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UNITED STATES
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GEOLOGICAL AND GEOPHYSICAL EVIDENCE OF STRUCTURES IN NORTHWEST-TRENDING WASHES, YUCCA MOUNTAIN, SOUTHERN NEVADA, AND THEIR POSSIBLE SIGNIFICANCE TO A NUCLEAR WASTE REPOSITORY IN THE UNSATURATED ZONE

by

Robert B. Scott, Gordon D. Bath, Vincent J. Flanigan,
Donald B. Hoover, Joseph G. Rosenbaum, and Richard W. Spengler

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ABSTRACT

Geological and geophysical evidence suggests that five prominent linear northwest-trending washes in the northeastern part of Yucca Mountain, Nevada, are underlain by zones of right-lateral strike-slip faults. Northwest-striking faults exposed along the washes are nearly vertical, have essentially horizontal striations on slickensides, and have small vertical offsets. Cores from drill holes within Drill Hole Wash contain northwest-striking steeply-dipping fault and fracture planes. Higher conductances and lower resistivities in zones within Drill Hole Wash are interpreted as zones of fractured rocks that are more highly altered or contain more water than adjacent, less fractured rocks. Little measurable horizontal offset of geomorphic features has occurred along these strike-slip faults, and strike-slip motion was probably small, even along the longest of these faults. The strikes, sense of motion, geographic position, and age of these Yucca Mountain strike-slip faults are similar to those of the regional Walker Lane-Las Vegas Valley shear zones.

Strike-slip faults in the northeastern part of Yucca Mountain will affect the stability of mined openings of the potential high-level nuclear waste repository at Yucca Mountain where brecciated or highly fractured zones are encountered. Because the repository is planned above the water table in unsaturated rocks, such faults may be favorable features where they allow recharge to drain rapidly from the repository. However, at greater depths these faults may be adverse features where they provide potential hydrologic conduits through unsaturated sorptive zeolitized nonwelded tuffs below the repository and within rocks below the water table in the saturated zone. Although these potentially favorable and adverse factors must be investigated and evaluated, present information does not rule out extension of the repository into the area northeast of Drill Hole Wash.

INTRODUCTION

Yucca Mountain, on the western boundary of the Nevada Test Site in the central southern Great Basin (fig. 1), lies between northwest-striking, right-lateral strike-slip faults of the Walker Lane and Las Vegas Valley shear zones. The mountain is a dissected Miocene volcanic plateau that has been broken into a series of gently east-dipping, north-trending structural blocks bounded by normal faults (Lipman and McKay, 1965; Christiansen and Lipman, 1965). Stratigraphically Yucca Mountain is rather simple; exposures consist largely of four ash-flow tuff members of the Paintbrush Tuff: The uppermost Tiva Canyon Member is dominantly densely welded and covers most of the mountain. Remnants of a resistant caprock of this compound cooling unit form plateau-like slopes that dip slightly eastward. Below the Tiva Canyon, the Yucca Mountain and Pah Canon Members are locally present as welded tuffs in the northern part of the mountain but are present only as nonwelded distal ends of cooling units in the southern part. The lowest member, the Topopah Spring Member, is largely a densely welded compound cooling unit. It is exposed only in the deepest wash, Yucca Wash, and on the upthrown side of large normal faults (fig. 2). Within the northeastern part of the mountain, deep northwest-trending washes locally have cut through the densely welded Tiva Canyon Member into the thin, less welded Yucca Mountain and Pah Canyon Members and associated nonwelded bedded tuffs. These unusually long and linear washes are Drill Hole, Teacup, Pagany, Sever, and Yucca Washes (fig. 1). In the northeastern part of Yucca Mountain where the northwest-trending washes occur, strata dip gently toward the southeast, but in the central southern part of Yucca Mountain, strata generally dip gently toward the east (fig. 2).

Four northwest-trending washes are incised as deeply as 150 m into the bedrock of the northeastern part of Yucca Mountain. Teacup Wash is the straightest of the washes; linear segments of Teacup Wash have an average trend of N. 36° W. Sever, Pagany, and Drill Hole Washes trend N. 33° W., N. 38° W. and N. 40° W., respectively. Yucca Wash, the northeastern border of the mountain, is deeply incised in bedrock for 8 km and has an average trend of N. 50° W. Trends for these washes are similar to dip directions for ash-flow strata, between S. 30° E. and S. 75° E. The dip direction is not truly parallel to the washes, however, but is offset about 10° in a more easterly direction. The drainage pattern in the northeastern part of Yucca Mountain is a linear, subparallel dentritic pattern that differs from the short dense dentritic pattern south and west of Drill Hole Wash (fig. 3). East-trending washes south of Drill Hole Wash are short, between 1 and 1.5 km long, and limited to the width of the structural block east of Solitario Canyon. Wash drainages consist of two parts; that part incised into the bedrock and the other part cut into alluvial terraces east of the bedrock. Thus, the combined lengths of Yucca, Sever, and Drill Hole Washes shown in figure 3 are 12 km, 9 km, and 7.5 km long, respectively.

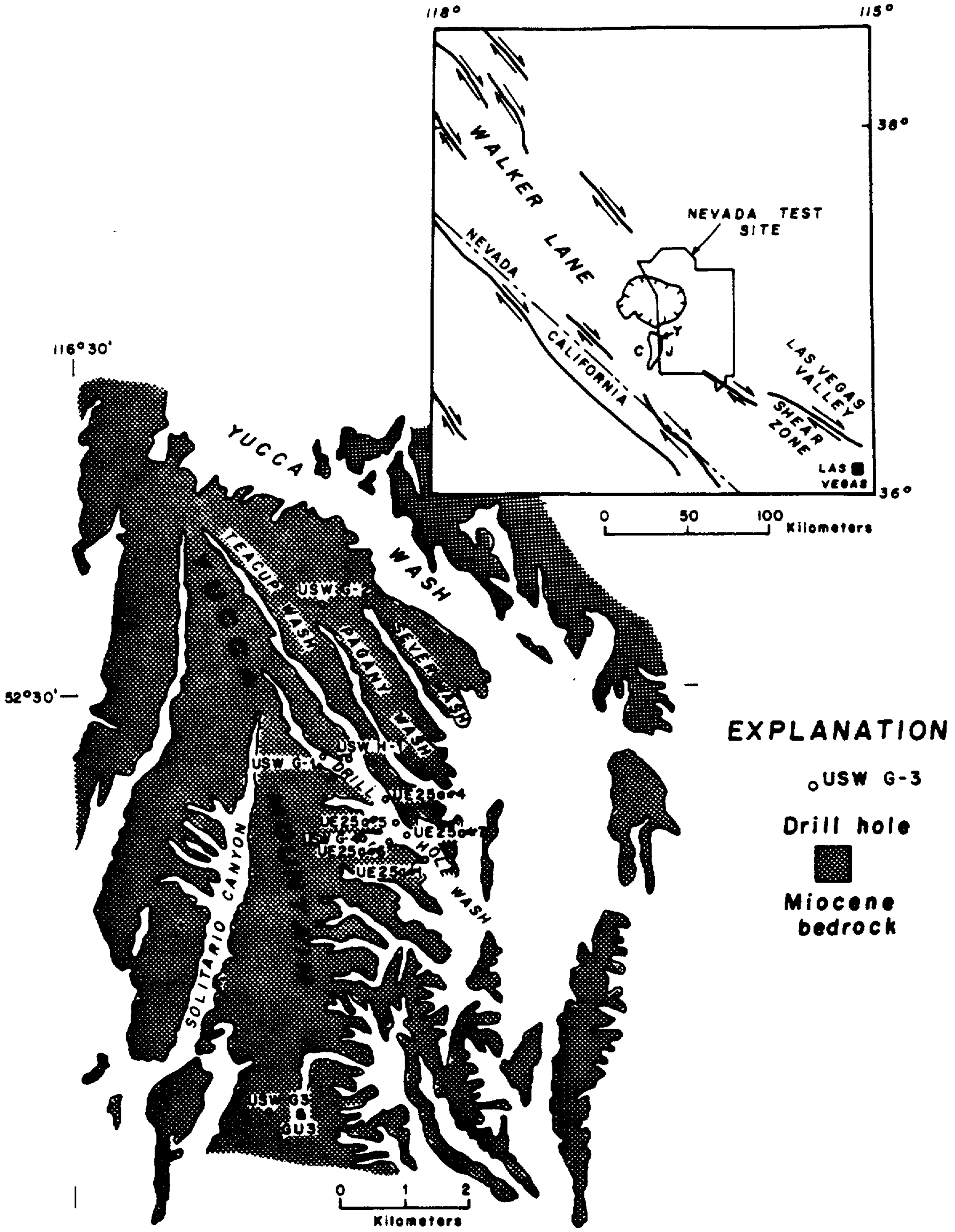


Figure 1.--Location of northwest-trending washes in Yucca Mountain. Exploratory drill hole locations are also shown. Upper right insert shows the regional setting of Yucca Mountain (Y) relative to the Nevada Test Site, the Miocene Timber Mountain-Oasis Valley caldera complex (hachured boundary; Byers and others, 1976), Jackass Flats (J), and Crater Flat (C). Major zones of right-lateral strike-slip faulting in the Walker Lane and Las Vegas Valley shear zones are from Carr (1974) and Stewart and Carlson (1978).

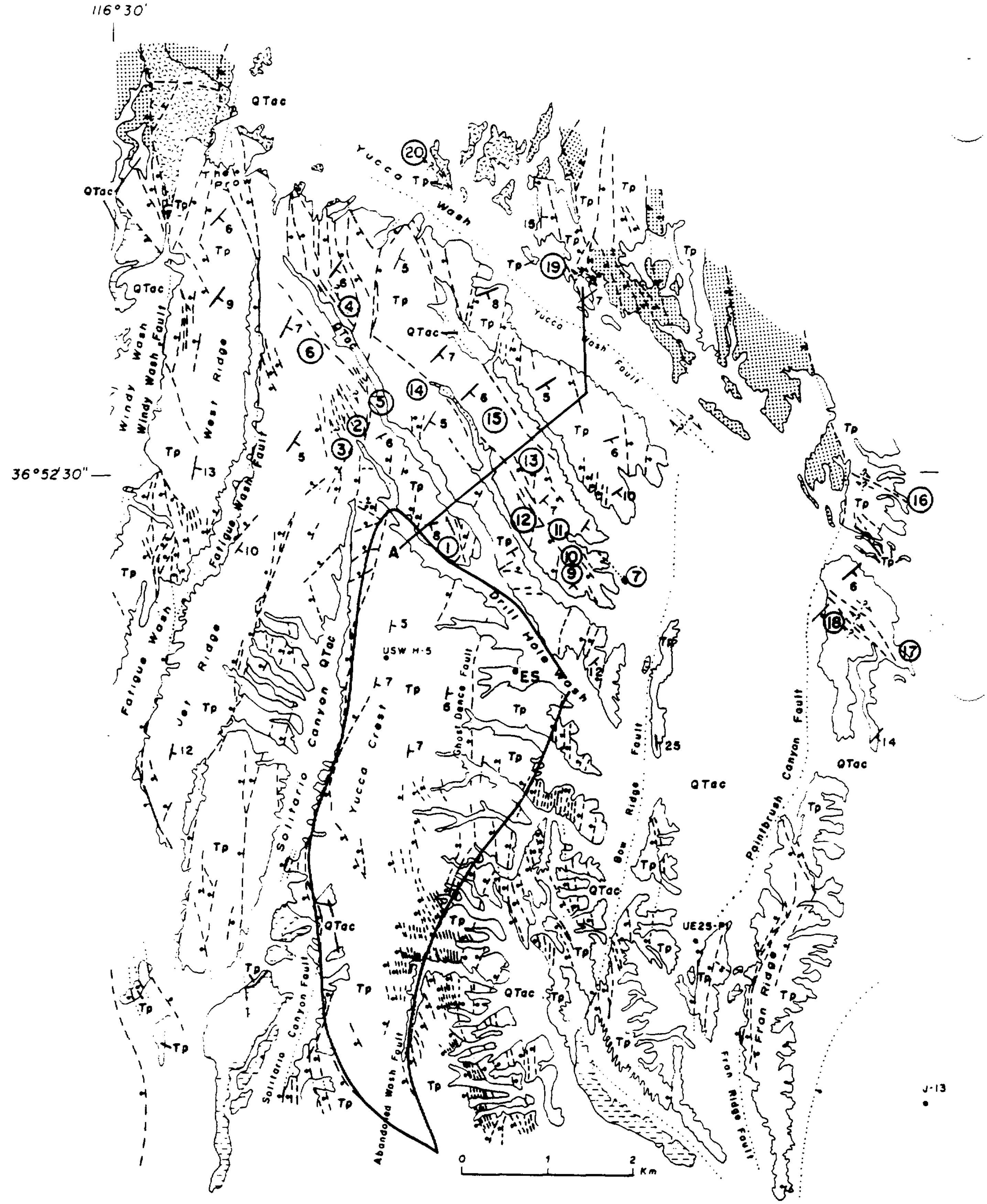


Figure 2.--Generalized geologic map of Yucca Mountain adapted from Scott and Bonk (1984).

EXPLANATION

☐	Alluvium and colluvium, QTac	Quaternary
▦	Rhyolitic lava flows	Miocene
▤	Rainier Mesa Member of the Timber Mountain Tuff	
☐	Paintbrush Tuff, Tp	
▨	Ash-flow tuff	

- - - —•— ····	Normal fault, dashed where known but position is approximated, dotted where concealed; ball and bar on downthrown side. Ball and bar are omitted from closely spaced faults
— ⇄ — ?	Strike-slip fault, dashed where known or inferred, arrows show relative directions of movement; queried where sense of motion is speculative, queried only on one side where space is limited
———	Contact
⊥ 7	Strike and dip of foliation in ash-flow tuff
———	Boundary of potential repository
A ——— A′	Line of cross section (fig. 8)
● ES	Proposed location of exploratory shaft
③	Strike-slip faults discussed in the text

Figure 2.--continued.

Previous explanations for northwest-trending washes reached differing conclusions. One explanation for these washes was based upon the observation of the sub-parallel trends of drainage and dip of bedrock; the linearity of the washes was assumed to be the consequence of the initial slope of the volcanic plateau. Published maps (Lipman and McKay, 1965; Christiansen and Lipman, 1965) identified few faults in (or) parallel to the washes, and aeromagnetic surveys have not located faults with significant vertical displacements along the washes (Bath and Jahren, 1984). In contrast, a second explanation assumed a structural control of the linear washes and required faults buried by alluvium along the washes. Dipole-dipole resistivity surveys and electromagnetic Slingram surveys of relative conductance indicated northwest-striking faults buried beneath Drill Hole Wash (Hoover, in Smith and Ross, 1982; Flanigan, 1981). Also, previous investigations of core from drill holes in Drill Hole Wash provided evidence of fractures or faults parallel to the wash (Spengler and others, 1979; Spengler and Rosenbaum, 1980; Spengler and others, 1981).

The resolution of these differing conclusions of the origin of the northwest-trending washes is the primary purpose of this report. The locations of boundaries of a potential high-level nuclear waste repository at Yucca Mountain will be affected by interpretations of the origin of the northwest-trending washes. Evaluation of the suitability of Yucca Mountain as a long-term nuclear waste repository has been the main objective of the Nevada Nuclear Waste Storage Investigations (NNWSI) project since 1978; the project is administered by the Nevada Operations Office of the U.S. Department of Energy (Interagency Agreement DE-AI08-78ET44802).

EVIDENCE FOR FAULTS WITHIN NORTHWEST-TRENDING WASHES

Three lines of evidence suggest that faults occur beneath Quaternary alluvium in northwest-trending washes in the northeastern part of Yucca Mountain: 1) surface geologic evidence based on detailed mapping; 2) subsurface geologic evidence based on study of cores from drill holes near Drill Hole Wash; and 3) geophysical investigations based on Slingram electromagnetic surveys and dipole-dipole resistivity surveys.

Surface Evidence

During detailed mapping (Scott and Bonk, 1984), numerous faults were found to parallel northwest-trending washes (fig. 2). A prominent northwest-striking fault (numbered 1 on figure 2) cuts the nose of the ridge that separates the upper part of Drill Hole Wash from Teacup Wash. In the upper part of Drill Hole Wash, a minor fault (2) occurs within the wash and at least two longer northwest-striking faults (3) occur on the southwest slopes of the wash. Teacup Wash contains the continuation of fault (1), and near the head of the wash it contains a minor fault (4), several minor splayed faults (5), and a longer fault (6). Close to the mouth of Pagany Wash several short faults (7 through 13) are sub-parallel to the wash, but the major fault is the Pagany Wash fault (14). Sever Wash contains the 3-km-long Sever Wash fault

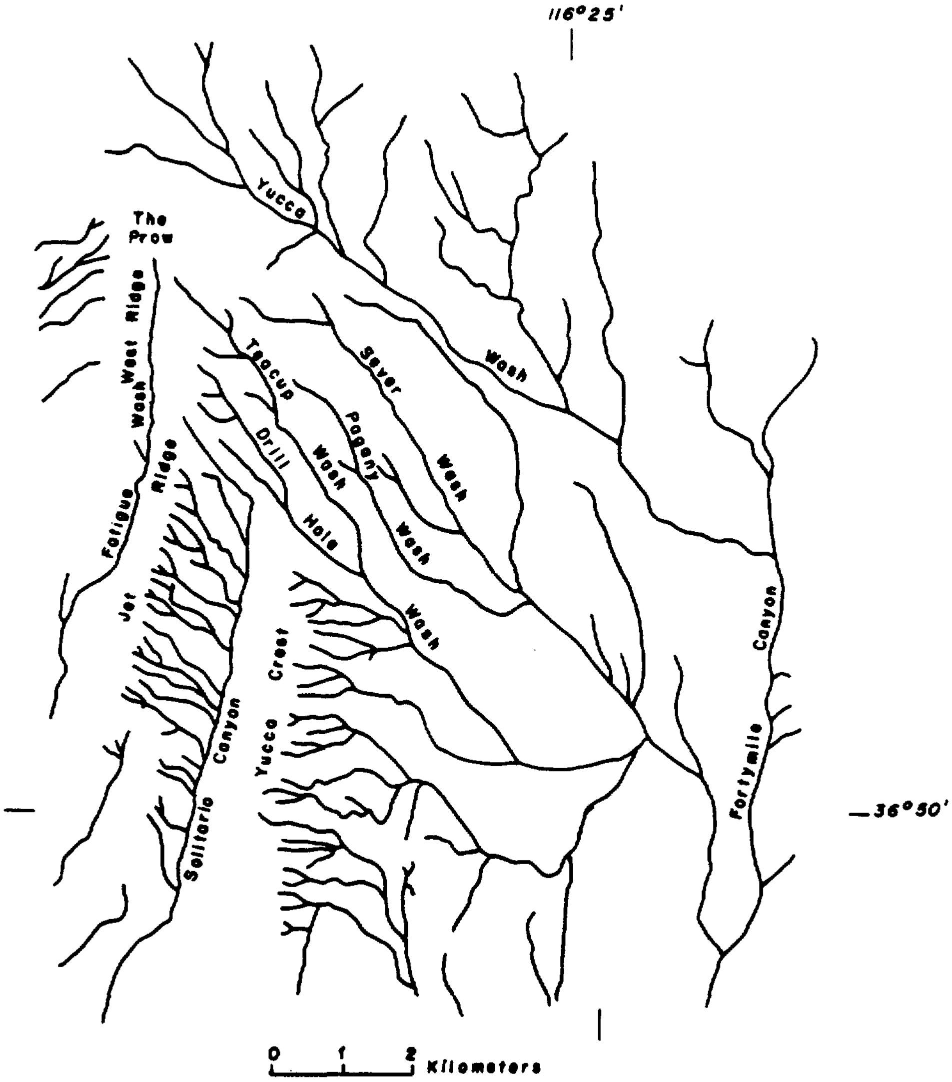


Figure 3.--Drainage pattern at Yucca Mountain showing the linear character of the northwest-trending washes and the densely spaced dentritic character of the washes on the east slopes of Yucca Crest and Jet Ridge.

(15). West of the junction of Yucca Wash and Forty Mile Canyon, three faults (16, 17, and 18) strike northwest, and in the central part of Yucca Wash two faults (19 and 20) are sub-parallel to the wash. Stratigraphic control used during mapping has established that vertical displacements greater than 10 m do not exist on faults beneath the wash alluvium.

Ash-flow tuffs south of Drill Hole Wash generally strike north and dip 5° to 7° to the east. North of Drill Hole Wash, however, the attitude of strata changes abruptly; they strike N. 15° E. to N. 60° E. and dip 5° to 8° southeast (fig. 2). Paleomagnetic measurements were made on samples of the Tiva Canyon Member from 10 sites at Yucca Mountain; these data (fig. 4) indicate no significant change in the remanent direction of the Tiva Canyon Member across Drill Hole Wash and, therefore, indicate that there has been little or no relative structural rotation of the area since the emplacement of this unit. Therefore, the change in attitude of the Tiva Canyon Member on either side of Drill Hole Wash (fig. 2) cannot be due to rotation about a vertical axis. Two possible explanations for the observed change in strike are 1) the dips are a depositional feature, and 2) the dips were created by small amounts of rotation around different horizontal or subhorizontal axes. These alternatives cannot be distinguished by paleomagnetic results because the dips are smaller than the paleomagnetic resolution. However, no faults are parallel to the northeast strike directions, down dip to the southeast-dipping block. Such fault attitudes would be conducive to horizontal axis rotation to produce the northeast strikes. The absence of such faults suggests a depositional explanation.

Subsurface Evidence

In the vicinity of Drill Hole Wash (fig. 1) many of the structural, stratigraphic, and petrographic features of cores from drill holes UE 25a#1, 4, 5, 6, and 7, USW G-1, and USW H-1 have been reported in Spengler and others (1979), Spengler and Rosenbaum (1980), Spengler and others (1981), and Rush and others (1983). In this report additional information from cores from drill holes USW H-1, USW G-4, and reentry drill hole UE 25a#7 are used to evaluate the structure of the northwest-trending washes.

In the summary of drilling results in UE 25a#4, 5, 6, and 7, Spengler and Rosenbaum (1980) observed no detectable relative vertical displacements of strata (<±4m) between drill holes and no pervasive alteration of tuffs, but they did observe steeply dipping faults striking N. 30° W. in drill hole UE 25a#4 near the northeastern margin of Drill Hole Wash. During reentry of slanted hole UE 25a#7 (26° inclination from vertical, in a S. 51° W. direction), a 10-m-wide brecciated zone was detected in core in the depth interval from 254 m to 274 m). The projected position of the shear zone is close to the southwestern margin of the wash; because this structure is not exposed, the zone probably underlies the alluvium in the wash.

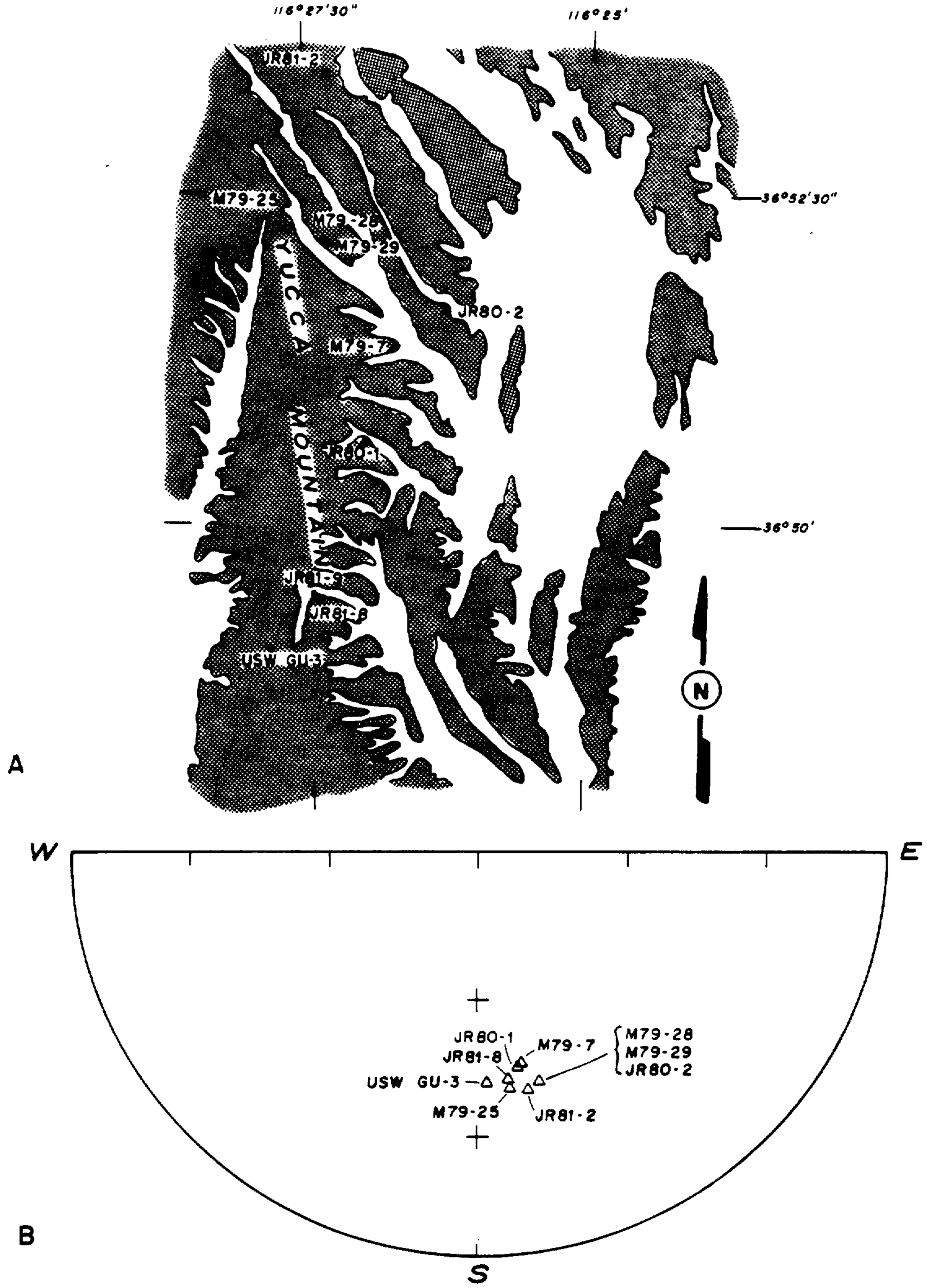


Figure 4.--A) Paleomagnetic sample localities for the reversely magnetized Tiva Canyon Member at Yucca Mountain. Bedrock is patterned. B) In situ mean directions of remanent magnetization after alternating-field demagnetization at peak fields indicated in table 1. Upper hemisphere of an equal area projection. Paleomagnetic data from the sample site JR 81-9 are included on figure 5.

Table 1.--Mean remanent direction of the reversely magnetized Tiva Canyon Member at Yucca Mountain [95 is half angle of cone of 95 percent confidence; K is Fisher precision parameter; a.f. is peak alternating field used for demagnetization in milliteslas].

Sampling Site	No. of Samples	Declination	Inclination	95	K	a.f.
M79-7	6	168.3	-45.8	5.3	163.7	20
M79-25	7	172.1	-40.6	3.6	281.3	20
M79-28	6	165.8	-40.9	3.5	359.0	20
M79-29	8	165.0	-41.3	1.5	1393.9	20
JR80-1	7	169.4	-44.9	2.8	461.3	20
JR80-2	7	164.7	-40.5	1.6	1396.4	20
JR81-2	9	167.9	-39.7	2.5	416.5	10
JR81-8	5	172.2	-42.8	2.3	1079.5	20
USW GU-3	11	177.5	-42.3	4.1	122.2	10

The attitudes of strata determined by pumice foliation planes and by remanent paleomagnetic directions of the Topopah Spring Member at drill holes UE 25a#4, 5, and 7 within Drill Hole Wash are different from those at drill hole UE 25a#6 outside the wash (Spengler and Rosenbaum, 1980). These differences were first interpreted to indicate a left-lateral strike-slip fault along the southwestern margin of the wash and counter-clockwise rotation of the Topopah Spring Member underlying Drill Hole Wash. However, subsequent paleomagnetic studies of oriented core from drill holes USW G-1, G-2, and GU-3, as well as from samples collected on the surface, demonstrate that the remanent directions within the Topopah Spring Member change markedly with depth. These variations may be due to changes in the ambient field direction during cooling of the ash-flow sheet or they may be caused by internal deformation of the flow at temperatures below the temperature at which magnetization was acquired. In either case, the discrepancy between remanent directions and ambient field probably would be less toward the top of the unit because this region would have cooled relatively quickly and would have been subjected to relatively small lithostatic loads while hot. The mean remanent directions for all sites collected in the upper 65 m of the Topopah Spring Member at Yucca Mountain are shown on figure 5, and the statistical data for alternating field demagnetization at peak fields is given in table 2. The declination of the mean remanent direction from UE 25a#6, and to a lesser extent that from USW H-1, are aberrant with respect to the other sampling sites. This difference indicates that the earlier interpretation, that the Topopah Spring Member within Drill Hole Wash had been rotated, was incorrect.

Core collected from USW H-1 at depths between 132.3 m and 133.8 m contains a nearly vertical shear zone within moderately to densely welded Topopah Spring Member. Pumice foliation, commonly inclined between 7^{o} and 10^{o} has been rotated to nearly vertical inclinations. This zone may have been affected by the subsurface expression of the northwest-striking fault mapped in outcrops northwest of USW H-1 or it may be related to similar features observed in areas characterized by closely-spaced normal faults at Yucca Mountain.

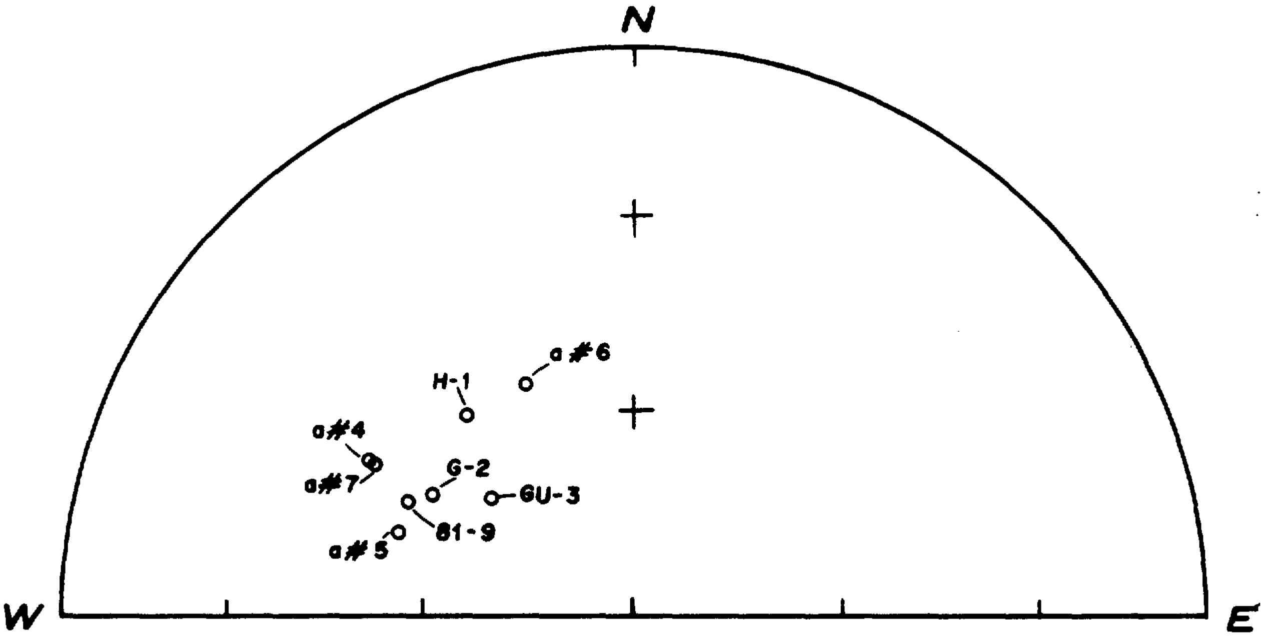


Figure 5.--Mean remanent directions for the upper 65 m of the normally magnetized Topopah Spring Member at Yucca Mountain plotted on a lower hemispheric projection. Numbers indicate drill holes from which core samples were taken (fig. 1) with the exception of sample 81-9 which was collected from site JR81-9 (fig. 4).

Table 2.--Mean remanent direction from upper 65 m of the normally magnetized Topopah Spring Member at Yucca Mountain [Symbols are the same as in table 1.]

Sampling Site	No. of Samples	Declination	Inclination	95	K	a.f.
UE 25a#4	16	301.2	45.1	3.2	130.0	20
UE 25a#5	16	290.3	54.0	1.6	504.2	20
UE 25a#6	12	335.3	52.7	5.1	73.6	20
UE 25a#7	12	301.1	46.2	4.3	102.7	20
USW G-2	12	301.7	56	2.4	318.2	10
USW GU-3	5	310.6	63.3	4.0	372.2	10
USW H-1	12	320.7	51.8	1.6	693.4	10
JR81-9	7	297.5	53.4	2.6	543.8	20

All the subsurface fault zones described above occur in moderately to densely welded Topopah Spring Member. Although slickensides were not observed, these highly brecciated zones contain abundant calcite veins. An interconnecting network of voids may exist where fracture planes are only partially coated with calcite. This partial calcite filling leaves open apertures as wide as 2 to 4 cm within fractures in the wash (Spengler and others, 1981); these aperture sizes rarely occur at this stratigraphic level in drill holes outside Drill Hole Wash.

One major goal of subsurface studies at Yucca Mountain has been to identify zones of high hydraulic conductivity within saturated rocks below the water table; suspected faults parallel to Drill Hole Wash have made the wash a principal target for such studies. Preliminary results indicate that transmissivities and hydraulic gradients within rocks below the wash are not significantly different from rocks below areas outside the wash (J. H. Robison, USGS, oral commun., 1983). Hydrologic investigations in Drill Hole Wash continue, but no evidence exists at this time to indicate that ground-water flow is concentrated beneath washes more than elsewhere in Yucca Mountain.

Geophysical Evidence

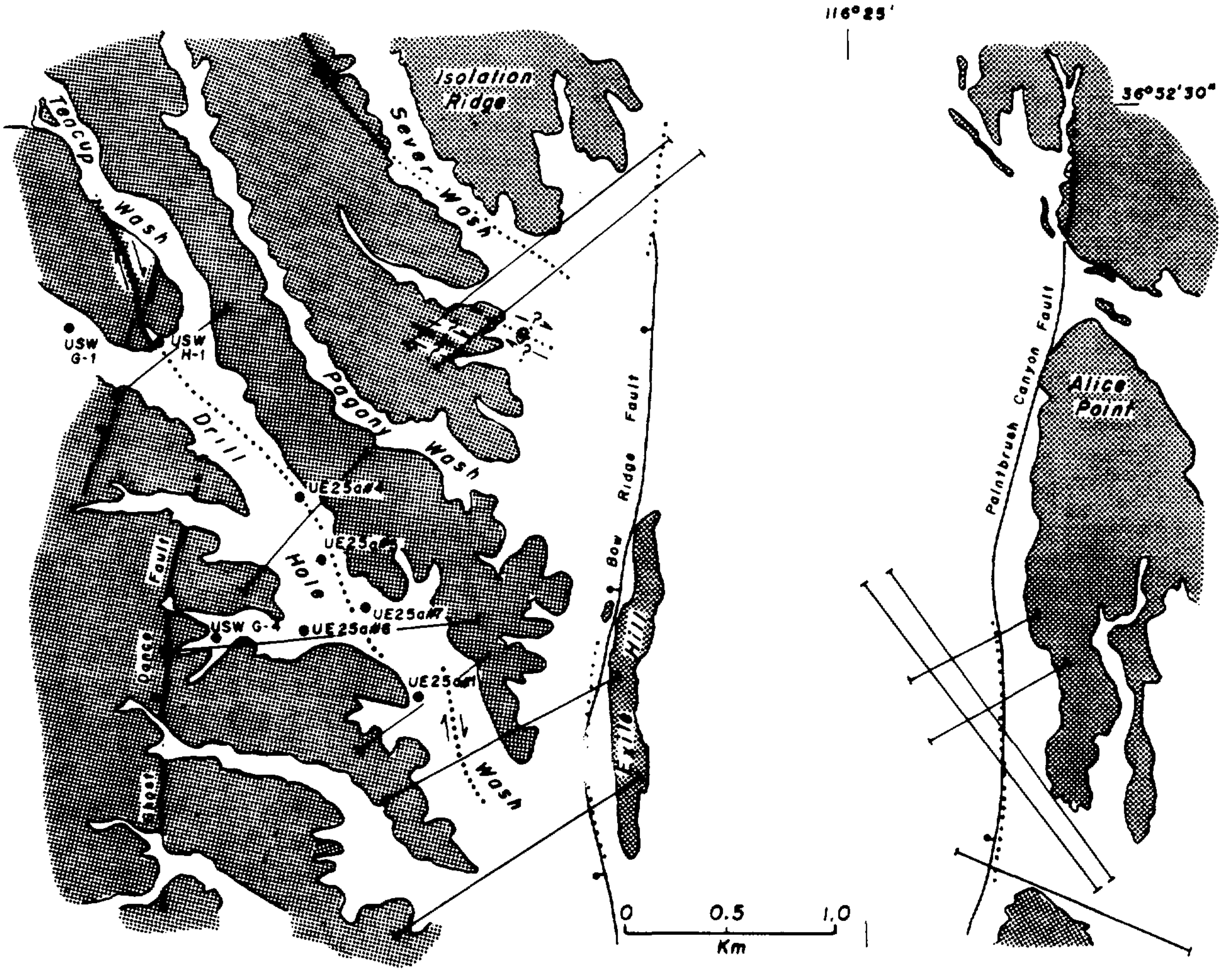
Electromagnetic Slingram surveys that measure relative conductance (Flanigan, 1981) and direct-current surveys that provide dipole-dipole resistivity and induced polarization data (Hoover, *in* Smith and Ross, 1982) support the presence of northwest-striking faults. Zones of abundant fractures and associated breccia related to faults generally have greater surface areas than unfaulted regions. These zones should be conducive to alteration of tuffs to clays and zeolites, and the zones should contain a higher water content; thus they should have lower resistivities and higher conductances than unfaulted zones in comparable rock types.

Three dipole-dipole and induced polarization survey lines (Hoover, in Smith and Ross, 1982) traversed Drill Hole Wash from southwest to northeast. Because distinct differences in the resistivities have been recorded with different depths, the comparisons between resistivities are made along one depth. Detailed mapping (Scott and Bonk, 1984) and stratigraphic correlation between drill holes (Spengler and Rosenbaum, 1980) have supplied suffient stratigraphic control to project stratigraphic horizons below the wash. Thus, in this report the average resistivities are calculated for a horizon 50 m below the wash, well below alluvial depths. The average resistivities on the southwestern side of Drill Hole Wash along the three traverses range from 695 to 3,860 ohm-m, those within the wash range from 300 to 565 ohm-m, and those on the northeastern side of the wash range from 585 to 1,380 ohm-m. Thus, resistivities are significantly lower in the wash.

Five electromagnetic Slingram survey lines cross Drill Hole Wash (Flanigan, 1981). Two zones of relatively high conductance exist parallel to the wash and are interpreted as faults (fig. 6). The largest zone occurs in the alluvial cover close to the fault (1) exposed on the ridge between Drill Hole and Teacup Washes (fig. 2). In Drill Hole Wash, this fault is traced very close to drill hole UE 25a#4; as mentioned above, core from this hole contained faults with a N. 30^o W. strike parallel to the wash. Extensions of both the Sever Wash fault and the Pagany Wash fault also are suggested by zones of low conductance toward the southeast.

An aeromagnetic survey, flown about 120 m above the surface with flight lines spaced about 0.4 km apart, has located major buried structures. These structures are interpreted as normal faults with at least 70 m of vertical displacement (Bath and Jahren, 1984). The traces of these faults are bounded by pairs of aeromagnetic anomalies, which are attributed to the magnetic effect of the Topopah Spring Member, the principal anomaly producer in the Yucca Mountain area. Five major north-striking faults were identified by these anomalies at Yucca Mountain; these faults were also located by mapping where exposed, but for the most part they are buried beneath alluvium. From west to east on figure 2, these faults are the Windy Wash, Fatigue Wash, Solitario Canyon, Bow Ridge, and Paintbrush Canyon faults.

Positions of normal faults interpreted from aeromagnetic surveys compare very well with those interpreted from electromagnetic surveys; good examples are the Paintbrush Canyon fault west of Alice Point and Bow Ridge fault west of Exile Hill and east of Isolation Ridge (fig. 6). Minor departures probably can be attributed to properties being measured: aeromagnetic surveys measure magnetization that locates vertical displacements greater than about 70 m, whereas electromagnetic surveys measure the relative conductance of rocks. Surface mapping commonly shows brecciated zones and anastomosing minor faults associated with major faults; these brecciated zones commonly do not occur along zones of major fault displacement in Yucca Mountain, but are offset on subparallel faults with minor displacements (Scott and Bonk, 1984).



Explanation

☐ Alluvium and colluvium

▨ Miocene bedrock

—•— --- Mapped normal fault in bedrock, ball and bar on downthrown side, dashed where inferred

⇌ -- Mapped strike-slip fault in bedrock, dashed where inferred; arrows show relative directions of movement; queried where sense of motion is speculative

.... Fault position determined by electromagnetic surveys

├──┤ Slingram survey line

──── Fault position determined by aeromagnetic survey within alluvium

● USW G-1 Drill hole location

Figure 6.-- Comparison between fault positions determined by aeromagnetic surveys (Bath and Jahren, 1984), electromagnetic surveys (Flanigan, 1981), and surface mapping.

Linear ground magnetic anomalies along the sides of Drill Hole Wash near drill hole USW G-1 are interpreted as edge effects created by erosion of the Tiva Canyon Member along the wash (figs. 7a and 7b). The anomalies trend along the wash for more than 700 m and are positive on the southwestern side and negative on the northeastern side. Anomaly analysis, using magnetization values of nearby surface samples of Tiva Canyon Member, indicates an edge thickness of about 8 m must exist on either side of the wash to explain the observed anomalies. This calculated thickness is similar to the thickness of the columnar zone at the base of the Tiva Canyon Member. Undercutting of the columnar zone by erosion of underlying nonwelded bedded tuffs has created steep-sided washes along the alluvium bedrock contact in this area. Aeromagnetic anomalies present along Drill Hole, Teacup, and Pagany Washes are also explained by erosion of the reversely magnetized Tiva Canyon Member along the washes.

Aeromagnetic survey lines have also located a strong anomaly along Yucca Wash (fig. 2) that, unlike the aeromagnetic anomalies along Drill Hole, Teacup, Pagany and Sever Washes, cannot be explained by topographic effects alone. Geologic mapping indicates that a fault with more than about 10 m of vertical displacement is unlikely to exist along the wash at this stratigraphic level. Probably the anomaly arises either from the distal ends of rhyolite flows in the tuffaceous beds of Calico Hills that underlie the Topopah Spring Member, from faults in the Crater Flat Tuff beneath the tuffaceous beds, or a combination of both effects.

Character of Northwest-Striking Faults

Recognition of both northwest-striking faults and north-to-northeast-striking faults in the area characterized by the northwest-trending washes is difficult where vertical offsets are less than 3 m, but where greater vertical offsets occur, faults are traced using stratigraphic control of distinctive subzones within the Tiva Canyon Member (Scott and others, 1983). For example, the north-northeast-striking fault crossing Drill Hole Wash near the lower end of Teacup Wash has about 5 m of offset (fig. 2). Vertical offsets along possible northwest-striking faults that parallel the washes can be determined by careful construction of geologic sections across the washes and by field observation where the washes are narrow; vertical offsets greater than 10 or 15 m can be locally detected across washes. The difference in orientation of the rocks on either side of Drill Hole Wash (fig. 2) makes detection of minor faults within the alluvium of the wash particularly difficult. However, in the vicinity of drill holes UE 25a#1, 4, 5, 6 and 7, Spengler and Rosenbaum (1980) used drill hole stratigraphic control to calculate a least squares fit of the plane of the base of the Tiva Canyon Member. With a 95 percent confidence level, they stipulate that no fault greater than 4 m of vertical offset is possible between these drill holes. No vertical offsets were detected along geologic section A-A' across Drill Hole, Teacup, Pagany, Sever, or Yucca Washes (fig. 8).

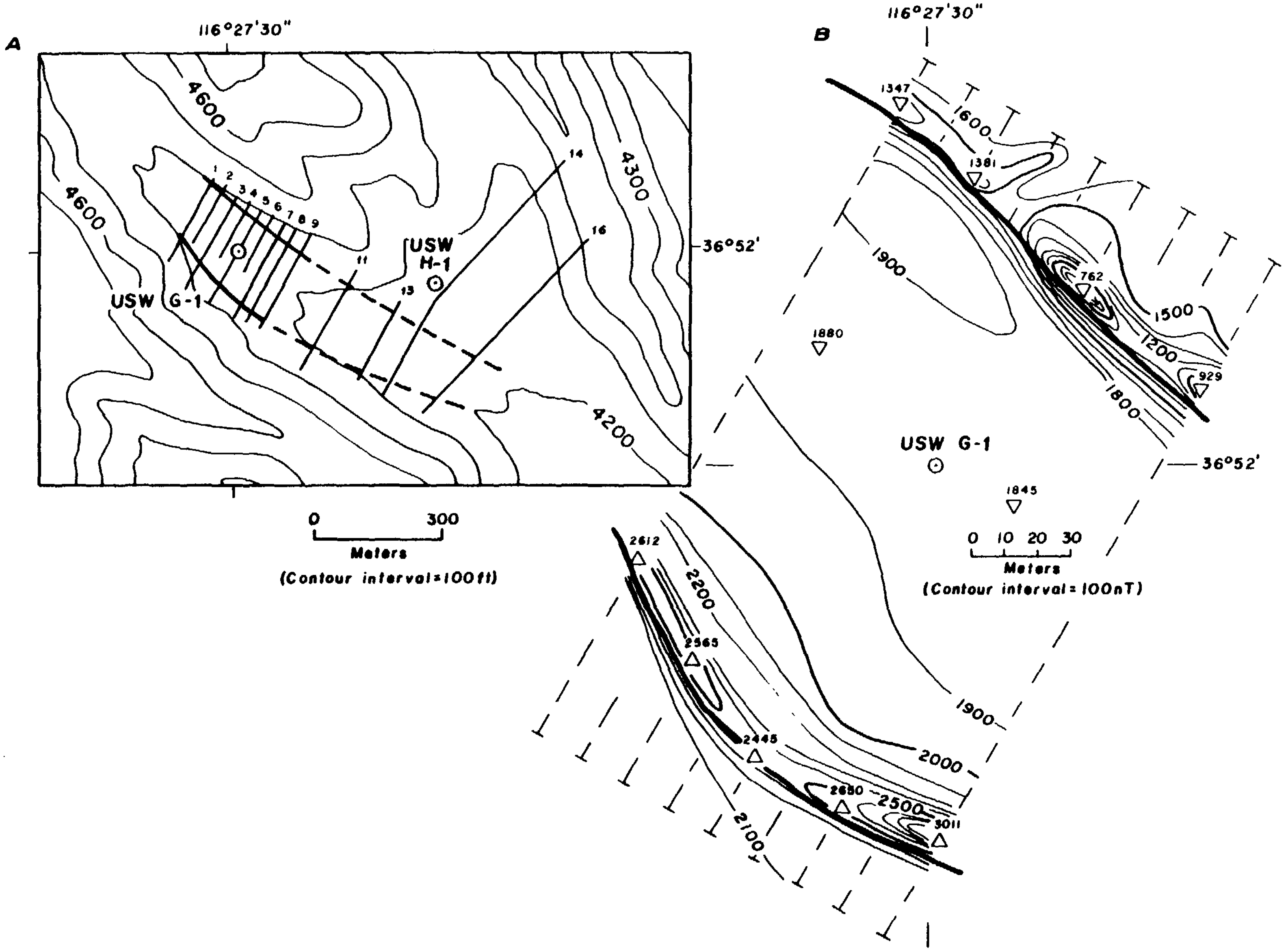


Figure 7.--(a) Ground magnetic survey lines (numbered) and mapped edges of the Tiva Canyon Member along Drill Hole Wash; (b) enlargement of USW G-1 area showing ground magnetic anomalies. Edges of Tiva Canyon Member shown in bold lines, dashed where inferred.

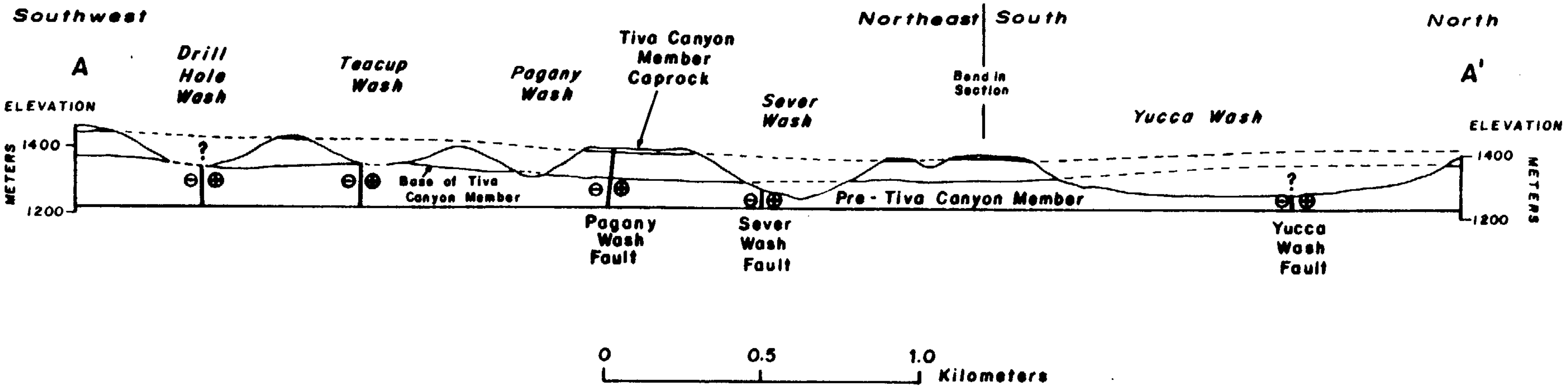


Figure 8.--Generalized geologic section across major northwest-trending washes in Yucca Mountain. The base of the caprock of the Tiva Canyon Member and the base of the Tiva Canyon Member are used as stratigraphic horizons for correlation. Although the surface of deposition of the Tiva Canyon Member appears to be slightly irregular and the unit becomes slightly thicker in the central part of the section, there is no demonstrable vertical displacement. Known strike-slip faults are shown in Sever and Teacup Washes and near Pagany Wash. Presumed strike-slip faults are shown in Yucca and Drill Hole Washes. The plus symbol indicates strike-slip motion out of the page; minus indicates motion into the page (line of section shown on fig. 2).

The northwest-striking faults mapped on Yucca Mountain generally dip more steeply than 75°; the surfaces of these faults contain slickensides that generally plunge within a few degrees of horizontal (fig. 2). The vertical offsets of these faults are very small, generally less than 5 m (fig. 8). These faults are interpreted as strike-slip faults. If the movement on these faults is essentially horizontal--as indicated by average attitudes of lineations of both slickensides and mullion structures--then the amount of lateral offset can be calculated from the dip of the beds. For example, fault (4) in Teacup Wash, shown on figure 2, has undergone about 5 m of vertical offset and exhibits striations on the slickensides that plunge 1° NW.; the strata cut by the fault dip 7° SE in a direction parallel to the fault trace. About 41 m of horizontal and total displacement is required if movement is parallel to the striations on the slickensides. The Sever Wash fault (15) cuts the Yucca Mountain Member of the Paintbrush Tuff with about 6 to 12 m of vertical offset, as estimated by comparison with the thickness of the unfaulted Yucca Mountain Member on the northeast side of Sever Wash. The average dip of strata is 8° SE. with a dip direction essentially parallel to the fault, and the average plunge of striations on slickensides is 4° SE. If only strike-slip motion parallel to striations on slickensides occurred, 43 to 85 m of lateral and total displacement is estimated. Fault (1) in Drill Hole Wash, shown on figure 2, has about 6 m of vertical offset; about 43 m of lateral and total movement would have occurred if the movement were horizontal. In all these cases, the accuracy of estimates of lateral and total slip are limited by the precision of measurements of strata and striation attitudes.

All faults discussed above, as well as the Pagany Wash fault (13), shown on figure 2, are also geometrically required to have right-lateral slip because their northeast sides are upthrown relative to their southwest sides. One northwest-striking fault (6) in the upper portion of Teacup Wash, shown on figure 2, however, underwent as much as 30 m of vertical displacement, down to the northeast. This apparently anomalous fault probably originated as a right-lateral strike-slip fault, similar to other northwest-striking faults in this area, but subsequently experienced normal fault displacement.

In contrast to these northwest-striking strike-slip faults, the north-to-northeast-striking faults have less steep dips, commonly have large vertical offsets with no significant lateral offsets, and have dominantly dip-slip striations and mullion structures. These are typical basin-range normal faults.

Within the densely welded ash-flow tuffs on either side of the Sever Wash fault, a zone of intense fracturing occurs, 20 to 30 m wide. These nearly vertical fractures have a strong preferred orientation, at about 20° to 30° to the strike-slip fault. The fault strikes about N. 35° W., and the fractures strike about N. 15° to N. 5° W. These fractures may be reidel shears (Riedel, 1929); if so, their presence suggests right-lateral displacement.

Although major displacement on normal faults can be bracketed between 13 m.y. (age of the Tiva Canyon Member) and 11.5 m.y. (age of Rainier Mesa Member of the Timber Mountain Tuff), northwest-striking strike-slip faults are more difficult to date. At no place in the Yucca Mountain area do northwest-striking strike-slip faults affect geomorphic features of the Rainier Mesa Member. However, strike-slip faults are cut by normal faults, as for example fault (4) in Teacup Wash. It is assumed, therefore, most if not all of this strike-slip faulting occurred prior to 11.5 m.y. ago.

Several large normal faults such as the Solitario Canyon and Paintbrush Canyon faults have a long history of movement. Although the majority of displacement occurred before emplacement of the Rainier Mesa Member 11.5 m.y. ago, movement as young as 260,000 to 40,000 years has been established where they cut Quaternary alluvium (Swadley and Hoover, 1983). Many of these normal fault surfaces contain horizontal and oblique striations on slickensides even though geometric constraints require that almost all the initial displacement was dip slip. These normal faults dip between 50^{0} and 70^{0} in contrast to the nearly vertical dips of strike-slip faults. Thus, it is assumed that these striations on slickensides on normal faults were formed during a later period of minor movement with a stress field distinctly different from the initial stress field that resulted in dip slip. The modern stress field indicated by earthquake focal mechanism solutions suggests that right-lateral movement on northwest-striking faults is no longer active. The stress field is now characterized by a northwest-directed least compressive stress and northeast-directed greatest compressive stress (Rogers and others, 1983). In the past, most of the displacement on these normal faults has been dip slip, but more recently left-lateral slip dominates on northeast-striking normal faults (Carr, 1974). No Quaternary alluvial scarps are recognized along northwest-striking strike-slip faults.

SIGNIFICANCE OF THE NORTHWEST-TRENDING WASHES TO NUCLEAR WASTE ISOLATION

As discussed by Roseboom (1983), fractures in a repository constructed within an unsaturated zone in an arid region may allow the small quantities of recharge water to move rapidly below the repository level, thereby decreasing the opportunity for corrosion of cannisters or transport of radionuclides. The presence of strike-slip faults and fractured zones in northwest-trending washes in the northeastern part of Yucca Mountain thus may not create adverse containment or isolation conditions for nuclear waste stored in the unsaturated zone. But, in contrast, the role that strike-slip faults might play in the saturated zone may be quite different. For example, such faults form conduits of high hydraulic conductivity. Study of surface exposures of strike-slip faults and of structures within drill cores in the Yucca Mountain area indicate that fault zones buried in the washes may be characterized by wide zones (20 m or more) of breccia with apertures as much as 4 cm wide, or they may be characterized by very narrow zones of fault gouge; large differences in hydraulic conductivity should distinguish these two contrasting fault characteristics. Perhaps the most significant hydrologic aspect of fault zones within both unsaturated and saturated zones may be their roles as major conduits for recharge under washes. However, as discussed above, initial hydrologic studies of drill holes along Drill Hole Wash indicate that ground-water flow in rocks beneath the wash is not significantly different from that estimated from tests of drill holes outside the wash. If this conclusion is supported during further investigations, the location of the repository boundary may not be affected by saturated zone conditions below the repository in the unsaturated zone. Potentially adverse mining engineering conditions may be encountered along these northwest-striking fault zones. If faulted rocks of the Topopah Spring Member can be mined and stabilized safely and economically by conventional methods, the repository may feasibly be extended beyond its present boundary.

CONCLUSIONS

Detailed surface, subsurface, and geophysical studies of the northeastern Yucca Mountain area has resolved differences in interpretation of the genesis of northwest-trending washes. We conclude that (1) The general direction of dip of ash-flow tuff strata approximates, but is significantly nonparallel to, the general trend of the washes. (2) Numerous faults that strike generally parallel to the washes have nearly vertical fault planes, nearly horizontal striations on slickensides, and small vertical displacements, all characteristic of strike-slip faults. The estimated age, geographic position, attitudes, slickensides, and sense of offset of these faults are coincident with the right-lateral strike-slip faults of the Walker Lane-Las Vegas Valley shear zones (Stewart and Carlson, 1978; Stewart and others, 1968). (3) Fractures and faults in oriented cores from drill holes in Drill Hole Wash have orientations and characteristics of strike-slip faults that strike generally parallel to the wash. (4) The lack of variation in the paleomagnetic attitudes of surface samples of the Tiva Canyon Member indicate that no significant structural rotation about a vertical axis has occurred across Drill Hole Wash, even though a 15° to 60° change in strike has been mapped. Presumably the change in strike is related to the original attitude of the depositional surface or possibly to small rotation about different subhorizontal axes. (5) Electromagnetic Slingram and dipole-dipole resistivity surveys indicate that zones of relatively high electromagnetic conductance and low resistivity generally parallel Drill Hole Wash. (6) Based on conclusions 1 through 5, it can be inferred that the trend of these northwest-trending washes was probably controlled primarily by the attitude of breccia zones and fault zones associated with these washes and secondarily by the dip of the strata. (7) The northeast boundary of the potential nuclear waste repository need not exclude northwest-trending washes and associated structures, particularly if the repository target zone is within unsaturated rocks. Roseboom (1983) discussed the possibility that faults and fractures within the unsaturated zone may act as conduits to transport infiltrating surface runoff rapidly away from emplacement tunnels following heavy precipitation events. Subsurface characteristics of the northwest-striking strike-slip faults may provide such conduits within the Topopah Spring Member. In a repository designed to take advantage of these potential conduits, cannisters could be maintained in a more nearly dry environment. (8) In the saturated rocks below the water table, zones of high hydraulic conductivity are likely to be associated with these faults, adversely affecting flow paths and groundwater travel times to the accessible environment. However, the absence of significant differences between the hydrologic flow properties of the saturated zone below Drill Hole Wash and those properties of the saturated zone elsewhere in Yucca Mountain suggests that the repository boundary may be extended to include washes northeast of Drill Hole Wash without compromising radionuclide isolation goals. Ultimate acceptance of this conclusion must await the results of more extensive hydrologic tests.

RECOMMENDATIONS

Potential mining stability problems expected during repository construction in the unsaturated zone and radionuclide isolation problems related to possible high hydraulic conductivities in the saturated zone must be evaluated in northeast Yucca Mountain. Therefore, several recommendations for future characterization of the area northeast of Drill Hole Wash are given below: (1) Slant holes should be drilled through the fault zones using oriented core techniques. (2) Several of these holes should be drilled in unsaturated rocks above the water table to intersect fault zones in the densely welded Topopah Spring Member; other holes should be designed to intersect the unsaturated zone in the tuffaceous beds of Calico Hills below the Topopah Spring Member. (3) Also several holes should be drilled to intersect fault zones in saturated rocks below the water table, in both moderately welded to densely welded tuff and in nonwelded to partially welded tuff. (4) Hydraulic testing in these holes should be performed within the fault zones in the saturated rocks. (5) One lateral exploration drill hole, or preferably, one mined drift, should be made from the Exploratory Shaft across Drill Hole Wash in order to evaluate potential mining stability problems. (6) Further resistivity surveys should be designed to explore the nature of strike-slip faults within the northeastern part of Yucca Mountain, and in particular, to determine if the magnitude of the resistivity decrease or conductance increase can be correlated with the degree of fracturing or alteration along the faults studied by drilling.

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