Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

EVALUATION OF OUTCROP FRACTURE PATTERNS OF GEOTHERMAL RESERVOIRS IN SOUTHWESTERN TURKEY

Tayfun Babadagli
Sultan Qaboos University, Dept. of Petroleum and Min. Res. Eng., PO BOX 33, Al-Khod, Muscat 123 OMAN

Key words: Geothermal fields, southwestern Turkey, fracture patterns, fractal, conductivity.

ABSTRACT

In modeling studies of geothermal reservoirs, quantitative characterization of fracture network systems is essential and fractal geometry has been recently shown to be useful for quantification. Fractal geometry not only provides a characterization and a quantification of fracture systems but it can be used to generate representative patterns synthetically. For this generation process, however, reliable estimates of fractal properties of the fracture network are required.

In this study, an extensive fractal analysis of fracture patterns collected from the outcrop of producing geothermal reservoirs in southwestern Turkey was performed and the preliminary results are presented. Data used throughout the study were collected at different scales, i.e., aerial (order of kilometers), outcrop (order of meters), rock (order of centimeters), and thin section (order of microns) photos. Outcrop photos were obtained on a field trip to outcrop locations of the production formations of different geothermal fields including the major ones, Kizildere and Germencik Fields. These patterns are generated from the photographic images through an image processing application.

First, the box counting technique is applied to fracture patterns at four different scales. It is observed that the box counting dimensions change with the scale of the fracture traces and, as the scale increases, more complex networks are obtained resulting in an increase in fractal dimension. This is an important issue because knowing the scale limits and selection of scale, at which the maps are prepared, are critical points in data preparation (e.g., conductivity data) for simulation studies.

Fracture properties that might be related to the conductivity of the fracture networks such as density, connectedness and length are also considered and the fractal dimensions of their distributions are measured by different methods. Box counting (to measure the "box dimension") and sand box techniques (to measure the "mass dimension") are applied for these measurements on natural fracture patterns at mega scale (order of meters). It is observed that the distribution of all these properties mostly represents fractal characteristics but different methods may yield notably different fractal dimensions for the same fracture property.

1. INTRODUCTION

In the quantification of the complex structure of fracture networks, fractal geometry has been in use since the first study was reported (Barton and Larsen, 1985). Fractal geometry is useful to quantify the size scaling or scale dependency of fracture systems. It also enables us to generate representative patterns synthetically (Barnsley, 1988).

The quantification of natural fracture patterns through fractal geometry is based upon the estimation of a non-integer number called a fractal dimension, *D*. The most common method applied for this purpose is the box counting technique (Barton and Larsen, 1985; Barton, 1995). La Pointe (1988) introduced another methodology to measure the fractal dimension of the matrix block distribution instead of the box counting method. Yamamato *et al.* (1993) measured the mass fractal dimension by investigating the number-radius relationship and obtained the fractal dimension of the distribution of fracture midpoints that represents fracture density.

The hydraulic conductivity of a fractured network is the property that represents scale-dependent behavior (Chang and Yortsos, 1990; Acuna and Yortsos, 1995). In the quantification of this scale dependency, a reliable estimate of fractal fracture properties is required. Several properties of a fracture network affect its hydraulic behavior. These are typically fracture density, length, orientation, connectedness and aperture. In a fractal description of fracture networks, the box counting technique is commonly applied to obtain the box dimension of the network. This technique provides a quantification of how space filling the fracture pattern is. In a sense, the box dimension implies how intense the fracture network is. It was observed that increasing fracture density gives rise to an increase in the box counting dimension (Acuna and Yortsos, 1995). However, the density of the fracture network may not be enough to represent the hydraulic properties of the network completely. Therefore, measurement of other fractal properties should be implemented. This sometimes requires an application of different measurement techniques, other than box counting, that are more suitable to measure the fractal dimension of different fracture properties. This issue has been discussed by La Pointe (1988) who proposed a fractal measurement method that honors the connectedness of the fracture network.

The main emphasis in the present study is to evaluate the fractal properties of natural fracture patterns. Fracture properties such as density, connectedness and length are considered primarily and the fractal dimension of their distributions is measured by different methods. Natural outcrop fracture patterns from the geothermal fields in southwestern Turkey are used in this attempt. Particular attention is devoted to the fracture properties that might directly influence the hydraulic behavior of fracture networks. In fact the study is intended to be extended in that direction and the observations on fractal behavior will be used later to assess re-injection applications.

2. CHARACTERIZATION OF NATURAL FRACTURE PATTERNS THROUGH FRACTAL GEOMETRY AT DIFFERENT SCALES

The analysis of fracture patterns collected at different levels from giga to micro scales was performed. This provides quite a large interval to determine the scale invariance range of natural fracture structures. This is an important issue in modeling the hydraulic behavior of the network. Once the conductivity is determined for a scale then it is used to obtain the one at higher scales as long as the network represents scale invariance in this particular range (Chang and Yortsos, 1990). When limited data and size are available such as core or log records, one has to extend this information to a larger scale, which is the grid-size level of numerical models used for performance estimation studies. Hence, the fractal behavior of a fracture network needs to be defined for this type of application.

To identify the fractal relationship between scales, fracture network maps of very broad scale range were analyzed by box counting. These maps are of a region in southwestern Turkey where high enthalpy geothermal reservoirs are located.

2.1 Preparation of fracture trace maps

Data used throughout the study were collected at different scales. Aerial photographs of the region provided an extensive view of fracture patterns at giga scale. The fracture patterns shown in Fig. 1 were created using aerial photographs of Kizildere and Germencik geothermal fields, which have the highest capacity in the region. In the preparation of fracture maps all the fractures were included except the major faults. Data at a lower scale were collected in the field at different outcrops representing the production formations of different geothermal fields. The main rock in most of these reservoirs is marble.

Some of the fracture traces obtained at this scale and used throughout the fractal analysis are given in Fig. 2. These patterns were generated using an image processing application. In the mapping study, all the fractures were included regardless of their size and type. The aperture of the fractures was not taken into account. Fracture patterns were also obtained at lower scales. Rock samples collected during the field trip were photographed and fracture traces were generated from these photos. Fig. 3 illustrates one of the fracture patterns generated using rock photographs. Thin sections of these samples were used to analyze the fractal characteristic at micro scale. Fig. 4 shows a fracture map generated from the thin section of the rock sample shown in Fig. 3.

2.2 Fractal analysis

The box-counting technique was applied to fracture networks at four different scales to measure the fractal dimension. The number of the box size, *r*, was selected as higher than five to minimize the error due to straight line fitting to data. Then, the fractal dimension was calculated according to the following relationship:

$$N \propto r^{-D} \quad (1)$$

where *N* is the number of boxes filled with fractures, *r* is the size of the square box and *D* is the fractal dimension of the fracture network.

<u>Scale – I (km level – giga scale)</u>

The box-counting technique was applied to two images shown in Fig. 1. The fractal dimensions were obtained as 1.575 and 1.583 for the Germencik and Kizildere Fields, respectively. As seen, the values are very close to each other.

<u>Scale – II (m level – mega scale)</u>

Mega scale study was performed on the fracture traces obtained from fifteen outcrop photos of the producing formations. Some of the fracture traces are given in Fig. 2. The range of the values is provided in Table 1 (first row) for all samples. It was visually observed that the higher the box counting fractal dimension, the denser the fracture network.

<u>Scale – III (cm level – macro scale)</u>

Fractal dimensions of the fracture traces obtained from the rock samples (Fig. 3 shows one of them) were measured by the box counting technique. The range of the fractal dimensions for seven patterns is given in Table 2 (first column).

<u>Scale – IV (μm level - micro scale)</u>

The same procedure was applied to the micro scale fracture traces obtained from the thin section of the samples taken from the rock pieces. Fig. 4 illustrates one of the thin section fracture maps. The range of the fractal dimension values obtained are given in Table 2 (second column) for seven samples. The fractal dimension values are significantly lower than the values of higher scales and close to unity. This can be attributed to a much lower density and complexity of fracture network at the micro scale. Having a fractal dimension very close to unity implies that the network approaches an Euclidean character and at this scale level (thin section) the fracture network system loses its fractal feature.

The box counting dimension values at different scales are plotted in Fig. 5 for the Kizildere Field. As the scale increases, more complex networks were obtained, as can be observed through Figs. 1 to 4, resulting in an increase in fractal dimension. This is an important issue because knowledge of the scale limits in self-similarity is a critical point in data preparation for simulation studies. Note that during the application of the technique, the box counting measurements were performed for the different parts of the fracture pattern. It was observed that the values were in accordance with the fractal dimension of the whole image.

3. FRACTAL ANALYSIS OF DIFFERENT FRACTURE PROPERTIES AT MEGA SCALE

The fractal characteristics of different fracture network properties that can affect the conductivity of the networks have been examined by applying different methods. Fractal geometry provides a single number to characterize or identify the complex structure of network quantitatively. However, different methodologies may yield different dimension values for the same fracture property. Also, different fracture properties may reflect different fractal dimension even though the same methodology is applied.

Fractal geometry also provides the incorporation of the scale effect into the hydraulic behavior of fractured rocks. In this case, the reliable estimation of the fractal dimension is essential for accuracy. In this section, different fracture properties such as fracture density, length, and connectedness that affect the hydraulic behavior of the network will be considered.

3.1 Methods applied to measure the fractal dimension of different fracture properties

The first issue that will be considered in this analysis is the fracture network property that should be analyzed to assess the hydraulic behavior of a fracture network. The fracture density, for instance, is a strong function of conductivity. However, if a percolating network never exists, no matter how dense the fracture network is, the network will never conduct. Thus, the connectedness is another critical property of the network as related to the conductivity. The fractal dimensions of different network properties that are pertinent to the hydraulic behavior of network are measured and evaluated using different methods.

Box dimension

The box counting technique is commonly applied to measure the fractal dimension of a fracture network (Barton and Larsen, 1985; Sammis *et al.* 1991; Chiles and de Marsily, 1993). The procedure, explained before, was applied using the correlation given in Eq. 1 for the fracture patterns at mega scale. The range of the values is given in Table 1. All patterns represent fractal characteristics with a good correlation coefficient of straight-line fitting and the fractal dimensions obtained are between 1.14 and 1.52. During the measurements all fractures are included in counting whether they are a part of the percolating network or not.

Note that what is measured in this application is how space filling the fracture network is. As mentioned earlier, it was also observed that increasing fracture density causes an increase in the fractal dimension of the network (Acuna and Yortsos, 1995; Barton, 1995) and the fracture density has an influence on the fracture network conductivity. However, the fractal dimension obtained by the box counting method is limited in evaluating the network conductivity (La Pointe, 1988). Many other fracture network properties that may affect the network conductivity should be evaluated as well.

Another fractal evaluation method is to measure the mass dimension (Feder, 1988). The sandbox technique that is commonly used to measure the mass fractal dimension (Bunde and Havlin, 1995) has been applied for this purpose. The fractal dimension values corresponding to different fracture network properties are compared.

Mass dimension (distribution of fracture mid-points, intersection points and number of fractures)

In this methodology, different size circles or squares with the same origin are selected. Then the number of points, $N(r)$ is counted in the square or circle. If the system represents fractal characteristic, the plot of number of points, $N(r)$ vs. the size of the square, r on a log-log paper would yield a straight line and the slope will give the mass fractal dimension according to the following relationship:

$$N(r) \propto r^D \qquad (2)$$

Squares were used in this study and the number of points within each square was counted for seven different size squares. This method has been applied first for mid-point maps and then for the intersection point maps. As an example, mid-point and intersection point distributions of two samples are given in Fig. 6. Notice that we considered fractures intersecting at least one other fracture. This fracture may not be a part of percolating cluster. The range of the sand box dimensions is tabulated for both mid and intersection points of fractures in Table 1 (rows two and three).

Another property of fracture networks that represents scale invariance, i.e., fractal feature, is its density. The fracture density can be defined as total number of fractures per unit area. The scaling of this property was examined for the same fracture traces at mega scale. The total number of fractures per unit area was counted for different size squares. All the fractures were included in the counting procedure even if some of their parts are out of the square. It should also be mentioned that the fracture length has been defined throughout the analysis as a fracture whose ends are either open or intersected by another fracture. The range of the fractal dimensions is given in Table 1 (row 4). In all measurements, the same region of fracture networks has been selected as in the box counting method.

3.2 Comparison of the fractal dimensions of different properties

The distribution of mid points and number of fractures per unit area are a measure of the fracture intensity. Both mid point and number of fractures per unit area measure the fractal dimension of fracture density but the fractal dimension of mid point distribution yields notably higher values. This can be attributed to the fracture length. In fact, the fractal dimension of mid point distribution is independent of the fracture length as opposed to counting the number of fractures per unit area. For mid point and intersection point distributions, the fractal dimension values are consistent since most of the fractures intersect each other resulting in similar distribution maps of mid and intersection points.

Acuna and Yortsos (1995) observed that, for both self similar and self affine synthetic fracture networks, box counting and fracture length distribution dimensions are highly consistent. Kranz (1994) computed correlation and box counting dimensions of eight fracture mid point and end point maps of natural fracture patterns. His comparative study shows that the correlation and box counting dimensions differ significantly.

4. DISCUSSION

Inconsistencies between fractal dimensions of the same fracture properties obtained through different methods were observed. This can be attributed to different fracture characteristics such as fracture length and orientation. It is arguable to use the mass dimension of mid point distribution or intersection point distribution as an alternative to fractal dimension of the number of fractures per unit area.

For a fracture network to be conductive there should be a spanning cluster to percolate. In order to satisfy this condition Barton (1995) suggested that the box dimension should be over 1.35. Although it was observed in this study that the box counting fractal dimensions of the images at mega scale (the scale at which Barton generated the fracture maps) are mostly over 1.35 and a percolating cluster exists, more experimentation is needed to verify this number.

The major issue raised by these analyses is which methodology should be applied in determination of the fractal dimension and which fracture property should be measured with respect to the hydraulic behavior of a fracture network. The above comparative study emphasizes and shows the importance of this issue. But, it is obvious that more research is required to find a solid answer.

5. CONCLUSIONS

An extensive fractal analysis of natural fracture patterns collected from the outcrops of producing geothermal reservoirs in southwestern Turkey was performed. The descending behavior of fractal dimension with scale was identified for a very wide range of scale. Different properties of natural outcrop fracture patterns at mega scale, such as fracture density and connectedness, represented fractal behavior, but the comparative study revealed that the different measurement techniques might yield significantly different fractal dimensions. The alternative to mid point distribution is the fractal dimension of intersection point distribution, that considers the connectedness and the fractal dimension of the number of fractures per unit area. But, the fractal dimension of the number of fractures per unit area considerably differed from that of both mid and intersection point distribution. The values of mid and intersection point distributions were observed as consistent because most fractures intersected each other and part of the percolating network.

ACKNOWLEGDMENTS

The main portion of this study was conducted when the author was with Istanbul Technical University. The financial support was provided by the Scientific and Technical Research Council of Turkey (YDABCAG-285) and the Turkish Prime Ministry State Planning Department (DPT-87). The author thanks U. Serpen and Dr. I. H. Karamanderesi and A. Gulgor for the help in data collection and T. Coskun and A. Erdemir for the help during the fractal measurements.

REFERENCES

Acuna, J.A. and Yortsos, Y.C. (1995). Application of fractal geometry to the study of networks of fractures and their pressure transient. *Wat. Res. Res.*, Vol. 31(3), pp. 527-540.

Barnsley, M.F. (1988). *Fractals Everywhere,* Academic, San Diego, CA.

Barton, C.C. and Larsen, E. (1985). Fractal geometry of two-dimensional fracture networks at Yucca Mountain, southwestern Nevada. *Proc. of Int. Symp. on Fundamentals of Rock Joints*, Bjorkliden, Sweden, pp. 77-84.

Barton, C. C. (1995). Fractal analysis of scaling and spatial clustering of fractures In: *Fractals in the Earth Sciences*. C. C. Barton and P. R. La Pointe (Eds)., Plenum Press, New York, 168 pp.

Bunde, A. and Havlin, S. (1995) Brief introduction to fractal geometry. In: *Fractals in Science.* A. Bunde and S. Havlin (Eds)., Springer-Verlag, Berlin, 298 p.

Chang, J. and Yortsos, Y. C. (March 1990). Pressure transient analysis of fractal reservoirs. *Soc. of Pet. Eng. Form. Eval.* pp. 31-38.

Chiles, J.P and de Marsily, G. (1993). Stochastic models of fracture systems and their use in flow and transport modeling. In: *Flow and contaminant transport in fractured rock*. J. Bear, C. F. Tsang and G. Marsily (Eds)., Academic Press, Inc., San Diego, 210 pp.

Kranz, R.L. (1994). Fractal point patterns and fractal fracture traces. *Rock Mechanics*, (Nelson & Laubach, eds.), Balkema, Rotterdam, pp. 793-800.

La Pointe, P.R. (1988). A method to characterize fracture density and connectivity through fractal geometry. *Int. J. Rock. Mech. Min. Sci. & Geomech. Abs.* Vol. 25, pp. 421-429.

Sammis, C. G., An, L. J. and Ershaghi, I. (1991). Fractal patterns in graywacke outcrops at the Geysers geothermal Field. 16th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

Yamamato, H., Kojima, K. and Tosaka, H. (1993). Fractal clustering of rock fractures and its modeling using cascade process. In: *Scale Effects in Rock Masses 93,* Pinto da Cunha (Ed)., Balkema, Rotterdam, pp.81-86.

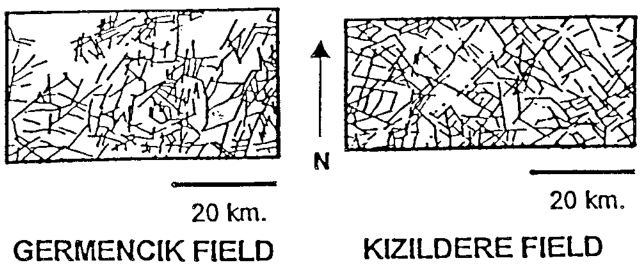

Fig. 1. Fracture pattern maps extracted from aerial photograph of the region for two fields.

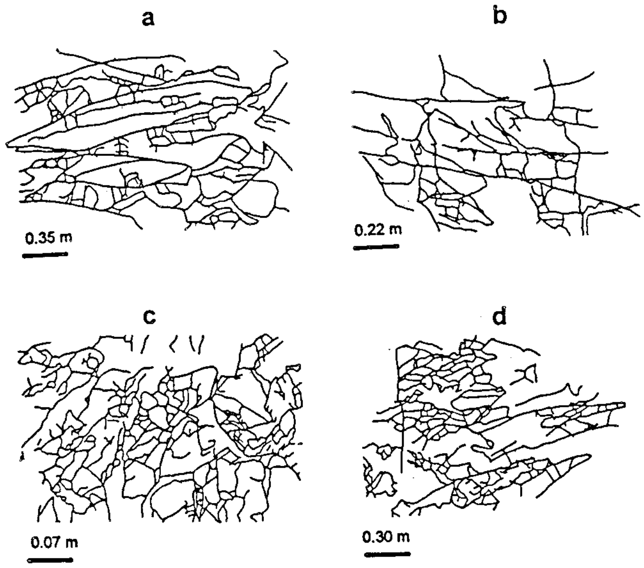

Fig. 2. Fracture pattern traces obtained from the outcrops of producing formations of three different fields in Southwestern Turkey.

(a) Germencik Field, marble.
(b) Kizildere Field, lower producing formation, metamorphized limestone.
(c) Kizildere Field, upper producing formation, limestone.
(d) Germencik Field, marble.

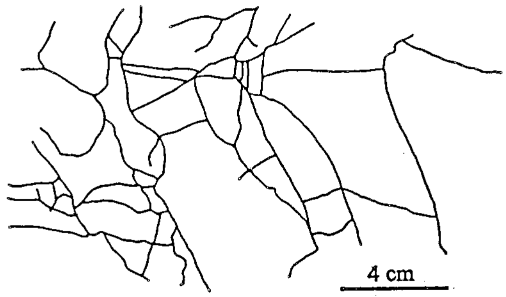

Fig. 3. An example of fracture pattern trace obtained from a rock sample (marble) collected during field trip.

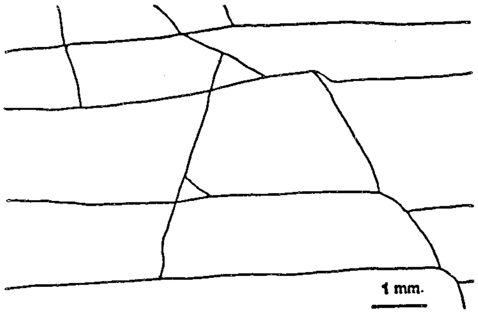

Fig. 4. An example of fracture pattern traces obtained from the thin section of sample shown in Fig. 3.

Table 1: Fractal dimension range of fractures traces in mega scale (meter level).

METHOD	FRACTAL DIMENSION
BC	1.14 – 1.52
MPD	1.71 – 2.00
IPD	1.10 – 1.81
NFA	1.07 – 1.89

BC: Box counting, MPD: Mid point distribution (by sand-box method), IPD: Intersection point distribution (by sand-box method), NFA: Number of fractures per unit area (by sand-box method).

Table 2: Fractal dimension range of fractures traces obtained from the outcrop rock pieces (cm, mega-scale) and thin sections (micron, micro-scale).

ROCK PIECES	THIN SECTIONS
1.161 – 1.257	1.011 – 1.039

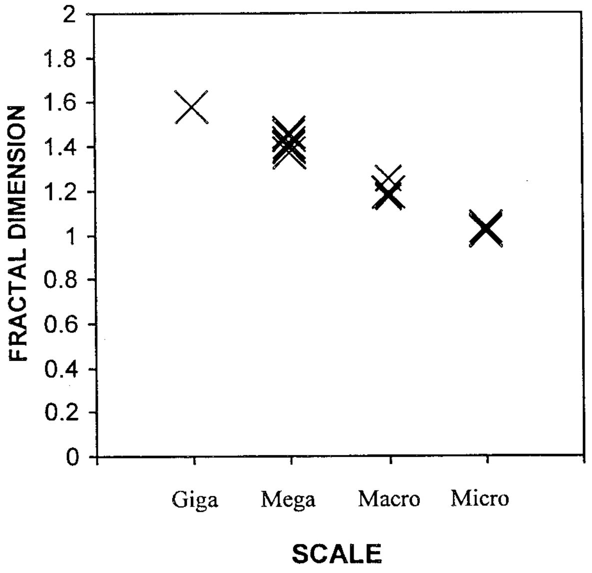

Fig. 5. The change of box counting dimension with scale for natural fracture patterns for Kizildere Field.

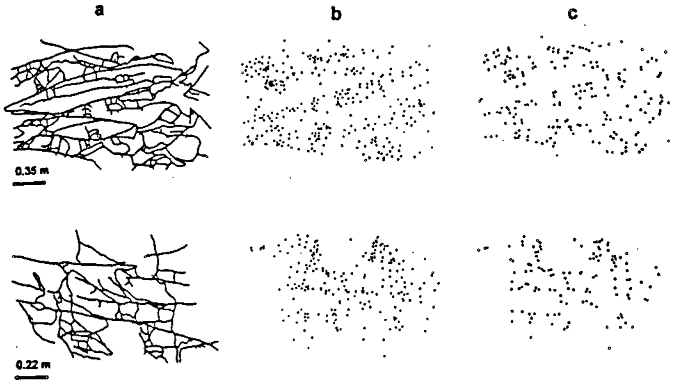

Fig. 6. (a) Fracture patterns at mega scale (Fig. 2-a and b), and their corresponding (b) fracture midpoint and (c) intersection point distributions.