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Fractal geometry of two-dimensional fracture networks at Yucca Montain, southwestern Nevada

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ABSTRACT

Fracture traces exposed on three 214- to 260-m^2 pavements in the same Miocene ash-flow tuff at Yucca Mountain, southwestern Nevada, have been mapped at a scale of 1:50. The maps are two-dimensional sections through the three-dimensional network of strata-bound fractures. All fractures with trace lengths greater than 0.20 m were mapped. The distribution of fracture-trace lengths is log-normal. The fractures do not exhibit well-defined sets based on orientation.

Since fractal characterization of such complex fracture-trace networks may prove useful for modeling fracture flow and mechanical responses of fractured rock, an analysis of each of the three maps was done to test whether such networks are fractal. These networks proved to be fractal and the fractal dimensions (D) are tightly clustered (1.12, 1.14, 1.16) for three laterally separated pavements, even though visually the fracture networks appear quite different. The fractal analysis also indicates that the network patterns are scale independent over two orders of magnitude for trace lengths ranging from 0.20 to 25 m.

1. INTRODUCTION

Fractures form three-dimensional interconnected networks in nearly all rocks at or near the Earth's surface. Open-fracture networks are the primary avenues of rapid transport for liquid and gaseous fluids through rock masses. In contrast to fracture flow, matrix flow generally is significant only for slow transport rates. For rapid transport, fracture flow generally dominates matrix flow in natural geologic systems of mineralizing fluids, petroleum, natural gas, and ground water. Fracture flow can exceed matrix flow particularly when the geologic system is disturbed by an induced pressure differential, such as the pumping of petroleum or ground water, the production of natural gas, or the ponding of water behind dams. Measured fracture-network permeabilities in some areas are 6-7 orders of magnitude greater than rock matrix permeabilities (e.g., Montezar and Wilson, 1985).

Efforts to quantitatively model and to understand flow properties of fracture networks are presently under way (e.g., Long and Witherspoon, 1985). The use of fracture-flow models to applied problems is contingent upon the size, shape, orientation, connectivity, aperture, surface roughness, and spatial distribution of fractures.

In this paper, we present maps of fracture-trace networks on two-dimensional sections through the three-dimensional fracture network. We then characterize the two-dimensional fracture-trace maps using fractal geometry.

2. FRACTURE MAPS

As part of an effort to characterize the fracture network at Yucca Mountain in southwestern Nevada (Fig. 1), we have prepared 1:50 scale maps of fracture traces exposed on three pavements from 214 to 260 m^2 in area in Miocene ash-flow tuffs. The pavements are subhorizontal planar surfaces that we cleared of talus, soil, and vegetation to provide complete exposure of the ash-flow tuff bedrock. The pavements are in the same ash-flow subunit, the upper lithophysal subunit of the Tiva Canyon Member of the Paintbrush Tuff (Scott and others, 1983). The pavements are designated by numbers 100, 200, and 300. Pavement 100 is located 500 meters south of pavements 200 and 300, which are 15 meters apart, east and west.

All fractures with trace lengths greater than 0.20 m were mapped. The maps for pavements 100, 200, and 300 are shown on Figures 2, 3, and 4, respectively.

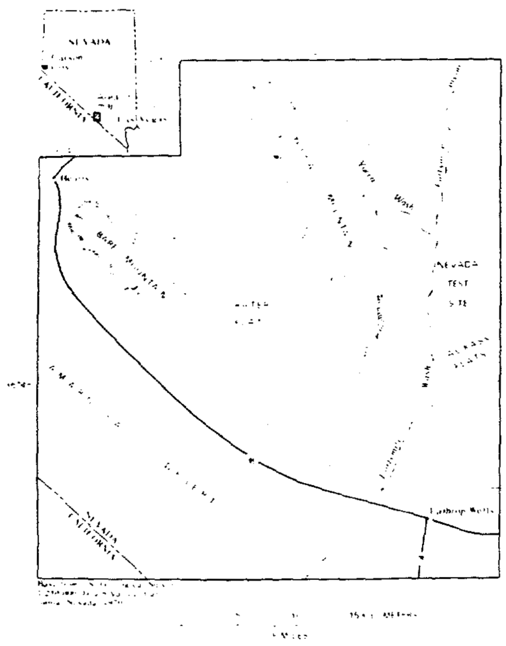


Figure 1. Location of Yucca Mountain, southwestern Nevada.

3. THE FRACTURES

The patterns of fractures on Figures 2, 3, and 4 are composites of cooling fractures with tubular structures (Barton and others, 1984) formed shortly after emplacement of the ash-flow tuff and later fractures formed in response to tectonic stresses that produced the Basin and Range province and possibly the Las Vegas-Walker Lane shear zone (Barton, 1984). The vertical extent of the fractures is limited by the lithology because the fractures are strata-bound within the upper lithophysal subunit.

3.1 Fracture orientations

The poles to fracture surfaces and bedding for all three pavements are plotted together in stereographic projection on Figure 5. The fractures

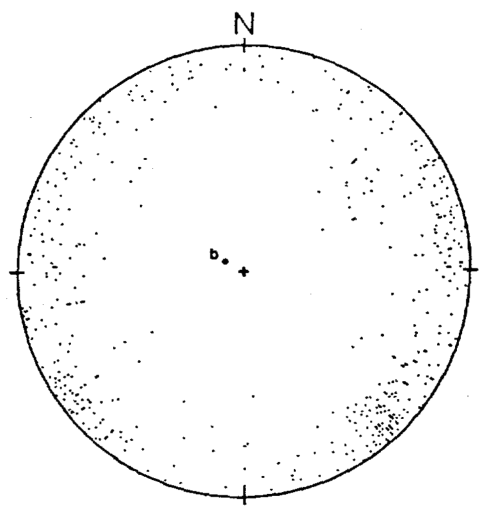
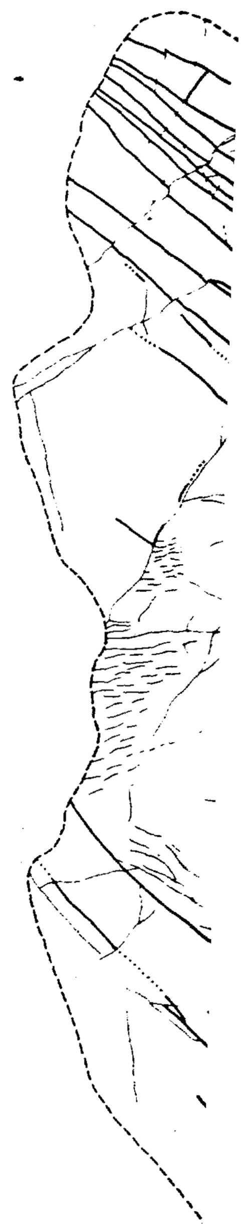


Figure 5. Combined poles to fracture surfaces for all three pavements. b is pole to bedding. Lower-hemisphere equal-area projection (580 poles).



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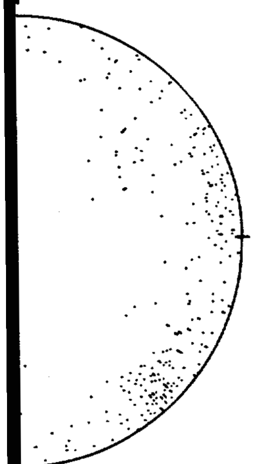

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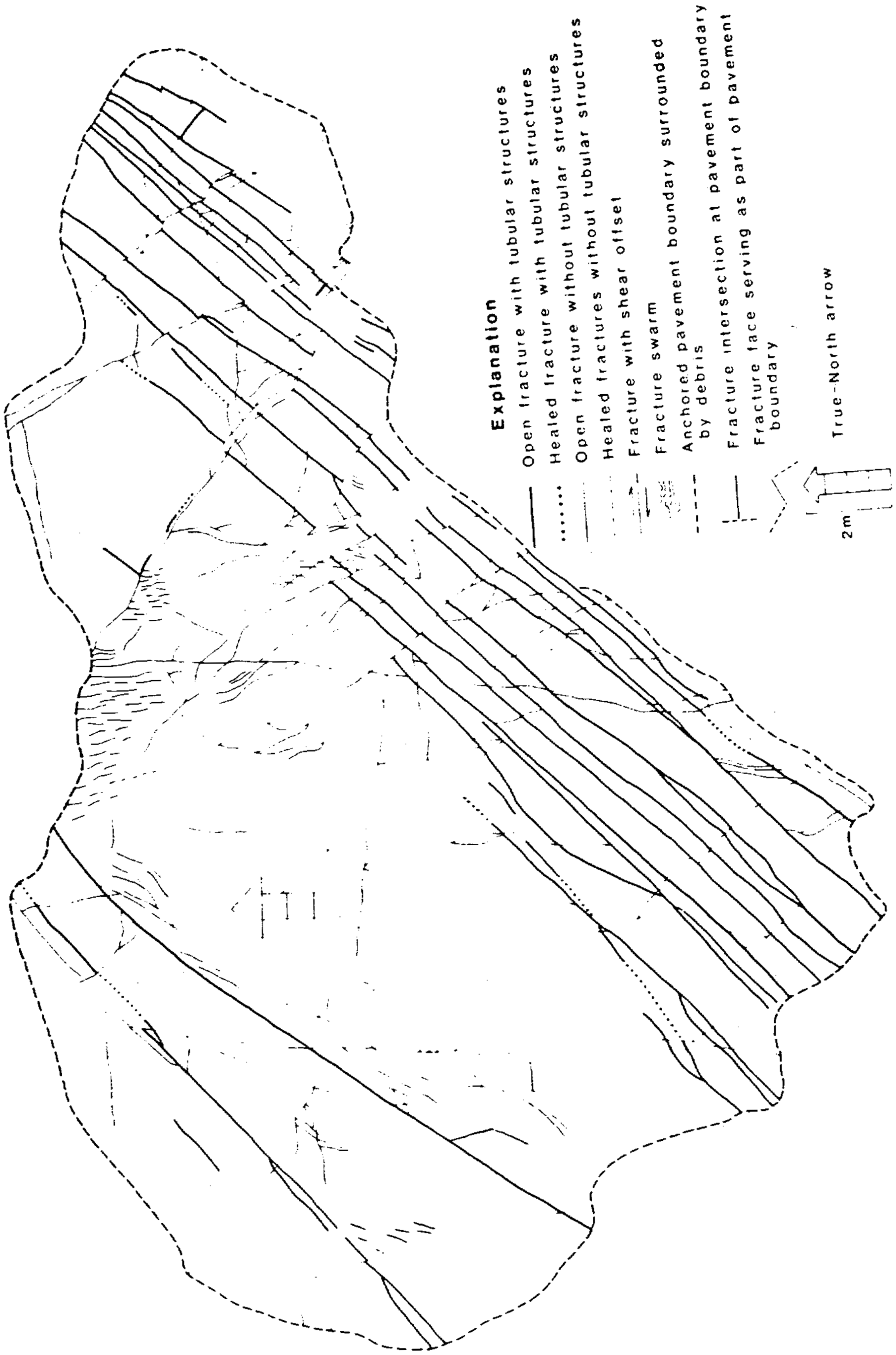

Figure 2. Fracture-trace map of pavement 100 (area = 214 m)^2.

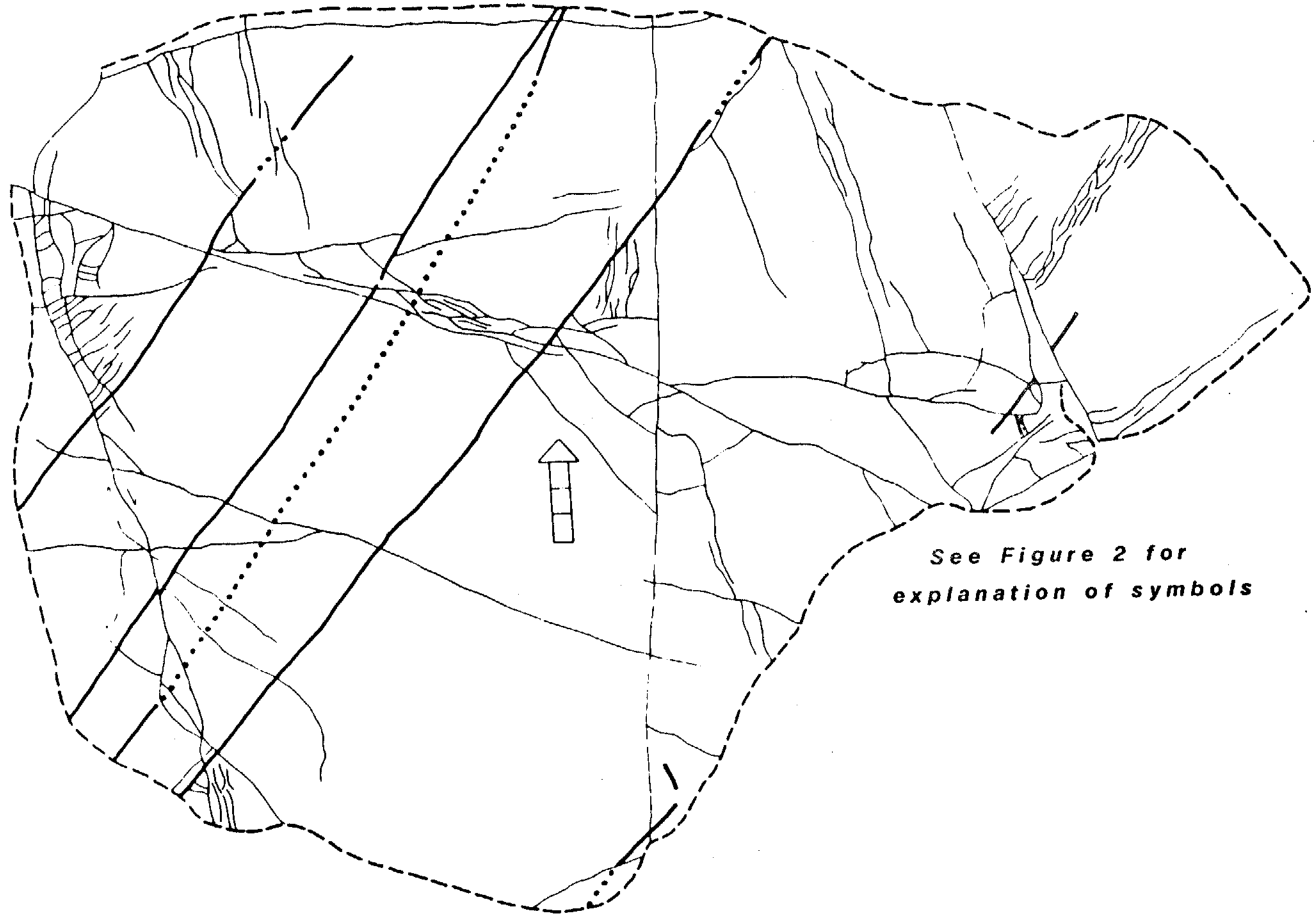

Figure 3. Fracture-trace map of pavement 200 (area = 260 m^2).

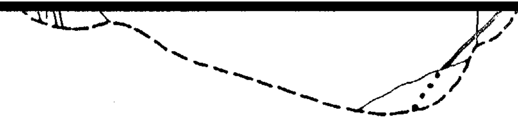

Figure 3. Fracture-trace map of pavement 200 (area = 260 m^2).

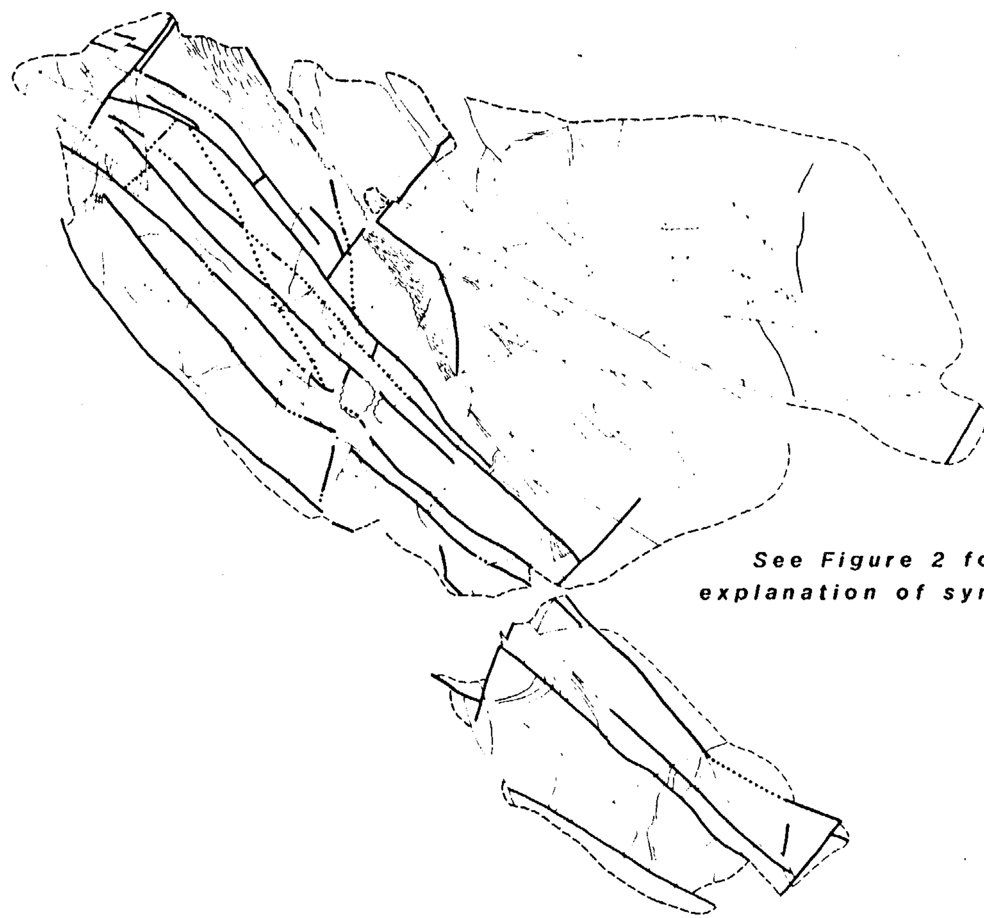

Figure 4. Fracture-trace map of pavement 300 (area = 221 m^2).

range in strike from 0 to 360° and in dip from 46 to 90° with slightly higher concentrations in the southeast and southwest quadrants; highest concentrations in dip are between 80 and 90°. The fractures cannot be grouped into well-defined sets based on orientation.

3.2 Distribution of fracture-trace lengths

The combined distribution of fracture-trace lengths for all three pavements is shown on Figure 6. The lower end of the distribution is truncated because no trace lengths less than 0.20 m were mapped. The upper end is truncated because many trace lengths exceed the dimensions of the pavements. The distribution is log-normal, even with the truncation of trace lengths less than 0.20 m (Baecher and Lanney, 1978).

3.3 Fracture networks

The fracture networks are quite complex and cannot be broken down into well-defined fracture sets, each having a characteristic orientation, spacing distribution, and trace-length distribution. Fractal characterization of such complex fracture networks may prove useful for modeling fracture flow and for modeling mechanical responses of fractured rock.

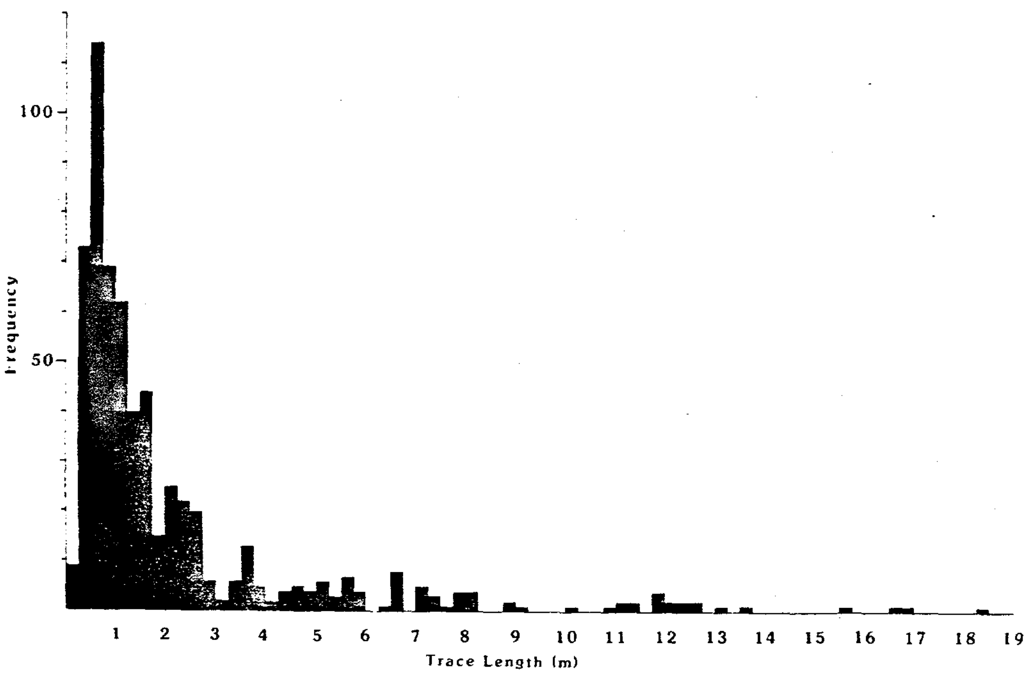

Figure 6. Combined distribution of fracture-trace lengths for all three pavements (580 fractures).

4. FRACTALS

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4. FRACTALS

Fractal geometry (Mandelbrot, 1982), has been applied by him and others to quantitatively describe complex patterns in nature. Fractal geometry applied to two-dimensional fracture networks simultaneously quantifies the spatial and trace-length distributions.

A fractal analysis for each of the three fracture maps plotted on Figure 7 was done by hand. Grids of various-sized square elements were placed over the maps, and the number of grid elements intersected by fracture traces was counted. The relative size (K) of the grid elements is plotted versus the Log_2 of the number of grid elements (N) intersected by fractures for each element size. For each pavement, the fractal dimension (D) is the absolute value of the slope of a straight line fitted to the points. When plotted this way, the fractal dimension (D) can be determined by the equation

$$D = \left|(\log_2 N(K) - b)/K\right|$$

where b is the y-intercept. The fractal dimensions of all three networks lie between 1 and 2, with confidence levels of 0.99. For comparison, the fractal dimension of a straight line is 1; for a plane, it is 2; and for a volume, it is 3. Pavement 100 has a fractal dimension of 1.16; pavement 200, a fractal dimension of 1.12; and pavement 300, a fractal dimension of 1.14.

Because the points can be fitted by smooth lines (either straight or curved), the networks can be said to be fractal over the scale range 0.20 to 25 m or two orders of magnitude. Because these lines are straight (not curved), the networks can also be said to be scale independent over the same range. Fracture networks with fractal dimensions close to one, such as these, are expected to have strongly directional flow anisotropy, a characteristic that is not obvious from the distribution of fracture strikes.

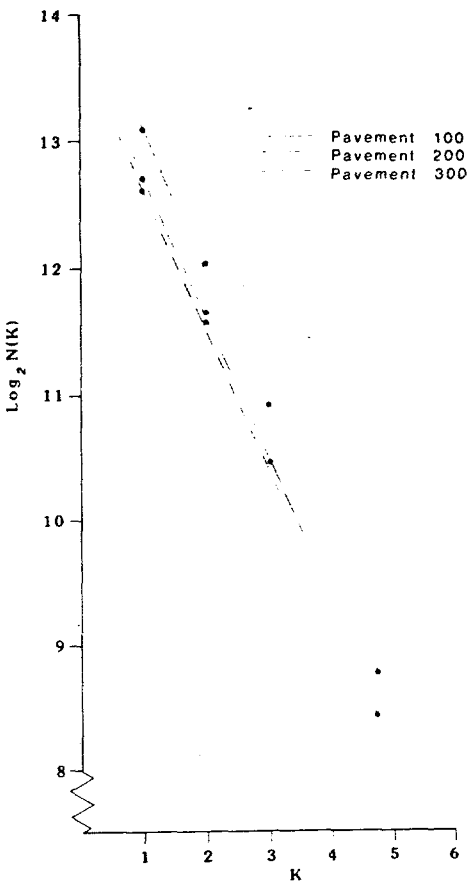

Figure 7. Fractal plot of fracture networks.

5. CONCLUSIONS

Complex two-dimensional fracture-trace networks can be described quantitatively using fractal geometry. The fractal dimensions (D) are tightly clustered (1.12-1.16) for three laterally separated pavements in the same stratigraphic subunit, even though the fracture networks visually appear quite different. Over two orders of magnitude, the networks are scale independent, even when the trace-length distributions are truncated.

We are presently investigating whether the fractal dimension of fracture networks varies with lithology for the strata-bound fractures at Yucca Mountain.

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REFERENCES

Baecher, G. B., and N. A. Lanney 1978. Trace length biases in joint surveys. Proceedings, 19th U.S. Symposium on Rock Mechanics. 1:56-65.

Barton, C. C. 1984. Tectonic significance of fractures in welded tuff, Yucca Mountain, southwest Nevada. Geological Society of America Abstracts With Programs 16(6):438.

Barton, C. C., T. M. Howard, and Eric Larsen 1984. Tubular structures on the faces of cooling joints: a new volcanic feature. EOS (Transactions of the American Geophysical Union) 65(45):1148.

Long, J. C. S., and P. A. Witherspoon 1985. The relationship of degree of interconnection to permeability in fracture networks. Journal of Geophysical Research 90(B7):3087-3098.

Mandelbrot, B. B. 1982. The fractal geometry of nature. W. H. Freeman and Co., San Francisco. 460.

Montezar, Parviz, and W. E. Wilson 1985. Conceptual hydrologic model of flow in the unsaturated zone, Yucca Mountain, Nevada. U.S. Geological Survey Water Resources Investigation Report 84-4345.

Scott, R. B., R. W. Spengler, Sharon Diehl, A. R. Lappin, and M. P. Chornack 1983. Geologic character of tuffs in the unsaturated zone at Yucca Mountain, southern Nevada: in J. W. Mercer, P. S. C. Rao, and I. W. Marine, editors, Role of the unsaturated zone in radioactive and hazardous waste disposal. Ann Arbor Science, Ann Arbor. 289-335.