# STRUCTURAL ANALYSIS OF PRECAMBRIAN ROCKS AT THE HOT DRY ROCK SITE AT FENTON HILL, NEW MEXICO

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## ABSTRACT

The subcrop of basement rock at Fenton Hill comprises Precambrian gneiss, schist, amphibolite, pegmatite, and granitoids with affinities in metamorphic and structural history to surface outcrops in the Tusas and Picuris Ranges. Televiewer measurements of structures were analyzed by taking advantage of the spatial continuity of foliations. Folds in the foliation are preaominantly conical forms due to interference between structures formed in F2 and F3 tectonic events. Field observations of outcrops in the Picuris Range show that the fractures are predominantly an X-T network controlled by the lithological layering, and statistical evidence indicates that this layer-controlled network persists to depth at Fenton Hill.

## INTRODUCTION

Drill hole GT-2 (Geothermal Test well no.2) was drilled in 1974 at the Fenton Hill geothermal site in the Jemez Mountains of northern New Mexico. This borehole, along with its neighbour EE-1 (Energy Extraction hole no.1) was used, in 1975-1980, to prove the scientific feasibility of extracting energy from hydraulically fractured rock.

Drilling, logging and testing of GT-2 was detailed in a series of reports by Pettitt (1975 a, b,c; 1978).

Televiewer studies at Fenton Hill to date have concerned problems in seating packers in hole EE-3A (Dreesen et al., 1986), and the estimation of in-situ stress in the same hole, summarized in Barton et al., (1988) and Burns (1988). Structural data from hole GT-2 was tabulated by Burns (1987 a, b, c), but this is the first analysis of structural data from televiewer logs at Fenton Hill.

## PRECAMBRIAN LITHOLOGIES AND METAMORPHISM

Lithologies at Fenton Hill: A lithological log representative of the Fenton Hill site is given in Figure 1. The major lithologies are biotite-granodiorite gneiss, biotite-amphibole schist, and granitoids.

The granitic gneiss is the predominant Precambrian rock in GT-2 and EE-1. It is banded and strongly foliated, and was formed from sedimentary precursors. The composition is mainly monzogranite, varying from syenogranitic to tonalitic. In some intervals the gneiss has augen texture.

Interlayered with the gneiss is a mafic (ferrohastingsite-biotite) schist which was

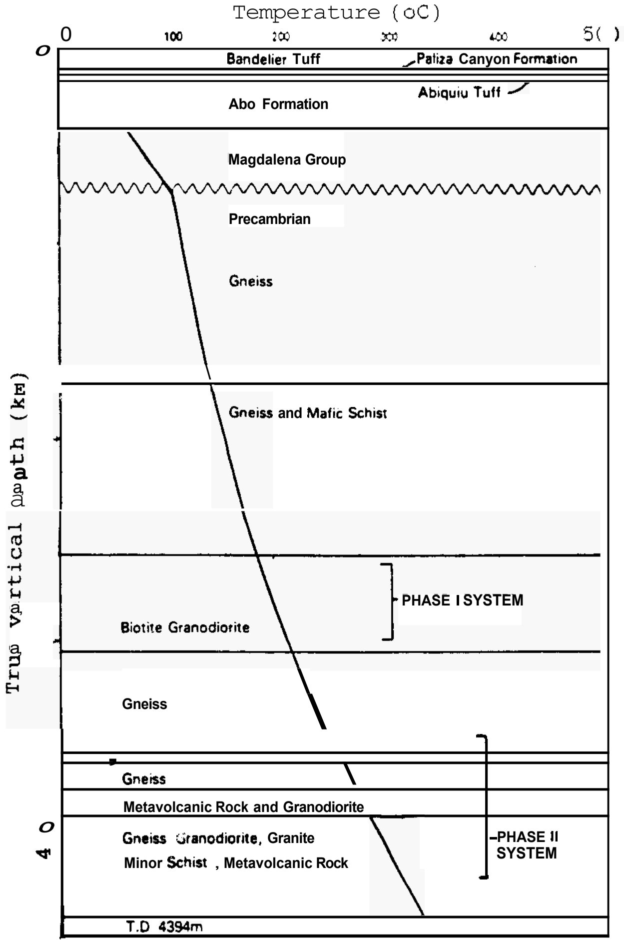


Figure 1: Depth ranges of major lithologies, Fenton Hill, with average temperature profile. From observations in wells GT-2, EE-1, and EE-2. After Laughlin et al., 1983.

formed from basaltic andesite. Sometimes the mafic schist grades into amphibolite, in which case the texture grades from strongly foliated to granoblastic.

Granitoid rocks range in composition from leucocratic monzonite to biotite granodiorite, and include some pegmatite. The rocks are homogeneous and granoblastic, and make good packer seats (Dreesen et al., 1986). In the upper part of GT-2 were found two unfoliated, equigranular, leucocratic monzogranite dikes, each 15 meters (50 ft) thick. A particularly large body, named the

Fenton Hill granodiorite, occurs below 2590 m (8518 ft). This is a relatively extensive, homogeneous, unfoliated biotite-granodiorite body, 338 m (1112 ft) thick. This was chosen as the host rock for the Phase I system.

The most abundant fracture filling is calcite, but there was also epidote, quartz, chlorite, clays and sulfides (Laughlin and Eddy, 1977).

Regional Metamorphic Events: The Precambrian basement rocks at Fenton Hill are part of a 1600- to 1800 m.y. mid-continent terrane extending across southern Colorado, northern New Mexico, and northeastern Kansas (Muehlberger et al., 1966). The nearest outcrops of this basement complex occur in the Sierra Nacimiento to the west, the Tusas Mountains to the north, and the Picuris Range and Truchas Peaks to the north-east.

Radiometric ages in the Tusas Mountains and Picuris Range of northern New Mexico define events at 1673, 1425, 1350 and 1250 m.y. (Gresens, 1975). Gneisses were formed in an "Embudo" metamorphic event at 1673 m.y. A tectonic and metamorphic event at 1425 m.y. was accompanied by pegmatite emplacement and formation of schist. A 1350 m.y. event is represented by pegmatite and red mica from the Picuris Range. The 1250 m.y. event was localized hydrothermal activity along zones of dislocation, probably post-metamorphic tectonic and hydrothermal activity.

Metamorphic Events at Fenton Hill: Rb-Sr ages from Fenton Hill indicate three rock-forming events: first, a metamorphic event at 1620 m.y., represented by coarse-grained gneiss, schist and amphibolite above the Phase I reservoir; second, a magmatic event at 1500 m.y., represented by unfoliated biotite granodiorite which encloses the Phase I reservoir: and third, a local dyke-emplacement event at 1440 m.y., comprising dykes of fine-grained leucocratic and biotite monzogranite intruding the more coarse-grained 1620 m.y. gneiss (dates revised from Brookins et al., 1977).

K-Ar ages from Fenton Hill micas provide information on later, relatively low-temperature, thermal events. Figure 2 shows a dichotomy, line C-C, at a depth of 2645 m (8700 ft). The mean age of the micas above is 1365 m.y. which is concordant with the Rb-Sr age for the leucocratic monzogranite dykes, leading to the conclusion that the magmatic event producing the dykes also produced a thermal event of sufficiently high temperature to reset the K-Ar mica ages. This correlates with the Picuris pegmatite event.

The mean age of the micas below the dichotomy is 1285 m.y., which Brookins et al.,(1977) attributed to additional argon loss, which might be a result of volcanism associated the Valles Caldera, but is more likely to be associated with the Picuris post-metamorphic hydrothermal event.

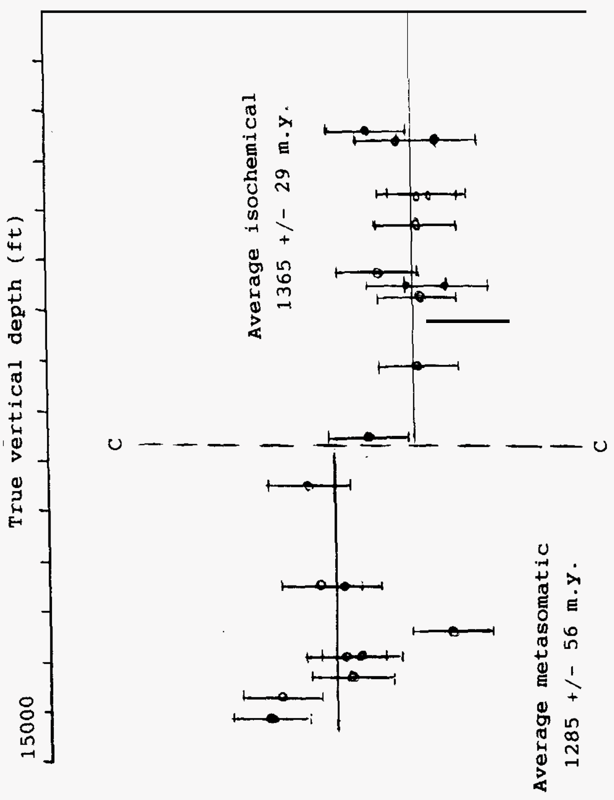


Figure *2:* Potassium-argon ages versus depth at from Fenton Hill. Compiled by R. Potter, Feb.6, 1985, from Brookins et al., (1977, see Fig.13) and other sources. C-C is approximately the upper contact of the granodiorite member that was the host rock for the Phase I reservoir.

## STRUCTURAL DATA ACQUISITION IN GT-2

The structural data obtained from coring runs was reviewed by Laughlin et al.,(1983). Three cores were successfully oriented, in the depth ranges 1127-1129, 1304-1306, and 1672-1674 m (3706-3713, 4289-4295, 5499-5505 ft), a total of 6 m (20 ft) in GT-2. Observations of orientation were limited to 34 fractures and eight foliations.

Televiewer logs were run in wellbore GT-2 between depths of 996-1021 and 1050-1094 m (3270-3350 and 3445-3590 ft) in mid-1974 by the USGS. These surveys were not oriented because of magnetometer failure (Pettitt, 1975a).

The logs used for this study were run by W. Scott Keys of the USGS/WRD in December 1974 (Sanyal et al., 1980, p.268, Keys, 1979). The logs were in the form of paper prints made by a Polaroid film recorder in the field. The prints for Run 1 covered the depth intervals 771-812, 818-1298 m (2536-2670, 2690-4270 ft), and for Run 2, the depth intervals 1216-1703, 1903-1928 m (4000-5600, 6260-6340 ft). The magnetometer was functioning properly so the structures could be oriented.

**An** interactive processing system was developed to extract structural data from the paper prints. The method was described in Burns (1987a,b,c), along with a tabulation of rectified measurements. In total, 517 structures were measured in the interval 771-1296 m (2536-4263 ft) of Run 1 (Burns, 1987b, Tab.V), and 216 structures in the interval 1216-1380 m (4000-4565 ft) of Run 2 (ibid., Tab.VI).

Run 2 is a repetition of part of the depth interval covered by Run 1. The two runs show few individual structures in common, due to differences in imagery, particularly depth calibration and scale, which was quite worrisome. Burns (1985) investigated the causes of the discrepancies in terms of the complicated relationship between signal and noise, and showed that while very few fractures were observed as individuals on both runs, there was at least a statistical correlation between runs.

STRUCTURE OF FOLIATIONS

Projective Representation: The orientation of layerings in rock is represented by poles, which are unit vectors normal to the layering surface. In bedded rocks, the usual representation is by unipolar vectors, that is, they point in only one direction, the "direction of facing", from younger to older strata. We use a similar representation for the gneissic foliation in Precambrian rocks. In this case, the facing direction is unknown, but is assumed to be downwards.

Orientations of foliations are plotted on stereographic projections in Figures 3 and 4. Each is a lower-hemisphere Wulff net, constructed by methods described by Turner and Weiss (1963). A point denotes the direction of the pole to the foliation surface. A line denotes the trace of the foliation surface on the direction sphere.

Regional Folding: Metasediments in the Picuris and Truchas Ranges have an early tectonic foliation (S0/S1), possibly associated with isoclinal recumbent folding (F1). The major folds (F2) trend E to ENE, tight, overturned to the north. The axial surfaces (52) trend ENE and dip steeply to the SSW, associated with the dominant cleavage in the area. A third generation of folds (F3) have axial surfaces striking NNW and dipping steeply WSW, associated with a crenulation cleavage (S3) which dips 66 deg. SW, strikes 336 deg. E of N, in the Picuris Range (Figure 3).

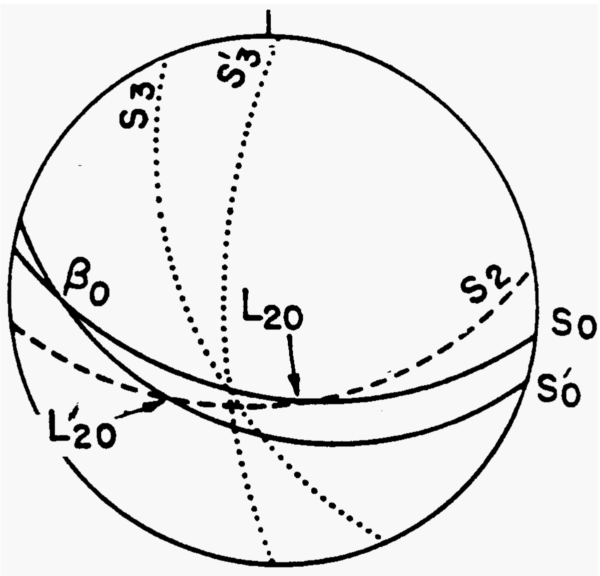

Figure 3: Synoptic diagram of structures in the Picuris Range. SO-SO' is the range in orientation of bedding transposition foliations; S2 is the dominant cleavage; S3-S3' is the range of crenulation cleavage. BO is an early lineation, forming a prominent feature of the microfabric. **L20-L20'** is the range of some prominent mesoscopic fold axes. After Holcombe and Callender (1982).

Orientation of Foliations at Fenton Hill: Figure 4 shows the distribution of poles to foliations, where the observations are all "lumped" together without regard to depth in the wellbore. The lumped distribution is almost isotropic, with large dispersion and no well-defined concentrations.

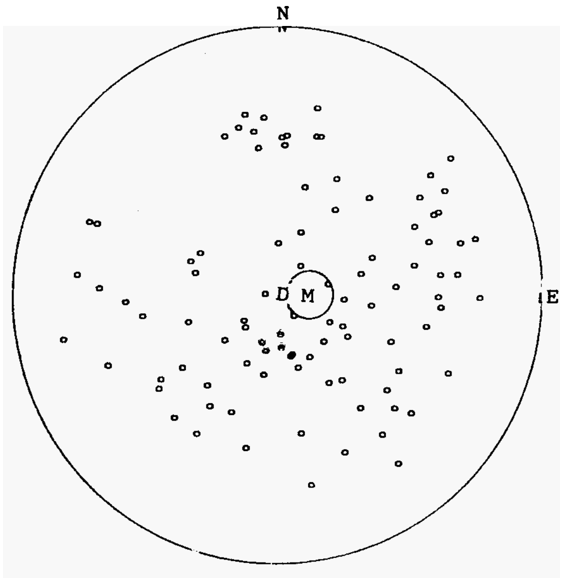

Figure **4**: Poles to foliations, wellbore GT-2, Run 2, 1217-1388 m (4001-4565 ft) depth. Wulff projection, lower hemisphere. Cardinal points are N,E,D = north, east, down. M is the vector mean with 90% cone of confidence.

This distribution is spatially heterogeneous. In any small part of the wellbore, the foliation is a continuous surface varying slowly in orientation, so a small sample, such as a piece of core, shows a concentration of orientations (Laughlin et al., 1983, Fig.8). However the combined distribution in Figure **4** is heterogeneous, made up by lumping together a number of different distributions. Accordingly, a method is needed to treat the spatial heterogeneity.

Spatial Representation of Foliations: The cardinal directions in geophysical horizon-centered coordinates are north (N), east (E) and down (D). The cardinal planes are normal to these three directions, that is, vertical N-S, vertical W-E, and horizontal. One way of representing orientation vectors from well logs in correct spatial position is to show projections of the vectors on the three cardinal planes, as in Figure **5**. In the three columns, left to right, the view is looking down, east, and north. The lines show the vector normal to foliation, projected onto the cardinal plane. The depth in the column indicates depth in the well.

The lines shown on the figure are not the individual measured normals to the foliation, but a nine-point "running mean". This is the vector mean (Mardia, 1972, p.20), calculated as the mean of the foliation measured at that point, along with the four previous and four succeeding foliations. The running mean is a vectorial "moving average", and it smooths out the noise in the raw data.

Folds at Fenton Hill: The projections of running mean vectors in Figure **5** show good serial correlation (spatial continuity). Figure **5** implies the existence of about five large folds, with wavelength about 85 m (280 ft).

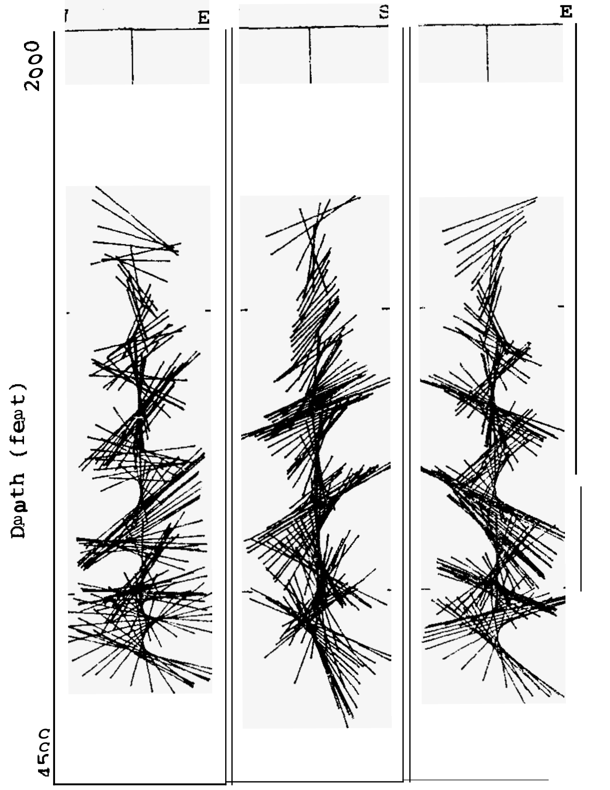


Figure 5: Projections of running mean of normals to foliations, wellbore GT-2. Run 1, 771-1298 m (2536-4268 ft) depth.

Superposed Folds at Fenton Hill: The methods of structural analysis may be applied to obtain a kinematic model of the foliations. This is **a** technique first developed by McIntyre, Ramsay and Weiss in the Precambrian metamorphic rocks of the Scottish Highlands (Turner & Weiss, 1963).

**A** computer program was devised to segment Run 2 into orientation figures - that is, into segments where the orientation of poles to foliation fit a defined figure. The procedure partitioned the log into segments of homogeneous distribution of orientatior.. It was not segmentation of the orientations into homogeneous clusters irrespective of location. The procedure will be described elsewhere. The distributions ("figures") used were the Selby girdle (cylindrical fold), Mardia-Gadsden cone (conical fold), and Fisher cluster (monocline), as described in Burns and Murdoch (1983).

The results in Figure 6 show that predominantly conical segments were found, marked by upright crosses. The axes of the cones themselves are interpreted as lying on two small circles. The modal axial surfaces are interpreted as lying where shown by the traces marked S2 and *S3*. The projective representation of Figure 6 is given spatial expression in the diagram of Figure 7.

STRUCTURE OF FRACTURES

Regional Fracture Pattern: An inspection of outcrops in the Picuris Range (R.H. Vernon, pers. comm. 11/17/84) shows that fractures in layered rocks are predominantly layer-controlled **X-** and T-networks (Gray et al., 1976) with intersections predominantly perpendicular to layering. The poles of

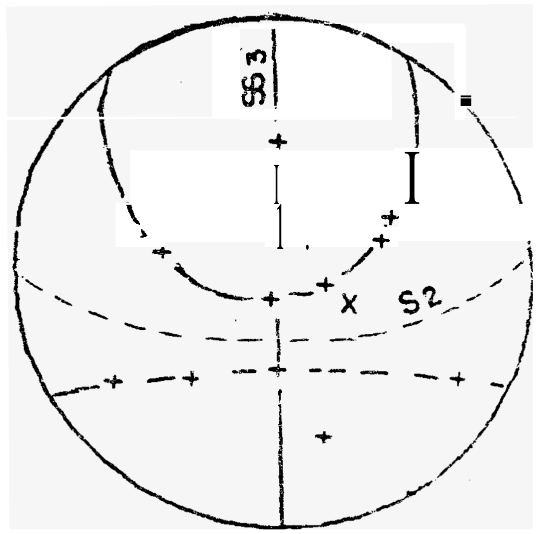


Figure 6: Partitioning of foliations in Run 2. The vertical crosses are best-fit axes to sets of poles of foliation forming Mardia-Gaasden conical figures. The diagonal cross is the best-fit axis to a set of poles forming a girdle figure (Selby distribution). The traces are interpretations of two opposed small circles of folds in SO, and imposed axial surfaces S2 and *S3*.

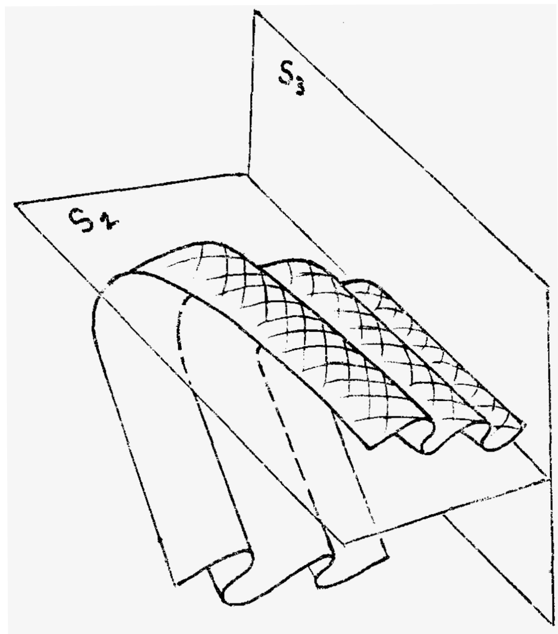


Figure 7: Synoptic diagram of structure in Precambrian gneissic foliation at Fenton Hill, looking NE. This shows the modal (typical) configuration of the structures in the subsurface.

fractures in layer-controlled networks have bimodal distributions of orientation, and are somrtimes termed 'conjugate **sets**" The predominant feature is **that** the fracrure planes and **their** intersections *tend.* to be perpendicular to layering. Where the layers are folded, the fracture network tends to follow the layering, so that the direction of fracture intersections changes around folds.

Projective Representation of Fractures at Fenton Hill: Fractures are represented, like foliations, by unit vectors oriented normal to the fracture surface, but are bipolar, that is, there are two opposed unit vectors, pointing in opposite directions. A fracture surface is thus represented by two direction points.

In Figure 8, the points shown are those poles of the fractures that point downwards. The matching poles on the upper hemisphere are not shown.

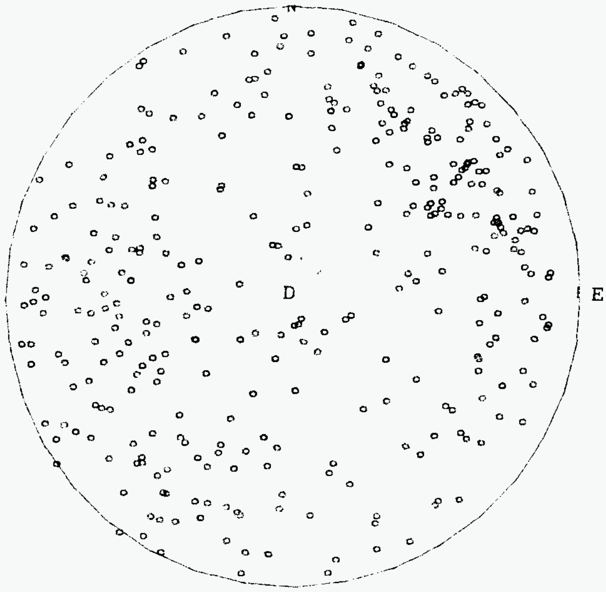


Figure 8: Poles to fractures, wellbore GT-2, Run 1, 771-1296 m (2536-4268 ft) depth. Wulff projection, lower hemisphere. Cardinal points are N,E,D = north, east, down.

Figure 8 shows the distribution of poles to fractures, where the observations are all "lumped" together without regard to depth in the wellbore. The lumped distribution is almost isotropic, with large dispersion and no well-defined concentrations.

Projective Relationships of Foliations and Fractures: The tern "orientation parameter" is used here in the sense of Mardia (1972, p.19), where it is termed "location on the direction sphere".

For unipolar structures such as foliations, an appropriate orientation parameter is the vector mean. However fractures are bipolar, and for them the vector mean is a null vector, so a different orientation parameter is required. Burns and Murdoch (1983) showed that, for distributions of poles to fractures drawn from the Breitenberger-Bingham distribution. the appropriate orientation parameter is the largest eigenvector. "Largest eigenvector" means the eigenvector assosiated with the largest eigenvalue.

The nine-point running principal axes of fractures cluster near-vertical [Figure 9), statistically coincident with the mean foliation vector in Figure 4. This association between fractures and foliations is consistent with an X-T fracture network controlled by layering which is, on the average, horizontal.

Spatial Relationships of Foliations and Fractures: If the foliations and fractures are related as postulated, the foliation mean vectors should show similarity in orientation to the largest eigenvectors of the fracrures, that is, to the most probable directions of lines of intersection.

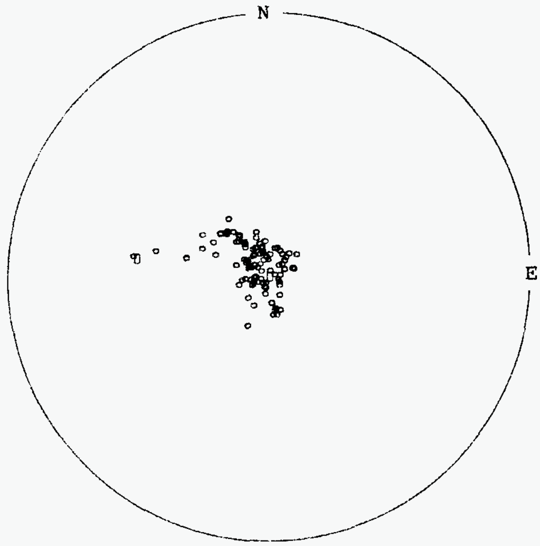


Figure 9: Principal axes of fractures, wellbore GT-2, Run 2, 1216-1387 m (4000-4563 ft) depth. Shown are the nine-point running eigenvectors corresponding to the largest eigenvalues. Wulff projection, lower hemisphere. Cardinal points are N,E = north, east.

Figure 10 compares the orientations of foliation (left column) to fractures (right column). There are many points of general similarity. In particular, the fold axes at points A. A; and the fault at point F, occur in both columns. This shows that generally, the mean vector of the foliations is correlated with the largest eigenvector of the fractures. Such a relationship would arise if the fractures were a layer-controlled X- or T-network, controlled by the foliation. This relationship is illustrated in Fiqure 7.

## CONCLUSIONS

The Precambrian basement rocks at the Hot Dry Rock development site at Fenton Hill have iithological and metamorphic counterparts in the Tusas and Picuris Ranges, implying a similar structural history.

Both foliations and fractures were observed in televiewer logs of wellbore GT-2.

Structural analysis of the foliations indicates the presence of superposed folds that match in style and orientation those analyzed from surface observations in the Picuris Range.

Fractures observed at the surface in the Picuris Range have the topological character of a layer-controlled X-T network. Statistical analysis shows that the same pattern can be detected at depth at Fenton Hill. The relationship of the fractures to the foliation, as a network controlled by the layering, is sketched on Figure 7.

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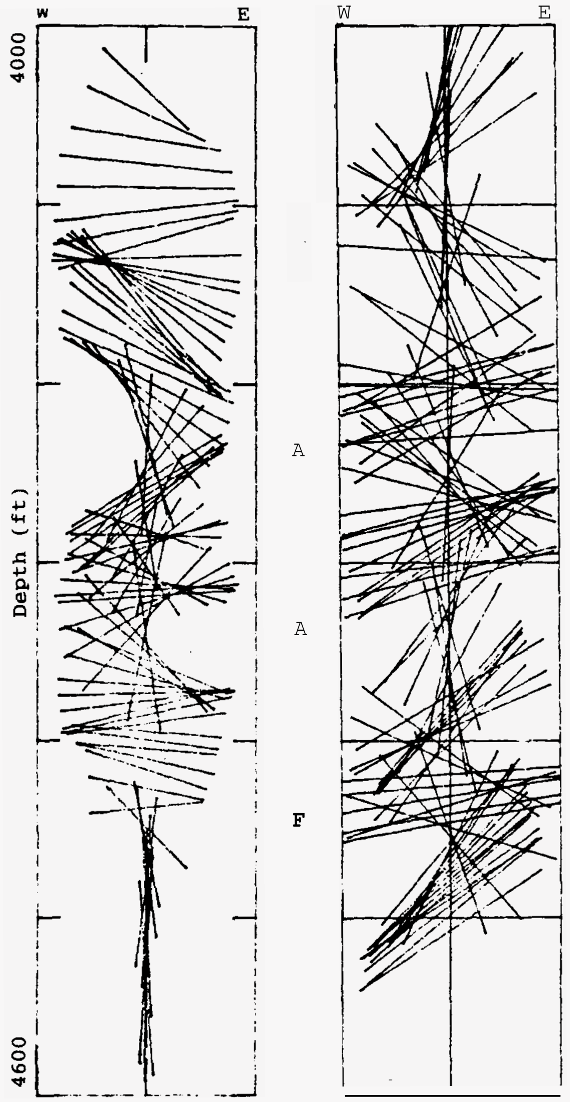


Figure 10: Spatial correlation of orientations of foliations and fractures, shown in the horizontal cardinal plane. Left column shows projections of the running mean vectors of foliations. Right column shows projections of the running eigenvectors of fractures. Data is from Run 2, depths 1217-1388 m (4001-4565 ft).

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