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The implication of fractal dimension in hydrogeology and rock mechanics. Version 1.1

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THE IMPLICATION OF FRACTAL DIMENSION IN HYDROGEOLOGY AND ROCK MECHANICS. VERSION 1.1

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THE IMPLICATION OF FRACTAL DIMENSION IN HYDROGEOLOGY AND ROCK MECHANICS

Version 1.1

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ABSTRACT

Since much of geology and hydrogeology is controlled by the geometry of geologic features such as faults, fractures, and stratigraphy, many researchers have proposed the use of fractal dimension as an index for comparing hydrogeologic environments. This report describes an investigation carried out by Golder Associates Geosystem AB to evaluate the use of fractal measures within the SKB site selection, evaluation, and characterization process.

This report defines fractal dimension and the methods available for calculating fractal dimension. The report then summarizes a literature survey carried out to identify and evaluate applications of fractal methods in hydrogeology. Preliminary hydrogeological fractal numerical simulations carried out with the FracMan package (Dershowitz et al., 1991) are then presented and discussed. These numerical simulations evaluate the application of fractal methods within the context of other geometric measures such as connectivity measures, percolation probability, and block size measures.

Based upon the literature survey and numerical simulations, recommendations are presented regarding the potential usefulness of fractal approaches. Fractal dimension can be used to distinguish hydrogeologic environments, provided the limitations of the approach are explicitly recognized. Recommendations are made for fractal dimension calculation procedures, specification of fractal dimension, and the use of fractal dimension in conjunction with other measures of hydrogeologic structure and heterogeneity.

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1. INTRODUCTION

A fractal, or a fractal set, is "a shape made of parts similar to the whole in some way" (Feder, 1988). A fractal set may be described by its "dimension" (Mandelbrot, 1975), which is an indication of the degree of heterogeneity or roughness of the shape. Fractal systems have similar geometries at different scales, such that measurements made at one scale can be used to predict geometries at other scales.

Since much of geology and hydrogeology is controlled by the geometry of geologic features such as faults, fractures, and stratigraphy, many researchers have proposed the use of fractal dimension as an index for replicating geologically realistic fracture patterns.

Golder Associates has carried out a literature survey and preliminary numerical simulations to evaluate the usefulness of fractal dimension as an index for comparing geological environments for radioactive waste disposal. Numerical simulations were carried out with the **FracMan** package (Dershowitz et al., 1991c).

The use of fractal dimension for characterizing diverse physical phenomena has increased exponentially over the past ten years (Figure 1). This may indicate the usefulness of fractal dimension as an index, or the tendency to calculate fractal measures even when they have little practical significance.

1.1 Background

Fractal geometry is an extension of classical Cartesian or Euclidian[1] geometry. Fractal geometries are distinguished by three key characteristics: self-similarity, non-differentiability and partial filling of Euclidian space (Figure 2).

Fractal dimension is a way to describe the pattern, shape or spatial distribution of geometric features. Just as a line has a Euclidian dimension E of 1, and a plane has a Euclidian dimension E of 2, a cluster of lines in a plane can have a dimension between 1 and 2. The fractal description of shape or pattern has been applied to fracture and fault patterns, fracture roughness, rock block and crystal geometry, and topography.

More than 20 different approaches have been defined for estimating the fractal dimension. Each of these approaches describes a different aspect of the pattern. Fractal measures are generally based upon a log-log relationship between a size measure and a count measure, with the fractal dimension defined by the slope (Figure 3).

$$N(L) \propto L^{-D}$$

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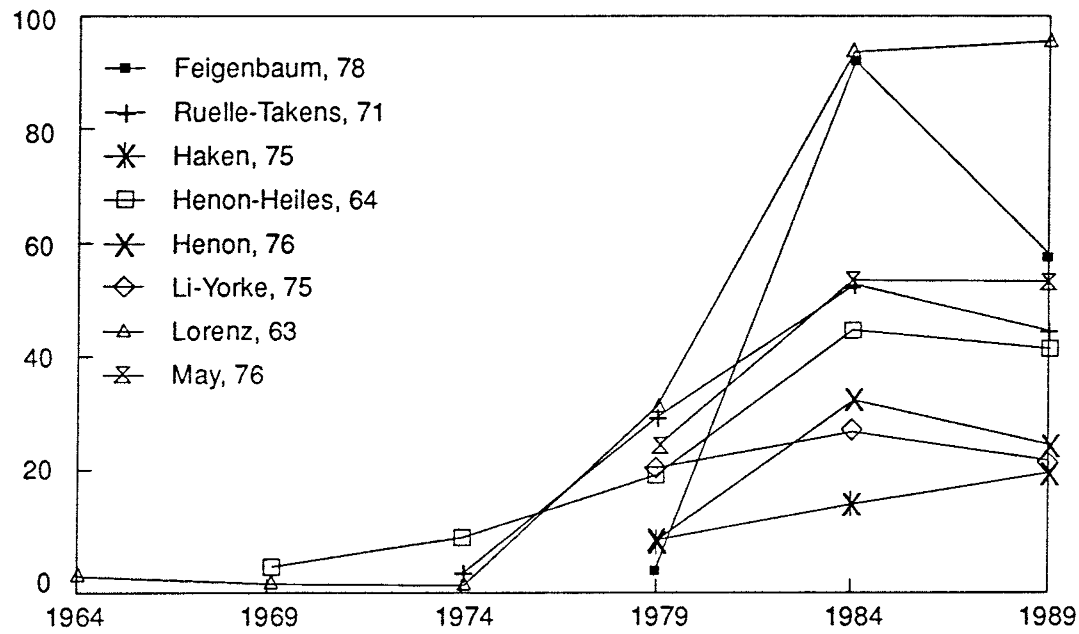
[1]For convenience in the ensuing disussion, we denote as E the Euclidian or Cartesian dimension, and fractal dimension as D.

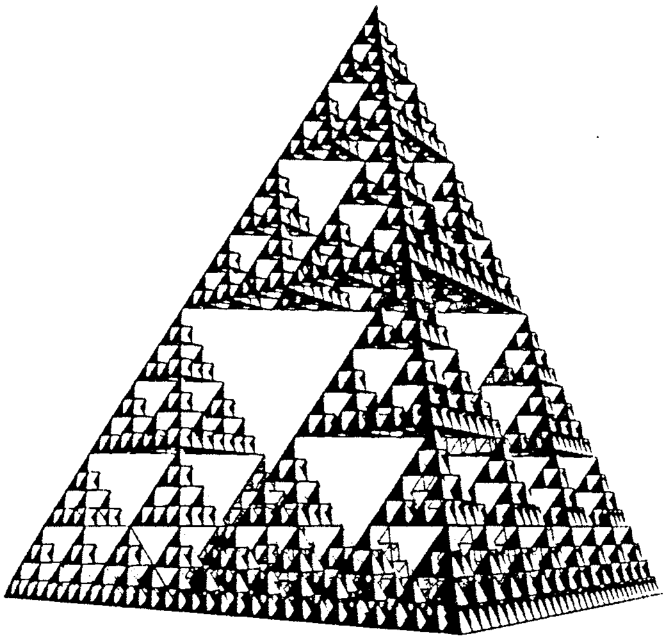


Data were taken from ***Science Citation Index***, Five Year Summary Volumes, and averaged for the years following the publication date. The data for 1989 are the number of citations recorded in the 1989 volume.

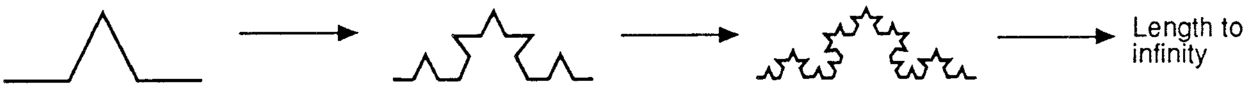
(After Middleton, 1991)

FIGURE **1**

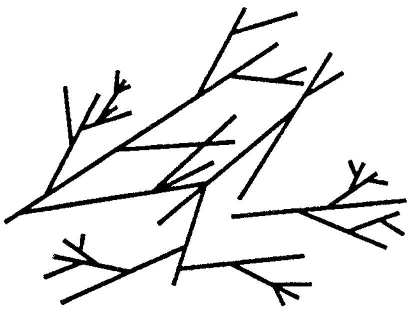
CITATIONS OF CLASSIC PAPERS ON CHAOS AND FRACTALS



(a) Self Similarity - each part of the shape resembles the whole.



(b) Non-Differentiable - first derivatives diverge to infinity.



(c) Partially Fill Euclidean Space.

FIGURE 2
PROPERTIES OF FRACTAL GEOMETRIES

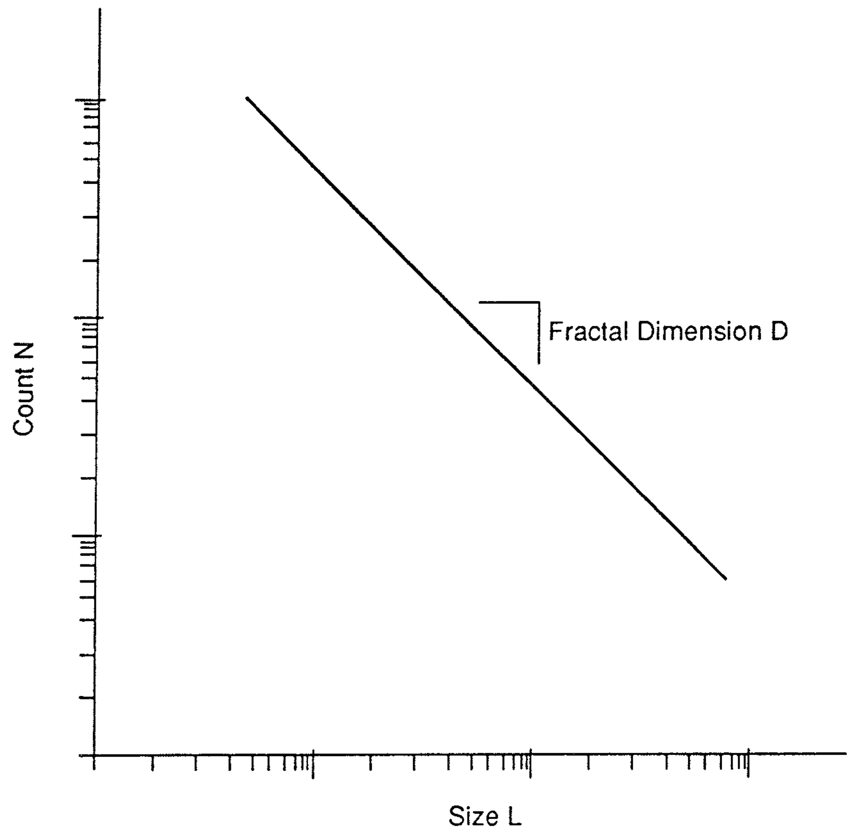


FIGURE **3**
LOG-LOG PLOT FOR FRACTAL DIMENSION

Fractal geometry of point patterns, for example, can be described by the box counting method, which relates the number of boxes containing points to the size of the boxes (Figure 4a). The fractal geometry of a rough surface may be defined by the ruler method, which relates the number of rulers necessary to traverse a surface to the length of the rulers (Figure 4b), although care must be taken if the surface is self-affine rather than self-similar. Each of these methods describes a different aspect of the pattern. As a result, fractal dimension should not be quoted without reference to the method used for calculating the dimension.

While fractal dimension can be a useful way to describe patterns and shapes, the ability to define a fractal dimension does not ensure a fractal pattern. To be fractal, a pattern must be either "self-similar" or "self-affine" (Figure 5). Self-similar patterns are defined as patterns which are the same at different scales, while self-affine patterns are similar at different scales only when scaled by different ratios in different coordinates. The existence of self-similar or self-affine fractal patterns can only be proven by comparison of the patterns at different scales. Barton et al. (1991) point out that approaches used for calculation of the fractal dimension of self-similar fractals may not be appropriate for self-affine fractals.

1.2 Definitions

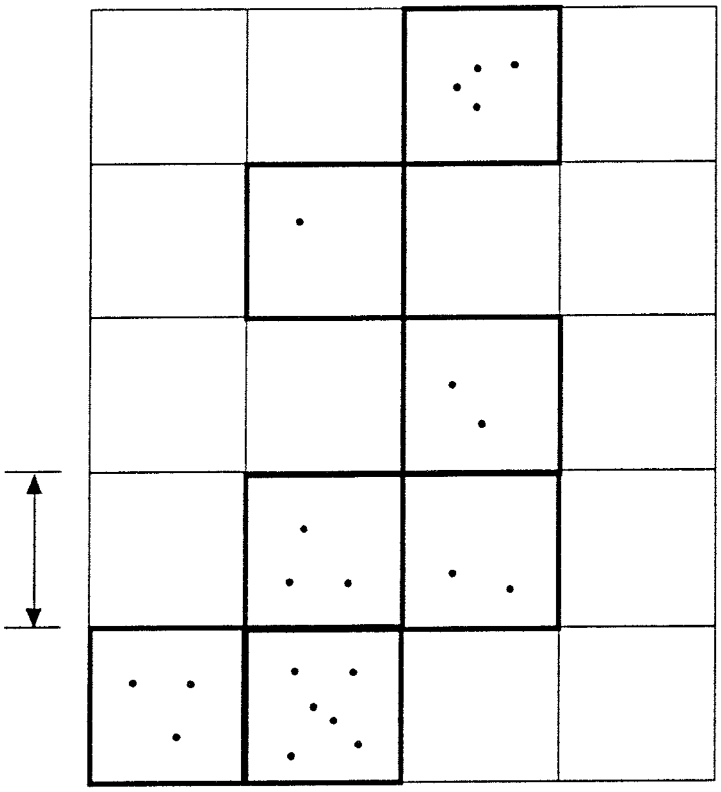
Fractal dimension is an extension of the standard notion of Cartesian (or Euclidian) dimension. Mandelbrot (1983, original publication 1977) defined a fractal to be a set with Hausdorff dimension[2] strictly larger than its topological dimension. Unlike Euclidian dimensions, fractal dimensions can take on both non-integer and integer values. The fractal dimension describes how a lower dimension feature (such as a set of fractures) fills a higher dimensional space (such as a rock mass). The dimension should be between that of the feature and the space in which the feature is defined.

Thus, fractal theory does not use the term "dimension" in a strictly topological sense, but rather as an index or "metric" to describe a pattern. Such an idea involves a geometric space that allows for some reasonable measure of distance. This means that when we use "fractal dimension" to describe geological features, we address a form of measurement of the phenomena and not the topology of the phenomena.

To further understand the interpretation of fractal dimension, consider the manner in which a fractal set is constructed following Mandelbrot (1983). For all D-dimensional parallepipeds defined by $D \leq E$, the fractal dimension D is functionally expressed as $D = \log N / \log (1/L)$. Then, as shown in Figure 6,

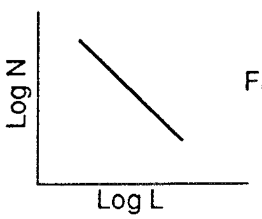
---

[2]The Hausdorff dimension is defined as the value of d for which the measure $M_d = N(L)^*L^d$ is finite and non-zero, where $N(L) \propto L^{-D}$. For Euclidian objects, D is an integer, so the measure is only finite and non-zero when d equals its topological dimension, whereas for fractals, the mmeasure is finite and non-zero only when d is a non-integer.



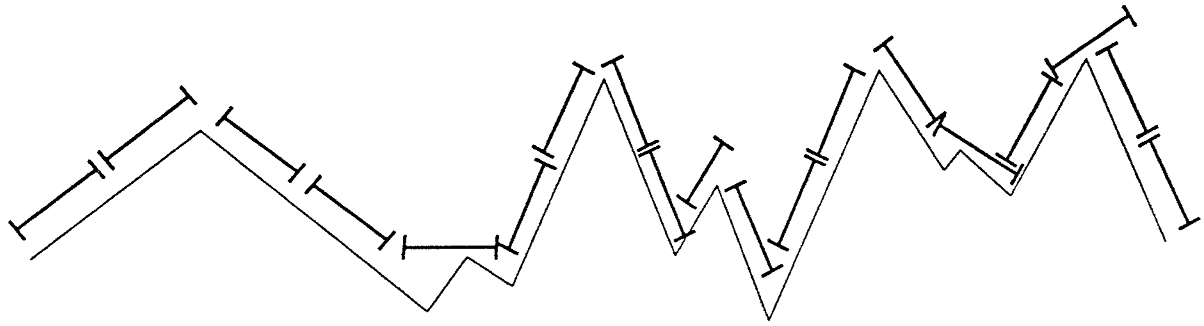
Count N = Number of boxes of Dimension L necessary to cover figure

Dimension L = Size of box



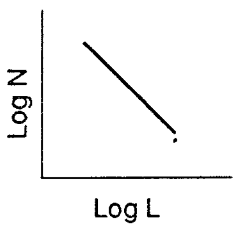
Fractal Dimension Plot

FIGURE **4a**
BOX COUNTING METHOD FOR FRACTAL DIMENSION



Count N = Number of rulers
necessary to cover figure, N

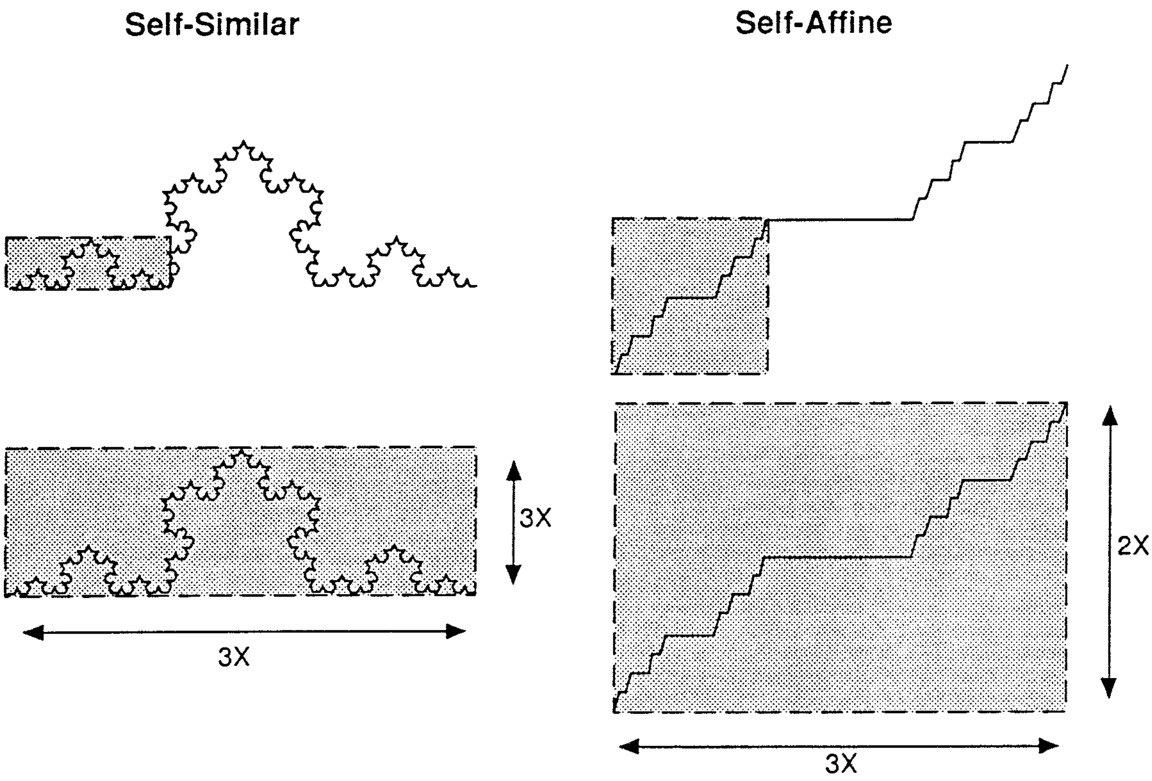
Dimension L = Ruler Length, L



Fractal Dimension Plot

FIGURE **4b**

RULER/DIVIDER METHOD FOR CALCULATING FRACTAL DIMENSION

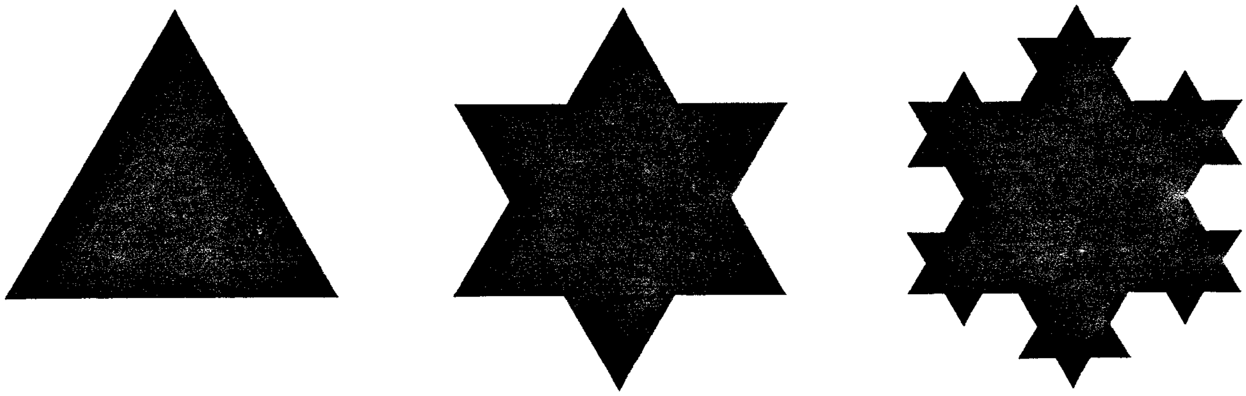


Portions of exactly self-similar fractals (e.g., the triadic Von Koch curve, left) are identical to the original when they are enlarged by the same factor in all coordinates. If the fractal is self-affine (e.g., the Devil's staircase, right) the enlargement is identical to the original if the enlargement factors are different.

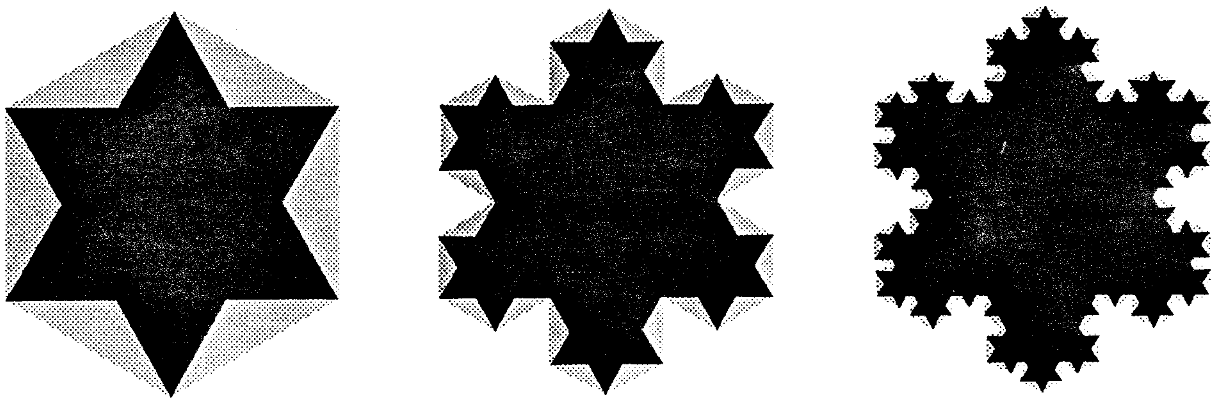
FIGURE **5**

SELF-SIMILAR AND SELF-AFFINE FRACTALS

(After Barton, La Pointe, and Malinvero, 1991)



Triadic Koch Island or Snowflake



Triadic Koch Island or Snowflake -
alternative construction

FIGURE **6**
KOCH ISLAND FRACTAL

(After Mandelbrot, 1983)

> the generator of the set is an oriented broken line composed on N equal sides of length L. Each stage of the construction begins with a broken line and consists in replacing each straight interval with a copy of the generator, reduced and displaced so as to have the same end points as those of the interval being replaced.

The fractal dimension may be restated $NL^D = 1$, which indicates that the fractal dimension represents a geometric weight between the oriented broken line of N sides and the side lengths, L.

A fractal that is invariant under ordinary geometric similarity is called "self-similar." Self-similar fractal sets are built from pieces similar to the entire set but on a finer and finer scale. For example, we would expect fracture tracelengths that are self-similar fractal sets at the kilometer scale to exhibit the same behavior at the millimeter scale. From a Euclidian perspective, a standard self-similar shape is a line segment divided into N equal parts of length L, a square is composed of N parts of area L^2, and a cube is composed of N parts of volume L^3, and so on, regardless of whether the unit of measurement was kilometers or millimeters.

Another example of a self-similar fractal is Brownian motion in the plane of a microscope slide. As shown in Figure 7 (after Mandelbrot, 1983, plate 13), we see that the path of a particle appears the same regardless of magnification. As a bounded random set, Brownian motion is statistically self-similar, namely, the distribution of any point in Brownian motion is identical to the distribution of the totality of the points. An alternative way of stating this is that all moments of the distribution of individual particles are identical to the moments of the distribution of all the particles.

A fractal that is self-affine is somewhat different than a self-similar fractal. As shown in Figure 5 (after Barton et. al, 1991), self-affine processes may scale anisotropically, provided the change in proportion is the same from any initial scale. Faults, fractures, and fracture roughness are all thought to be self-affine (Barton et al., 1991).

1.3 Calculation of Fractal Dimension

There are several techniques used to estimate fractal dimension in geologic applications. Each describe a different type of feature. Many are restricted to use only on self-similar fractals. Measures for calculating fractal dimension are summarized in Figure 8. They can be summarized by the x and y axes used in their log-log plots (Table 1).

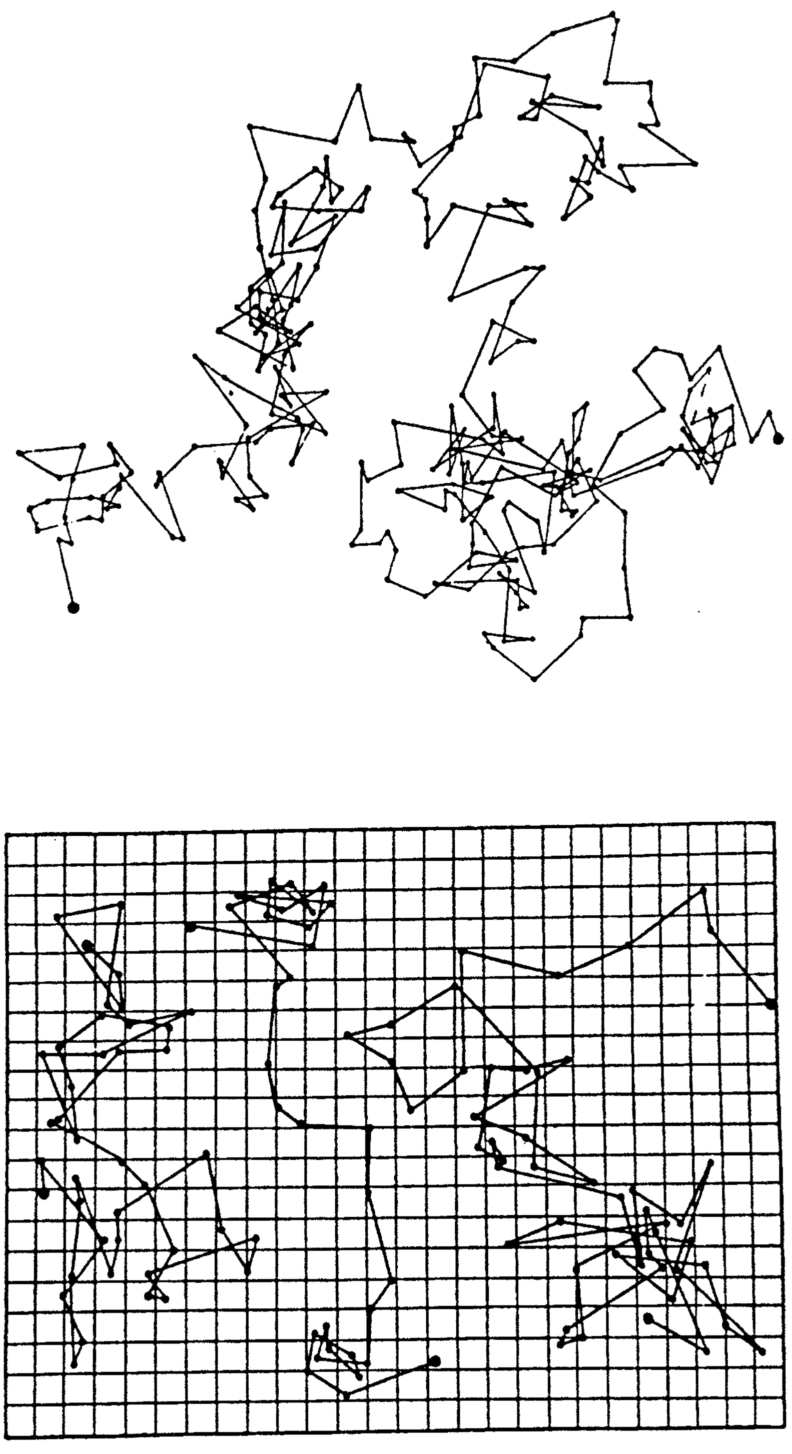


FIGURE 7
FRACTAL BROWNIAN MOTION

(After Mandelbrot, 1983)

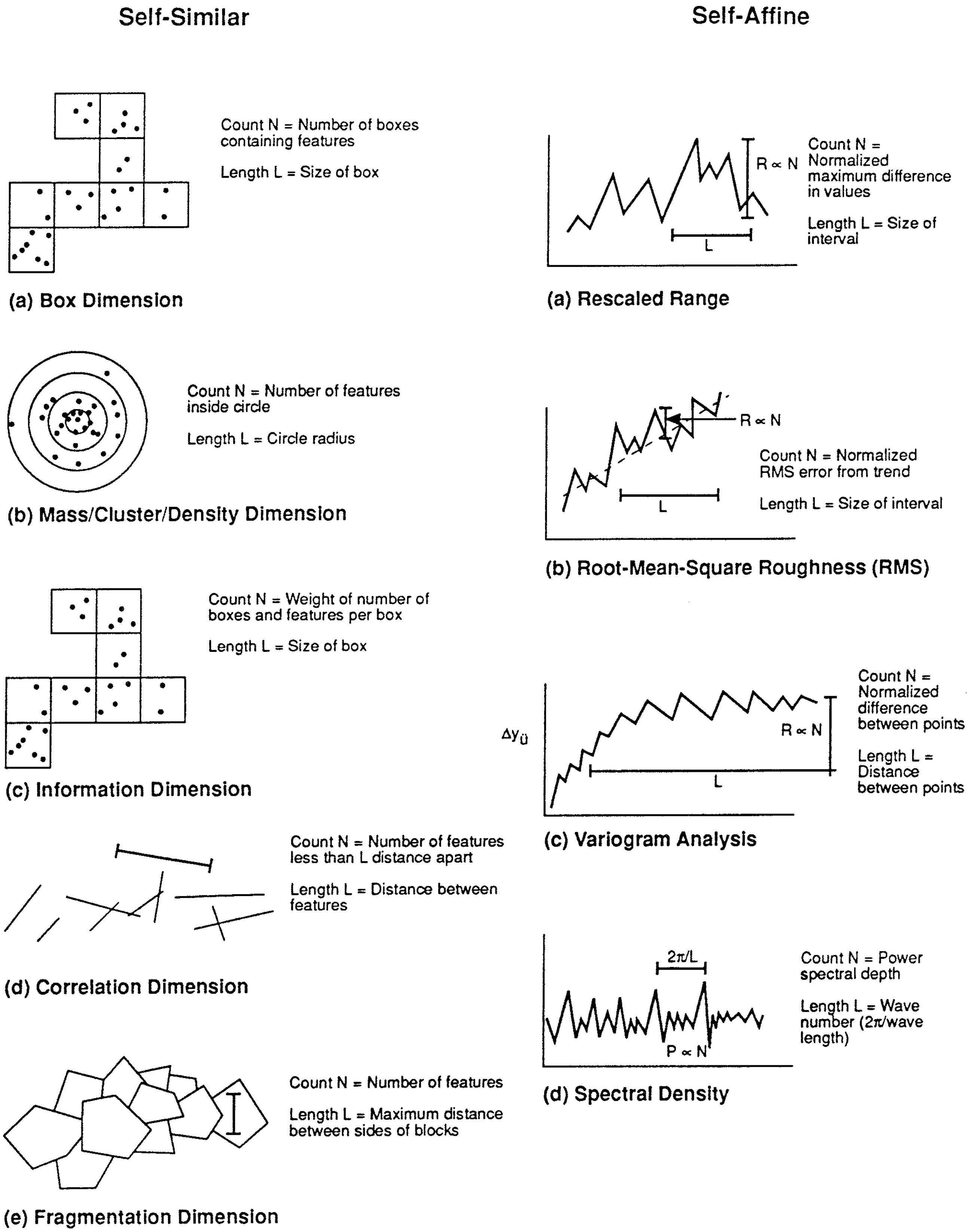


FIGURE **8**
MEASURES FOR FRACTAL DIMENSION

Table 1: Methods for Fractal Dimension Calculation			
Method	**Length L**	**Count N**	**Self Similar (S) or Self Affine (A)**
Box	Box Side	Number of Boxes to Cover Figure	S
Mass/Density	Circle Radius	Number of Points in Circle	S,A
Information	Box Side	Weighted Number of Boxes to Cover Figure	S
Correlation	Distance Between Features	Number of Features within Distance	S
Fragmentation	Block Width	Number of Blocks	S
Spectral Density	Wave Number	Power Spectral Density	A
Rescaled Range	Interval Length	Normalized Maximum Difference in Values	A
RMS Roughness	Interval Length	Normalized RMS Error from Trend	A
Variogram	Distance Between Points	Normalized Difference in Values	A

The box method is basically a two-dimensional yardstick. There are two variations of this approach. In one variation, Brown (1987a), the fractal is first scaled (usually by several orders of magnitude) in order to minimize crossovers, and then, a grid of square boxes is overlaid on the fractal such that a constant aspect ratio on the fractal is maintained. The log-log relationship between the number of divisions of the grid and the number of boxes required to cover the fractal is determined. A second variation, Feder (1988) uses a similar box size method, but instead determines the relationship between the box-size multiplier and the number of boxes required to cover the fractal. The former method is computationally simple, and is expressed as log N = A + D log b, where N is the number of boxes required to cover the fractal, b is the number of box-grid divisions in the x and y directions, and A is y-intercept. The slope of this function is D, the fractal dimension. The box dimension is described by a plot of the equation,

$$N(L) = L^{-D}$$

where N(L) is the minimum number of boxes of size L necessary to include every feature. Find N(L) by counting the number of boxes which contain features using a regular grid of boxes.

The divider method is equivalent to placing a yardstick of composed of fixed common intervals over the fractal. The number of intervals required to cover the entire fractal is counted, and then multiplied by the size of each interval to give an estimate of the fractal length, L. The measurement interval is changed and the process is repeated. This is performed several times. The fractal length, L, is linear in a log-log relationship to the interval size, r, in the following manner: log L = A + (1 - D) log r, where D is the fractal dimension. In this notation, A is the y-intercept. The slope of the log-log plot of L and r is some value B, and B = 1 - D. Thus, D = 1 - B. The divider method has been used for measuring fracture roughness (which is self-affine). The method is only appropriate for self-similar fractals, however.

The modified divider method consists of using equally-spaced horizontal divider intervals (i.e., x-axis increments) and connecting the points at which x-axis values intersect the fractal. The lengths of each connecting segment, L_i, are determined, and the total number of segments are added together to compute the total length, L. The x-axis measurement interval is changed, and the process is repeated. The manner of computing D is the same as the divider method.

The spectral density method assumes that the fractal has a spectral density that follows a power law relationship, i.e., the spectral density of the frequency, f, is proportional to f^{-b}, such that the fractal dimension, D, is related to b as b = 2D - 5. As with any spectral estimation procedure, assumptions regarding the stationarity and the ergodicity of the process greatly influence the validity of the spectral estimates. The spectral density method is only appropriate for self-affine fractals.

The Mass/Cluster/Point method is a variant of the box dimension, designed to be useful for both self-similar and self-affine fractals. In this method, a series of circles are defined, starting at the center of a cluster of fractures, and the number of points inside each circle is plotted against the circle radius,

$$\mu(r) = r^{D}$$

where $\mu(r)$ is the number of features inside a circle of radius r, starting from the center of a cluster. This approach is referred to as the "Levy-Lee" method in the FracMan model, since it provides the dimension necessary for the Levy-Lee fracture conceptual model. However, it depends upon the definition of circles starting from the center of clusters - calculations based upon circles not located around cluster centers are not meaningful.

The Information Dimension combines the information on the number of features in the mass dimension with the box dimension concept of coverage of a figure.

$$I(L) = -\sum_{i=1}^{N(L)} \mu_i \log \mu$$

$$I(L) = -D_I \log(L)$$

Additional measures for fractal dimension include,

- Correlation Dimension: Based upon the distribution of distances between features
- Ruler Dimension: Based upon the number of straight rules needed to cover a curve for different ruler lengths
- Perimeter-Area Dimension: A ruler dimension for comparing perimeters and areas of two dimensional features
- Fragmentation Dimension: Based on the distribution of block sizes as measured by the longest ruler which would fit into each block

2. TASK 1: LITERATURE REVIEW

The primary questions to be addressed by the literature survey were as follows:

- Can the fractal dimension be used to compare geologic environments?
- What is the geological explanation for variation in the fractal dimension between geologic environments?

A total of over 430 citations of fractal dimension and geology and hydrology were identified by a computer literature search of Georef, NTIS, USDOE, and Compendex data bases. Of there, 78 were selected for close evaluation. An additional 53 references were identified and reviewed based upon references found in the literature.

This literature search did not identify applications in which fractal dimension was used as a primary index for comparing geologic environments, or where processes of non-linear dynamics and the fractal dimension were directly related to the genesis of geologic settings. However, experts in the U.S. oil industry contacted as part of this project indicated that fractal dimension is used to distinguish well locations. In addition, a number of citations were found which indicated that settings with higher fractional dimension could be expected to have higher fracture connection and greater heterogeneity. This has two contradictory implications for repository site selection:

- Higher fracture interconnection indicates the potential for greater radionuclide transport, and thus a less attractive site.
- Greater fracture system heterogeneity indicates the potential for larger blocks of rock without significant fracturing, and thus a more attractive site.

The literature review concentrated on the following topical areas:

- Data indicating fractal scaling in the geometry and heterogeneity of discrete features (e.g., fractures, faults, lineaments, karsts) and physical properties (e.g., conductivity, deformability/elasticity/stress distribution, strength, storativity, diffusivity, connectivity / percolation probability).
- Indications of the relationship between the physical mechanisms of rock fracturing and fractal dimension
- Indications of the relationship between fracture connectivity and fractal dimension,
- Relationships between fractional dimensional flow and fractal dimension of fracture patterns.

2.1 General

Modeling of geologic geometries has been historically approached from a stochastic or random field modeling perspective. Complementing, but not replacing random field approaches, fractal sets have offered the potential for a more succinct understanding and a different perspective of fracture geometries and mechanics.

A fundamental assumption of stochastic field theory is that the random process is ergodic and stationary implying that the pattern of heterogeneity is spatially periodic. If a rock mass is described by a conventional stochastic field, parametric evaluations of the stochastic and statistical properties of permeability, fracture structure, boundary conditions (including heterogeneity, anisotropy, and spatial variability) may be performed. Such evaluations are constrained by each measurement scale of interest, from the scale of an individual canister to the scale of kilometers. Although powerful from an estimation and inference perspective, no single statistical measure is available. Succinct and detailed random field discussions for transport and flow phenomena in fracture structures are well documented in Dershowitz et al. (1991a, 1991b), Geier and Axelsson (1991), Ababou et al. (1988, 1990), Gelhar and Axness (1983), Dagan (1982, 1990).

Employing fractal geometry to describe fracture heterogeneity offers an approach that is independent of the scale of observation. The fractal description combines heterogeneity and connectivity at all scales, such that an observation at one scale can be interpreted at a different scale of interest. As a seminal work on fractals, Mandelbrot (1983) remains a first source. Covering a broad range of physical phenomena, Mandelbrot intimates that fractals are reasonable models for discrete fracture features to include fractures, faults, lineaments, and karsts.

More recently, Dershowitz (1991) calculated the fractal dimension for a variety of fracture pavements at the Yucca mountain nuclear waste repository study site in the U.S. Ericsson (1991) carried out a study of the fractal dimension of fractures at Äspö, Sweden. Geier et al. (1987) carried out a similar study for fractures at the Stripa site. These studies indicate that fractal dimensions can be calculated for fracture patterns, faults, and lineaments.

What remains to be demonstrated, however, is the extent to which the single measure of fractal dimension provides a unique index for site hydrogeology. Having established that fractal dimension can be calculated from lineaments, does the existence of a fractal dimension necessarily imply a self- similar geometry at different scales? Does fractal dimension relate directly to geologic properties important to site suitability such as fracture network connectivity and rock block size ?

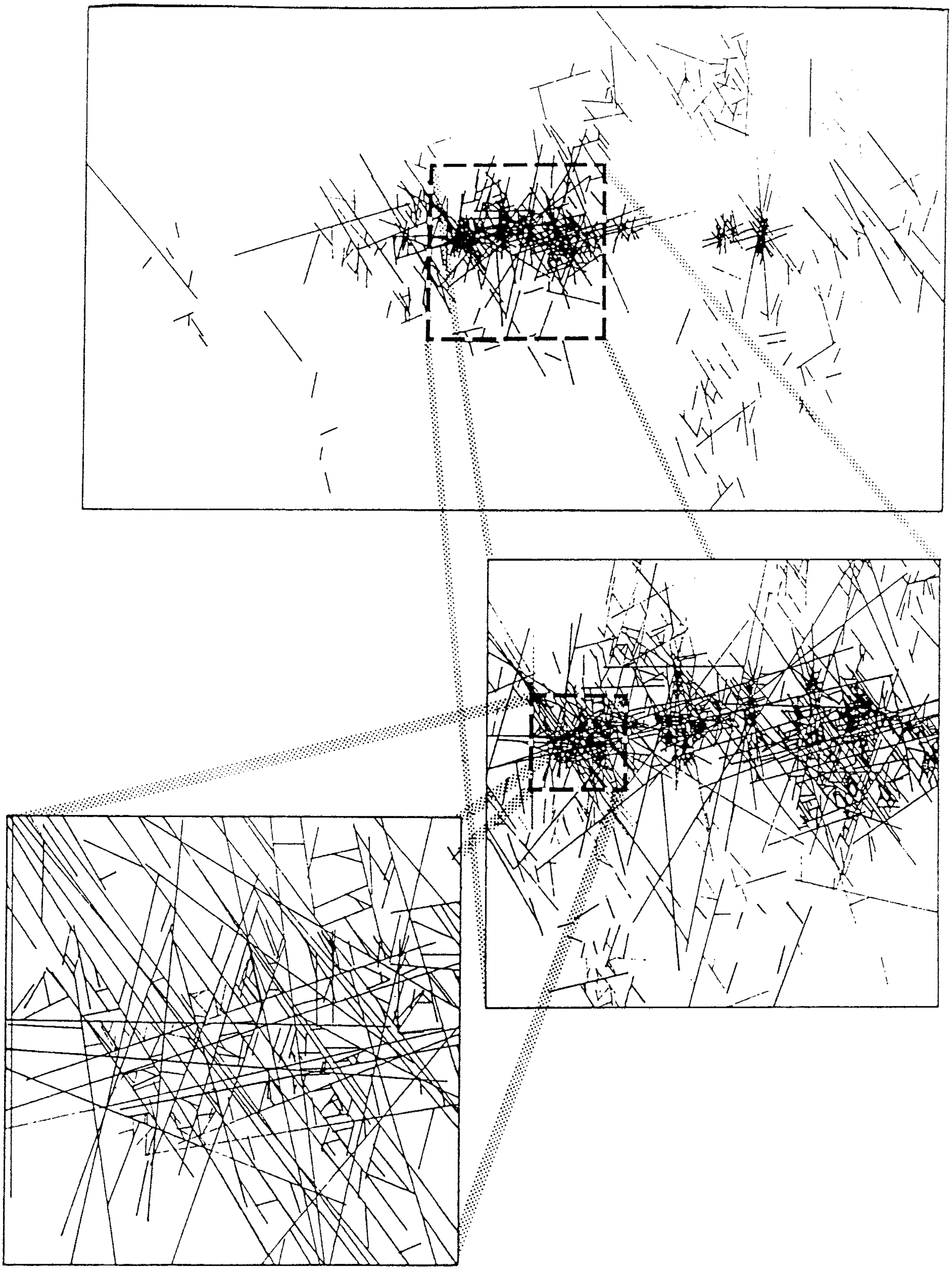
2.2 Fractal Scaling in Geometry and Heterogeneity of Discrete Features and Physical Properties

A primary research direction in the use of fractal dimension has been in the area of scaling in the geometry and heterogeneity of discrete features. Most efforts have been directed toward the estimation of the fractal dimension, fractal dimension as an input for fracture network simulations, and the incorporation of fractal dimension in simulation and geostatistical characterizations of hydrogeological environments.

Geier and Axelsson (1991) performed discrete fracture modeling using FracMan to analyze discrete fracture geometrical and hydrological data. Constant-pressure packer tests were analyzed using fractional dimensional methods to estimate effective transmissivities and flow dimensions for the packer test intervals. Fractal dimension values ranged from 1.13 to 2.75. Discrete fracture data on orientation, size, shape, and location were combined with hydrologic data to develop a preliminary conceptual model for the conductive fractures at the site. This model was used to simulate three-dimensional populations of conductive fractures in 25 m and 50 m cubes of rock. After calibrating the model, components of effective conductivity tensors were estimated. The results provided preliminary estimates of the effective conductive heterogeneity and isotropy on the scale of the cubes and provided a demonstration of how the discrete fracture network concept can be applied, in conjunction with fractal dimension as an input, to derive data necessary for stochastic continuum and channel network modeling.

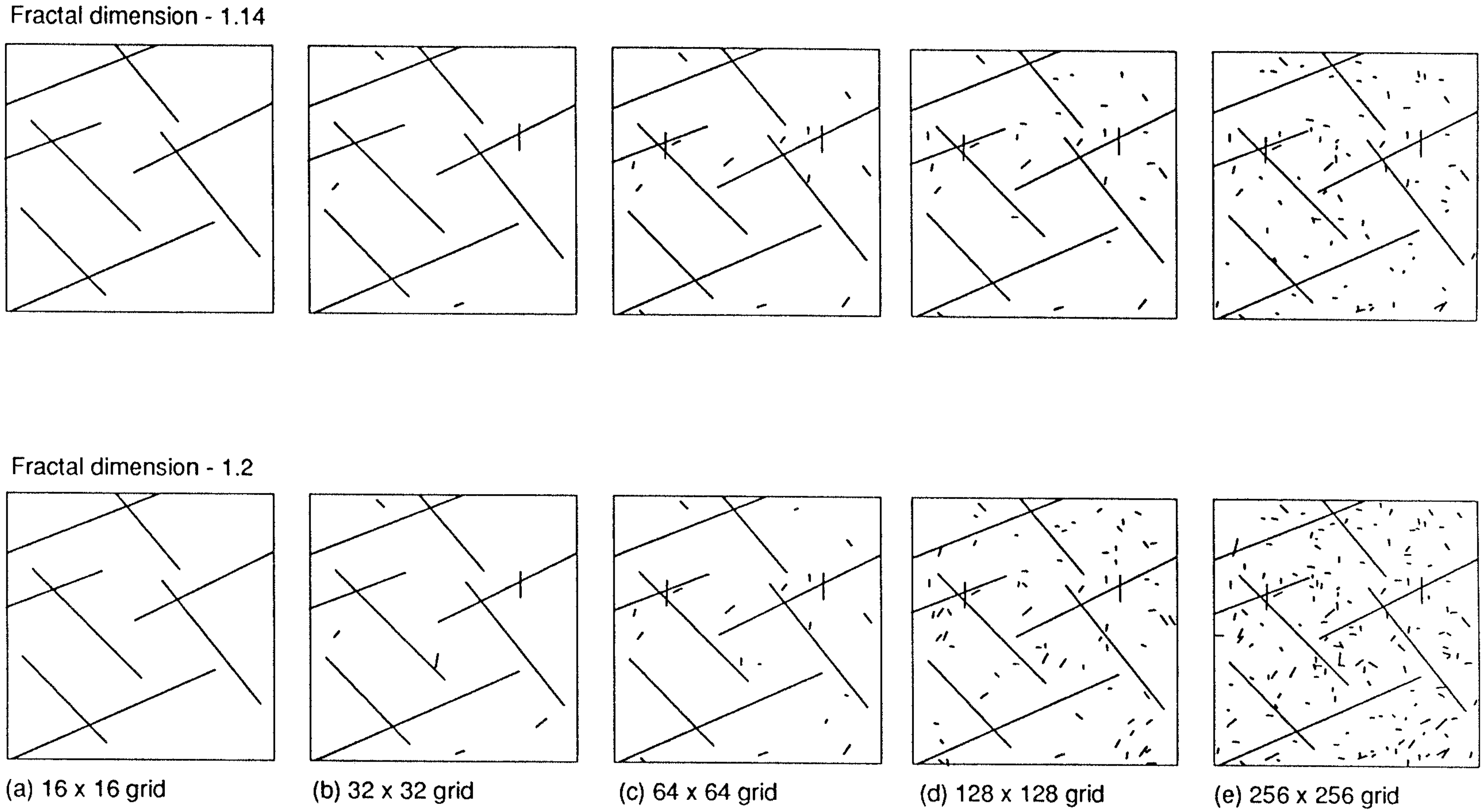
Lee (1988) developed a number of methods for simulating two and three dimensional fractal fracture patterns. The Levy-Lee model is based upon the use of Levy flight (a fractal process of Brownian motion) to describe the locations of fracture centers (Figure 9). In this method, only the centers of fractures are fractal - the networks themselves may not be fractal. Levy-Lee networks using power-law fracture size distributions may be more likely to be fractal than networks using other length distributions. Lee (1988) also developed algorithms for the generation of fractal fracture networks (Figure 10), although these algorithms were too computationally intensive for application in three dimensions. Acuna and Yortsos (1992) developed a method for generating two dimensional, self-similar fracture patterns, and used those models for flow simulation. Analysis of these networks indicated that different dimensions might be obtained by box counting, fracture length, and fragmentation approaches (Figure 11).

In an extremely comprehensive paper, Sahimi and Yortsos (1991) present a review of the application of fractal geometry to porous media. They address four general classes of application of fractal geometry. These applications include: (i) characterization and properties of porous fractal surfaces, (ii) miscible and immiscible displacement processes leading to fracture structures, (iii) gradient transport over fractal objects, and (iv) the representation of property heterogeneity by fractal statistics. An extensive bibliography is contained to include implications in future research addressing a better understanding of fractal surfaces and pore space, the origin of fractal statistics in property distributions, and quantifying fractal behavior in unstable processes.



(After Lee, 1987)

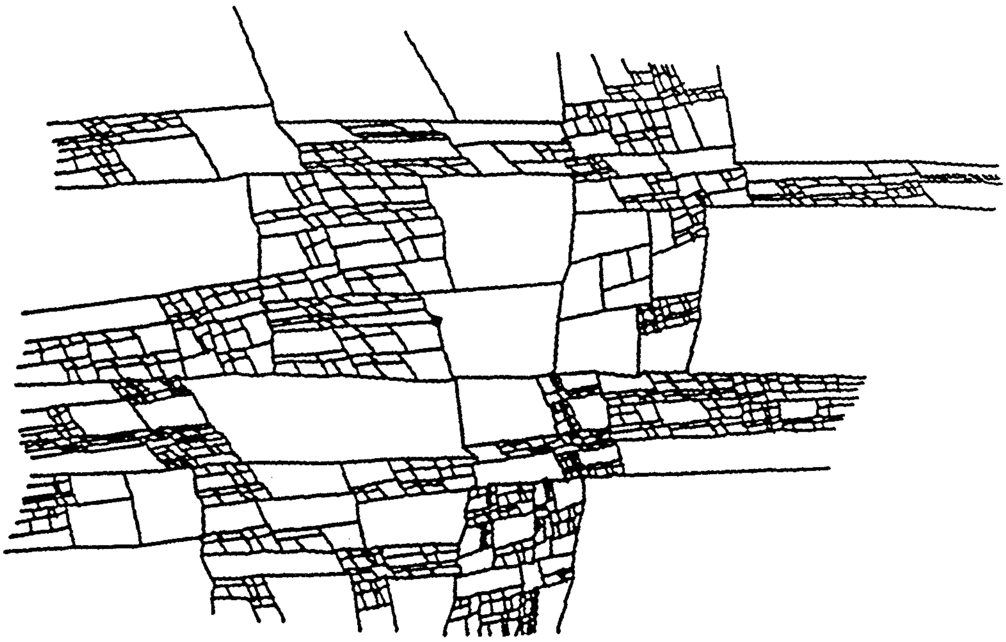
FIGURE **9**
TWO DIMENSIONAL LEVY-LEE MODEL
SKB/FRACTAL/SWEDEN



(After Lee, 1987)

FIGURE **10**

FRACTAL FRACTURE TRACE NETWORK MODEL



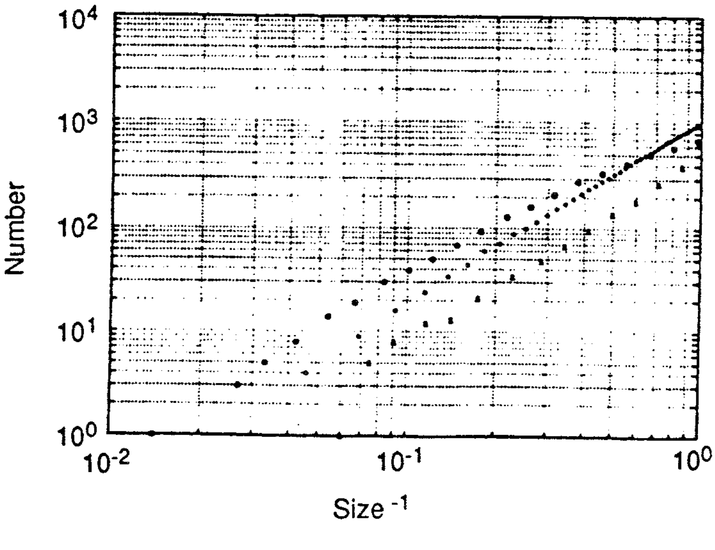


FIGURE **11**
TWO DIMENSIONAL FRACTAL FRACTURE GENERATION

(After Acuna and Yortsos, 1992)

Miller et al. (1990) examined divider, modified divider, box, and spectral method methods for the calculation of the fractal dimension of fracture surfaces. Roughness profiles from basalt, gneiss, and quartzite were used to evaluate both fractal dimension as a roughness measure and the effect of the estimation method for fractal dimension. Analytical results indicated that calculated fractal dimension values were negatively correlated with nonfractal roughness measures and matched poorly with subjective, visual rankings of profile roughness. The four estimation methods were inconsistent in the computed dimension values, and the sensitivity to input parameters (e.g., box size, divider spans, and spectral density parameter estimation). Only the modified-divider method provided consistent agreement with visual interpretations. Scale dependent measures were also examined, and these correlated well with visual assessments. They conclude that the benefit of fractal dimension is its ability to support simulations and visualizations rather than as a means to uniquely describe roughness.

Barton and Larsen (1985) analyzed the fracture traces exposed on three 214- 260 m^2 pavements in the same Miocene ash-flow tuff at Yucca Mountain in southwestern Nevada. Fracture trace lengths followed a log normal distribution. Although the areal fracture networks appeared visually different, the fractal dimension D of the networks were quite similar (D = 1.12, 1.14, 1.16). Furthermore, the network patterns are scale independent for trace lengths ranging from 0.20 to 25 meters indicating that the fracture network exhibits a self-similar fractal.

A continuing analysis on six 205 - 1,726 m^2 laterally separated, subhorizontal subpavements in the same Miocene ash-flow tuff at Yucca Mountain was performed by Barton et al. (1986). Computed fractal dimensions ranged from D = 1.10 to 1.18. As in earlier investigations, the fracture trace lengths followed a log normal distribution, the networks appeared visually different, and self similarity of the fracture network fractals was apparent. The authors did not, however, reach any conclusions about the usefulness of the fractal dimension calculated.

Adler (1985) examined the problem of Taylor dispersion in capillary networks which exhibit fractal behavior. Two fractals are considered - an infinite tree of degree 3 and the Sierpinski gasket. Taylor dispersion along a tree can be solved analytically, specifically as a Poisson distribution. Evaluation of Taylor dispersion on a Sierpinski gasket is performed, and it is concluded that the larger the network, the longer the tracer particle is retained. This is because of the regular presence of bottlenecks that alter the large-time behavior of the various moments.

Brown et al. (1986), while examining the mechanical and transport properties of rock joints, considered the correlation between the surfaces and the distribution of apertures in natural rock joints. Using empirical data, the power spectral density of two natural joints was examined. Estimates of correlation lengths demonstrated the differences between the surface topography and the composite topography of the natural joints.

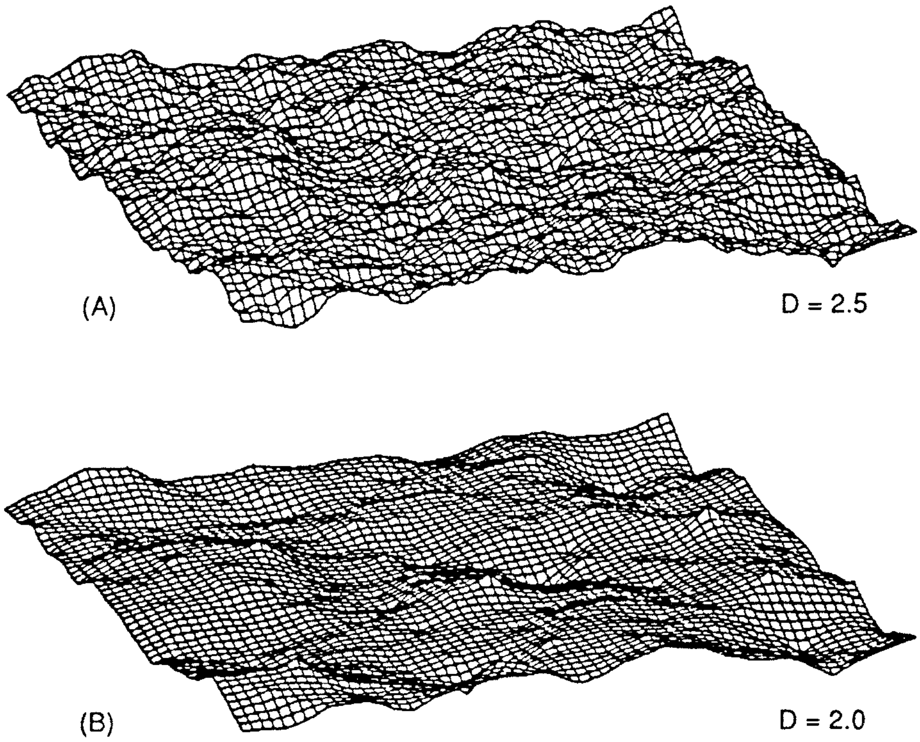
Wheatcraft and Tyler (1988) examined scale dependent dispersivity in heterogeneous aquifers. Analytic expressions were developed to describe transport in a single fractal streamtube and transport through a set of fractal streamtubes. A random walk model of solute transport in a fractal porous medium is developed to verify and elaborate upon the analytical expressions. They conclude that it is possible to obtain the fractal dimension from a tracer experiment in which the breakthrough curve is obtained for at least two travel distances. As long as the fractal dimension remains constant, it is then possible to predict solute migration at scales larger than the scale of observation in which the fractal dimension and the dispersivity were obtained.

La Pointe (1988) discusses the development of an index of fracture density based upon fractal dimension ($2 < D < 3$) for two dimensional visualizations of fractures. Two formulations are used: (i) the number of fractures per unit area and (ii) the density of fracture-bounded rocks. A combination of randomly generated fractures and natural (field) data was used in the fractal dimension computation. It is determined that fracture density, as defined by either formulation, is fractal and scale invariant. For formulation (i), the fractal dimension will be higher for a greater number of lines, bigger or longer lines, and the more the lines are randomly distributed in space. Under formulation (ii), a higher fractal dimension seems to occur as the number of blocks increase. Computer simulations suggest that D may be more sensitive to the number of fractures or blocks (and their spatial distributions) rather than size and orientation. Most importantly, La Pointe indicates that block size distributions may be controlled significantly by the fractal dimension of the geology.

Methods of computing fractal dimension for fracture surfaces were evaluated by Carr (1989). The methods evaluated are the divider method, the spectral method, and a method for estimating joint roughness coefficient (JRC). Simple statistical correlation estimates between the three methods are computed. Carr has concluded that the divider method is preferred for the Yucca Mountain fracture surfaces when correlation with the JRC is desired.

Brown (1987 and 1989) used fractal dimension as a basis for the generation of rough surfaces (Figure 12) to evaluate fluid flow and conduction of electricity on simulated fractures composed of rough surfaces, and to simulate flow between rough surfaces. A fractal model of surface topography was used to generate pairs of rough surfaces. He determined that variations on fractal dimension produce only a second order effect on the fluid flow. Additionally, Brown (1987) concluded from examination of surface roughness that the divider method and the spectral method will yield the same results if horizontal resolution at which the profile is measured is smaller than the crossover length. For resolutions greater than the crossover length, the divider method always yields fractal dimensions close to 1.

Fractal processes in soil water retention were investigated by Tyler and Wheatcraft (1990). Although the research addresses soil pore size and distribution, their approach may have application to the density of fractures and the area of fractures by volume. Using the Sierpinski gasket model of soil pores and expanding on the previous work of Adler (1989), functional relationships in terms of water content and capillary pressure are developed for the Burdine and the Mualem models of soil conductivity. Such an effort may serve to integrate soil mechanics with aspects of physical fracture processes.



Examples of fractal surfaces used in the simulations. Both surfaces have the same rms height σ. Both were generated with the same set of random numbers but have different fractal dimensions. The fractal dimensions shown (D = 2.0, 2.5) represent the limiting values observed by *Brown and Scholz* (1985b).

FIGURE **12**
FRACTAL FRACTURE SURFACES

(After Brown, 1989)

Kumar and Bodvarsson (1990) expand the use of fractal networks and dimensionality in terms of characterizing fracture roughness. Their work addresses both isotropic and weakly anisotropic surfaces. The algorithms they employ may be directly transferable to existing fracture network models for representation of weakly anisotropic surfaces and profiles exhibiting a corner frequency in their power spectrums.

2.2.1 Summary

Ample evidence exists that lineaments, faults, fracture traces, and fractures can be characterized by a fractal dimension. These features have been found in some cases to be self-similar at different scales, indicating that large scale surface observations of fractal dimension may be useful in characterizing smaller scale features at depth. Fractal dimension can vary spatially, and can be defined by several overlapping fractal processes ("multifractals"). Fractal dimension can be useful as a tool for generating geologic fracture patterns similar to those observed in the field.

2.3 Relationship Between Physical Mechanisms of Fracturing and Fractal Dimension

The relationship between physical mechanisms of rock fracturing and fractal dimension has not been studied as extensively as the fractal statistics calculated from lineament and trace maps and fracture surfaces. For example, although the Geologic Association of Canada (Middleton, 1991) published a detailed guide to nonlinear dynamics, chaos, and fractures, only passing mention is made of the possibility that the non-linear dynamics of processes such as plate tectonics, earthquakes and fluid flow may cause the fractal patterns observed empirically.

Several references exist describing the nature of the processes behind observed patterns. Reches (1986), for example, examines fault networks from a laboratory perspective. Fault properties considered include sets of similar orientations, fault zones, fault growth, and the statistical characterization of the length of fault traces. It is possible that a review of the literature of fracture mechanics could identify references to application of processes of non-linear dynamics and resulting fractal geometries.

Ongoing research on the relationships between fractal patterns and geologic/geomechanical processes is being carried out by Pyrak-Nolte, Nemant-Nasser, Ingraffia, and others.

2.3.1 Summary

Very limited references were found to mechanisms explaining observed fractal patterns in geology. Given the intensity of academic interest in fractals at the present time, we expect that literature in this area will become available over the next few years.

2.4 Relationship Between Fracture Connectivity and Fractal Dimension

Research into the relationship between fracture connectivity and fractal dimension is limited. Emphasis in this area has concentrated on the means by which fractal dimension may be incorporated with geostatistical methods for fracture networks and aperture correlations. No citations were found comparing fracture connectivity in the field to fractal dimension directly. Several citations are available that describe the collection of fractal statistics for fractures and fracture surfaces, and evaluate their implication on the basis of simulations.

Axelsson et al. (1990) presents rock block permeability analyses for both fractal and non-fractal fracture patterns. These simulations indicate the increased connectivity and heterogeneity of fractal patterns.

Unpublished sources identified through contacts in the oil industry (Dershowitz personal communication, 1991), state that fractal dimension is commonly used to select well locations, since higher fractal dimensions are known to indicate more connected sites with better oil production potential. These sites also have greater heterogeneity, and thus a greater probability of being completely dry. However, this is not as significant as the potential for improved production if the well is not dry. It is expected that papers on the fractal screening of well locations will appear in the petroleum literature within 6 to 10 months.

Chiles (1988) examined a fracture network containing some 6,000 fracture traces having extents of 0.20 to 20 meters at the Fanay-Augeres uranium mine from both a geostatistical and a fractal perspective. Based upon the author's analysis, the network cannot be considered as a fractal with constant dimension, nor can it be evaluated as a set of randomly located fractures. Thus, neither a fractal nor a geostatistical characterization is sufficient. The authors conclude that the fractal model is easy to fit and simulate along a line, but, in two and three dimensions, simulations are considerably more difficult than a geostatistical model, which, although considerably more complex, can be easily simulated in three dimensions. Generalized algorithms for each form of simulation are presented.

In Wang, Narasimhan and Scholz (1988), an analytic expression is derived that relates the variogram of the spatial correlation of the aperture of a fractal fracture to the dimensionality of the aperture. The aperture of a rough fracture with low fractal dimension is highly correlated over distances much larger than the shear displacement. The aperture of a rough fracture with a high fractal density becomes uncorrelated within a range shorter than the shear displacement. When the fractal dimension characterizes a Brownian fractal, an analytical measure of proportionality is developed.

Bruno and Raspa (1989) demonstrate that fractal dimension is a reasonable method of describing the behavior near the origin of variograms of random surfaces. This means that the irregularity has often been qualitatively examined by the geostatistics community without a reasonable metric for describing such an irregularity. However, the utility of fractal sets is considered limited in that the only information obtained is the fractal dimension and a scale factor.

LaPointe (1988), Turcotte (1986), and other references identify a strong connection between rock block size distributions and fractal dimension (Figure 13). Increased fractal dimension may smooth the distribution of block sizes, increasing both the frequency of relatively small rock blocks and the frequency of relatively large rock blocks. This may indicate the suitability of high fractal dimension sites, which have large blocks of rock with few conductive features, as sites for waste repositories, since regions with small rock blocks (such as fracture zones) would be avoided in any case.

2.4.1 Summary

Although references directly relating empirically measured fractal dimension to empirically measured rock mass connectivity were not identified, information from oil industry contacts, and papers on rock blocks indicate that fractal dimension is directly related to rock block connectivity in situ. Studies of empirical measurements of fractal dimension in fracture patterns and fracture surfaces have indicated that fractal fracture patterns are not necessarily self-similar at different scales, and that fractal dimension by itself is not an adequate index for comparison of geologic geometries.

2.5 Relationship Between Fractional Dimensional Flow and Fractal Dimension

Significant work has been done relating fractional dimensional flow (Barker, 1988) to the connectivity of fractured rock. Although Karasaki et al. (1988) assert that fractional dimension flow is related to the fractal dimension measured from lineaments and fracture traces, no empirical evidence of this has been reported. The fractional dimension of flow is defined by the increase in flow area, A_f, with distance from the source, r, for an equation of the form $A_f \propto r^D$. For linear flow, area is constant with distance r, such that the increase is r^0. For radial and spherical flow, D is 1 and 2, respectively. Any change in flow area for this value of D is non-integer is term fractional dimensional flow (Doe, 1991).

Doe and Geier (1991) and Geier and Axelsson (1991) demonstrate that flow dimensionality is directly related to rock connectivity. However, these studies cannot be interpreted directly in terms of fractal dimension.

Emanuel et al. (1989) proposed a method for combining fractal statistics, detailed geologic data, finite difference solution, and streamtube models into a systematic approach for reservoir performance. This approach is based upon first determining the porosity/permeability character of the reservoir and the determination of the statistical structure using fractals. A random fractal interpolation scheme is then employed to project well data to the interwell region. Fluid flow parameters are then established, and the heterogeneity is modeled at a similar level of granularity as the field data. Phase fractional flow at the producer is then related to pressure and volume of the fluid injected. A streamtube model is then coupled with the characteristic solution to estimate field-wide

Object	Reference	Fractal Dimension D
Projectile fragmentation of gabbro with lead	*Lange et al.* [1984]	1.44
Projectile fragmentation of gabbro with steel	*Lange et al.* [1984]	1.71
Meteorites (Prarie Network)	*McCrosky* [1968]	1.86
Artificially crushed quartz	*Hartmann* [1969]	1.89
Plane of weakness model	this paper	1.97
Disaggregated gneiss	*Hartmann* [1969]	2.13
Disaggregated granite	*Hartmann* [1969]	2.22
FLAT TOP I (chemical explosion, 0.2 kt)	*Schoutens* [1979]	2.42
Asteroids (theory)	*Hellyer* [1971]	2.48
PILEDRIVER (nuclear explosion, 61 kt)	*Schoutens* [1979]	2.50
Broken coal	*Bennett* [1936]	2.50
Interstellar grains	*Mathis* [1979]	2.50
Asteroids (theory)	*Dohnanyi* [1969]	2.51
Projectile fragmentation of basalt	*Fujiwara* [1977]	2.56
Sandy clays	*Hartmann* [1969]	2.61
Terrace sands and gravels	*Hartmann* [1969]	2.82
Pillar of strength model	*Allégre et al.* [1982]	2.84
Glacial till	*Hartmann* [1969]	2.88
Stony meteorites	*Hawkins* [1960]	3.00
Asteroids	*Donnis and Sugden* [1984]	3.05
Ash and pumice	*Hartmann* [1969]	3.54

FIGURE **13**

FRACTAL BLOCK SIZES

(After Turcotte, 1986)

project performance, historical data is used for model validation, and planned injection rates are then incorporated to forecast future performance. The use of fractal interpolation methods and the fractal distribution of heterogeneity is considered effective to be included in the simulation models and for estimating vertical sweep efficiency.

Incorporation of fractal dimension in the use of conditional simulation as a tool in modeling reservoir heterogeneity is presented in Hewett and Beherns (1990). The article concentrates on the use of field data and simulation to estimate flow properties and associated uncertainties. As part of the estimation procedures, it is observed that since geologic structures often exhibit high correlations, a power-law variogram can be constructed to account for the spatial structure of property variation. A specific component of the power-law variogram is the fractal codimension (the difference between the Euclidian dimension and the fractal dimension of the distribution). Kriging of the fractal variogram is then performed to construct realizations of random fields. Fractal dimensionality serves as the basis for generating an 850 ft geologic cross section which is then used to define the simulation domain for scale averaging of absolute permeability, dispersivity, and relative permeability.

Chang and Yortsos (1990) developed a general formulation for single-phase flow in a system that consists of a fractal fracture network embedded in a Euclidian matrix. Two cases were examined: where only the fractal fracture network participates in the flow and where both the matrix and the fractal fracture network participate. Their results indicate that identification and description of reservoirs with a high spatial disorder, poor connectivity, and multiple property scales is possible.

Ababou and Gelhar (1990) investigated the use of spectral conditioning as a means to examine the effective characteristics of flow in a medium having many scales of heterogeneity. Fractal dimension is discussed as one way to describe the heterogeneity of the medium. Closed form solutions were developed for the scale-dependent variance of hydraulic head and for the effective conductivity in a finite flow domain of size L. These statistical quantities were shown to be subject to inherent uncertainty due to unresolved heterogeneities at a larger scale. Their approach illustrates the distinction between spatial variability and uncertainty for finite scale hydrological phenomena.

Neumann (1990) postulated that dispersivity in both fractured and porous media may be a fractal process, defined by log-log scale relationships (Figure 14). Based upon this theory, a different dispersion would be appropriate to every modeling scale, with little variation between media. This work illustrates the practical application of fractal concepts in hydrogeology.

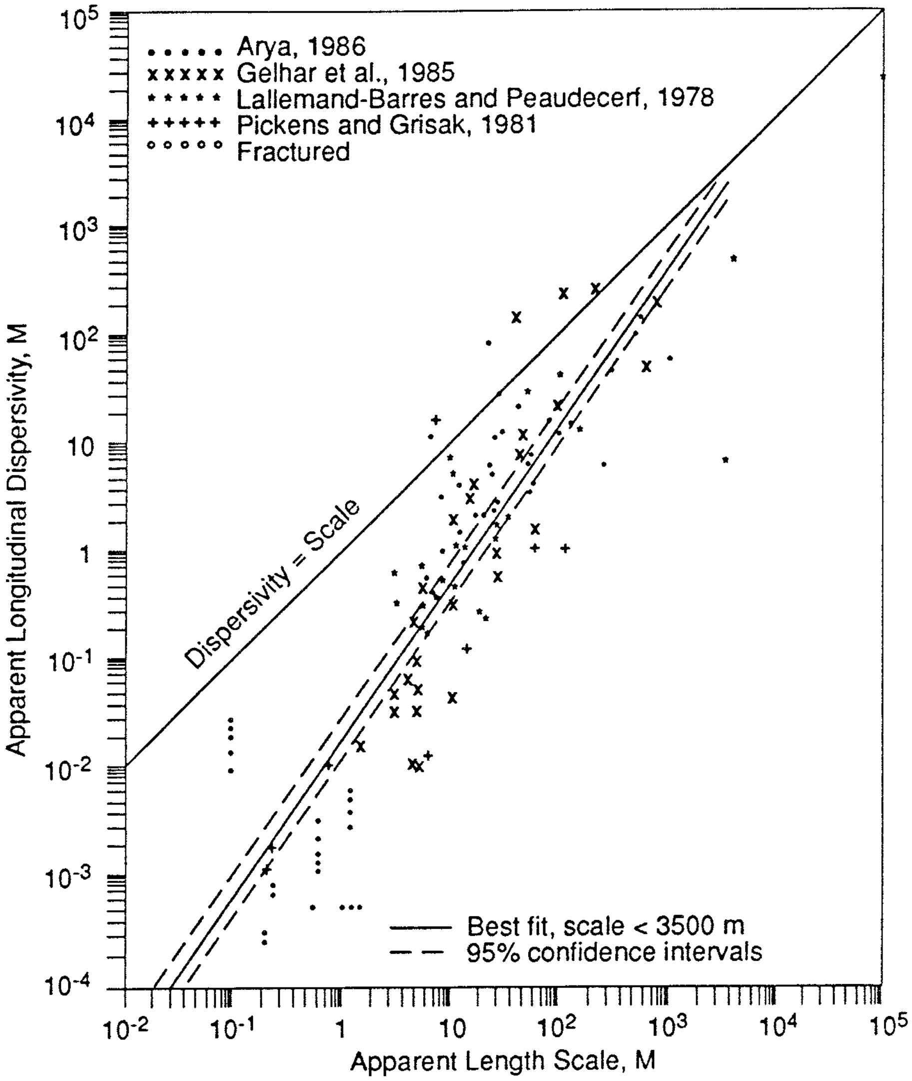


FIGURE **14**

FRACTAL (LOG-LOG) SCALING OF DISPERSIVITIES

(After Neuman, 1990)

2.5.1 Summary

The relationship between fractal dimension, fractional dimensional flow, and fracture connectivity is a three sided equation. The relationship between fractal dimension and fracture connectivity, and the relationship between fractional dimensional flow and fracture connectivity are both well established. The relationship between fractal dimension and fractional dimensional flow is intuitively reasonable, but can not be established on the basis of documents reviewed here.

3. TASK 2: SIMULATION OF ROCK WITH VARYING FRACTAL DIMENSION

Based upon the literature survey carried out to date, no field study has been carried out comparing the hydrogeology of sites with varying fractal dimension. Therefore, in order to evaluate the potential usefulness of fractal dimension as a metric and an index, geologic environments with a range of fractal dimensions were compared based upon simulations.

Simulations were carried out using the FracMan package (Dershowitz et al., 1991c).

Table 2 provides the parameters used in simulations. Figure 15 illustrates the discrete fracture conceptual model used in simulations.

Table 2. Parameters used in FracMan Simulations

Parameter	Value	
Geologic Conceptual Model	Levy-Lee Fractal Model 1000 m x 1000 m x 1000 m domain	
Intensity*	Varying P_{32} (m^2/m^3) from 0.0015 m^{-1} to 0.0075 m^{-1}	
Fractal Dimension	Varying D from 0.5 to 3.5	
Orientation	Mean Pole Trend	45°
	Mean Pole Plunge	45°
	Dispersion	Fisher κ=1 (uniform dispersion on the sphere)
Size	Mean	25 m
	Standard Deviation	25 m
	Distribution	LogNormal
Transmissivity	Mean	2.3 10^{-8}
	Standard Deviation	4.18 10^{-7}
	Distribution	LogNormal

Scoping simulations were carried out using the fractal Levy-Lee discrete fracture model (Geier et al., 1987) with levels of fractal dimension between 0.5 and 3.5, for a range of fracture intensities. Note that the Levy-Lee model is based upon a three dimensional process of fractal fracture centers, and does not ensure that the fractures themselves are self-similar, although trace planes through Levy-Lee clusters do appear fractal (Figure 10).

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*Intensity P_{32} is defined as fracture area per unit volume using the notation of Dershowitz and Herda (1992). P_{32} is a robust, scale invariant intensity measure.

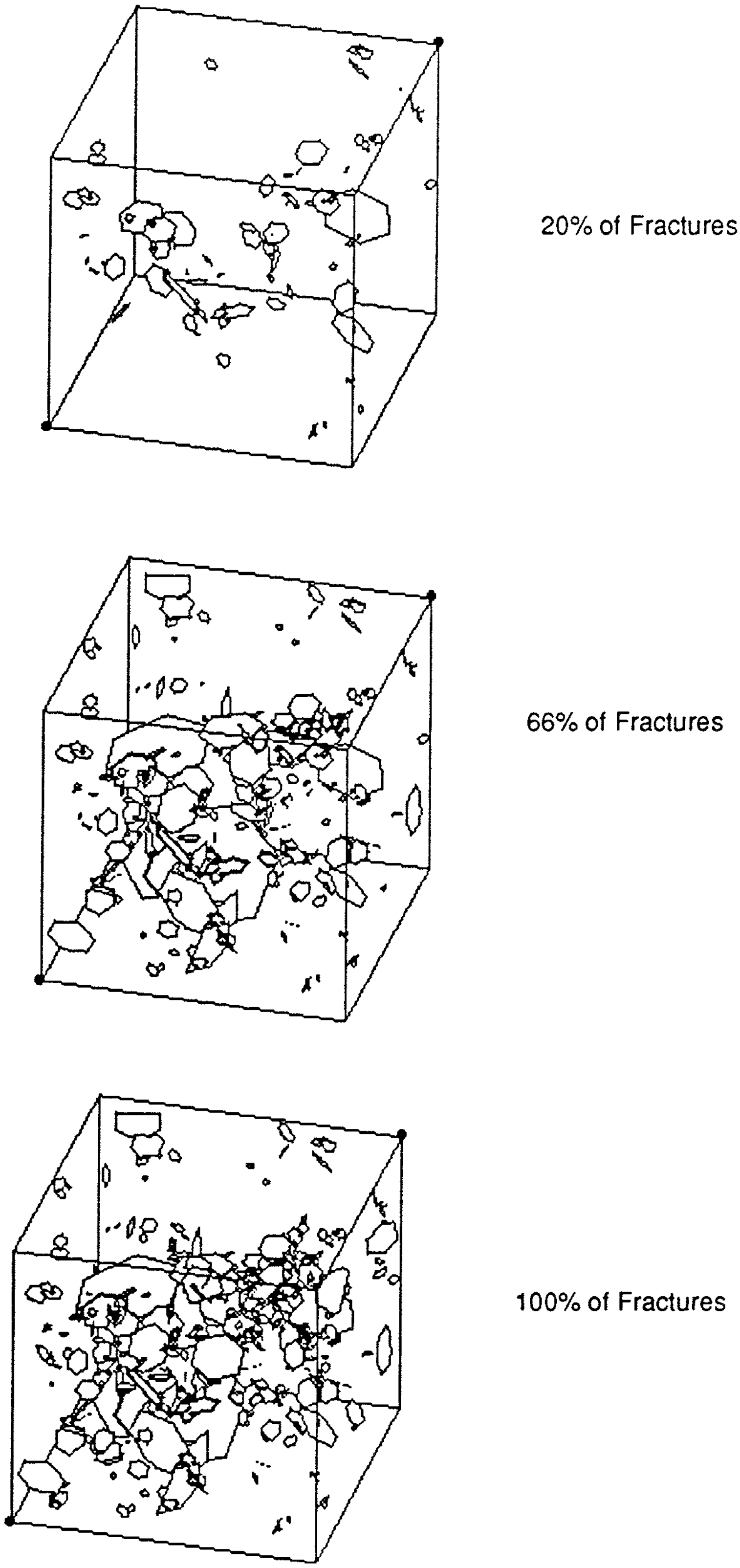


FIGURE **15**
DISCRETE FRACTURE MODEL USED FOR SIMULATION

Figures 17 through 29 show the relationships found between fractal dimension and other measures of rock mass hydrogeology. Fracture connectivity measures are explained in Figure 16. Throughout this section, "Fractal Dimension" refers to the mass density measure of dimension used in the Levy-Lee model.

- Figure 17: Connectivity measure C_1 (fracture intersections/m^3) increases dramatically with fractal dimension for the fracture geometry and range of fracture intensities simulated. Surprisingly, the importance of fractal dimension in determining connectivity measure C_1 is at least as great as intensity. This indicates that, as an index of connectivity, fractal dimension may be quite useful. Figure 18 presents the same information shown in Figure 17, with bounds indicating the range of results obtained in simulations for each level of fracture intensity.

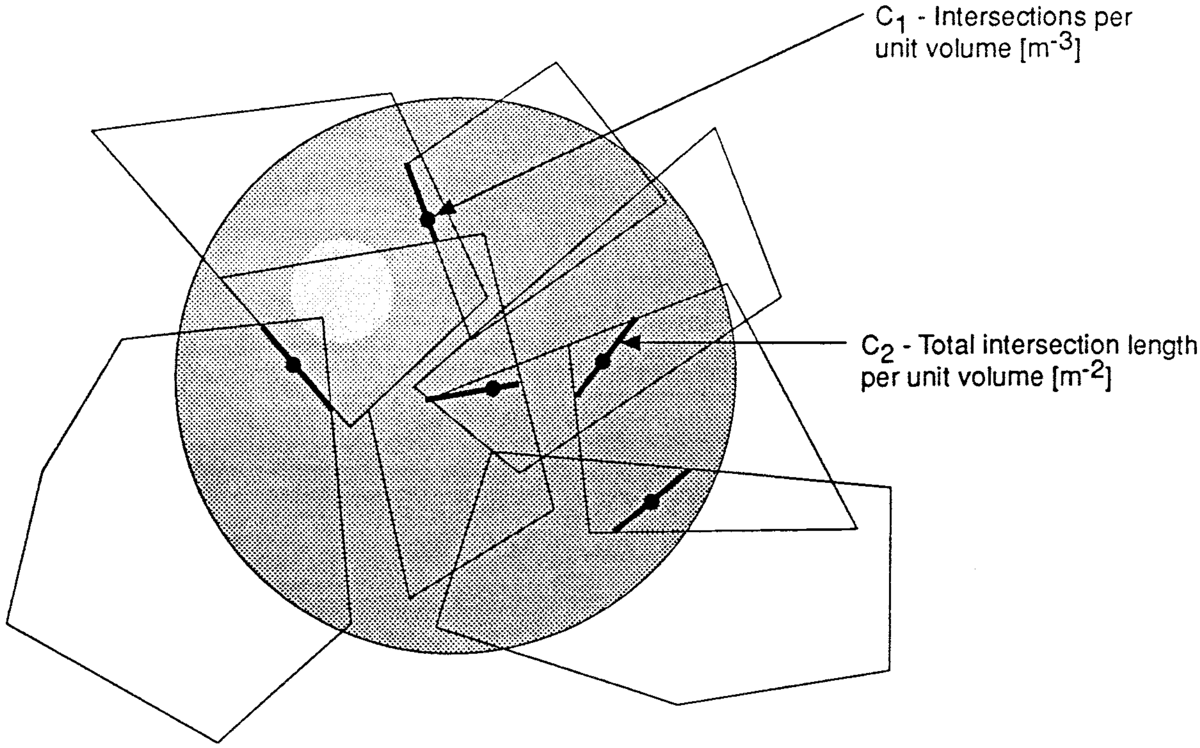
- Figure 19: Connectivity measure C_2 (fracture intersection length/m^3) follows approximately the same relationship with fractal dimension as C_1 . Figure 20 presents the same information shown in Figure 19, with bounds indicating the range of results obtained in simulations for each level of fracture intensity.

- Figures 21 to 23: Percolation probability is the probability of conductive pathway between locations in rock mass as a function of the distance between the locations. Figures 21 to 23 show the decrease in connection between boreholes as a function of the distance between the boreholes for fractal fracture systems at 5 levels of fracture intensity. Percolation probability is one of the best measures for the transport behavior of fractured rock, since percolation probability can be related directly to the probability that a pathway for solute transport will exist at a given scale. Comparison of figures 21, 22, and 23 indicates that fractal dimension is a good index for percolation probability, but must be considered within the context of the fracture length and intensity, which determine the scale of flow and transport.

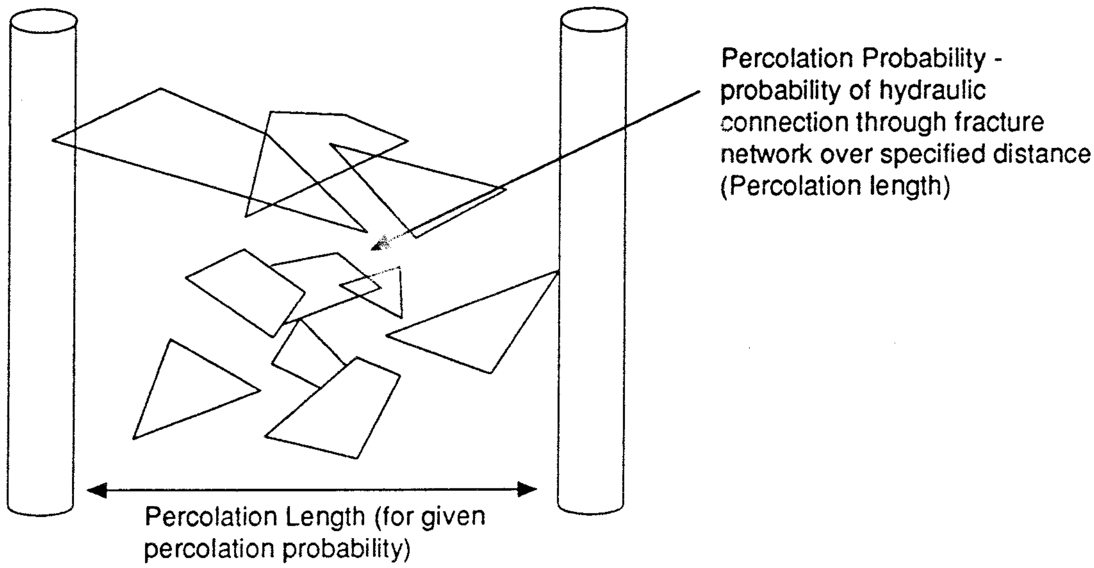
- Figure 24: Percolation length is the distance between points in the network for a given probability of connection. For the range of fracture intensities studied, it was not possible to clearly define the length for a 95% percolation probability. Figure 24 plots percolation length for a 50% percolation probability. For the Levy-Lee fractal geologic conceptual model, there appears to be a near-linear relationship between fractal dimension and the 50% percolation length.

- Figure 25: The conductance of fracture pathways (when pathways exist) generally increases more rapidly with fractal dimension than with fracture intensity in the range studied. This again indicates that fractal dimension may be a good indicator of site suitability.

- Figures 26 to 29: The equivalent block size measures calculated by FracMan are defined in Figure 26. These block size measures are defined as 1-D (width), 2-D (surface area), and 3-D (volume) measures. All of these measures are approximate, since stochastic discrete fractures do not define completely distinct



ⓐ Connectivity Measures C_1 and C_2



ⓑ Percolation probability and percolation lengths

FIGURE **16**

CONNECTIVITY MEASURES

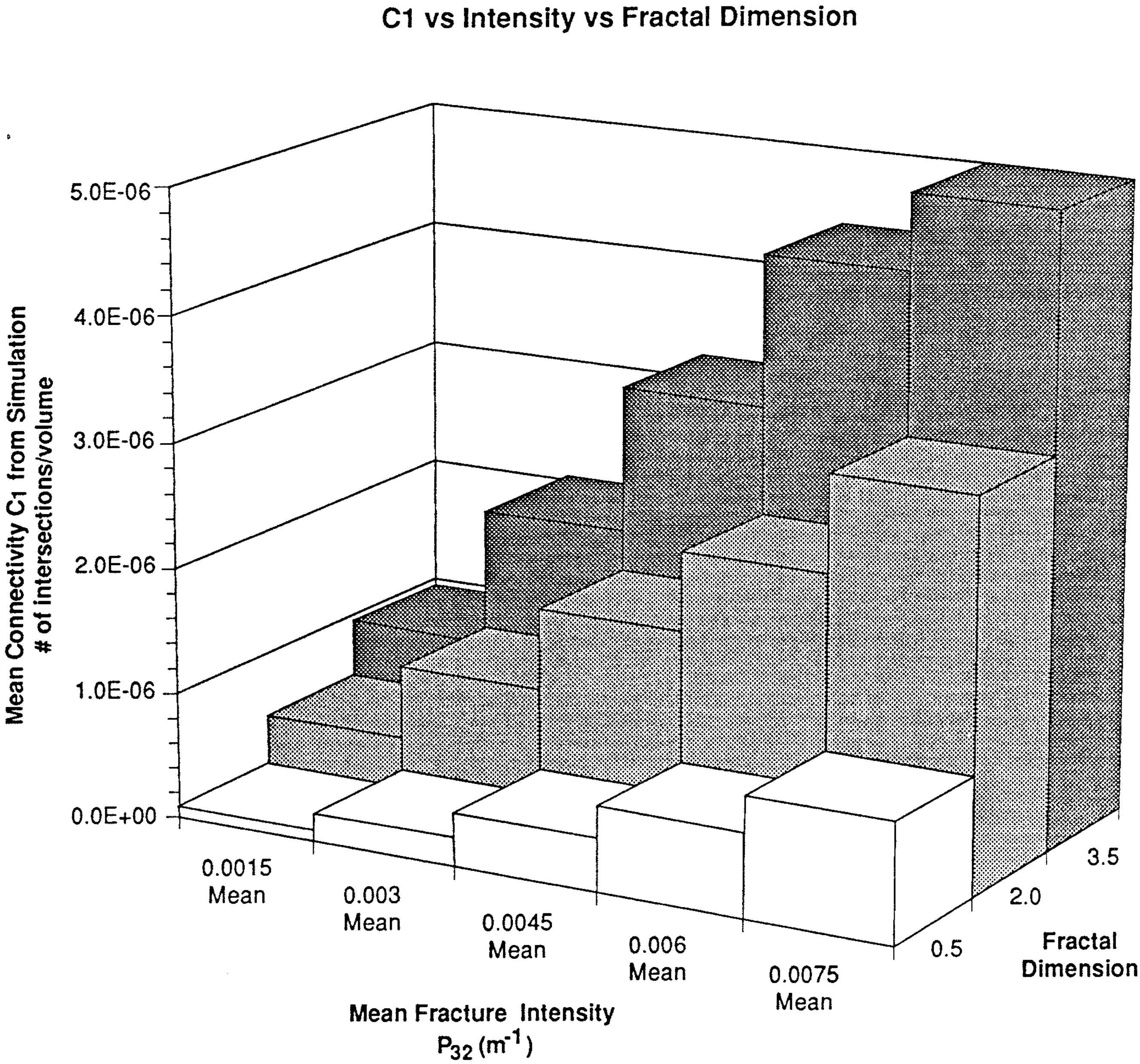


FIGURE 17
C1 VS INTENSITY AND FRACTAL DIMENSION

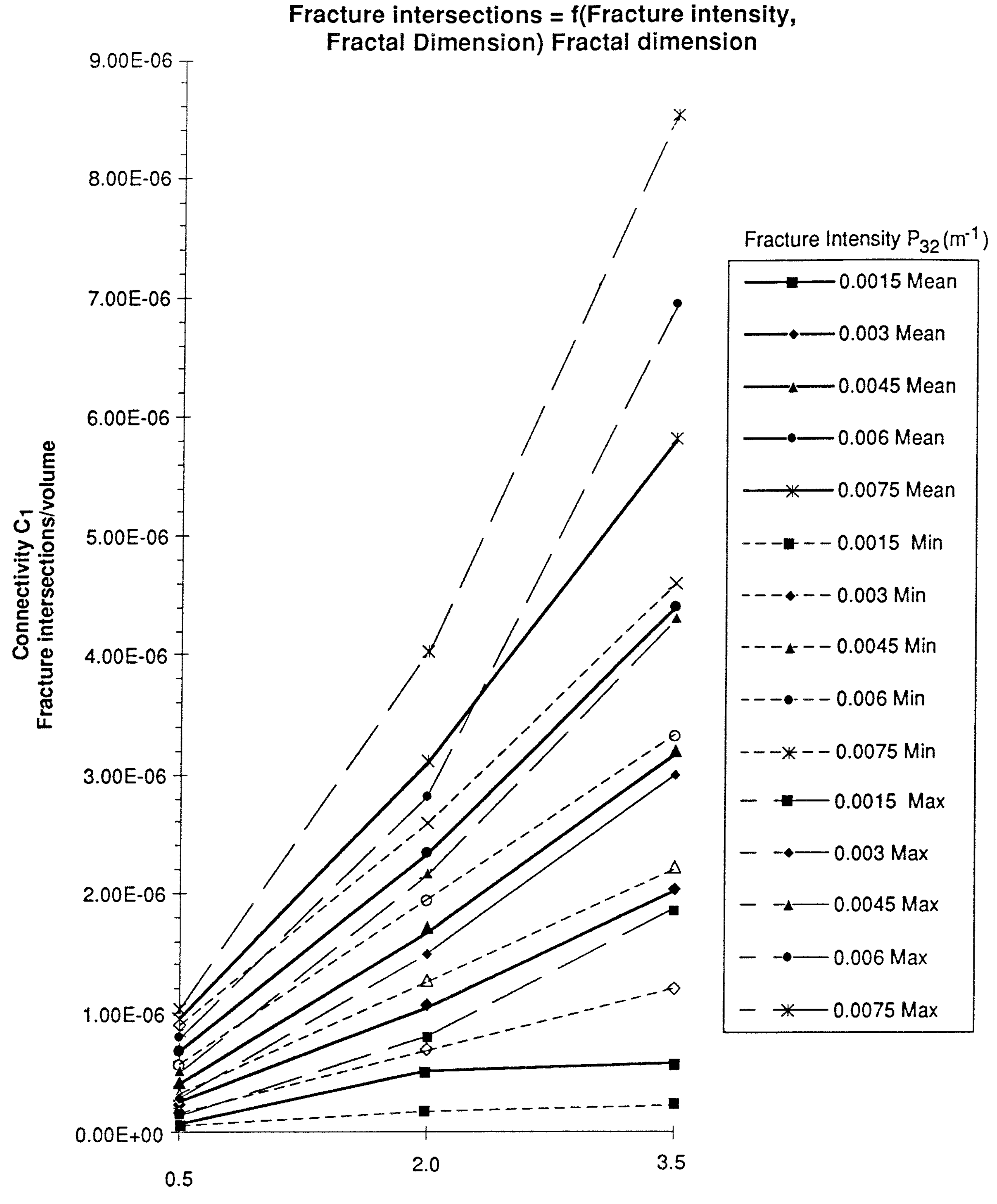


FIGURE 18

CONNECTIVITY C_1 FROM SIMULATION, WITH MINIMUM, MAXIMUM, AND MEAN SHOWN

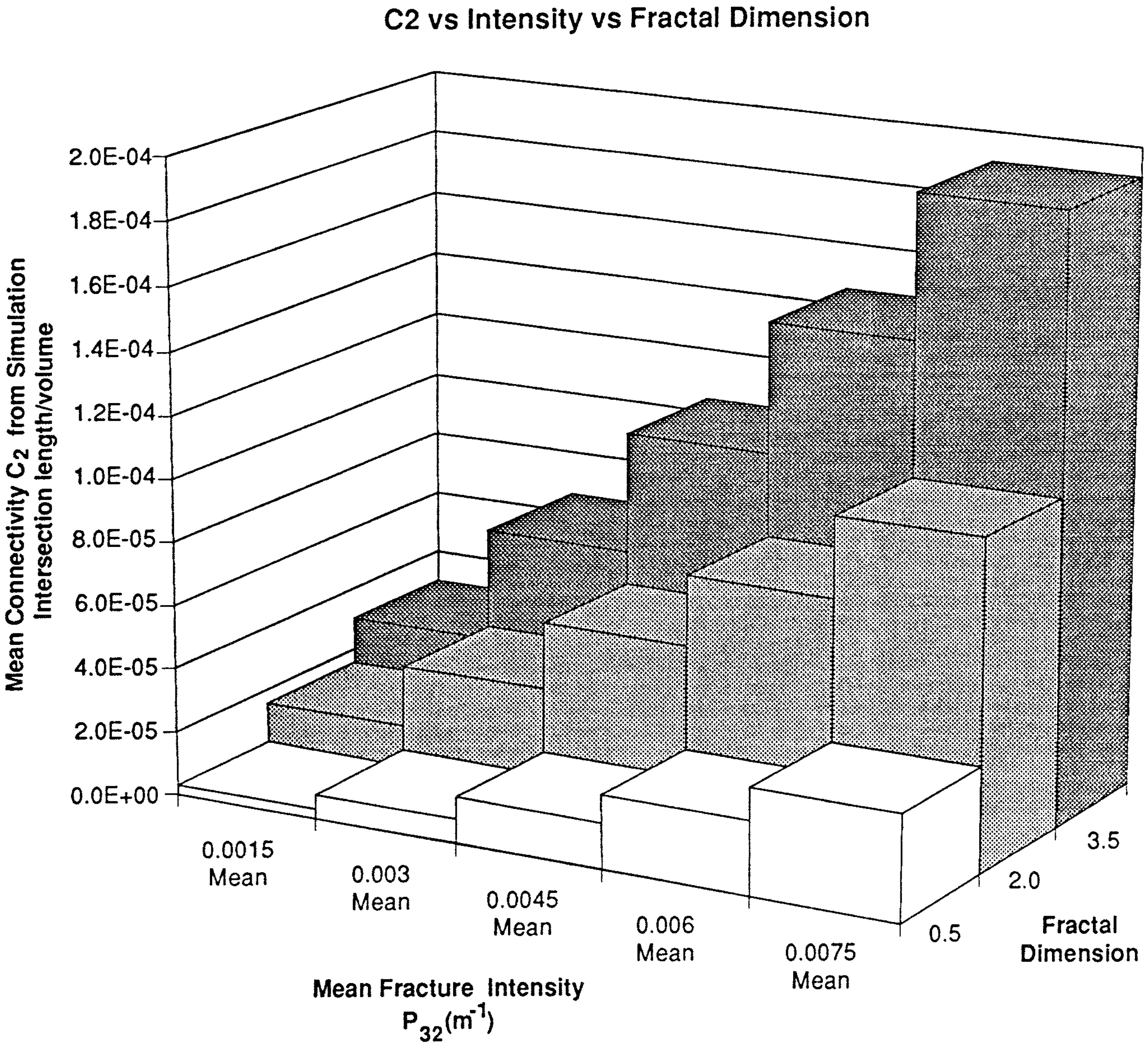


FIGURE 19
C2 VS INTENSITY AND FRACTAL DIMENSION

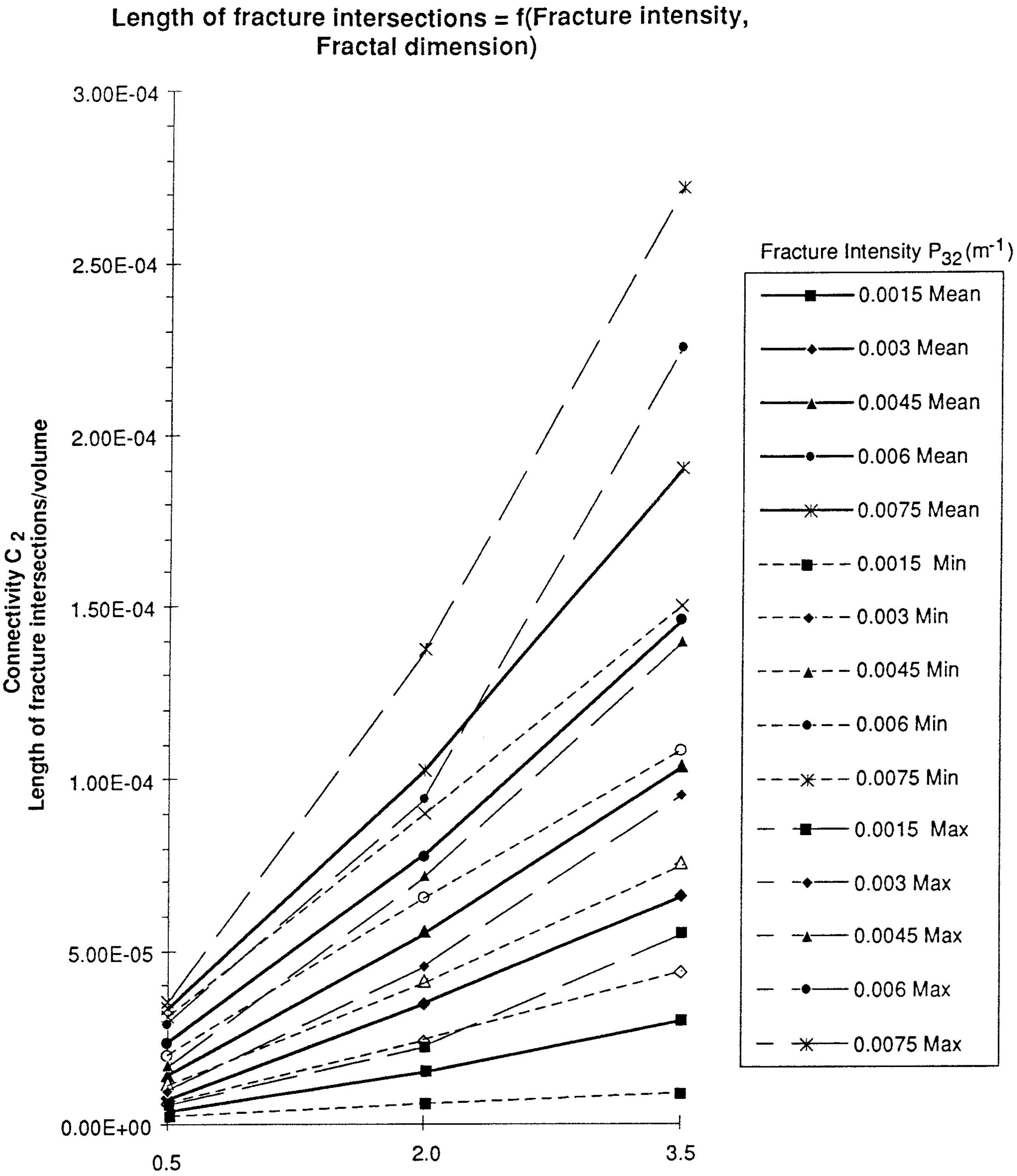


FIGURE **20**

CONNECTIVITY C_2 FROM SIMULATION, WITH MINIMUM, MAXIMUM, AND MEAN SHOWN

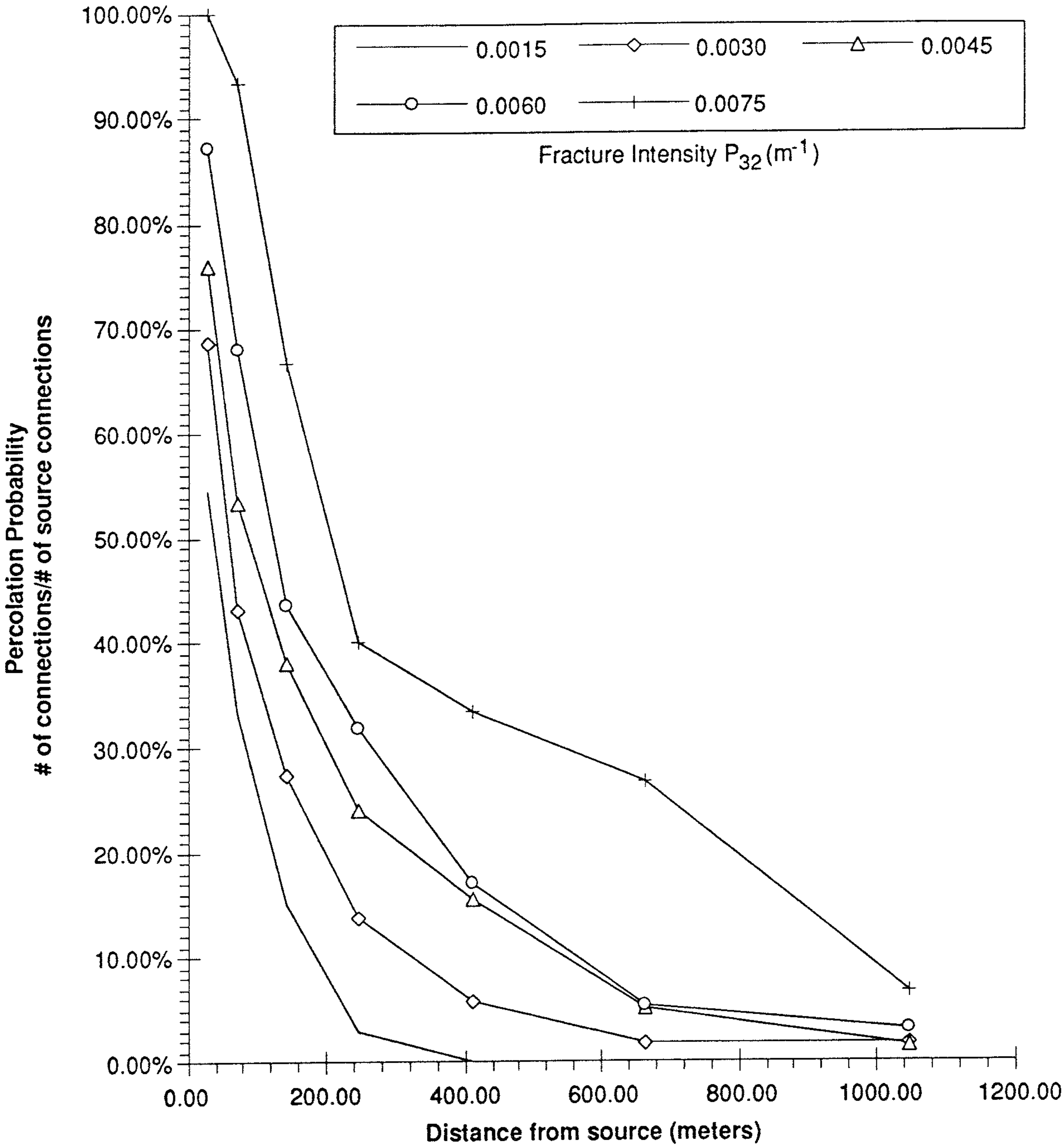


FIGURE **21**

PERCOLATION PROBABILITY FOR FRACTAL DIMENSION = 0.5

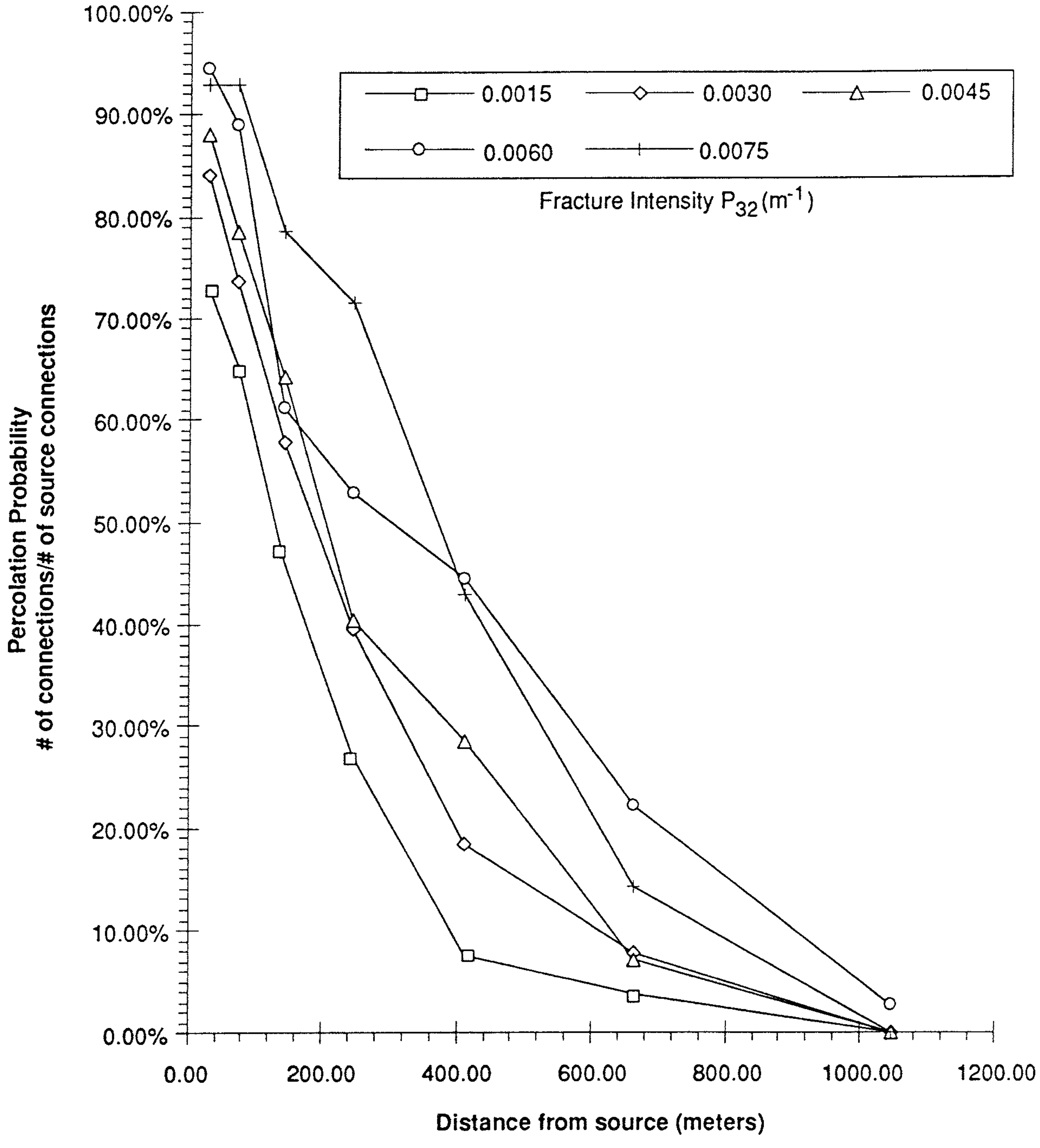


FIGURE **22**

PERCOLATION PROBABILITY FOR FRACTAL DIMENSION = 2.0

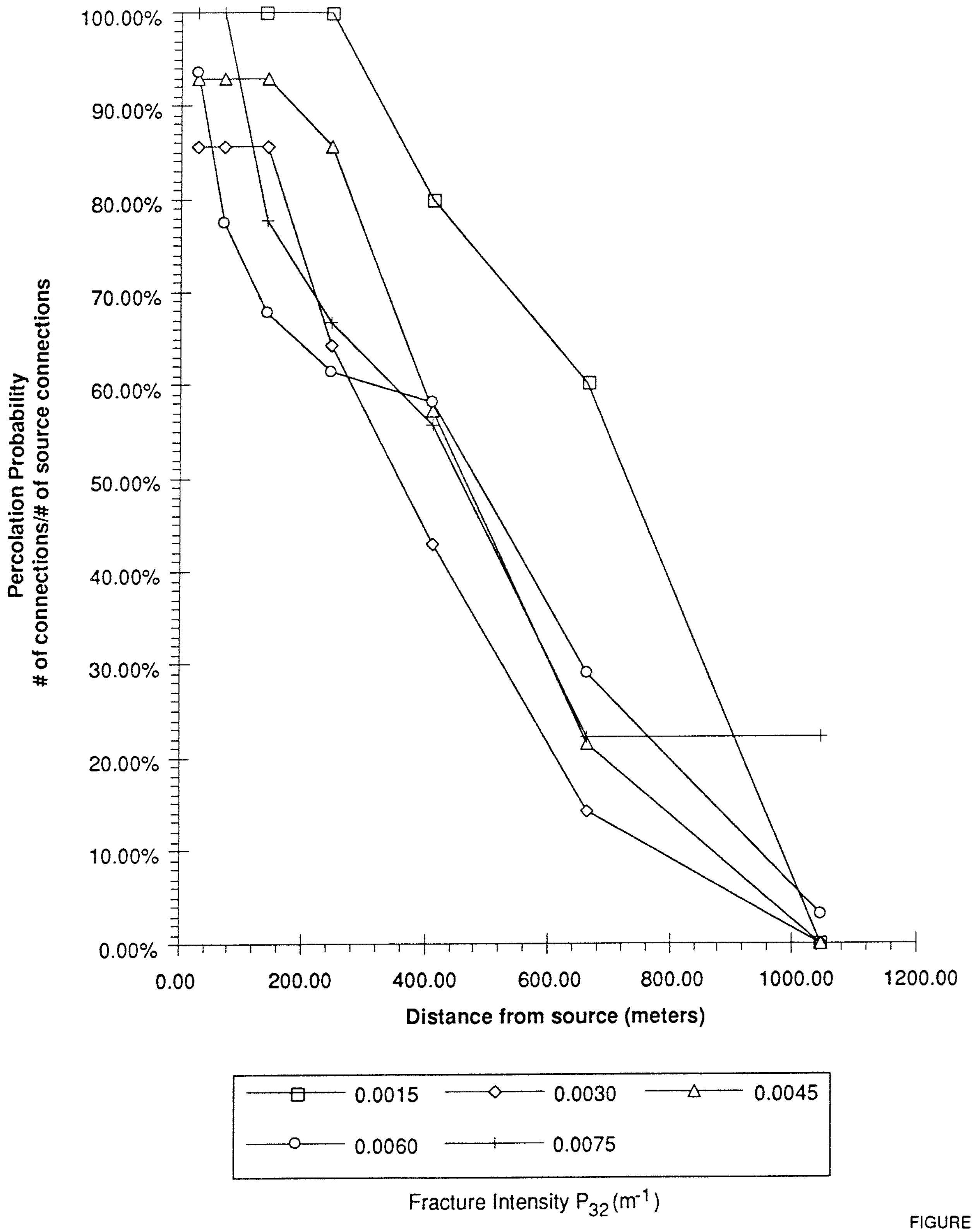


FIGURE **23**

PERCOLATION PROBABILITY FOR FRACTAL DIMENSION = 3.5

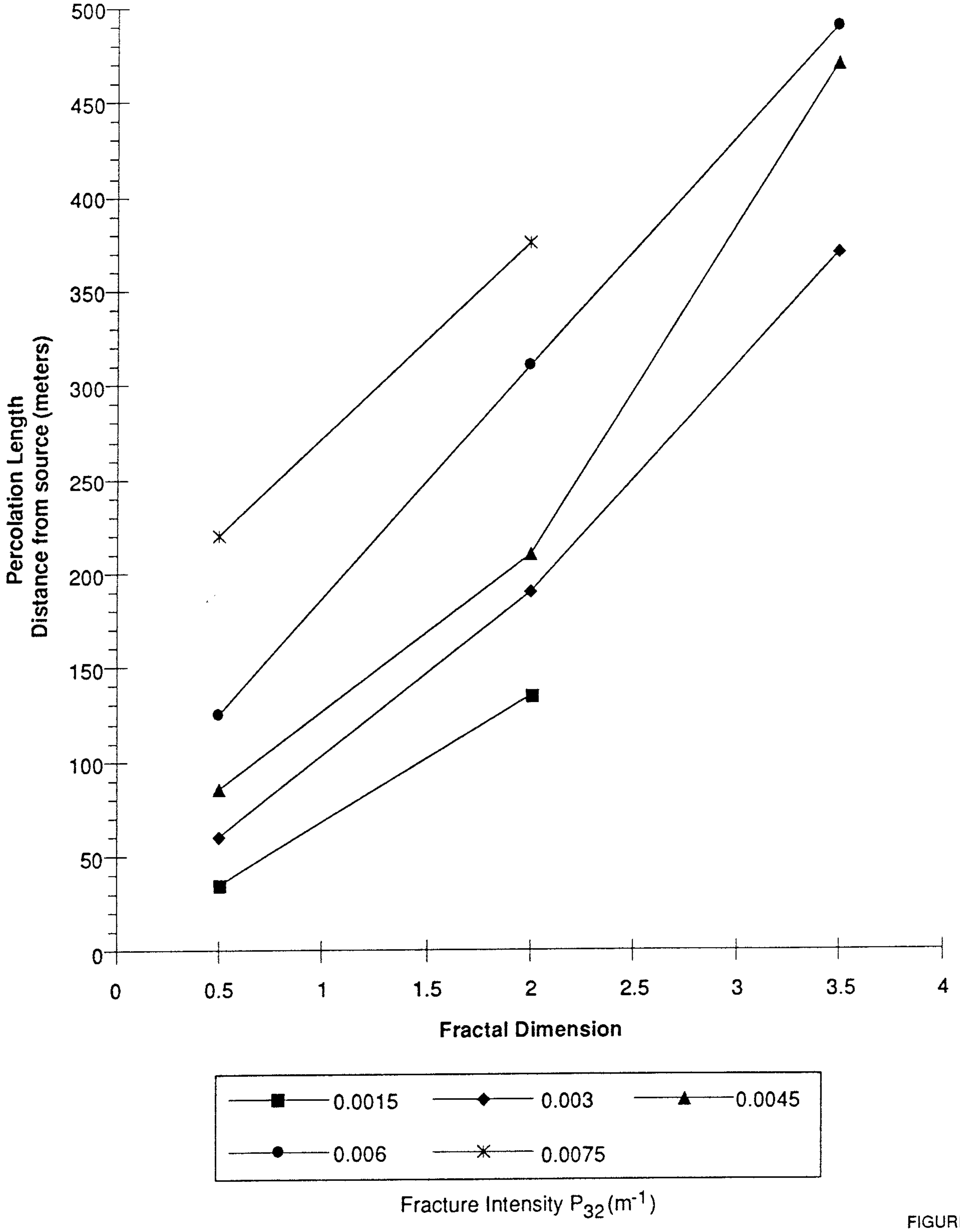


FIGURE **24**

PERCOLATION LENGTH FOR 50% PERCOLATION PROBABILITY

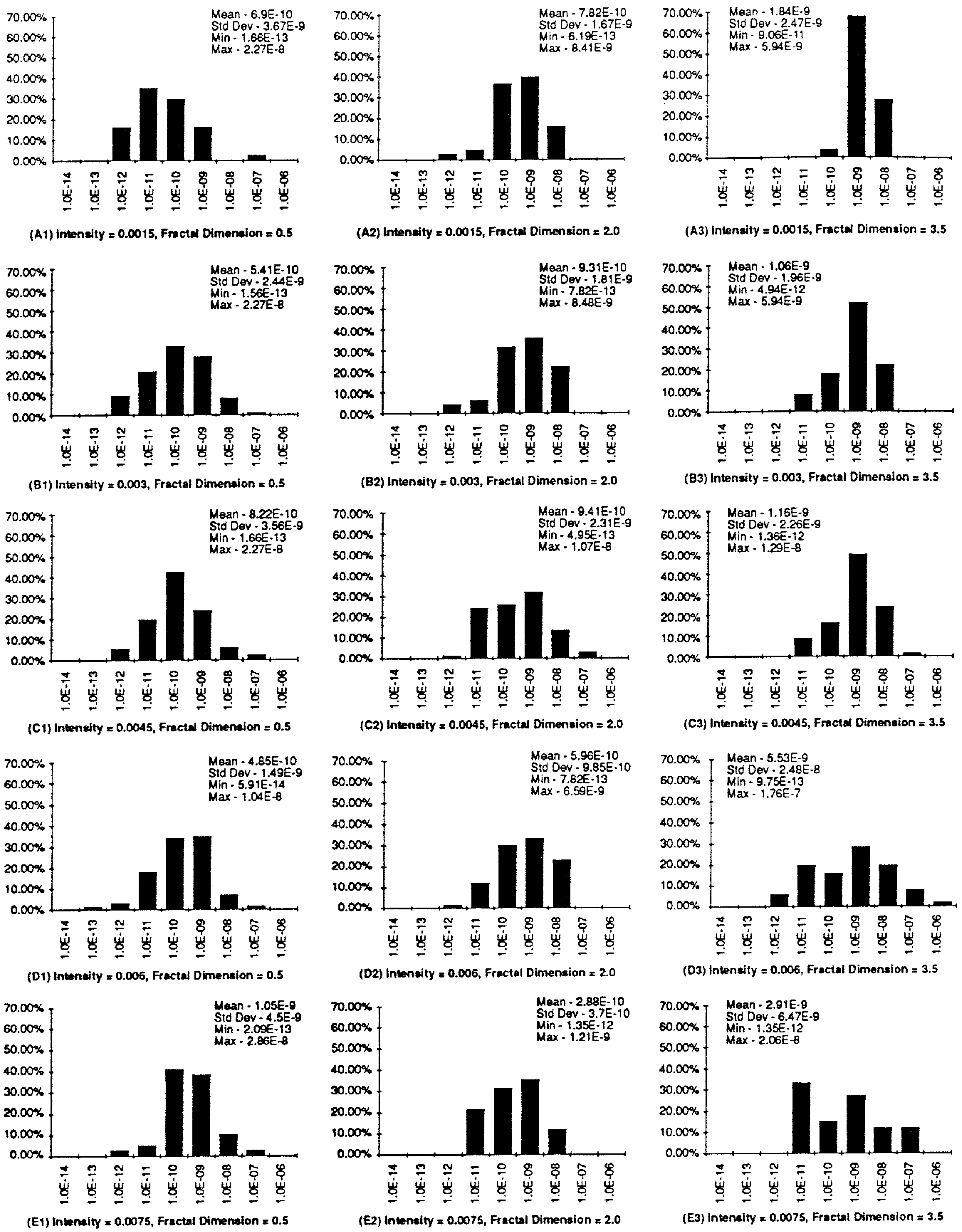


FIGURE 25
PATHWAY CONDUCTANCE
DISTRIBUTION FROM SIMULATION

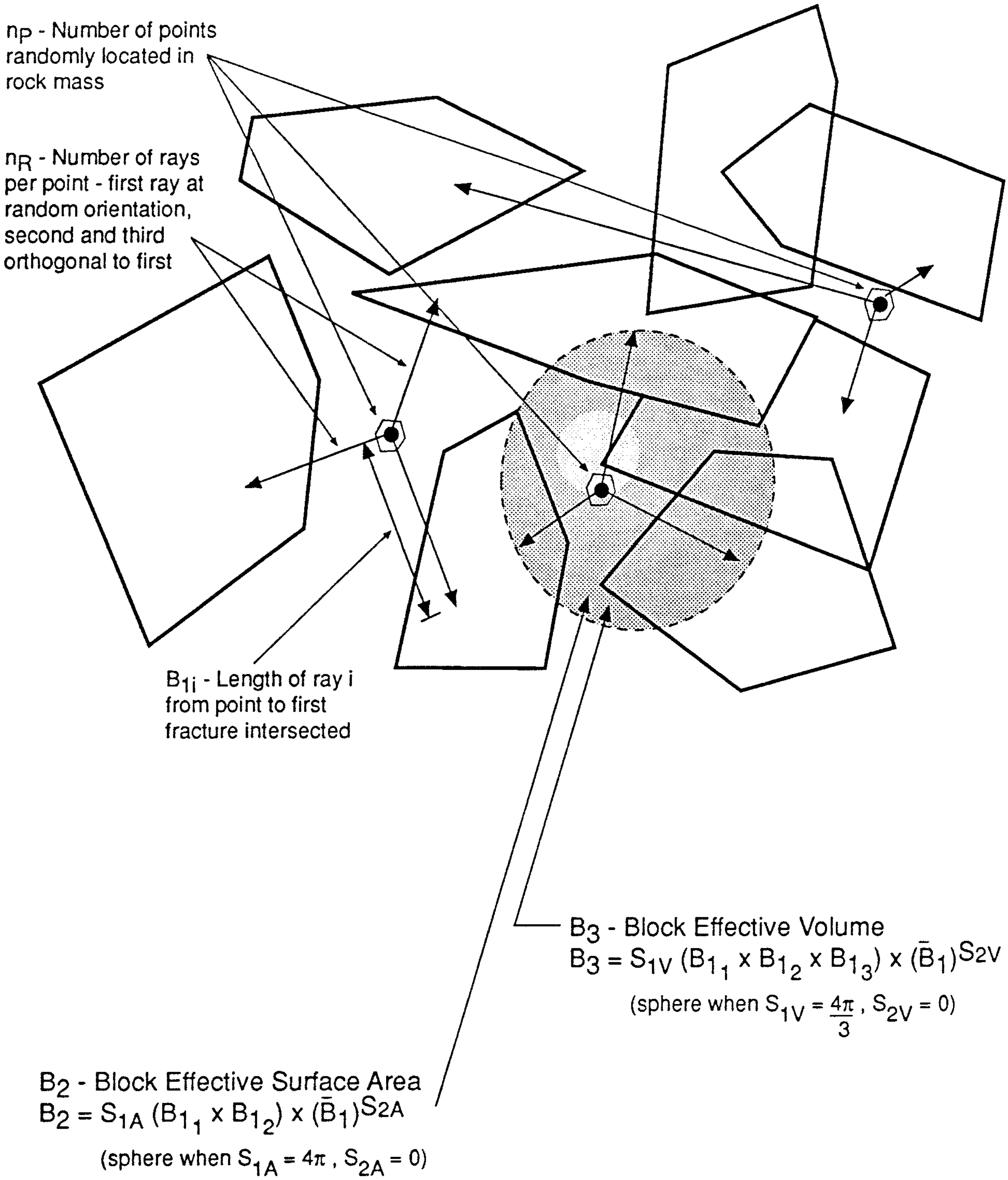


FIGURE **26**

BLOCK SIZE MEASURES

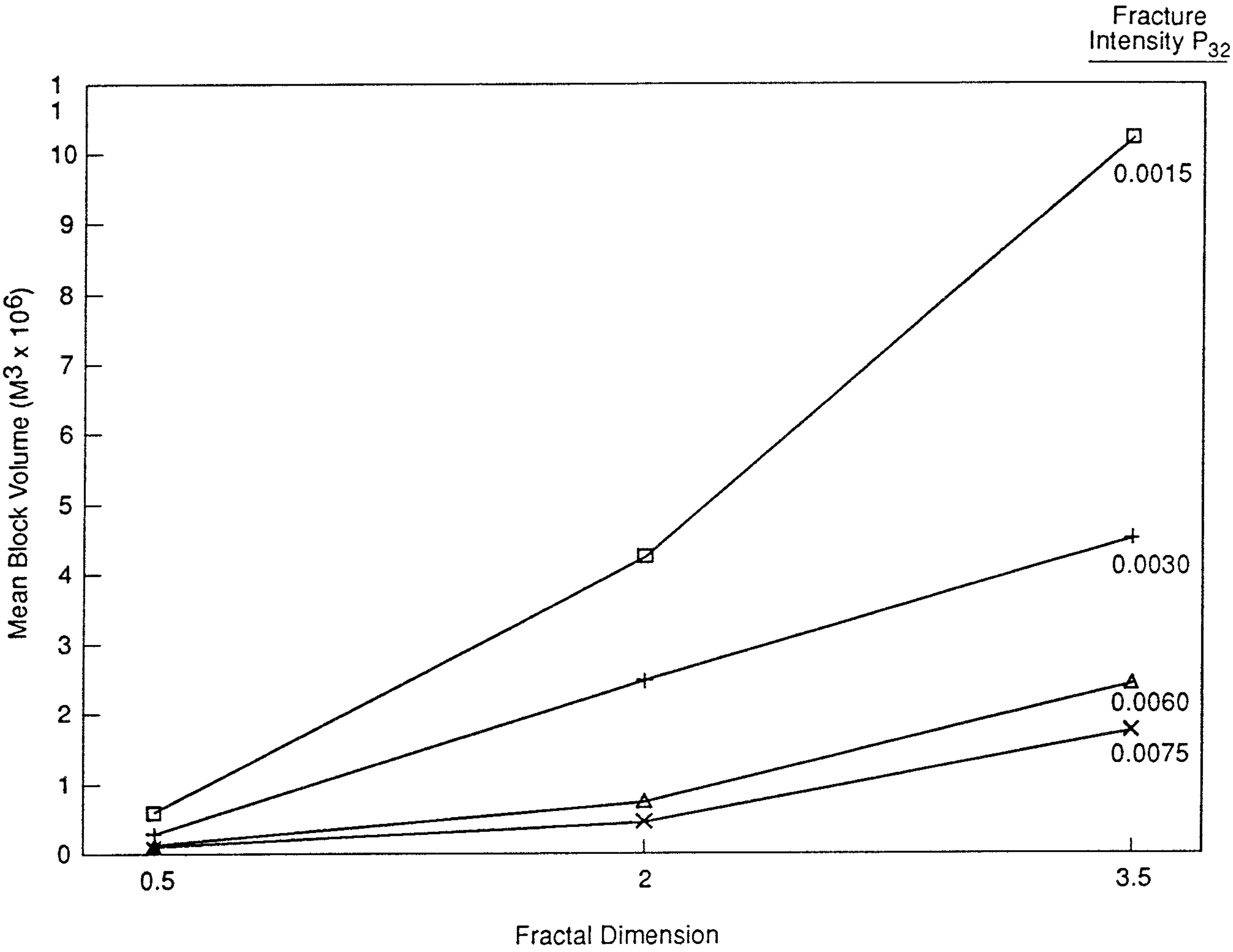


FIGURE **27**
MEAN BLOCK VOLUME VS FRACTAL DIMENSION D

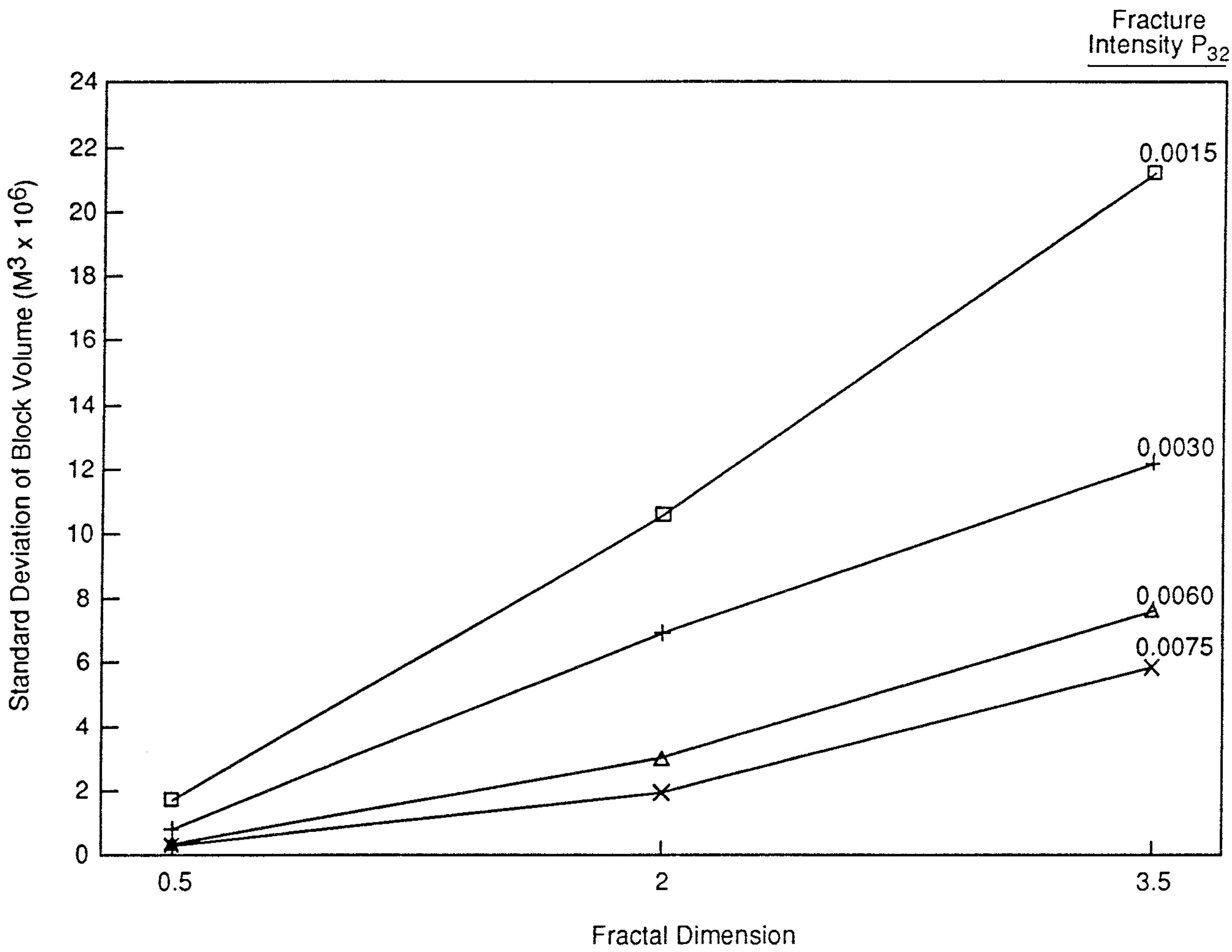


FIGURE 28
STANDARD DEVIATION VS FRACTAL DIMENSION D OF BLOCK VOLUME

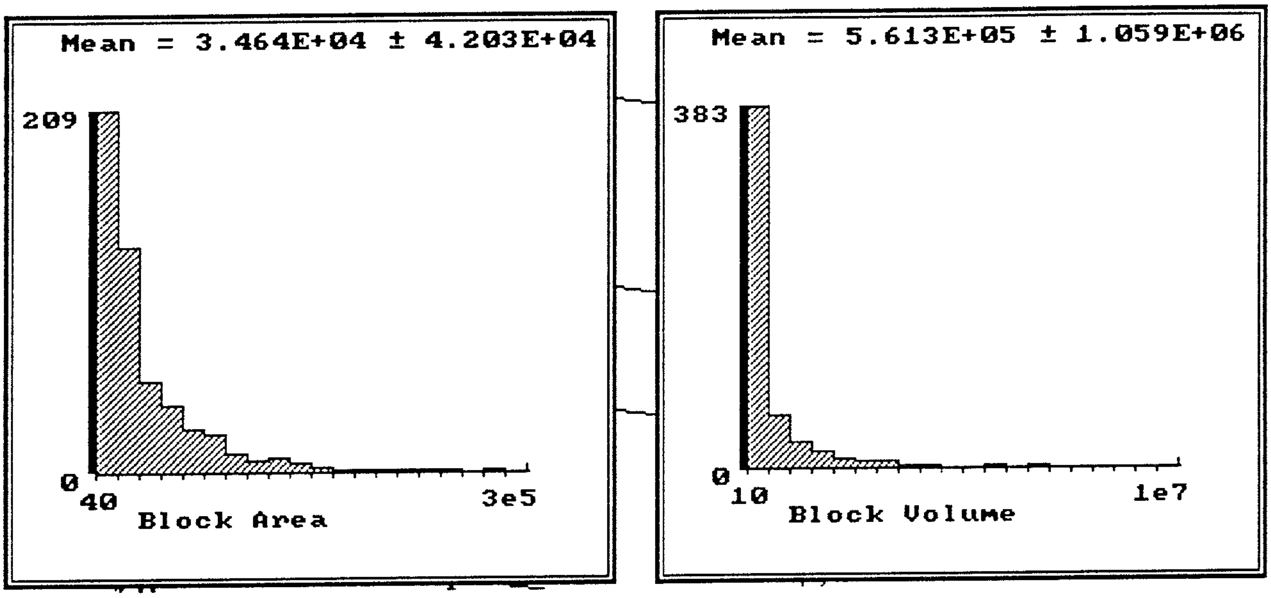


FIGURE 29
ROCK BLOCK SIZE DISTRIBUTIONS
P_{32}=0.0015
D=0.5

rock blocks, except for cases with high fracture density or fracture size. Block measures are defined based upon analysis of lengths from randomly oriented rays between randomly located points within a rock mass and the first fracture intersected. These measures are relatively efficient computationally, and are well correlated to block surface area and dimension measured in regular fracture patterns.

Figures 27 and 28 show the mean and standard deviation of rock block volume measure B_v for the range of intensities and Levy-Lee fractal dimensions simulated. As with connectivity measures, rock block size measures are strongly influenced by fractal dimension. Figure 29 shows example block surface area and block volume measure results from a FracMan simulation.

Analysis of variance under a random effects model of the data contained in Figures 17 and 18 indicates that connectivity measure C_1 (fracture intersections/m^3) is significantly ($P < 0.01$) affected by both fractal dimension for the fracture geometry and the range of fracture intensities (0.0015 - 0.0075). The same conclusion was found for rock block volume measures shown in Figures 27 and 28. However, the connectivity and rock block size measures may provide a more directly useful measure of fracture heterogeneity and pattern than fractal dimension, for evaluation of potential repository sites.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 General

An extensive literature survey was carried out on the application of fractals for comparison of hydrogeologic environments. Although no applications were identified that directly applied fractals as a hydrogeologic index, personal contacts in the oil industry indicated that fractal dimension is used to select locations for production and exploration wells. Extensive references were found to empirical studies of the fractal nature of fracture geometry and fractured rock hydrogeology. These papers demonstrated that consistent and meaningful fractal dimensions can be derived from lineaments, fracture maps, and fracture surfaces, and that the fractal dimension can be used to compare different geologic geometries. A further significant indication of the potential usefulness of fractal indices is the relationship found between rock block size distributions and the fractal dimension for a wide variety of fracture patterns cited in the literature.

Numerical simulations carried out with the FracMan model indicate that fractal dimension appears to be a useful index for fracture connectivity and block formation. Since fracture connectivity is strongly related to both large scale and small scale radionuclide transport, this indicates potential usefulness of the fractal dimension as an index for site comparison. Surprisingly, fractal dimension seems to have as strong an effect on connectivity and block formation as fracture intensity, at least within the range simulated.

Based upon both the literature survey, and numerical simulations, it appears that fractal dimension can be used to distinguish geologic environments. However, further study will be required to determine which values of fractal dimension are preferable for repository location in particular geological environments.

4.2 Limitations

This study has identified the following constraints on the practical application of fractal methods for comparison of hydrogeologic environments:

- Fractal dimension must be defined in the context of the method used to calculate dimension.

- Fractal dimension calculation approaches are limited to the analysis of self-similar or self-affine patterns. While most methods are applicable to self-similar patterns, most geologic processes can be expected to be self-affine. Further, most methods for defining heterogeneity are limited to analysis of rough surfaces or point processes, rather than processes of lines in a plane (e.g., lineaments and traces) or planes in three dimensional space.

- Lineament or trace density should be defined in terms of lineament length per unit area (P_{21}), rather than conventional concept of "spacing", which is limited to specific directions. P_{21} can be readily converted to three dimensional intensity P_{32} (area per unit volume). These transformities are described in Dershowitz and Herda (1992).

- Features formed by different geologic/tectonic processes may have different fractal dimension. This may result in superposed dimensions (multifractals), which make it difficult to extrapolate between scales, since different effective fractal dimensions may apply at different scales.

- A wide variety of index measures are available to describe the pattern of geologic features, including geostatistical variograms, spatial process statistics, and percolation measures. In this study, connectivity measures C_1, and C_2, block size measures, and percolation probabilities were evaluated. These measures may be more directly correlated to hydrologic behavior, and may be preferable to fractals as index measures for site comparisons.

4.3 Recommendations

Recommendations to SKB for the application of fractals in evaluation and comparison of potential repository sites are summarized as follows:

- Calculation of fractal dimensions for lineament patterns is an easy and inexpensive method to obtain useful, quantitative information about the heterogeneity of discrete features. Fractal dimensions should therefore be calculated as a standard procedure as part of the analysis of fracture and fault patterns.

- Multiple methods should be used for calculating fractal dimensions, including methods designed for both self-affine and self-similar fractures. The Box, Density, Spectral Density, and Variogram methods are recommended.

- In addition to fractal dimensions, intensity, connectivity, and block size measures should be calculated from discrete feature patterns. Connectivity measures may be particularly valuable for comparing sites in terms of the probability of significant pathways for radionuclide migration, and block size measures may be valuable for analysis of the potential for significant "rock cans" suitable for canister placement.

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