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Determining the 3-D Fracture Structure in the Geysers Geothermal Reservoir

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Introduction

The bulk of the steam at the Geysers geothermal field is produced from fractures in a relatively impermeable graywacke massif which has been heated by an underlying felsite intrusion. The largest of these fractures are steeply dipping right lateral strike-slip faults which are subparallel to the NW striking Collayomi and Mercuryville faults which form the NE and SW boundaries of the known reservoir. Where the graywacke source rock outcrops at the surface it is highly sheared and fractured over a wide range of scale lengths. Boreholes drilled into the reservoir rock encounter distinct "steam entries" at which the well head pressure jumps from a few to more than one hundred psi. This observation that steam is produced from a relatively small number of major fractures has persuaded some analysts to use the Warren and Root (1963) dual porosity model for reservoir simulation purposes. The largest fractures in this model are arranged in a regular 3-D array which partitions the reservoir into cubic "matrix" blocks. The net storage and transport contribution of all the smaller fractures in the reservoir are lumped into average values for the porosity and permeability of these matrix blocks which then feed the large fractures. Recent improvements of this model largely focus on a more accurate representation of the transport from matrix to fractures (e.g. Pruess et al., 1983; Zimmerman et al., 1992), but the basic geometry is rarely questioned. However, it has long been recognized that steam entries often occur in clusters separated by large intervals of unproductive rock (Thomas et al., 1981). Such clustering of fractures at all scale lengths is one characteristic of self-similar distributions in which the fracture distribution is scale-independent. Recent studies of the geometry of fracture networks both in the laboratory and in the field are finding that such patterns are self-similar and can be best described using fractal geometry. Theoretical simulations of fracture development in heterogeneous media also produce fractal patterns. However, a physical interpretation of the mechanics which produce the observed fractal geometry remains an active area of current research. Two hypotheses for the physical cause of self-similarity are the Laplacian growth of fractures in a self-organized critical stress field, and the evolution of percolation clusters in a random medium. Each predicts a different fractal dimension. The more important questions from a reservoir engineering point of view are: 1) is the network of fractures in the Geysers reservoir fractal and if so over what range of fracture sizes is the self-similarity observed and what is its fractal dimension, and 2) do the conventional dual porosity numerical simulation schemes provide an adequate description of flow and heat mining at the Geysers? Other papers in this volume by Acuna, Ershaghi, and Yortsos (1992) and Mukhopodhyoy and Sahimi (1992) address the second question. The primary objective of this paper is to try to answer the first. Toward this goal we have mapped fracture patterns in surface exposures of the graywacke source rock at the outcrop scale (meters), at the road-cut scale (tens of meters) and at the regional scale (kilometers). We have also examined cores collected at depth from the graywacke reservoir rocks, and analyzed drilling logs making use of the pattern of steam entries as well as the fluctuations in drilling rate.

Mapping fracture patterns at The Geysers field

The graywacke reservoir source rock outcrops at several locations in the Geysers geothermal field. One particularly good location is at well site GDC-21 where the drilling pad has been cut from the hillside revealing a near vertical wall of graywacke which is about 100 feet long and 40 feet high. The graywacke at this location has a cataclastic texture where the largest clasts are on the order of 10 feet in diameter. Although the outcrop appears to have a fluction structure suggesting a component of ductile deformation, close inspection of the folds shows that they are composed of multiply fractured graywacke layers in which virtually all the strain appears to have been accommodated by brittle fracture. The largest clasts contain complex fracture patterns which are easily visible due to the infilling with minerals of a contrasting color. In fact, at this outcrop virtually all of the fractures have been filled. The fracture patterns in three such clasts were mapped from photo mosaics and one example is shown as Fig 1. A sec-

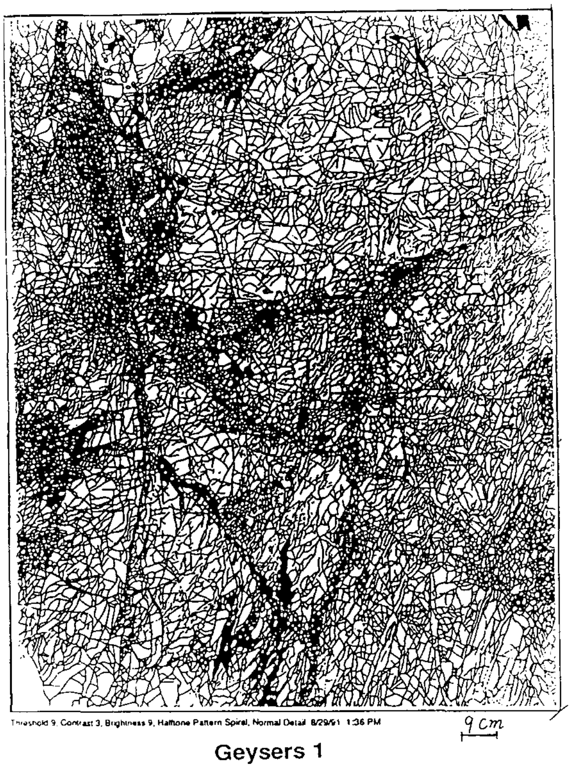

Figure 1: Fracture patterns of the Graywacke outcrop.

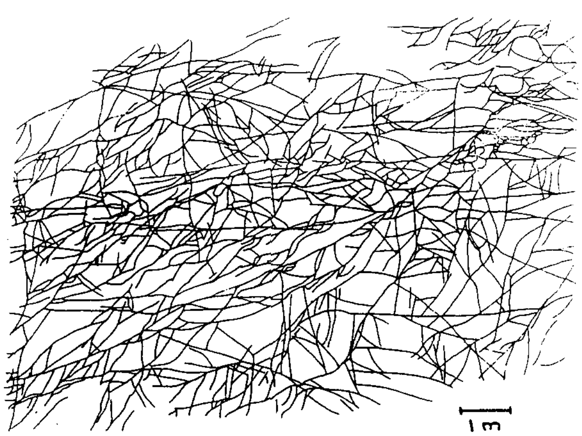

Figure 2: Fracture pattern from the road cut outcrop.

ond outcrop occurs in a road cut. The graywacke at this site is also highly fractured but more uniform in texture so that one continuous fracture pattern covers the entire roadcut. A map was prepared from a photo mosaic and is shown in Fig 2. The fractures at this outcrop were also mineralized. Finally, a fault map for the entire field was prepared using fault maps in the literature. Hebein (1986) mapped the regional fracture pattern under the assumption that local drainage patterns are fault controlled. He showed that the drainage pattern is consistent with the hierarchical pattern of conjugate shears expected in the regional stress field. In Fig. 3 we show the fault map plus the regional drainage pattern.

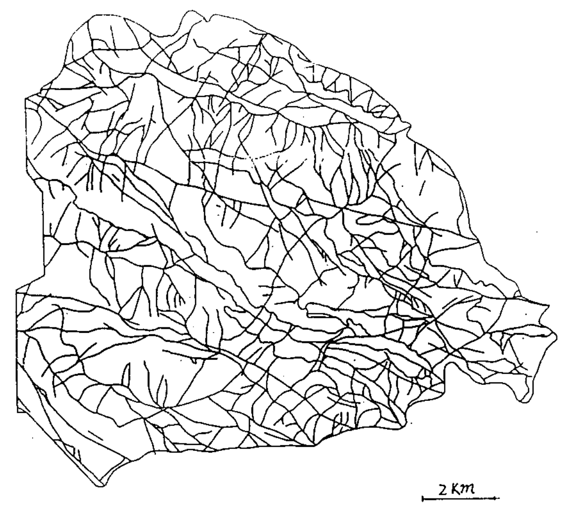

Figure 3: Fault and drainage pattern in The Geysers geothermal area.

Testing the fracture patterns for self similarity and measuring the fractal dimension

The fracture patterns in Figures 1, 2 and 3 were tested for self-similarity using the box counting method used by Barton and co-workers to characterize fracture patterns at a site under consideration for nuclear waste disposal at Yucca Mountain, Nevada (Barton and Hsieh, 1989; Barton, 1992). In this method the minimum number of square tiles which are required to completely cover the fracture pattern, N_r, is determined as a function of the edge length, r, of a tile. If the pattern is self-similar, then $N_r \propto r^{-D_f}$ where D_f is the fractal capacity dimension of the pattern. In essence, one is measuring how the open area between fractures changes with scale. Hence this may also be viewed as a measure of the clustering of the fractures. If the fracture pattern is very homogeneous with little clustering, then D_f approaches 2. Such a pattern, if it extended over all scale lengths, would fill the plane with fractures. At the other extreme, as the fractures become increasingly clustered, D_f approaches 1. In this limit, all fractures lie on a line (and hence have dimension one). A schematic illustration of the box counting method is given in Fig. 4.

For any physical system, the self-similarity can only extend over a limited range of scale-lengths. The largest scale length to which self-similarity extends we call the upper fractal limit, while the shortest we call the lower fractal limit. These limits may be set by the physical limits of the system or, possibly, by the degree of evolution of the physical process

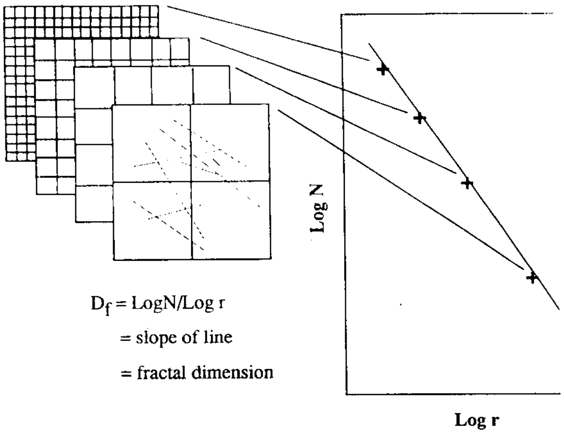

Figure 4: Schematic representation of box counting method for measuring fractal dimension.

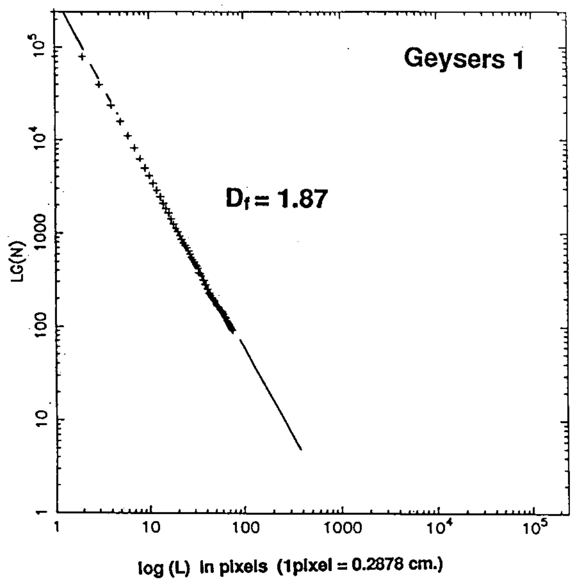

Figure 5: Fractal analysis of the fracture pattern in the Graywacke outcrop.

which is producing the self-similarity. The fractal limits are determined by the box counting algorithm as the limits between which the log(Nr) vs. log r plot is linear. A computer program has been developed which covers the digital image of a fracture pattern with a square grid and finds the minimum number of occupied squares with respect to rotation and translation of the grid. The procedure begins with a fine grid at the smallest resolved scale of the data. The grid size is then systematically increased until all the squares are occupied. The program was tested by measuring geometrical fractal gaskets and random fractals of known dimension. When applied to the outcrop scale fracture pattern in Fig. 1 it yielded Fig. 5. The other two small-scale outcrop patterns were similar. All were self-similar over a range of scales from about 0.5 to 20 centimeters and had fractal dimensions between 1.8 and 1.9. The road cut pattern in Fig. 2 is analyzed in Fig. 6 where it has a fractal dimension of 1.9 between scale lengths of about 0.3 and 4 meters. The regional fault

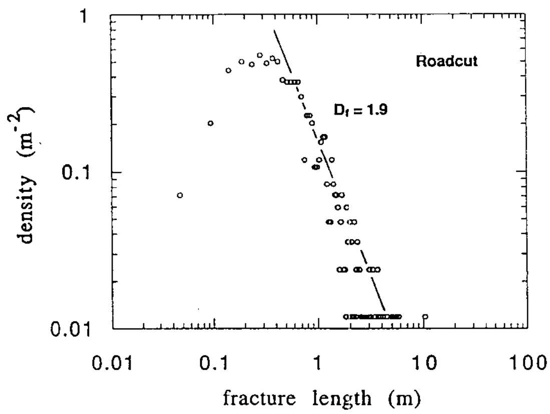

Figure 6: Fractal analysis of road cut fracture pattern in the Graywacke.

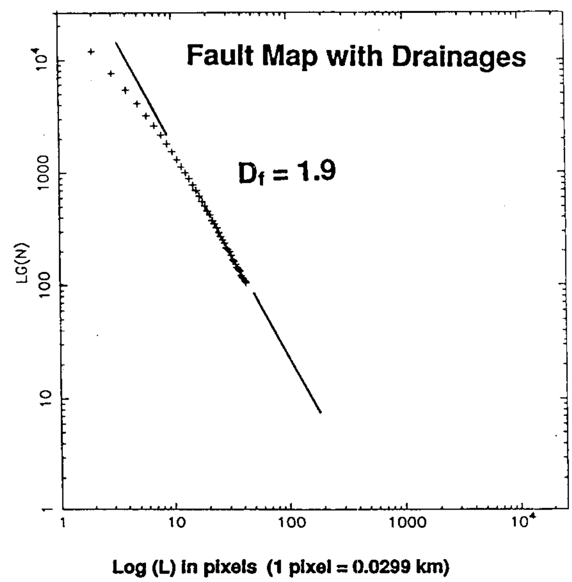

Figure 7: Fractal analysis of the pattern of faults and drainages.

pattern including the drainage pattern in Fig. 3 is analyzed in Fig. 7. It has a fractal dimension of about 1.9.

Each pattern is thus self-similar with a fractal dimensions between 1.8 and 2.0. This implies only moderate clustering. It is, in fact, possible to show that all three fracture patterns are mutually self-similar across the entire range from outcrop to regional scale. To demonstrate this global self-similarity, the number of fractures per unit area was determined as a function of fracture length for each pattern. When the log of the area density is plotted as a function of the log of the fracture length in Fig. 8, all three distributions lie on a line with slope 2. This is precisely the requirement for self-similarity. Because the number of fractures per unit area scales as their length squared, then the number of fractures in an area scaled to the fracture length will be a constant. Stated another way, it is impossible to tell at what scale a given fracture diagram was mapped.

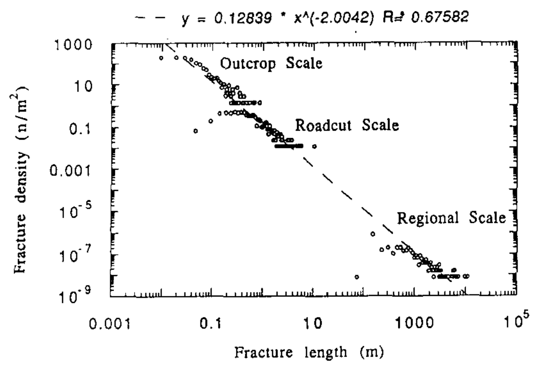

Figure 8: Self similarity of fracture density over a wide range of scales.

Examination of cores from the reservoir

Examination of cores from the graywacke reservoir rock led to two significant observations. First, many cores contained numerous fractures at the same scale as those observed in outcrop. Like the outcrop fractures, the core fractures were sealed by mineralization. Other sections of the recovered core were completely granulated. The surfaces of the rock fragments showed mineral deposition and alteration suggesting that the rock had been fragmented in the reservoir and not as a result of drilling induced fractures. Our tentative conclusion from these core observations is that many of the smaller fractures in the reservoir are sealed and that most of the storage and transport may occur through larger shear fractures which are multiply fractured cataclastic zones of finite width. It should be emphasized that this is only a tentative conclusion. Thin open fractures which cut the borehole are difficult to distinguish from breaks in the core caused by drilling stresses. Even if the distinction could be made, the core recovery is rarely complete enough to allow a meaningful analysis of the intervals between such breaks. Having said this, the presence of sealed fractures throughout the reservoir, and the common occurrence of cataclastic zones several feet in width are unambiguous.

Analysis of steam entries

Borehole deviation and steam entry data for about 200 wells were analyzed. We observed that wells which deviate in the NE and SW directions tend to intersect more steam entries. This is consistent with the hypothesis that steam entries correspond to near vertical NW striking fractures which are parallel to the regional shear fabric. However, the weakness of the anisotropy suggests that the pattern is more complex - a conclusion which is supported by the complexity of the regional faulting pattern in Fig. 3. If the pattern of fractures in the Geysers reservoir is self-similar and isotropic, then this geometry should be reflected in the spatial pattern of steam entries. For example, the intervals between steam entries should follow a power law distribution. Also, if the pressure jump associated with a fracture is proportional to its size, then number of steam entries should also vary as a power of their size. To test the intervals between steam entries for a power law distribution, the log of the number of intervals is plotted as a function of the log of the interval length in Fig. 9. If the fracture distribution in the reservoir were self-similar and isotropic with dimension comparable to that observed in outcrop (D_f = 1.8 - 1.9), then the intervals should be distributed according to a power law with slope 1-D_f = 0.8 - 0.9. The line in Fig. 9 has slope 0.9. Note that it only fits the data for intervals between about 300 and 900 meters. One possible interpretation is that many of the smaller fractures spaced more closely that 300 meters are either sealed by mineralization or yield too small a steam entry pressure jump to be reliably recorded. The observation that too few larger intervals are recorded may be a sampling error because few of the wells intersect more than 1000 meters of reservoir rock. In Fig. 10 the log of the number of steam entries is plotted as a function of the log of the pressure jump. The distribution is not power law over any range. This may be due in part to

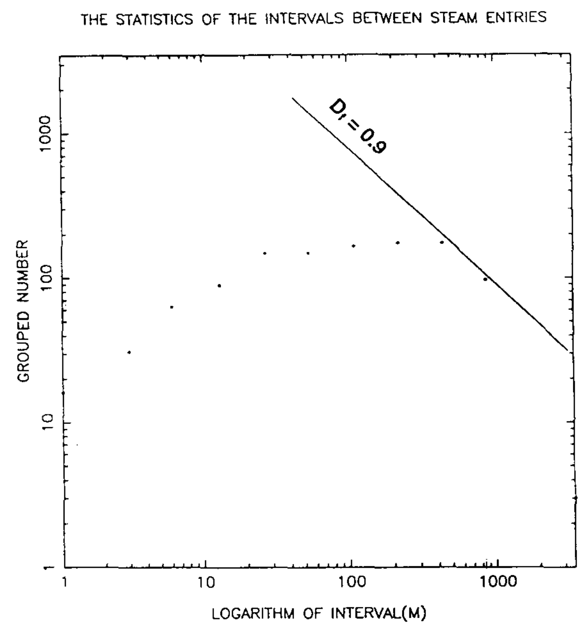

Figure 9: Statistical distribution of spacing between steam entries as sampled by boreholes.

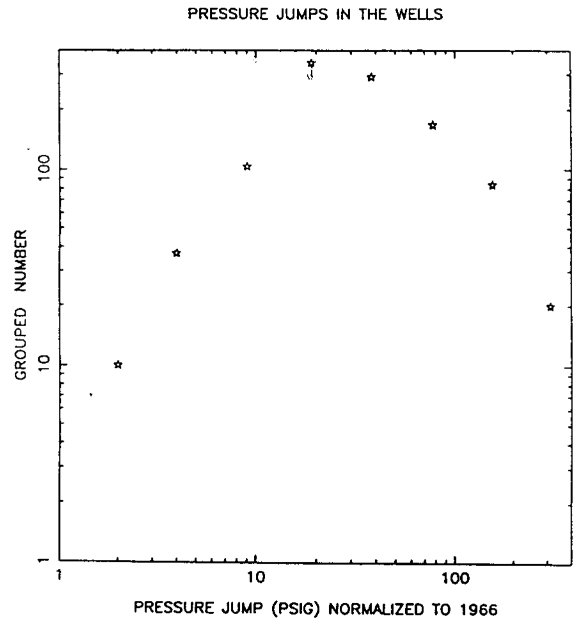

Figure 10: Statistical distribution of pressure jumps from steam entries.

the mineralization and sampling problems discussed above, but may also imply that the pressure jump does not scale with the fracture size. As a final analysis of the steam entries, the well head locations and deviation data were used to find the latitude, longitude and true depth (with respect to sea level) of all the steam entries. A 3-D box counting algorithm was used to test the pattern for self-similarity. The 3-D box counting is directly analogous to the 2-D technique discussed above except that the minimum number of cubes required to contain all the points is determined as a function of the length of the cube edge. The resultant log-log plot is shown in Fig. 11 where the pattern is seen to be self-similar for length scales between 1,000 and 10,000 feet with a fractal dimension of $D_f = 2.1$. This dimension is significantly lower than $D_f = 2.8$ which would be expected if the patterns observed in outcrop were typical of the 3-D patterns in the reservoir. However, Sahimi (1992) predicts that the fractal dimension of fracture networks which develop in 3-D can not simply be found by adding one to the dimension measured in 2-D section. Numerical simulations of the nucleation and growth of fractures in random media predict $D_f = 2.5$. The slightly lower observation of $D_f = 2.1$ is consistent with the hypothesis that the wells under sample the fracture network which produces the steam entries (Robertson et al., 1991).

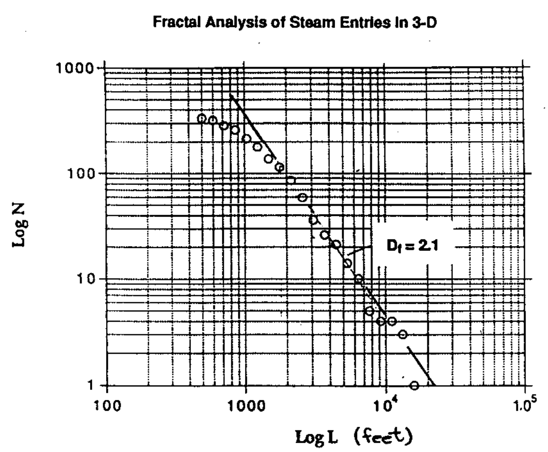

Figure 11: Three-dimensional fractal analysis of steam entries.

Analysis of drilling records

The drilling records or "mud logs" contain more information than simply the location and size of steam entries. They also contain a continuous record of the drilling rate of penetration, as well as a record of the rotation rate and weight on the bit. The lithology is also recorded. Because the lithology does not change significantly for large distances within the reservoir, it is reasonable to associate changes in the penetration rate with changes in the fracture density in the graywacke. The basic assumption is that penetration is more rapid in highly sheared rock than it is in unfractured rock. The raw penetration rates were corrected for changes in rotation rate and weight on bit by calculating a drilling factor dexp defined by Jorden and Shirley (1966). The drilling exponent is plotted as a function of depth in Fig. 12.

Fluctuations in the drilling factor as a function of depth were analyzed using the fractal analysis technique discussed by Hewett (1986) and used by Leary (1992) to characterize sonic and electrical resistivity logs from the 3.5 km deep well near the San Andreas fault at Cajon Pass, southern California. In this method, the drilling parameter data are rescaled to have a zero mean and a unit variance and a cumulative sum is computed as a function of depth. This cumulative sum is then partitioned into segments of length L, and for each segment the range of variation R and the standard deviation S of the data

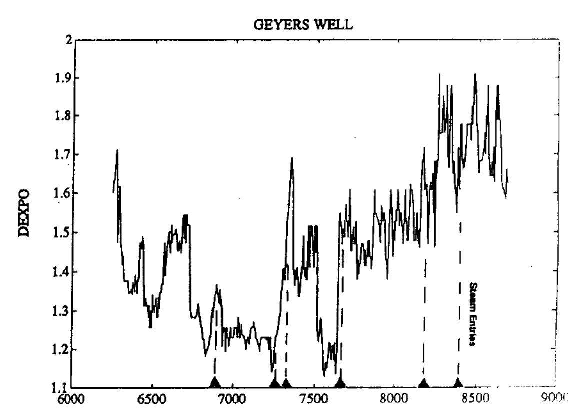

Figure 12: D-exponent representation of drilling rate.

within that segment are computed. This procedure is repeated for a number of different values of L ranging from the shortest resolved length of the data to the entire length of the mud log. For scale invariant fluctuations, the ratio R/S scales with the interval length L as L^H where H is called the Hurst exponent. If the observed Hurst exponent is $H = 0.5$, then the data fluctuations are uncorrelated. This is the case for Brownian motion. If $H > 0.5$ then the fluctuations are positively correlated (i.e. they have persistence). In our case this would imply that zones of fractured rock are spatially clustered. If $H < 0.5$ then the data fluctuations are negatively correlated (they have anti persistence). Note that many values of R/S are obtained for each value of L - more for short values of L, less for long values, decreasing to one value when L equals the length of the data set. In Fig. 13 the average value of log (R/S) is plotted as a function of $\log L$ for the drilling data in Fig. 12. The linear trend indicates scale independence over the entire range while the slope $H = 0.56$ indicates weak clustering. How do the drilling rate fluctuations correlate with the steam entries? Figure 12 shows that there is not a one-to-one correlation between increases in the drilling rate and the location of the steam entries. Rather, the steam entries tend to cluster in the broad bands of rapid drilling. The rough structure in Fig. 12 shows two fractured zones approximately 300 feet wide which have their centers separated by about 1000 feet. In analyzing

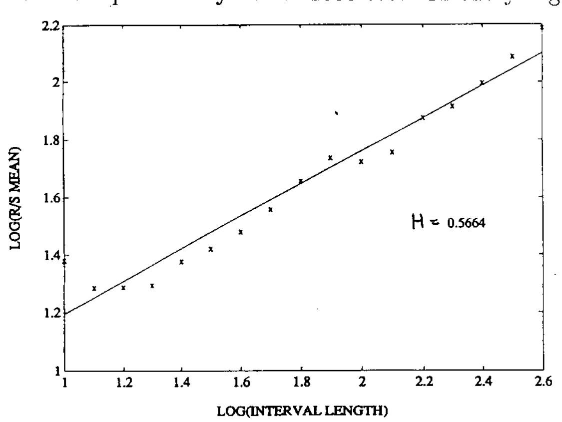

Figure 13: Estimation of H-exponent for R/S analysis of D-exponent data.

steam entries from six other wells, we find that they are also generally clustered in bands a few hundred feet thick with a spacing of about 1000 feet.

Summary and Discussion

The study of the fracture patterns at the Geysers geothermal field has led to the following general conclusions:

1. The fractures mapped in surface exposures of the Graywacke reservoir rock are fractal with dimension $D_f = 1.9$ in 2-D planar section. This is true at the outcrop, roadcut, and regional scales.
2. When the logarithm of the fracture densities measured at the three scales above are plotted as a function of the logarithm of the fracture length, all three measurements lie on the same line with slope 2. This implies that the fracture distribution is scale independent over a range of scales from centimeters to kilometers.
3. Most fractures mapped at the outcrop and roadcut scale are sealed by mineralization.
4. Cores recovered from the reservoir also show that many of the smaller fractures are filled by mineralization. However, many sections of the core are totally fragmented. Mineral deposits on the fragments imply that the break up was not due to drilling damage, but that such cores probably represent cataclastic zones associated with larger shear fractures (faults).
5. Steam entries are highly clustered in the reservoir. They appear to be fractal with a capacity dimension of $D_f = 2.1$.
6. Drilling records show that the steam entries in each well are clustered in bands a few hundred feet wide spaced at about 1000 foot intervals.
7. Drilling rate records also show a fractal clustered structure having a Hurst exponent of 0.56. We make the assumption that drilling rate is correlated with fracture density since it does not appear to be sensitive to variations in graywacke lithology. However no direct correlation was observed between increases in drilling rate and steam entries. Rather, steam entries tend to cluster in broad zones of rapid drilling which are several hundred feet wide.

The picture of the reservoir which emerges is one in which the steam is stored and transported the multiply fractured conduits several hundred feet wide and spaced roughly one thousand feet apart. This scale is on the order of the regional faulting pattern in Fig. 3 which suggests that the steam conduits are the major shear fractures in the reservoir. Smaller fractures (many of which are tensile) appear to be sealed both in surface exposures of the reservoir rock and in cores take directly from the reservoir.

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