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Fracture Patterns in Graywacke Outcrops at The Geysers Geothermal Field

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Introduction

The Geysers geothermal field covers an area of more than 35,000 acres and represents one of the most significant steam fields in the world. The heterogeneous nature of the reservoir, its fracture network and non-sedimentary rock distinguish it from ordinary sandstone reservoirs in terms of reservoir definition and evaluation (Stockton et al. 1984).

Analysis of cuttings, record of steam entries, temperature and pressure surveys and spinner logs have contributed to an understanding of the subsurface geology and rock characteristics of the Geysers. Few conventional electrical log data are available for the main body of the reservoir. It is generally believed that while the fractures are the main conducts for fluid transport through the reservoirs, tight rocks between the major fractures contain the bulk of the fluid reserves. No independent measurement of liquid and vapor saturation can be made from the existing downhole tools.

Pressure depletion in The Geysers geothermal field has become a major concern to the operators and utility companies in recent years. Plans for further development activities and future field management are contingent upon accurate computer modeling and definition of the field. The primary issues in reliable characterization of The Geysers field are the role of the rock matrix in holding liquid reserves and providing pressure support, the nature of fracture network, extent of liquid saturation in the reservoirs and injection pattern strategies to maximize heat recovery.

Current modeling of The Geysers field is done through the use of general purpose geothermal reservoir simulators. Approaches employed include treating the reservoir as a single porosity equivalent or a dual porosity system. These simulators include formulation to represent transport of heat, steam and water. Heterogeneities are represented by spatial variations in formation or fracture permeability-thickness product, porosity or fluid saturations. Conceptual models based on dual porosity representations have been shown to duplicate the history. Prediction of future performance is, however, not reliable because of uncertainties in assumptions of the initial state of the reservoir. Specifically, several different initial state conditions have led to a fairly good match of the historical data. Selection of the exact initial conditions is a major dilemma. In dual porosity models, the complex nature of fracture network is formulated by a systematic, well-organized set of orthogonal fractures. Also, the exact nature of matrix-fracture interaction, and the role of adsorption and capillarity in pressure support are not well-defined.

In The Geysers geothermal field, steam production is mainly from a system of fractures in the otherwise tight graywacke reservoir rock. Structure of other rocks such as felsite making limited steam flow contribution to the production will not be included in the study. These highly fractured reservoir rocks are sealed by cap rocks consisting primarily of serpentinite, greenstone, and melange (McLaughlin 1977). The producing steam field lies within a wide shear zone bounded by the right lateral Maacama and Collayomi Fault zones (Fig. 1).

The accommodation of simple shear by brittle fracture has produced the network of cracks from which steam is currently produced; older Franciscan imbricate thrust faults are assumed to be inactive and hydrothermally sealed (Hebein, 1985, 1986). The largest fractures in the reservoir can be detected during drilling as they produce a sudden and measurable increase in steam pressure. The average spacing between these major steam producing fractures is on the order of 100-500 feet.

The complexity of multiphase flow in fractured systems requires careful measurements to obtain representative fracture models that can be used for local as well as regional studies. One approach is based on the equivalent porous medium concept, where the fractured medium is treated as a heterogeneous, anisotropic continuum with no distinction between fractures and the rock matrix. Next is the approach based on discretization where each fracture is explicitly defined. Under this procedure, a numerical code is used with individual elements defining the matrix and fractures of the network model (Shapiro and Anderson 1985). Other approaches include statistical methods (Long et al. 1987) and multiporosity models (Barenblatt et al. 1960, Warren and Root 1963, Huyakorn et al. 1983, Abdassah and Ershaghi 1986 and Arbogast 1986). However, as far as modeling of the simultaneous flow of steam and water is concerned, no rigorous attempt has been made to use modern ideas involving fractal statistical models.

Conventional reservoir simulations of the Geysers field (Pruess and Narasimhan 1985) typically use a double porosity model (Warren and Root 1963). This model considers production from a regular network of fractures (in this case the largest fractures) which are embedded in a porous matrix (assumed here to represent the porosity and permeability of all the smaller fractures in the networks. The matrix is usually assumed not to be interconnected so that flow to and from wells occurs only through the fracture network which is assumed to be perfectly connected. Although various improvements and modifications of the original model have been proposed, they all pertain to the well-ordered but rather restricted structure described above.

Although such a model may be appropriate for production from a uniform set of fractures which drain porous reservoir rock, the fracture network produced by shear in the otherwise impermeable Geysers reservoir rock differs from these idealized models in one very important way. Beal and Box (1989) from the steam entry data observed that there are variations in geometry, density and permeability of the fractures in The Geysers.

It has been widely observed that the fracture pattern in crustal shear zones is developed over a wide range of scales (Tchalenko 1970). Thus, a single matrix block size may not be adequate. It has also been observed that fracture patterns in shear zones are "self-similar" in the sense that the fracture pattern observed at the largest scales is reproduced over and over again at ever decreasing scales (Sammis et al. 1987, Barton and Hsieh 1989). Such hierarchical systems are best described using the language of fractal geometry. Transport processes in fractal systems are totally different from those in non-fractal media and cannot be adequately described by the classical differential equations of transport. Lumping the transport properties of all but the largest fractures of a fractal network into a "matrix porosity and permeability" is a gross and unphysical approximation. Recent success in simulating fractured petroleum reservoirs using a fractal network of fractures (Matthews et al. 1989) suggests that the same approach may be useful in simulating and predicting the production of The Geysers reservoir.

Reservoir Fracture Characterization at The Geysers

The ultimate value of a numerical simulator for The Geysers depends on an accurate characterization of the fracture pattern. Hebein (1986) has mapped the fracture pattern at the Geysers at scales on the order of 10-100 meters under the assumption that local drainage patterns are fault controlled. The drainage patterns are consistent with the hierarchical pattern of shears expected in such a shear zone. He concludes: "Considerably more work is required to adequately map fracture trends and enhancements in the Geysers steam field." We propose to extend Hebein's work to smaller scales by accurately mapping fracture patterns at the outcrop scale from centimeters to tens of meters.

A similar analysis has been carried out by the U.S. Geological Survey as part of the effort to characterize the geologic and hydrologic framework at Yucca Mountain, Nevada (Barton and Larsen 1985; Barton et al. 1986; summarized in Barton and Hsieh 1989). The site is currently being evaluated by the U.S. Department of Energy as a potential underground repository for high-level radioactive waste. The primary objective of the mapping studies is to use the methods developed by Barton and co-workers to characterize the fracture patterns observed in the outcrops and cores from The Geysers and, thereby, to place realistic constraints on the proposed numerical reservoir simulations.

For our two-dimensional study at The Geysers, we chose a graywacke outcrop in which a fresh vertical wall (about 30 m high by 100 m wide) had been cut to form a pad for one of the steam wells. Fracture traces were highly visible on the face of the wall because most had been filled with hydrothermal mineral deposits of contrasting color to the graywacke. Fracture maps were prepared from photomosaic images; three examples are shown in Figures 2,3, and 4.

These patterns were tested for self-similarity using a box counting algorithm illustrated schematically in Figure 5. In this method, the minimum number of boxes, N, required to cover all the fractures, is determined as a function of the size of the box $r(r =$ the length of one edge). Self-similar distributions are characterized by a power-law relation between N and r

$$N \; \alpha \; r^{D_f}$$

where D_f is the fractal dimension.

As an example of how this method works; consider first a line. The number of boxes required to cover a line is directly proportional to their dimension r. Hence the dimension of a line is 1. Now consider a regular homogeneous pattern of lines. The number of boxes required to cover such a pattern increases as r^2, and the fractal dimension is 2 - such patterns uniformly fill a plane. Finally, consider the fractal pattern shown in Figure 6. Because of the spatial clustering in this pattern, the number of boxes required to cover only increases by a factor of 3 each time the box size is reduced by a factor of 1/2. The fractal dimension in this case is $D_f = 1.58$.

Application of the box counting algorithm to the fracture patterns at the Geysers gives the log N vs log r plots shown in Figures 7, 8 and 9. These patterns are seen to be self-similar over a range of scales which vary by about a factor of ten. The dimensions are in the range $1.7 < D_f < 1.9$, similar to the results obtained by Barton and Hsieh (1989) for fracture patterns at Yucca Mountain.

The known steam entry depths in many wells of the field can be used to help characterize the geometry of the fracture depth pattern and test for fractal structure. Assuming that steam depths represent locations where the borehole intersects the fractures, the distribution intervals between such fractures gives a measure of the self-similarity of the network. If the pattern is fractal, then the intervals between fractures should follow a power law distribution where the power is a measure of the fractal dimension of the reservoir (it should be 1 less than the fractal dimension of a 2-D planar section mapped at the surface).

Discussion

Having established the self-similarity of fracture patterns at the outcrop scale, we now wish to see if this self-similarity extends to the regional scale. That is, we wish to see if the larger steam-producing fractures are part of this same hierarchal pattern which may then be exploited to model the heat extraction process. This will be accomplished by extending the fracture mapping to a more regional scale, by examing the core from the reservoir and by analyzing the pattern of steam entries in the large number of wells where they have been recorded.

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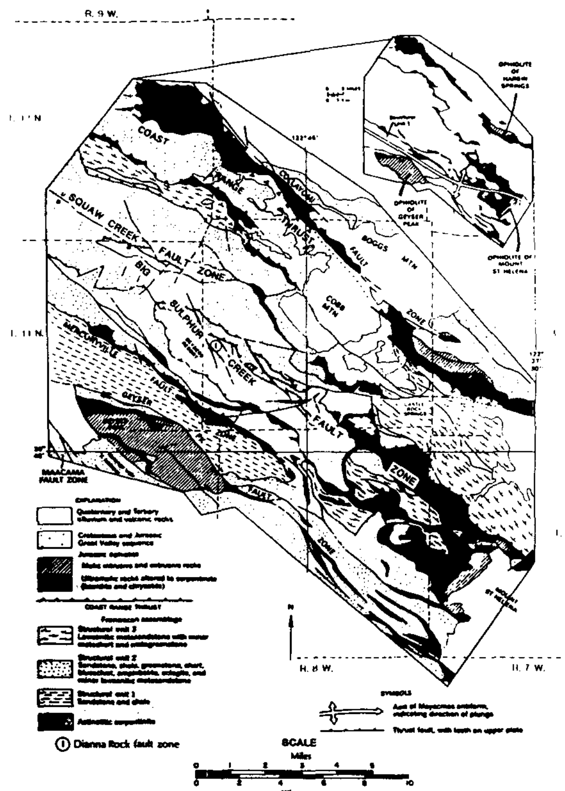

Fig. 1. Geologic map of The Geysers Geothermal Field. (After McLoughfin 1977)

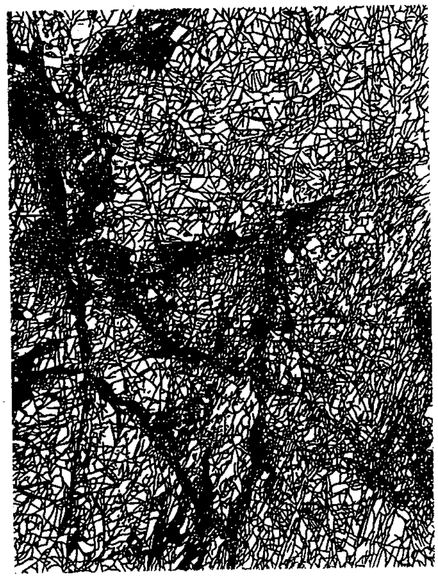

Fig. 2. Fracture map for a graywacke outcrops at The Geysers geothermal field. The area shown is about 2 meters by 1 meter.

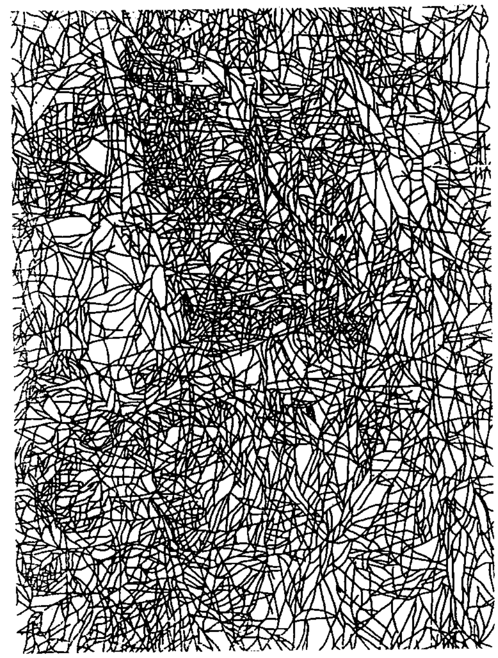

Fig. 4. A fracture map from a graywacke outcrop at The Geysers geothermal field. The area shown is about 0.5 meters by 1 meter.

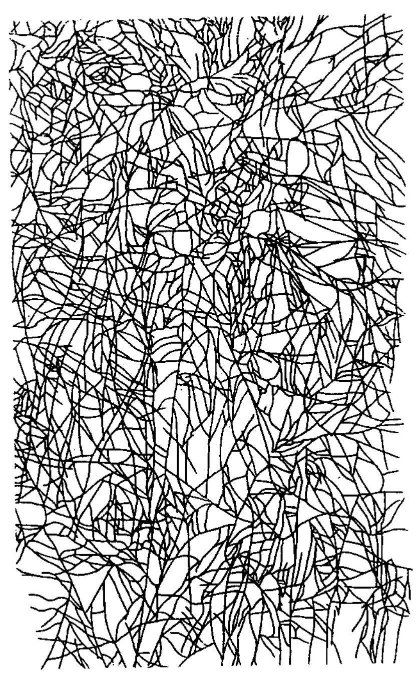

Fig. 3. A fracture map from a graywacke outcrop at The Geysers geothermal field. The area shown is about 0.5 meters by 1 meter.

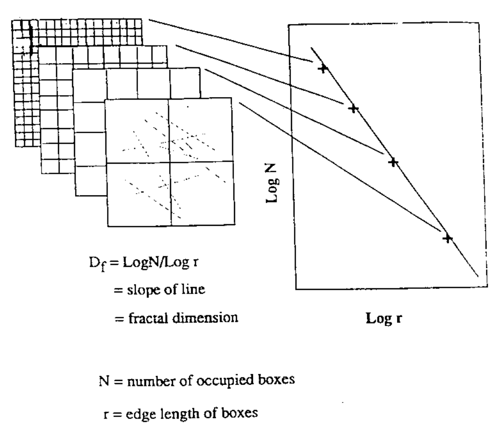

Fig. 5. A schematic diagram showing how the box counting algorithm is used to measure the fractal dimension of a fracture pattern. The grid is moved until the number of occupied boxes is a minimum.

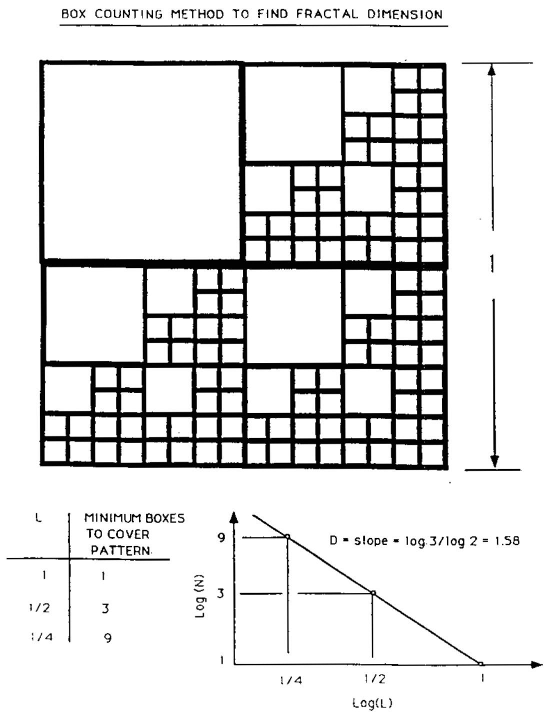

Fig. 6. An example of how the box counting algorithm is used to measure the fractal dimension of a specific fractal pattern. Note that the clustering at all scales produces a fractal dimension between a line (1) and a plane (2). The dimension of this pattern is D_f= 1.58.

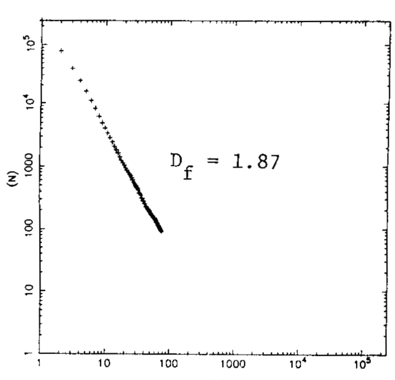

Fig. 7. Results of the box counting fractal analysis of the pattern in Fig. 2.

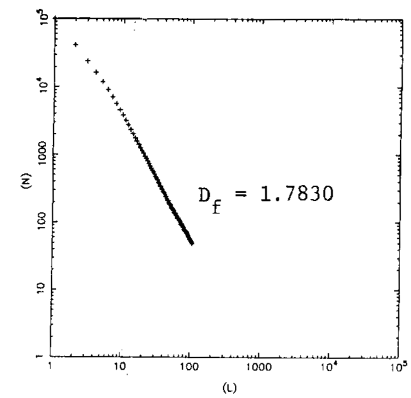

Fig. 8. Results of the box counting fractal analysis of the pattern in Fig. 3.

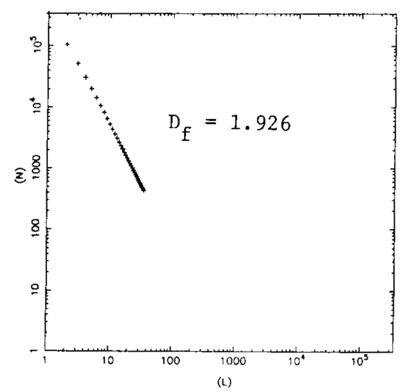

Fig. 9. Results of the box counting fractal analysis of the pattern in Fig. 4.