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PRELIMINARY ASSESSMENT OF IN-SITU GEOMECHANICAL CHARACTERISTICS IN DRILL HOLE USW G-1, YUCCA MOUNTAIN, NEVADA

By

W. L. Ellis and Henri S. Swolfs

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ABSTRACT

Observations made during drilling and subsequent testing of the USW G-1 drill hole, Yucca Mountain, Nevada, provide qualitative insights into the in-situ geomechanical characteristics of the layered tuff units penetrated by the hole. Substantial drilling-fluid losses, and the occurrence of drilling-induced fracturing, are understandable in terms of the low, minimum horizontal stress magnitudes interpreted from six hydraulic-fracturing stress measurements conducted between hole depths of 640 and 1,300 meters. Although not confirmed directly by the hydraulic-fracturing data, other observations suggest that the minimum stress magnitudes in the more densely welded and brittle tuff layers may be even smaller than in the less welded and more ductile rocks. Stress-induced borehole ellipticity observed along most of the length of USW G-1 indicates that the horizontal stress components are not equal, and that the concentration of these stresses around the hole is sufficient to locally exceed the yield strength of the rock. The low, minimum horizontal stress magnitudes, perhaps variable with lithology, and the indications from borehole ellipticity of a high in-situ stress/strength ratio, indicate the need for further studies to characterize the structural and geomechanical properties of the rocks at depth in Yucca Mountain.

INTRODUCTION

Yucca Mountain, located near the western boundary of the Nevada Test Site (NTS) in southern Nevada (fig. 1), is currently being investigated as a potential site for the underground storage of nuclear wastes. The U.S. Geological Survey (USGS), in cooperation with the U.S. Department of Energy (DOE), is actively involved in surface and subsurface geologic investigations of the volcanic rocks of Yucca Mountain. As part of this effort, during March to August 1980, exploratory drill hole USW G-1 was continuously cored from a depth of 89 m to a total depth of 1,829 m. Drill hole USW G-1 is located in the northeastern part of Yucca Mountain at approximately lat 36°52' N. and long 116°27 1/2' W. (fig. 2). The drill-hole site, which is in a prominent northwest-trending wash, has a ground-surface elevation of 1,325.5 m.

During December 1981, hydraulic fracturing stress measurements were conducted in the USW G-1 drill hole. These measurements (M. D. Zoback, U.S. Geological Survey, written commun., 1982) in combination with data from geophysical logging and observations from drilling records have provided important qualitative information about the in-situ geomechanical characteristics of the rock mass penetrated by the drill hole. Currently, these observations and data provide the only reasonably direct means of inferring the geomechanical characteristics of the rocks and rock mass in situ. The purpose of this report is to discuss the USW G-1 observations, show how the observations and hydraulic-fracturing data are mutually supportive, and to briefly discuss the geomechanical inferences.

Acknowledgments

The hydraulic fracturing and borehole televiewer logging of drill hole USW G-1 was conducted in the field by M. D. Zoback, J. Healey, S. Hickman, and J. Svitek of the USGS. The borehole televiewer log and results of the hydraulic-fracturing stress measurements were provided by M. D. Zoback, whose oral and written communications also contributed significantly to this report. Geophysical-logging data was provided by D. C. Muller of the USGS, and the drill-hole history data was compiled by Fenix & Scisson, Inc., Mercury, Nev.

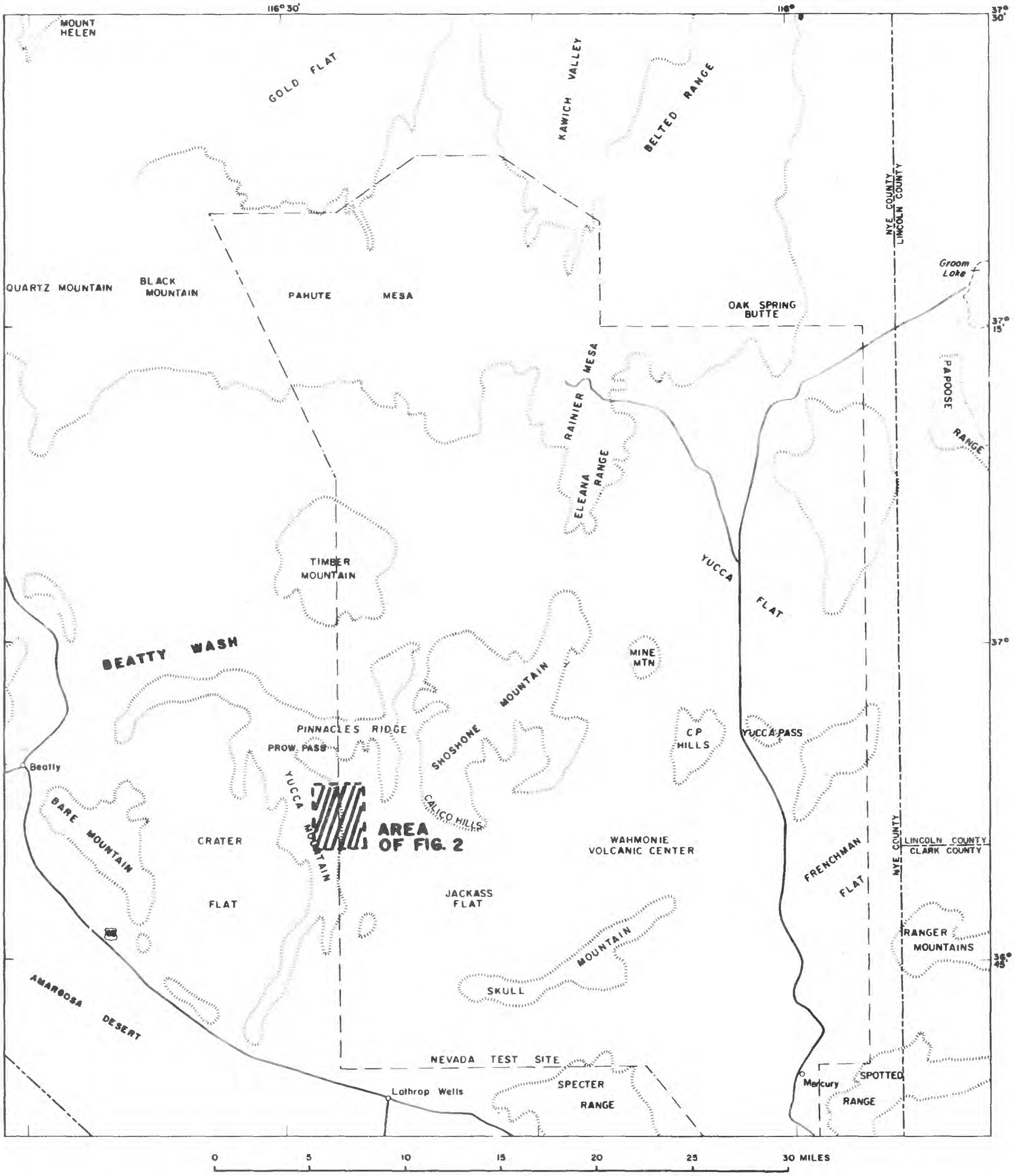

Figure 1.--Index map of the Nevada Test Site and vicinity showing location of Yucca Mountain.

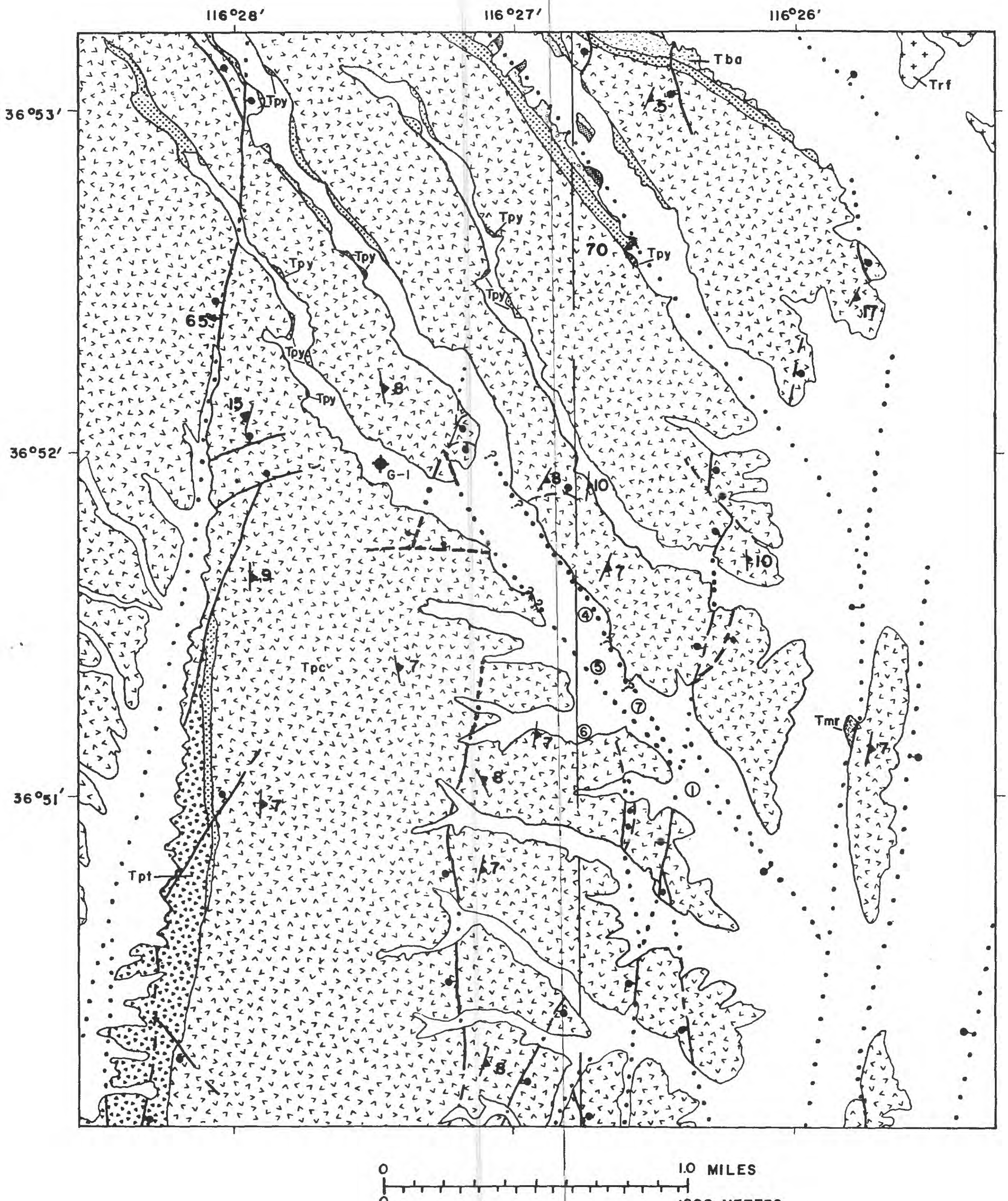

Figure 2.--Generalized geologic map of the northeast portion of Yucca Mountain showing location of USW G-1 drill hole (after Spengler and others, 1981).

EXPLANATION

QUATERNARY

ALLUVIUM AND COLLUVIUM (Qac)

TERTIARY

MIOCENE

(± 9my old) RHYOLITES OF FORTYMILE CANYON (Trf)

RAINIER MESA MEMBER OF TIMBER MOUNTAIN TUFF (Tmr)

PAINTBRUSH TUFF

TIVA CANYON MEMBER (Tpc)

BEDDED TUFF (Tba)

YUCCA MOUNTAIN MEMBER (Tpy)

PAH CANYON MEMBER (Tpp)

TOPOPAH SPRING MEMBER (Tpt)

7 STRIKE AND DIP OF FOLIATION

70 FAULT- BALL AND BAR ON DOWNTHROWN SIDE, DASHED WHERE INFERRED, DOTTED WHERE CONCEALED, ARROW INDICATES MEASURED DIP OF FAULT, QUERIED WHERE UNCERTAIN

CONTACT

NTS BOUNDARY

APPROXIMATE LOCATION OF DRILL HOLES UE25a-1, -4, -5, -6, -7

APPROXIMATE LOCATION OF USW G-1

FIGURE 2.-- CONTINUED

GEOLOGY

A comprehensive summary of the volcanic rocks penetrated by drill hole USW G-1 is given by Spengler and others (1981). Briefly, the stratigraphic section is composed of thick sequences of ash-flow tuff and minor volcanic breccia interbedded with subordinate amounts of fine- to coarse-grained volcaniclastic rocks of Tertiary age. The major stratigraphic units and their respective thicknesses are shown in table 1.

Figure 3 is a graphic representation of the major stratigraphic and lithologic units, showing generalized variations in dynamic Young's modulus and Poisson's ratio as determined from sonic-velocity logging. These were derived by visual averaging from a continuous plot of dynamic Young's modulus and Poisson's ratio versus depth (D. C. Muller, unpub. data, 1982). Figure 3, in effect, provides a simplified mechanical stratigraphy of the rock mass penetrated by drill hole USW G-1 between depths of about 400 and 1,800 m. Sonic-velocity logging could not be done above the fluid level in the hole at the time of logging.

OBSERVATIONS FROM DRILLING RECORDS AND HYDROFRACTURE TESTING

During the drilling of USW G-1, return circulation of drilling fluid was rarely achieved. Even after casing was set to a depth of 310 m, circulation could not be maintained, and more than 44,000 barrels of drilling fluid were lost to the formations below the casing. Because the matrix permeability of tuff is low, the loss of such a large volume of fluid and the difficulty in establishing return circulation suggest a high fracture permeability in the drill hole. Figure 4 shows the rate of drilling fluid loss in barrels per meter drilled for each core run, and the cumulative fluid loss versus drill-hole depth.

In constructing figure 4, it was anticipated that large increases in the rate of fluid loss might correlate with obvious structural features in the drill hole, such as fracture zones, faults, or stratigraphic and lithologic units. Although some subtle correlations with stratigraphic and lithologic units may be present, a strong correspondence of fluid losses with structural features is not apparent. The most obvious feature is the increase in rate of fluid loss as drilling progressed below about 1,036 m. As will be shown later, the drilling records indicate that pumping pressures during drilling were substantially increased below about 975 m. The increase in mud loss below 1,036 m would therefore appear to correlate with increased drill-hole pressures during drilling. Whether or not this indicates drilling fluid loss at these depths is uncertain, as the increased circulating pressure could have

Table 1.--Major geologic units identified in drill hole USW G-1

[After Spengler and others, 1981]

Age	Rock unit		Thickness (ft)	Thickness (m)
Quaternary	Alluvium and colluvium		60	18.3
Miocene	Paintbrush Tuff	Yucca Mountain Member	75	22.9
		Pah Canyon Member	100	30.5
		Topopah Spring Member	1,190.5	262.9
	Tuffaceous beds of Calico Hills[1]		376.0	114.6
	Crater Flat Tuff	Prow Pass Member	372.5	113.5
		Bullfrog Member	466.4	142.2
		Tram unit[1]	918.8	280.1
	Flow breccia		387.6	118.1
	Tuff of Lithic Ridge		994.4	303.1
	Older ash-flow and bedded tuffs		>1,059.8	>323.0

[1] Informal name.

effectively raised the fluid level in the hole, and thus the pressure gradient, sufficient to inject fluid into preexisting fractures at depths above 1,036 m. The level of the fluid column during drilling is not accurately known. However, while coring below the water table, drilling specialists of Fenix & Scisson, Inc., reported the fluid level to fluctuate between a depth of 365 and 427 m, an estimate derived while lowering the sandline to retrieve core samples (Spengler and others, 1981).

The pressure gradients induced in the drill hole during drilling can be estimated from the weight of the drilling fluid in the drill string plus the pressure provided by the circulation pump. The density of the polymer mud used in drilling the hole was about 1.007 gm/cc, essentially the same as that of water. Figure 5 shows the hydrostatic pressure profile due to the weight of the drilling fluid in the drill string as a function of increasing hole depth. Also, where data are available, the circulating pump pressures have been added to the hydrostatic pressures, as shown by the dotted line on figure 5. The dotted line represents the estimated bottom hole pressures as a function of increasing drilling depth.

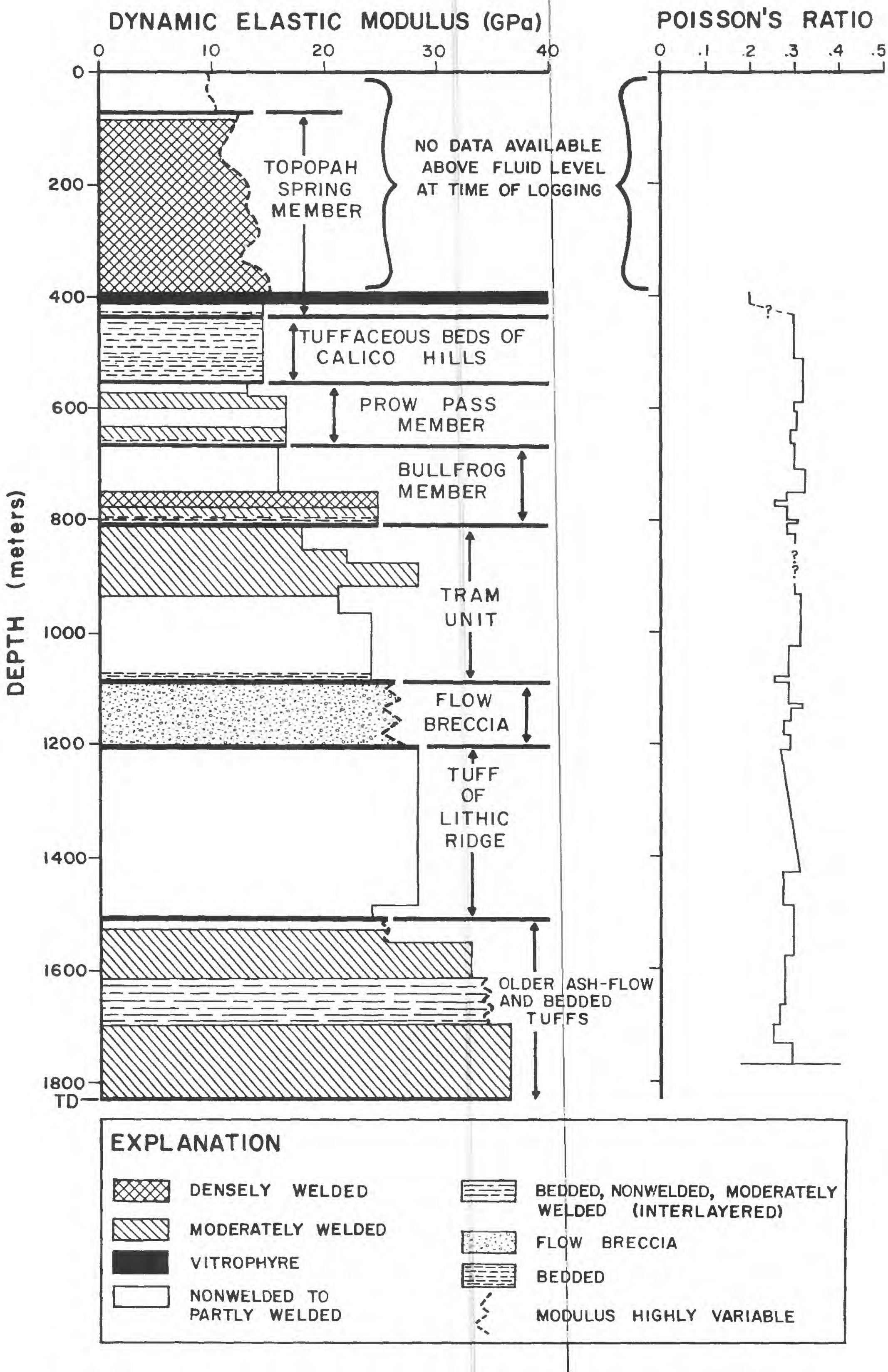

Figure 3.--Stratigraphic and lithologic units of drill hole USW G-1 showing generalized variations in dynamic elastic modulus and Poisson's ratio.

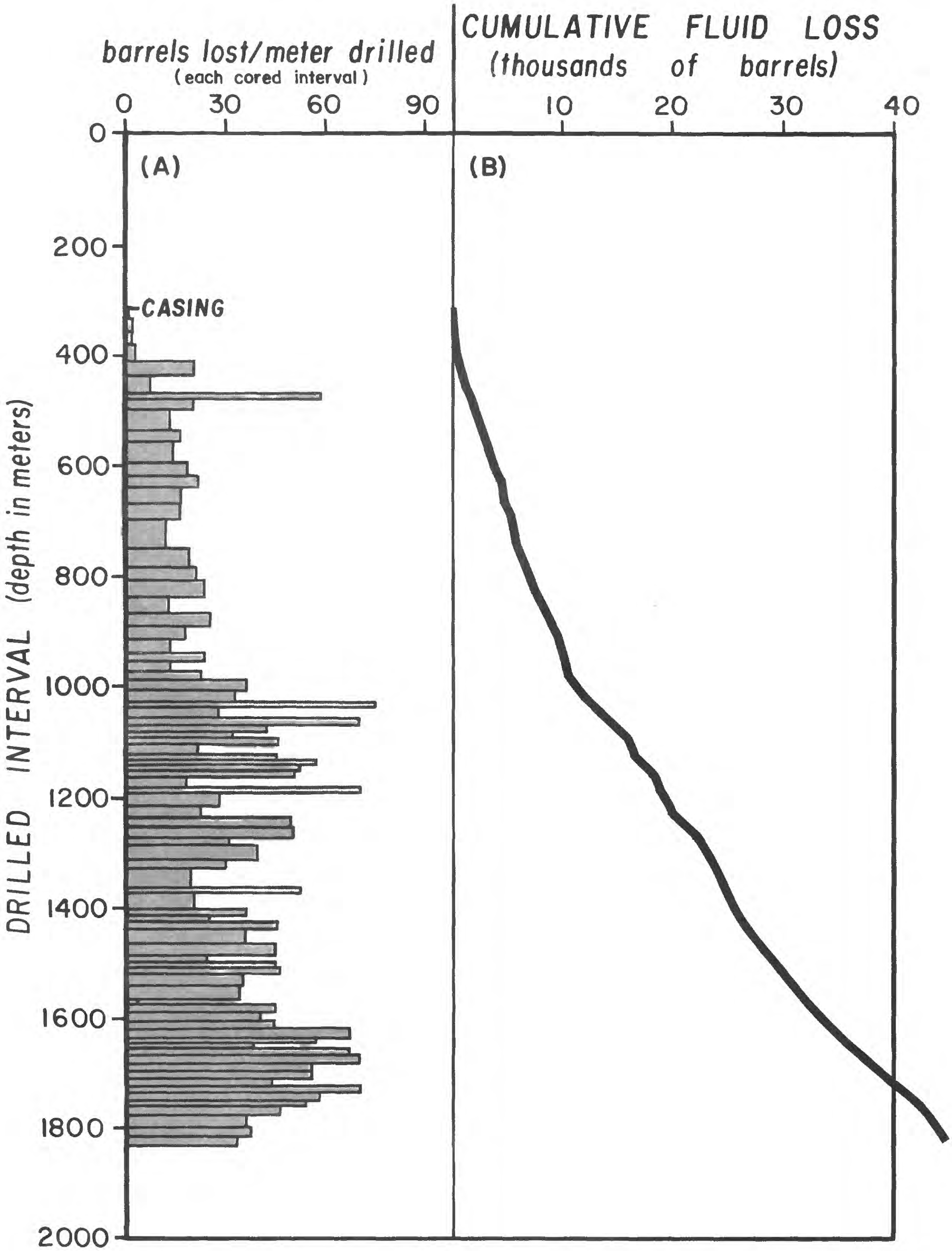

Figure 4.--Summary of drilling-fluid losses for drill hole USW G-1. (A) Rate of loss for each cored interval as a function of depth. (B) Cumulative loss as a function of depth.

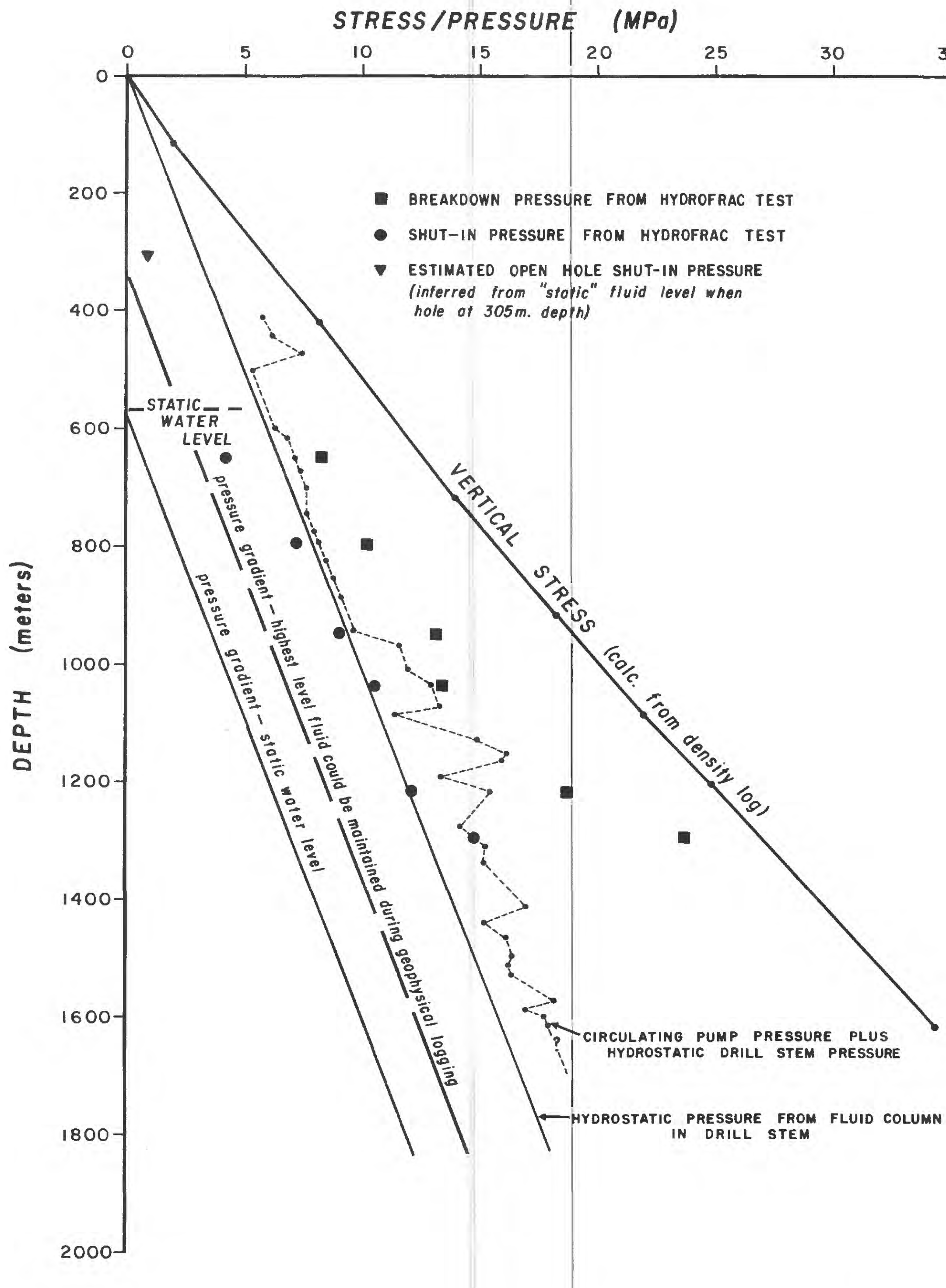

Figure 5.--Drilling-induced pressures and hydrofracture test results versus depth in drill hole USW G-1. Also shown are the pressure gradients for the highest level that fluid could be maintained in the hole during geophysical logging, the pressure gradient from the static water level, and the vertical stress as calculated from a density log.

Circulating pump pressures were not continuously monitored during coring operations, and possible short-term pressure fluctuations during each core run therefore would not be indicated in the circulating pump pressure data. Also, because the circulating pump pressures were read from a dial gage on the pump, the values would include a component of pressure due to frictional losses between the pump and drill string head.

Also plotted on figure 5 are the breakdown and shut-in pressures recorded during the six hydraulic-fracture stress determination measurements conducted in the drill hole (M. D. Zoback, written commun., 1982). Shut-in pressure is interpreted to be equal to the minimum horizontal stress magnitude, and is the pressure above which favorably oriented fractures will open and accept fluid. As can be seen from figure 5, shut-in pressures are less than the estimated bottom-hole pressures during the drilling operation. Additionally, at some depths the estimated bottom-hole pressures approach the magnitude of the measured breakdown pressures, suggesting the potential for drilling-induced fracturing. As will be discussed later, the borehole televiewer log of the hole does show several near-vertical fractures between a depth of 500 and 870 m that are interpreted as being drilling induced.

The pressure history during the drilling of the hole, when compared to results of the hydrofracture tests, provides a reasonable explanation for the inability to establish return circulation during drilling. Apparently, the minimum horizontal-stress magnitude is not sufficient to prevent the flow of drilling fluid into preexisting fractures, and, in some portions of the hole, may not be sufficient to prevent hydraulic-fracturing of the rock formation by the drilling fluid. Both the qualitative observations of fluid loss and the quantitative results of hydrofracture tests are mutually supportive and demonstrate the presence of a low-magnitude horizontal confining stress in the vicinity of USW G-1. Because drilling circulation problems have been common in other Yucca Mountain drill holes, it is possible that the stress state inferred in USW G-1 is characteristic of the Yucca Mountain area, although confirmation of this will require additional hydraulic-fracturing tests at other locations.

Some additional observations shown on figure 5 warrant further discussion. The criterion of selecting unfractured zones in which to conduct the hydrofracture tests resulted in most of the tests occurring in nonwelded to partially welded tuff, which was generally less fractured than the more welded tuffs. Only one of the six hydrofracture tests (at 646 m) was conducted in a moderately welded tuff. Of the other five tests, four were conducted in non- to partially welded tuff and one was conducted in bedded tuff. Warpinski and others (1981) reported results of hydrofracture measurements in Rainier Mesa, Nevada Test Site, in which shut-in pressures in a welded tuff unit were less than one-half those obtained in the overlying and underlying nonwelded tuffs. It is likewise possible that the minimum stress magnitudes in the more densely welded tuff layers at Yucca Mountain are less than in the nonwelded to partially welded tuffs. This condition could result from gravity-induced lateral spreading in the more ductile, nonwelded tuffs, which enclose and tend to pull apart, or cause extension of, the more brittle welded tuff layers (Griggs and Handin, 1960; Sowers, 1973). The possibility that this type of process may be occurring at Yucca Mountain is consistent with the higher frequency of fracturing observed by Spengler and others (1981) in the more densely welded tuffs penetrated by the USW G-1 drill hole.

The data on figure 5 also suggest another possibility with regard to the stress profile in USW G-1. The minimum stress gradient indicated by the hydrofracture shut-in pressures, if extrapolated upward to the surface, suggests that in the upper portion of the hole the minimum stress magnitude may be low. Some qualitative indications suggest that this indeed may be the case. After drilling and reaming the hole to approximately a depth of 305 m, the fluid level was measured at 213 m. If this fluid level is taken as an estimated open-hole shut-in pressure, it indicates a lower estimate of the minimum stress magnitude of about 0.9 MPa at the 305-m depth (fig. 5), a value quite consistent with extrapolation of the hydrofracture data. Another indication of a low confining stress in the upper portion of the drill hole is the high degree of fracturing in the welded Topopah Spring Member.

Finally, another feature shown in figure 5 is the nearly constant bottom-hole pressure gradient of 0.01 MPa/m in the depth interval between 500 and 950 m. In this interval, the recorded circulating pump pressures were between 0.3 and 0.7 MPa. If these low pumping pressures were due to frictional losses between the pump and drill-string head, it would indicate that drilling fluid in the 500- to 950-m-depth interval was being lost to the formation at a volume equal to or greater than that supplied by the circulating pump. As such, bottom-hole pressures in this interval may have been less than indicated by the dashed line in figure 5. This depth interval includes the interval (500-870 m) in which long axial fractures were observed in the televiewer survey, as discussed in the following section on drilling-induced fractures.

BOREHOLE TELEVIEWER OBSERVATIONS

An acoustic borehole televiewer log (Zemanek and others, 1970) was run between depths of 451 and 1,325 m in drill hole USW G-1 in order to select competent, unfractured zones in which to conduct the hydraulic-fracturing tests. In addition to providing data on fracturing within the rocks penetrated by the hole, the televiewer log also indicates the presence of stress-induced borehole ellipticity (M. D. Zoback, written commun., 1982). Figure 6 summarizes the major features observed on the televiewer log as a function of drill-hole depth between 451 and 1,295 m (the quality of the televiewer log below 1,295-m depth was not sufficient to adequately resolve borehole wall fractures). These consist of (1) fractures interpreted as drilling induced, (2) highly fractured intervals, (3) distribution of individually recognizable fractures, and (4) zones of stress-induced borehole ellipticity. The fracture data (item 3) is unavoidably biased because the detection of fractures by the televiewer is related to their aperture at the drill-hole wall. Also, because of the rapid speed with which the tool moves in the hole (compared to the transducer rotation speed), the detection of fine fractures decreases with decreasing dip angle. It is estimated that in drill hole USW G-1, fine fractures dipping less than about 50° probably were not observed on the televiewer log (M. D. Zoback, written commun., 1982). However, the combination of steep dips and greater aperture that makes fractures more easily detectable by the televiewer, also makes them more significant from a geomechanical and hydrological standpoint.

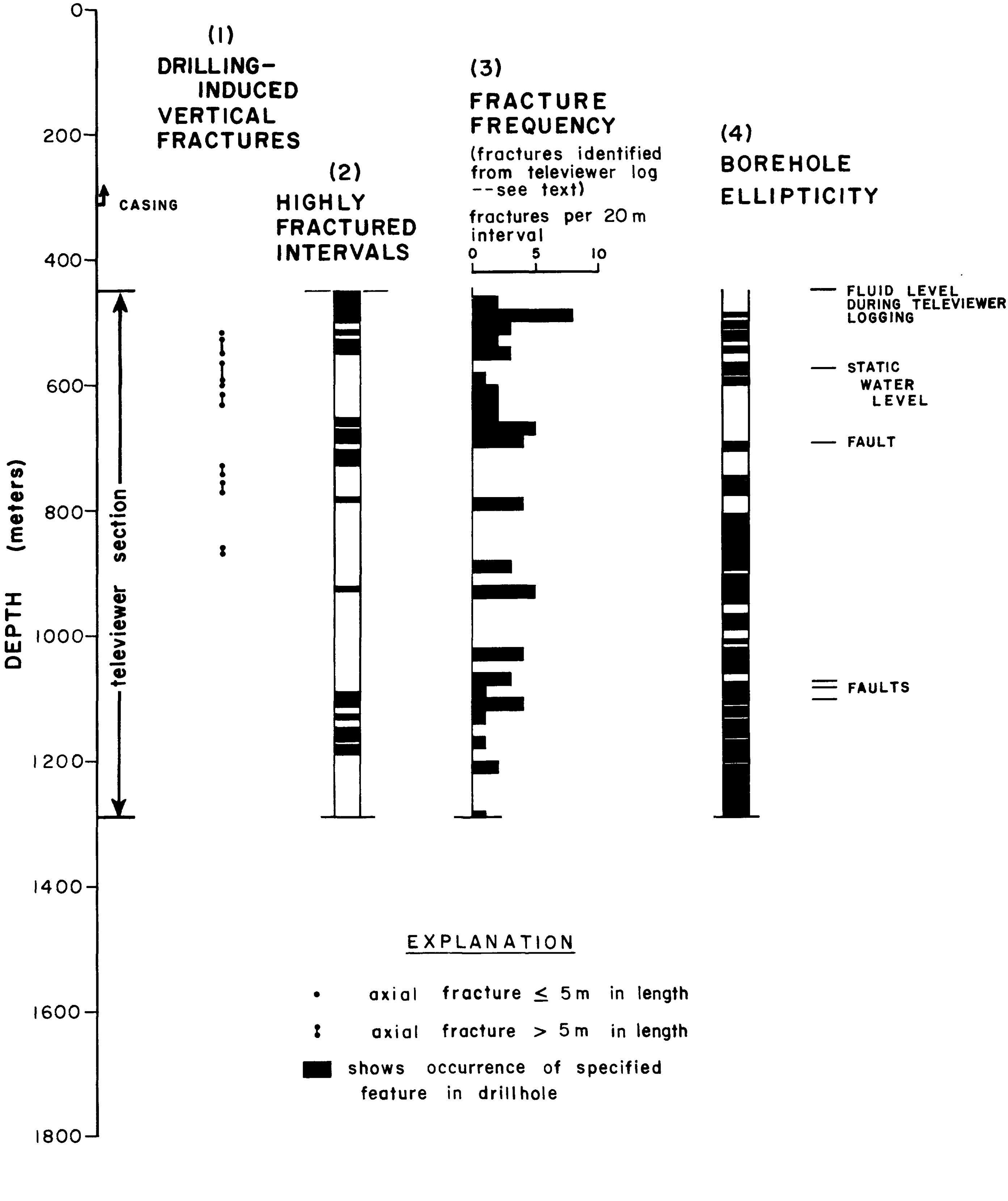

Figure 6.--Summary of major features observed on borehole televiewer log of drill hole USW G-1.

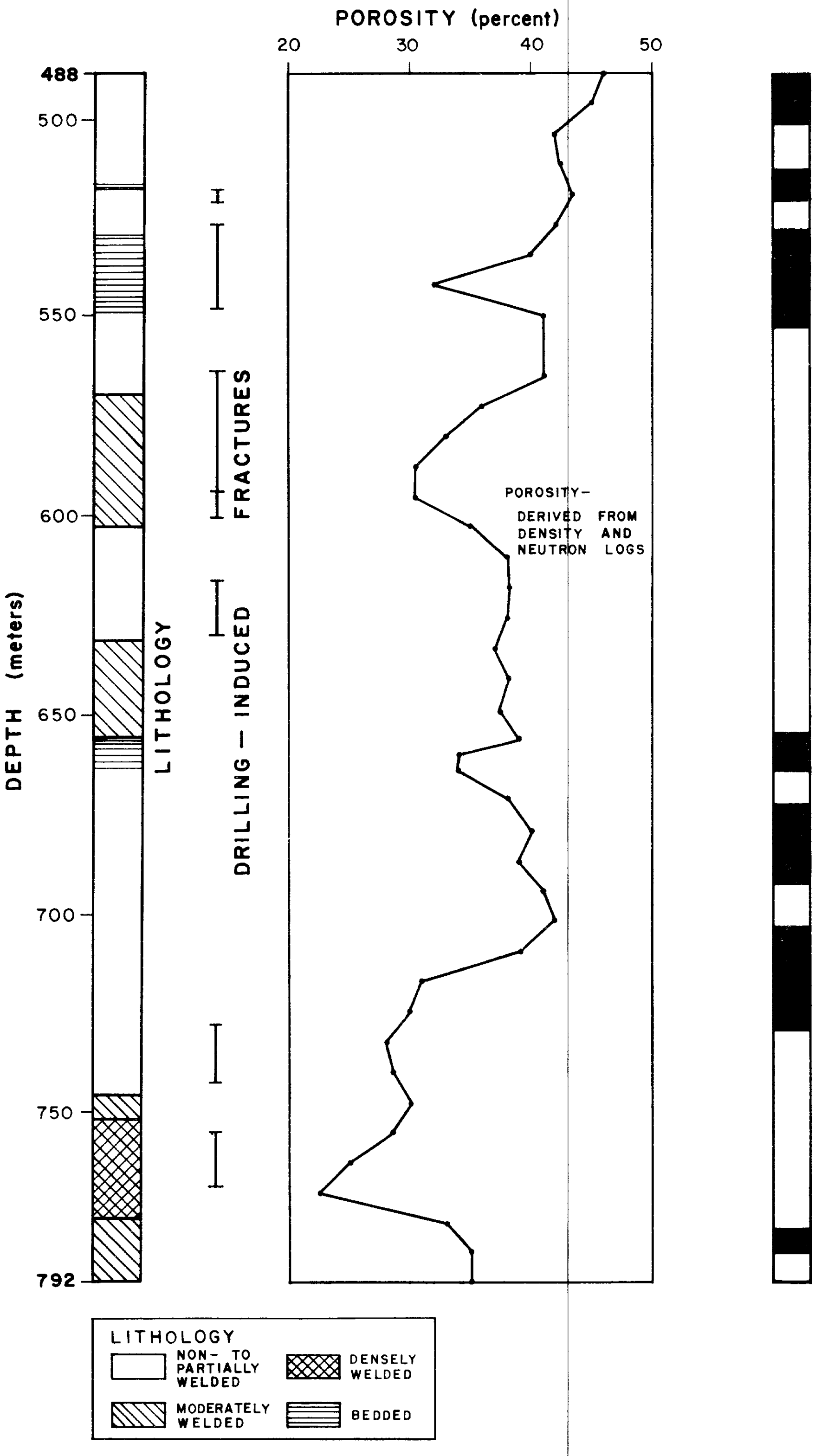

Figure 7.--Relationship of lithology, drilling-induced fractures, highly fractured intervals, and log-derived porosity for a section of drill hole USW G-1.

Drilling-Induced Fractures

Several fractures detected by the televiewer log have been interpreted as drilling induced (M. D. Zoback, written commun., 1982). This interpretation is based on (1) the fact that the fractures parallel the drill hole for long vertical distances, (2) examination of the core does not indicate such continuous fractures at comparable depths, and (3) the fractures occur normal to the direction of maximum borehole ellipticity, which should be expected for a hydraulically induced fracture (see following section on borehole ellipticity).

Figure 6 shows the depths and lengths of these drilling-induced fractures in the drill hole. Fractures like those interpreted as drilling-induced did not appear on the televiewer log below about 870-m depth, although figure 5 suggests that drill-hole pressures during drilling may have been sufficient to induce fracturing at least to a depth of about 1,200 m. It is possible that drilling-induced fracturing occurred at depths greater than 870 m, but because of increased confining stress with depth they remained tight and thus were not detected by the televiewer.

Note that these drilling-induced fractures tend to correspond in depth to lower porosity zones, which in turn also correspond to the more densely welded intervals (fig. 7). The correspondence of drilling-induced fractures with the more brittle, low-porosity zones may be an indication that the minimum horizontal stress magnitude is less than in the more porous, less brittle zones. This would be consistent with the previously discussed possibility that the more brittle layers are being subjected to extensional strain by lateral spreading in the more ductile, nonwelded horizons, resulting in a lower horizontal minimum stress magnitude in the welded layers.

Fractured Rock Intervals

The borehole televiewer also indicates the presence of several intervals of highly fractured rock within the drill hole. These are zones in which the degree of fracturing was noticeably greater than in adjacent sections of the borehole. On the televiewer log these intervals give the appearance of zones of either shattered rock, closely spaced parallel fractures, or abundant discontinuous, nonplanar cracks. The depths of these intervals are shown on figure 6. The fracture features are significant because they could represent potentially permeable zones. With the exception of the interval at around a depth of 470 m, no obvious correlation exists between these intervals and zones of excessive fluid loss during drilling (fig. 4). Note also in figure 7 that the fractured rock intervals, unlike the drilling-induced vertical fractures, do not show a strong correlation with the lower porosity zones.

Fracture Frequency

Figure 6 shows the fracture frequency distribution as determined from the televiewer log. This distribution includes those fractures recognizable as planar features intersecting the borehole for which attitudes (dip and strike) could be adequately determined, but does not include the vertical fractures interpreted as being drilling induced. As mentioned previously, this fracture data is biased toward those fractures most easily detectable by the borehole televiewer, and is therefore not necessarily representative of the total fracture population.

As can be seen on figure 6, the relative frequency of fracturing appears greatest above a depth of 700 m in the hole. Also, it appears that a slight increase in fracture frequency may occur between about depths of 1,000 and 1,200 m, possibly related to small faults at about a depth of 1,100 m. The greater incidence of fracturing above 700 m is qualitatively consistent with the inference of low confining stress in the upper portions of the hole.

Borehole Ellipticity

Perhaps the most significant feature observed on the borehole televiewer log is the borehole ellipticity. Borehole ellipticity occurs when stress concentrations around the drill hole are sufficient to exceed the local in-situ shear strength of the rock, causing spalling of the borehole walls. This spalling occurs along the azimuth of the greatest concentration of stress; that is, perpendicular to the maximum horizontal stress direction, causing an elongation of the hole diameter in the direction of least horizontal stress (assuming isotropy of rock strength properties). Borehole ellipticity was observed in a consistent east-west orientation throughout most of the logged section of drill hole USW G-1, as shown on figure 6. The primary factors influencing borehole ellipticity are the rock strength and the magnitude of the in-situ stress difference normal to the hole axis. Although the existence of stress-induced borehole ellipticity is recognized (Leeman, 1964; Carr, 1974; Bell and Gough, 1979; Hoek and Brown, 1980), little or no work has been done to quantitatively relate the controlling parameters. Nonetheless, the presence of borehole ellipticity demonstrates that the in-situ stress/strength ratio and the stress concentrations induced by the drill hole are sufficient to cause spalling of the wall rock in a preferred direction.

The most important consideration with regard to stress-induced borehole ellipticity is that it indicates localized failure of the intact rock in situ. If such failure occurs as a result of stress concentrations around a 10-cm-diameter drill hole, it is reasonable to expect that it may also occur around larger diameter shafts and underground excavations, especially if they are not favorably oriented to the existing in-situ stress field. The significance of this failure process to overall excavation stability is uncertain; however, it could reflect the potential for engineering problems attendent to underground construction in Yucca Mountain. Another point for consideration is the potential mechanical response of the tuff under increased thermal loads. Little data is currently published regarding the effects of elevated temperature on tuff strength. Olsson and Teufel (1980), however, reported that elevated temperature tests on a welded and a partially welded tuff sample from the UE25a-1 core hole at Yucca Mountain (fig. 2) each showed approximately a 30-percent reduction in strength at 200°C as compared to room temperature. Because borehole ellipticity at USW G-1 indicates an already high stress/strength ratio in situ, any reduction in tuff strength due to thermal loads could increase this ratio, possibly resulting in thermally induced fracturing and localized failure of intact rock. Continued studies of elevated temperature effects on tuff strength will provide much needed data for assessing the thermomechanical properties of the tuffs at Yucca Mountain.

SUMMARY

Preliminary assessment of field data and drilling records of drill hole USW G-1 has resulted in the following observations regarding some of the in-situ geomechanical characteristics of the rock mass penetrated by the drill hole.

1. The minimum horizontal-stress magnitude in the non- to partially welded tuff units in the depth interval between 640 and 1,300 m of USW G-1 is lower than the vertical-stress magnitude by about one-half.

2. The possibility exists that the minimum stress magnitude in the moderately to densely welded tuff units may be even smaller than those measured in the less welded units. Also, there is reason to suspect that the minimum stress magnitude in the welded tuff units above the static water level at USW G-1 may be less than one-half the vertical-stress magnitude.

3. Borehole pressures during drilling operations were apparently sufficient to induce hydraulic fracturing, and to reopen and inject drilling fluid into favorably oriented preexisting fractures. This probably accounts for the difficulty in maintaining drilling-fluid circulation, and is consistent with the low-magnitude horizontal stresses measured by the hydrofracture method.

4. Stress-induced borehole ellipticity (spalling) indicates that the horizontal stresses are not equal in magnitude, and that concentration of the horizontal-stress difference around the borehole is sufficient to exceed the strength of the rock at depth.

With the exception of the hydraulic-fracturing results, these observations are mostly qualitative and in part inferred from indirect evidence. Although tentative, they do provide a preliminary indication of the geomechanical conditions that might be encountered at depth in Yucca Mountain. Better characterization of these important conditions will result from additional studies currently in progress at other Yucca Mountain exploratory boreholes.

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