency on development of anisotropic transmissivity in areas, like the Yucca Mountain (Nevada) region, where the minimum principal compressive stress (σ3) is horizontal.
Please note change of venue:
Royal Holloway University of London, Egham, Surrey, UK

Conference Purpose and Objectives
Many rifted volcanic margins (<200 m.y. old) are in close proximity to mantle plumes, but the causal relationship between plumes and rifting remains highly controversial. Do plumes drive continental breakup, or are they channeled into areas of thinned lithosphere? In addition, the relative timing of surface uplift, extension, and magmatism has been predicted by theoretical plume models, but their validity hinges on actual field examples. The North Atlantic and southern Red Sea margins appear to have evolved in a similar way, with minimal uplift and much of the flood magmatism pre-dating break-up. Why does this differ from theoretical models? This conference will bring together scientists working on theoretical, field, and geophysical aspects of rifts, in a stimulating environment.

Field- and laboratory-based scientists with diverse areas of expertise, including landscape evolution and geomorphology, the chronology and geochemistry of continental volcanism, lithospheric extension, mantle and crustal geophysics, thermo-chronology, and theoretical modeling of rift settings, will be invited to the conference. The main topics will include: extent and amount of uplift and subsidence; relative timing of geological processes on volcanic rifted margins; absolute dating techniques for extension, magmatism, and exhumation; use of volcanic products to understand rift geodynamics; style of, and mechanisms for, lithospheric thinning; syn- and postrift exhumation, sediment budgets and basin formation; thermal history of volcanic rifted margins using dating and modeling techniques.

Field Trips
A premeeting six-day trip to the Deccan Traps will cost an estimated $1000, and a postmeeting five-day trip to the Isle of Mull, Scotland, will cost an estimated $650.

Registration
Limited funding will be available to help cover conference expenses for academics from developing countries, young scientists, and graduate students. Early applications are recommended if you are seeking funding. The conference is limited to 80 participants; selection will include a broad range of disciplines. Costs are currently estimated at $400 for the conference. Interested parties should contact Julie Brown (brown@gl.rhbnc.ac.uk); identify the e-mail as “Penrose Conference.” Registration deadline is August 31, 1999. Please include in your e-mail a brief statement of your field of interest, relevance of your research work to the conference theme, proposed title of a poster presentation, a title of topic for discussion (maximum 10 minutes, with a maximum of five overhead projections or slides). Let us know whether you would be interested in participating in the field trips. Invitations will be based on your e-mailed application. Participants will be notified on September 14, 1999, by e-mail.

For more information, contact Ian Davison, Royal Holloway, University of London, Egham, Surrey TW20 OEX UK, phone 44-1784-443615, fax 44-1784-471780, davison@gl.rhbnc.ac.uk.

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ent of the potentiometric surface. This is true only if the transmissive properties of the aquifer are isotropic, or if the major or minor semi-axis of the transmissivity tensor is everywhere parallel to the potential gradient.

Recent studies, including one example from Yucca Mountain, have shown that faults favorably oriented for slip in the ambient stress field tend to be the most active groundwater flow pathways (Barton et al., 1995; Finkbeiner et al., 1997). This observation has been explained by increased small-scale fracturing and faulting in the vicinity of faults on the verge of shear failure (Barton et al., 1995). The ability to recognize such faults allows us to identify the loci of increased fracturing.

A secondary but measurable influence on permeability is the effect of contemporary stress on reducing apertures of existing faults and fractures (Carlsson and Olson, 1979; Barton et al., 1995; Finkbeiner et al., 1997). Faults and fractures perpendicular to the maximum principal stress are preferentially closed, thereby reducing permeability perpendicular to the maximum principal stress. Permeability perpendicular to the minimum principal compressive stress direction is relatively enhanced because lower resolved normal stress results in less fracture aperture reduction (e.g., Carlsson and Olson, 1979).

Here, we examine how regional stress combined with existing faults and fracture systems at Yucca Mountain influences permeability and groundwater flow in the saturated zone beneath Yucca Mountain. We then test the model using data from a long-term aquifer pumping test at Yucca Mountain, and consider possible implications for the proposed high-level waste repository at Yucca Mountain.

SLIP TENDENCY AND DILATION TENDENCY

Our approach to stress analysis involves calculating resolved stresses on fault and fracture surfaces to analyze like-

Sue Beggs Retires

After almost 20 years as the Meetings Manager for GSA, Sue Beggs retired in January 1999. She spearheaded the planning and staging of GSA annual meetings ranging from 4,000 to 7,500 attendees.

Beggs is now a meeting planning consultant in Boulder, Colorado. Kathy Ohmie Lynch, who has been with GSA for 25 years, has assumed the directorship of the GSA Meetings Department.
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...lihood for slip or dilation in crustal stress fields. The resulting slip and/or dilation tendency data are displayed by color coding three-dimensional models (Fig. 3) or trace maps of the fault and fracture array (Fig. 4).

![Figure 3](image)

**Figure 3.** (a) Three-dimensional structure contour map of layer (top of upper lythophysal zone of the crystal-poor member) within the Tiva Canyon Tuff in the western Yucca Mountain, Nevada, area. Irregular white lines represent data points from the three-dimensional outcrop trace of the mapped horizon (from Day et al., 1998a, 1998b). Gray indicates fault gaps for Northern Windy Wash (NWW), Fatigue Wash (FW), Boomerang Point (BP), Solitario Canyon (SC, subdivided into northern, middle, and southern sections), and Iron Ridge (IR) faults. Coordinates are UTM zone 11, elevations are in meters above sea level, and vertical exaggeration is 2.5x. See Figure 4 for location.

(b) Three-dimensional model of western Yucca Mountain fault system with fault surfaces colored according to slip tendency. The slip tendency plot (equal-angle stereographic projection colored according to slip tendency as defined in this text) shows poles to planes (measurements from Simonds et al., 1995 and Day et al., 1998a) of the Windy Wash, Fatigue Wash, Boomerang Point, Solitario Canyon, and Iron Ridge faults. The area is the same as in part a; no vertical exaggeration.

(c) Three-dimensional dilation tendency model of western Yucca Mountain fault system. The dilation tendency plot (equal-angle stereographic projection colored according to dilation tendency as defined in this text) shows poles to planes of the Windy Wash, Fatigue Wash, Boomerang Point, Solitario Canyon, and Iron Ridge faults. The area is the same as in part a; no vertical exaggeration.

**Slip Tendency**

Slip tendency analyses are applicable to planar discontinuities like faults, extension fractures, or layering (Morris et al., 1996; Ferrill et al., 1998). For faults and fractures, slip is likely to occur on a surface when the resolved shear stress, \( \tau \), on that surface equals or exceeds the frictional resistance to sliding. Frictional resistance is proportional to normal stress, \( \sigma_n \), acting across that surface (Jaeger and Cook, 1979). The slip tendency, \( T_s \), of a surface is the ratio of shear stress to normal stress acting on that surface (Morris et al., 1996):

\[
T_s = \frac{\tau}{\sigma_n}
\]

As such, \( T_s \) depends solely on the stress field (stress tensor) and surface orientation. Whether or not a surface slips depends upon its cohesive strength, if any, and the coefficient of static friction, \( \mu \). The coefficient of static friction, \( \mu \), is the value of \( T_s \) that causes slip on a cohesionless surface and is often referred to as the fault “strength” in earthquake focal mechanism analysis (e.g., Harmsen, 1994). Under most crustal conditions, faults with \( T_s \geq 0.6 \) are ideally oriented for slip (Byerlee, 1978). Analysis of slip tendency provides a way to assess which faults are near the ideal orientation for slip and are the most likely to be associated with zones of increased fracture density and enhanced fracture permeability.

**Dilation Tendency**

Dilation of fractures is largely controlled by the resolved normal stress, which is a function of lithostatic and tectonic stresses and fluid pressure. The normal stress that a fracture feels depends on the magnitude and direction of the principal stresses relative to the fracture plane. The ability of a fracture to dilate and transmit fluid is directly related to its aperture, which in turn is a function of the effective normal stress acting upon it. The magnitude of the normal stress can be computed for surfaces of all orientations within a known or hypothesized stress field. This normal stress can be normalized by comparison with differential stress. The resulting dilation tendency (\( T_d \)) for a surface is then defined as

\[
T_d = (\sigma_1 - \sigma_n) / (\sigma_3 - \sigma_n)
\]

where \( \sigma_1 \) is the maximum principal compressive stress, and \( \sigma_3 \) is the minimum principal compressive stress.

**BULK TRANSMISSIVITY ANISOTROPY**

A population of steep, aligned, relatively permeable faults and fractures cutting a less permeable rock mass will tend to orient the maximum directional transmissivity parallel to the structural grain. In the case of unequal horizontal stresses acting on a population of steep faults and fractures, those with strikes parallel to the maximum horizontal compressive stress tend to open. Those with strikes perpendicular to the maximum horizontal stress tend to close. Similarly, some faults in an anisotropic stress field will be more ideally oriented for slip and others for locking. Thus, even if fault and fracture orientation distribution is isotropic, transmissivity in the maximum horizontal stress...
direction can be enhanced, producing transmissivity anisotropy. Because fault and fracture populations commonly exhibit preferred orientations and in situ horizontal stresses are commonly unequal, both are likely to occur together in nature and lead to anisotropic transmissivity. For example, in cases where \( \sigma_3 \) is horizontal, vertical faults and fractures perpendicular to \( \sigma_3 \) have the highest dilation tendency and are likely to be more conductive than those in other orientations (Fig. 2a). Faults and shear fractures are sensitive to the \( \sigma_1 \) direction and commonly form two conjugate sets intersecting at an acute angle (~60°) centered on \( \sigma_1 \) (Fig. 2b, c). In normal fault regimes where \( \sigma_1 \) is vertical, two sets of opposite-dipping conjugate normal faults commonly develop (Fig. 2d). In strike-slip fault regimes where \( \sigma_1 \) is horizontal, two sets of vertical conjugate strike-slip faults commonly develop (Fig. 2c). In areas where \( \sigma_1 \) is horizontal, fault and fracture preferred orientations, and slip tendency and dilation tendency all promote development of a net bulk transmissivity anisotropy with a maximum horizontal transmissivity perpendicular to \( \sigma_3 \) (Fig. 2d). The interaction of aquifer transmissivity with faults and fractures can be field tested by aquifer pumping tests. As done below, the results can be used to determine the full transmissivity tensor and to compare the orientation of the principal components of this tensor with the maximum and minimum in situ horizontal stress orientations and the distribution of faults and fractures.

**PREDICTION OF ANISOTROPIC TRANSMISSIVITY AT YUCCA MOUNTAIN**

The pattern of faults and fractures in the Yucca Mountain region (Fig. 1) resulted from deformation in a regional stress field that evolved from east-west extension before 10 Ma to west-northwest-east-southeast extension after 10 Ma (Zoback et al., 1981), and from thermelastic contraction during cooling of the ash-flow tuffs (Sweetkind and Williams-Stroud, 1996). The result is a dominant population of north-south to northeast-southwest-trending normal faults, a subordinate population of northwest-southeast-trending strike-slip faults, and a group of minor connecting faults and curved fault tips (Day et al., 1998b; Ferrill et al., 1999). Fault growth by connection of overlapping fault segments produced irregular fault traces with cusp apertures at fault intersections (Fig. 3a). Although faults at Yucca Mountain are related to several deformational episodes, some faults are unlikely to slip because of unfavorable orientations relative to the contemporary stress state.

Yucca Mountain lies within the western Basin and Range in a region characterized by both normal and strike-slip earthquakes. The regional occurrence of both normal and strike-slip earthquakes indicates that the maximum (\( \sigma_1 \)) and intermediate (\( \sigma_2 \)) principal compressive stresses have similar magnitudes (Zoback, 1992; Zoback et al., 1992). The least principal compressive stress (\( \sigma_3 \)) is approximately horizontal and trends west-northwest-east-southeast. Therefore, \( \sigma_3 \) is the “odd axis” (Krantz, 1988) and has the most direct control on the pattern of fault slip tendency. Stock et al. (1985) estimated the following effective principal stresses at Yucca Mountain (corrected for fluid pressure) at a depth of 1 km: \( \sigma_1 = \text{vertical} = 21 \text{ MPa} \), \( \sigma_2 = N25°–30°E = 17 \text{ MPa} \), and \( \sigma_3 = N60°–65°W = 11 \text{ MPa} \) for the region.

**Slip-Tendency Analysis of Yucca Mountain Faults**

Slip-tendency analysis of Yucca Mountain faults was performed using the relative stress values of Stock et al. (1985) given above, a three-dimensional fault model for western Yucca Mountain (Fig. 3b), and the faults mapped by Simonds et al. (1995; Fig. 4a). Faults that strike parallel to the north-northeast-trending maximum horizontal stress (025°–30°; 028° in Figs. 3 and 4) and dip 55° have the maximum slip tendencies. Slip tendencies are also near maximum (>0.3) for faults that are moderately to steeply dipping (40°–65°), and north-south to northeast-southwest (000°–055°) striking. Faults at 1 km depth have moderate slip tendencies relative to typical failure conditions. In contrast, at depths of earthquake rupture initiation (e.g., 5–15 km), stresses resolved on similarly oriented faults produce near-failure slip tendencies (Morris et al., 1996). As described by Harmsen (1994), the pattern of slipped faults in the Little Skull Mountain (Fig. 1) earthquake sequence is dominated by dip-slip on southeast-dipping normal faults and right-lateral strike-slip on vertical north-south trending faults.
faults. This is the pattern predicted by slip tendency analysis of the Yucca Mountain stress field and supports simultaneous activity of strike-slip and normal faults in this area (Morris et al., 1996).

Examination of the faults mapped by Smoands et al. (1995) reveals that nearly all faults with known or suspected late Quaternary displacement are in orientations of high slip tendency (Fig. 4a). Some noteworthy examples are the Northern and Southern Windy Wash, Fatigue Wash, Solitario Canyon, Iron Ridge, and Stagecoach Road faults (Fig. 4a). In contrast, the Solitario Canyon, Iron Ridge, and Short-and Southern Windy Wash, Fatigue Wash, noteworthy examples are the Northern Quaternary displacement are in orientations of strike-slip and normal faults in this area (Fig. 4a) and lack evidence of late Quaternary slip (Smoands et al., 1995).

Dilation-Tendency Analysis of Yucca Mountain Faults

Dilation-tendency analysis of faults and associated fractures at Yucca Mountain (e.g., Figs. 3c and 4b) was performed assuming the same relative stresses and mapped faults used for slip-tendency analysis. The results show that vertical faults and fractures that strike parallel to the maximum horizontal stress (025–030; 028 in Figs. 3 and 4) have the maximum dilation tendencies. Faults trending 028 ± 35° and dipping 65° to 90° have dilation tendencies of 0.8 or greater in the present stress field (Fig. 3c). Dilation-tendency analysis of faults at Yucca Mountain illustrates an abundance of steeply dipping north-northeast–trending faults that have high dilation tendency.

Implications for Anisotropic Transmissivity at Yucca Mountain

Faults with favorable orientations for slip or dilation present potential flow pathways. Although we explicitly consider only large map-scale faults, the processes that alter permeability of large faults and fracture systems also apply to abundant smaller scale fractures and faults like those seen in outcrops, boreholes, and the Exploratory Studies Facility (cf. Sweetkind and Williams-Stroud, 1996), resulting in an effective hydraulic continuum. The dominant trend of faults at Yucca Mountain is approximately north-south (005; see rose diagrams in Fig. 4). The strike, maximum slip tendencies, and maximum dilation tendencies of the fault population indicate the possibility of anisotropic transmissivity, with the direction of maximum transmissivity in the azimuth range between 005 (based on dominant fault trend) and 030 (based on slip- and dilation-tendency constraints).

ESTIMATION OF ANISOTROPIC TRANSMISSIVITY AT YUCCA MOUNTAIN

A long-term aquifer pumping test was conducted at the C-well complex on the eastern flank of Yucca Mountain from May 1996 to March 1997 (Geldon et al., 1997). The C-well complex consists of three wells (UE-25c #1, UE-25c #2, and UE-25c #3) that are separated by distances of 30–77 m and form a right triangle. During this aquifer test, well UE-25c #3 was pumped at a rate of 9.5 L/s. Water levels in four observation wells (USW H-4, ONC-1, UE-25 WT #3, and UE-25 WT #14; Fig. 1), located at distances of 0.84–3.5 km, were monitored at 15 min intervals.

We estimated horizontal anisotropy of aquifer transmissivity on the basis of data from the four distant observation wells, using the method of Papadopulos (1965) for homogenous, anisotropic aquifers of infinite areal extent. Data from two other wells (UE-25c #1 and UE-25c #2) were not used because of complications related to their proximity to the pumped well. The technique requires the following data from at least three observation wells: (1) the directional azimuth (θ) to the monitored well from the pumped well; (2) bulk aquifer transmissivity (a scalar quantity equal to the geometric mean of the minimum and maximum directional transmissivities); and (3) the directional hydraulic diffusivity (a vector quantity). Directional hydraulic diffusivity

\[ D(\theta) \]

is defined as the directional transmissivity

\[ T(\theta) \]

a vector quantity divided by the dimensionless bulk aquifer storage coefficient (S). Although we are primarily interested in T(θ), neither T(θ) nor S can be estimated separately from D(θ) until both the ratio of maximum to minimum D(θ) and the direction of maximum D(θ) are known. These are determined by fitting an ellipse to a polar plot of the square root of D(θ).

Our analysis differs in two ways from the interpretation of Geldon et al. (1997). First, we performed a two-step correction that accounts for the influence on water levels exerted by both direct borehole coupling to atmospheric pressure changes and the delayed atmospheric pressure signal that arrives through the overlying geologic formation. Second, we assume that S is constant throughout the aquifer, and thus differences in D(θ) between observation wells are attributed to T(θ). The bulk aquifer transmissivity estimates obtained from our analysis (Table 1) are broadly consistent with, but less variable than those in Geldon et al. (1997).

We began our analysis of aquifer anisotropy by testing the assumption of a homogenous aquifer system. In a purely homogenous aquifer, the bulk transmissivity estimates obtained from each observation well should be the same. With the exception of well USW H-4, aquifer transmissivity estimates are quite similar (Table 1). Because the transmissivity estimate for well USW H-4 could be affected by a fault system between it and the pumped well, this well was excluded from the analysis of horizontal anisotropy. A polar plot of the square root of D(θ) for the remaining three wells shows that an exact-fitting ellipse could not be obtained from the data, consistent with the fact that not every set of three points defines an ellipse (Fig. 5).

<table>
<thead>
<tr>
<th>Well I.D.</th>
<th>Direction azimuth (θ)</th>
<th>Distance from pumped well (m)</th>
<th>Bulk aquifer transmissivity (m²/d)</th>
<th>Square root of directional hydraulic diffusivity [√D(θ); m²/d²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>USW H-4</td>
<td>310</td>
<td>2245</td>
<td>670</td>
<td>510</td>
</tr>
<tr>
<td>ONC-1</td>
<td>327</td>
<td>843</td>
<td>1340</td>
<td>416</td>
</tr>
<tr>
<td>UE-25 WT #3</td>
<td>161</td>
<td>3526</td>
<td>1230</td>
<td>506</td>
</tr>
<tr>
<td>UE-25 WT #14</td>
<td>050</td>
<td>2249</td>
<td>1370</td>
<td>980</td>
</tr>
</tbody>
</table>

| Table 1. Directional Hydraulic Diffusivities Estimated for Observation Wells from Long-Term Pumping Test at C-Wells |
Although the ellipse in Figure 5 is not an exact fit, it closely matches the observation well data with major semi-axis oriented 030. Because of uncertainty associated with aquifer pumping tests, and the limitation of having only the minimum number of data points to constrain an ellipse, the ratio of minimum to maximum directional transmissivity is poorly constrained. With this in mind, we estimate from Figure 5 a maximum $T(\theta)$ of 5400 m$^2$/d (azimuth 030), a minimum $T(\theta)$ of 315 m$^2$/d (azimuth 120), and a bulk $S$ value of 0.002. This analysis indicates a northeast trend in the direction of maximum $T(\theta)$ consistent with the north-northeast (025–030) trend inferred from the slip and dilation tendency.

**IMPLICATIONS FOR PROPOSED YUCCA MOUNTAIN REPOSITORY SITE**

Current groundwater flow models at Yucca Mountain (e.g., Czamnecki et al., 1997, Department of Energy, 1998a, 1998b) do not incorporate anisotropy of transmissivity. A flow pattern parallel to the hydraulic gradient, as expected in an isotropic aquifer (Freeze and Cherry, 1979), would result in relatively short southeast-directed travel distances in the unconfined welded-tuff aquifer before the flow enters alluvial deposits. In contrast, by taking into account the orientation of maximum horizontal transmissivity and the inferred presence of fault- and fracture-controlled flow conduits, we propose a model in which more southward-directed flow paths would increase travel distances in the tuff aquifer and reduce the amount of flow in alluvium between Yucca Mountain and the receptor location. Such a difference in direction is important, because relative flow velocities should be faster in the lower porosity tuff and slower in the alluvium, owing to its larger lower surface area of sorbing mineral grains (e.g., clays, iron oxides, and calcite).

**CONCLUSIONS**

In the contemporary stress state at 1 km depth at Yucca Mountain, slip and dilation tendency analyses indicate the following: faults that strike north-northeast (000–055) and dip 40°–65° have high dilation tendencies, the maximum being for faults that strike north-northeast (025–030) and dip 53°; and faults that strike north-northeast (350–065) and dip 65°–90° have high dilation tendencies, the maximum being for vertical faults that strike north-northeast (025–030).

The dominant north-south (~005) trend of faults at Yucca Mountain, coupled with slip-tendency and dilation-tendency considerations suggest anisotropic transmissivity, with maximum transmissivity in the azimuth range between 005 and 030.

The anisotropic transmissivity estimated at Yucca Mountain has a maximum principal direction of approximately 030, consistent with the hypothesis that anisotropy is controlled by faults and fractures in the present-day in situ stress field. Note: For more information on the Yucca Mountain site, see www.ymnp.gov/va.htm.

**ACKNOWLEDGMENTS**

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**REFERENCES CITED**


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