FRACTAL CHARACTERIZATION OF THE FRACTURE DISTRIBUTION AND THE PERMEABILITY IN GEOTHERMAL RESERVOIRS

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Abstract
A basis for modeling geothermal reservoirs using a fractal model for fracture size and distribution **was** studied. Core samples and lost-circulation data from geothermal wells in the Kakkonda geothermal field, Japan were investigated and statistically analyzed. The results of the core analysis show a fractal distribution of fracture width and spatial distribution. Results of the analysis of lost circulation data also indicates that the fracture size and continuity are fractal in geothermal reservoirs. These results show that the modeling of the fracture system in geothermal reservoirs using fractal theory is possible.

Key words: geothermal reservoir, fractal geometry, fracture system, Kakkonda, core observation, lost circulation.

1. INTRODUCTION

It is obviously an important task to evaluate fracture size, distribution and permeability distribution within geothermal reservoirs. However, the complexity of the fracture network requires s many different types of investigation to reveal the detail and it is therefore desirable to devise evaluation and modeling techniques requiring as few parameters as possible.

Recently, fractal distributions have been utilized to evaluate fracture networks. Fractal geometry applied to the study such features such as fracture length and spatial distribution has been described by many authors (e.g. Meredith, 1990, Ohno et al., 1992, 1993 and Tsuchiya et al., 1993). Sammis et al. (1992) have used fractals to investigate the fracture structure in the Geysers geothermal reservoir by investigating outcrop and core samples. Pressure transient analysis of geothermal reservoirs with fractal characteristics has also been studied (e.g. Chang and Yortsos, 1990). However, insufficient research **has** yet been done on the fractal characteristics of fractured geothermal reservoirs to allow fractal geometry to be applied on a routine basis. Therefore, this paper describes the results of an analysis of fractures, in terms of their spatial distribution, width and permeability, using core samples and lost circulation data from the Kakkonda geothermal field in Japan. The main purpose of this study is to develop an understanding of the fracture geometry and sampling problems in geothermal fields **in** terms of fractals as a preliminary to developing a fractal based on reservoir evaluation system.

2. OUTLINE OF THE KAKKONDA GEOTHERMAL FIELD

The Kakkonda (Takinoue) geothermal field is located about 600km northeast of Tokyo and is one of the most active liquid-dominated geothermal areas in Japan (Fig.1). The first power plant, Kakkonda Unit1, 50MW, has been in operation since 1978 by Tohoku Electric Power Inc., where Japan Metals and Chemicals Co.. Ltd. (JMC) **is** a steam supplier. Currently, development of the Kakkonda Unit2, 30MW, **is** being continued by the same method. In the Kakkonda geothermal field, more than 30 production wells and more than 20 reinjection wells were drilled in **1 x** 2.5km areas. These wells were drilled at eleven drilling pads as shown in Fig.2.

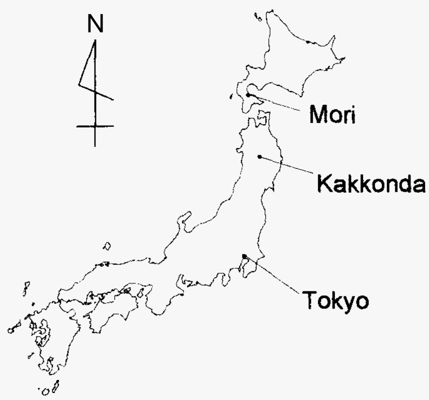


Fig.1 Location of the Kakkonda geothermal field, Japan

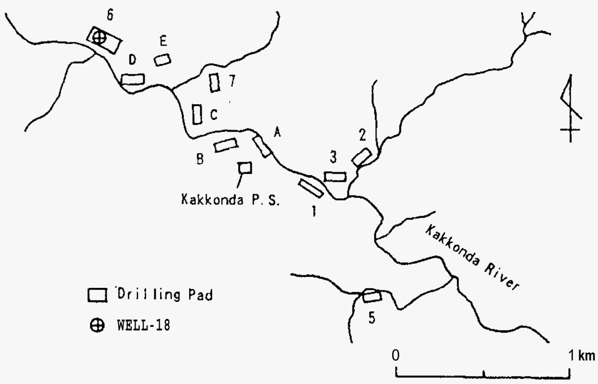


Fig.2 Location of the drilling pads and Well-18 in the Kakkonda geothermal field

The geologic column of the Kakkonda geothermal field comprises the Tamagawa Welded Tuffs, Miocene formations, Pre-Tertiary formations, old intrusive **rocks** and the neo-granitic pluton (Nakamura and Sumi, 1981, Sato, 1982, Doi et al., 1988, Kato et al., 1993, Koshiya **et** al., 1993). **The** Kakkonda hydrothermal system was found to consist of two reservoirs with different characteristics, shallow reservoir and deep reservoir. The boundary between the two reservoirs is indicated by a rapid increase in bore-hole temperature around the 1,500m depth (Doi et al., 1988, Kato and Doi, 1993). The shallow reservoir has temperatures in the range 230-260℃ with high permeability while the deep reservoir is less permeable and has temperatures of 300–350℃ and above.

At outcrop, many hydrothermal veins are seen (Muramatsu, 1987). NW–SE striking and NE–SW to E–W striking fractures, steeply dipping, dominate (Koshiya **et** al., 1994). In the shallow reservoir, permeable **zone** mainly extends NW–SE with branches towards the NE–SW direction (Doi **et al.,** 1988).

3. EXAMINATION OF FRACTURES OBSERVED IN CORES FROM A GEOTHERMAL RESERVOIR

Fractures observed in core from exploration hole Well–18 were used to study the fracture geometry in geothermal reservoirs.

Well–18 (Fig.2) was drilled to explore the deep reservoir and is almost vertical to its final depth of 2,126m. Figure.3 shows the lithology, lost circulation horizons and the results of temperature logging. Coring was continuous from 690m to the bottom. Core diameter between 690m and 1,800m is 63mm; below 1,800m it is 45mm. Many instances of lost circulation caused by hctures were encountered during drilling.

3.1 Core Investigation

Three fracture types were defined; vain, slickenside and open.

Vein fractures are filled with hydrothermal minerals; some of these may also be open with drusy mineralization lining the open cavities. A slickensided fracture show the results of shear displacement in the development of mechanical slip lines on the fracture surface. Open fractures are divided into drusy (see above) and altered. *An* altered open fracture does not have any hydrothermal minerals. All open fractures are potential pathways for geothermal fluids. Maximum thickness of veins and the width of open fractures were measured, with the exception of fractures bounding pieces of separated core. Altered open fractures above 1,300m were not measured.

Figure 4 shows the number of veins, slickensided, drusy and altered open fracture for each 10m of core. Veins are found in every rock type. Slickensided fractures are found mainly in shale and muddy rock while virtually none are found below 1,500m. Altered open fractures are found mainly between 1,300 and 1,400m. Drusy open fractures are found mainly around 1,000m and 1,600m while virtually none are distributed between 1,100 and 1,500m. The distribution of slickensided and altered open fracture appears to be similar. Also, the distribution of veins and drusy open fractures appears to be similar. There is a tendency for episodes of lost circulation to be concentrated around formations in which many veins and druses are found.

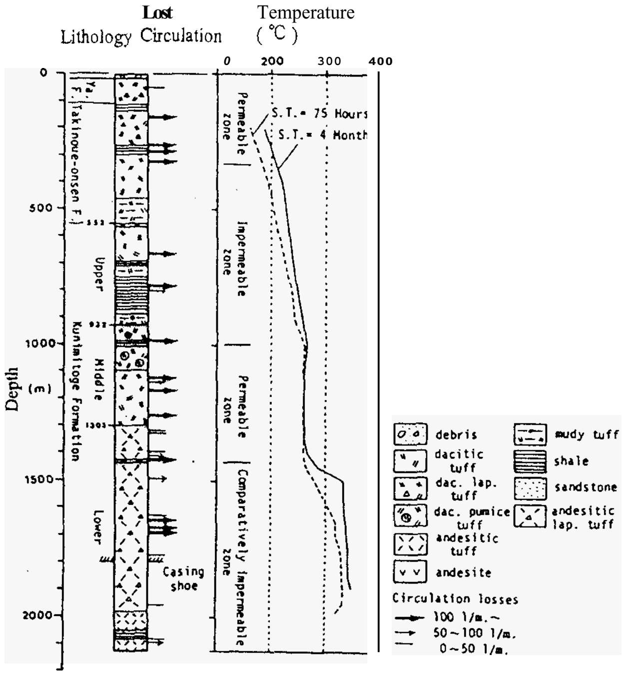


Fig.3 Lithology, lost circulation and temperature of Well–18 (after Doi et al., 1988).

3.2 Fractal Analysis of Fracture Thickness and Width from Cores

Apparent maximum vein thickness and open fracture widths from the core of Well–18 were examined for presence of hctal distributions. Figure **5** shows the cumulative frequency of vein thickness plotted on log–log paper.

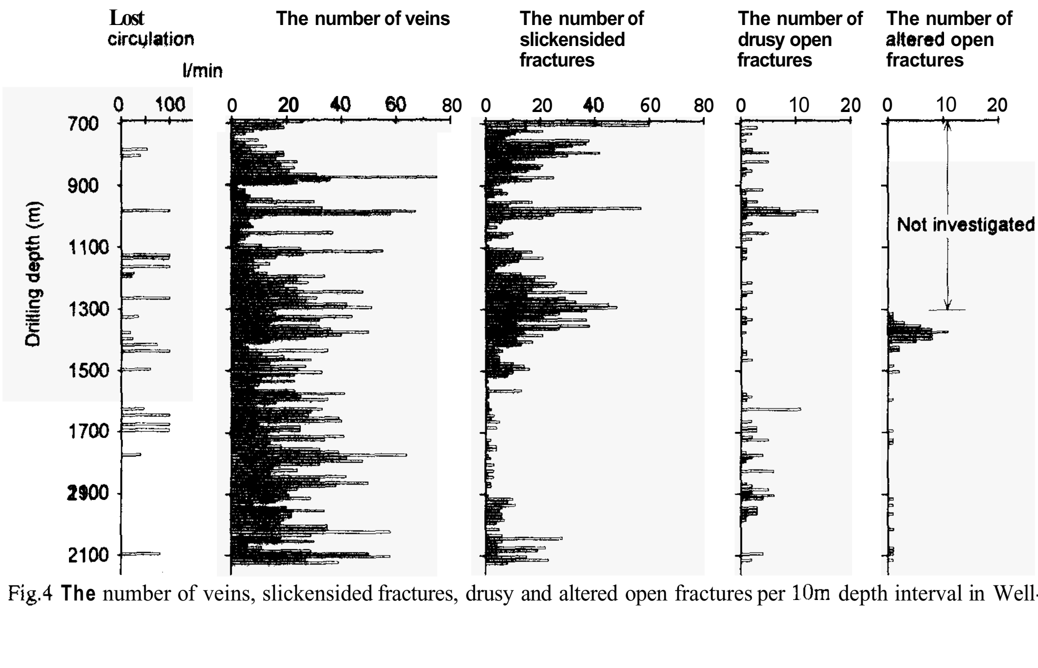


Fig.4 The number of veins, slickensided fractures, drusy and altered open fractures per 10m depth interval in Well–18

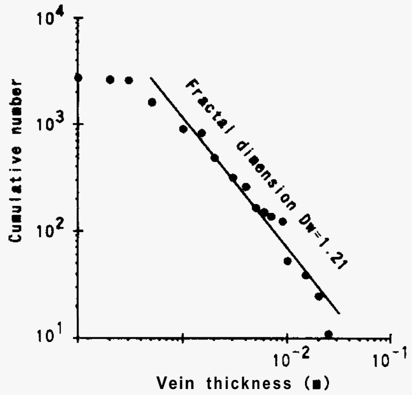


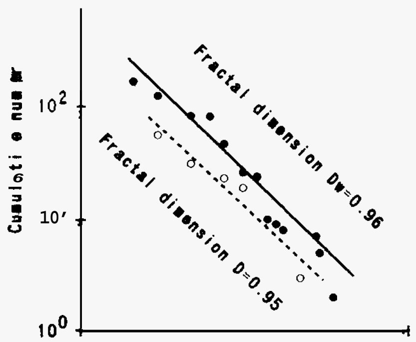
Fig.5 Cumulative frequency distribution of the vein thickness

Figure 6 shows the log–log cumulative frequency plots of the altered open fracture widths and of the drusy open fracture widths. All of these relationships are approximately linear on the log–log plot and therefore the distributions of the vein thickness and the open fracture width can be regarded as fractal. Such relationships could be expressed by follows:

$$Nw = Cw\ W^{-Dw}, \qquad (1)$$

where *Nw* is the cumulative number of veins or open fractures, *Cw* is a constant and *Dw* is a fractal dimension of the fracture thickness or width. In this investigation, the fractal dimension Dw is 1.21 for the veins, 0.96 for the drusy fractures and 0.95 for the altered open fractures. In Figure 5 and 6, the logarithmic relationship between thickness and width and cumulative number is not linear when the thickness is greater than 10^{-2} m or less than 10^{-3} m. This shows the effect of the resolution limits of observation and that there are some fractures the thickness of which was not measured due to core separation.

The difference in fractal dimension between veins and open fractures is thought to be caused by different formation process and chronologies. Veins are produced by filling up open fractures with hydrothermal minerals and the consequent blockage of the fracture. This suggests that veins are older than most open fractures. As Figure 4 shows, the difference in the distribution of veins and open fractures also reflects differences in their spatial fractal dimension, *Ds*, examined in the next section.



3.3 Fractal Analysis of Spatial Distribution of Fractures from Cores

The spatial distribution of fractures seen in core from Well–18 was examined for a fractal distribution using the "Cantors Dust" method (Mandelblot, 1982). Fractal dimension is obtained as follows:

- Divide an interval of the core under investigation τ_0 into 2^n (n=1,2,3,...N) intervals of length τ defined by:

$$\tau = \tau_0 / 2^n, \quad n=1,2,3,\cdots,N \qquad (2)$$

- Count the intervals that include at least one fracture for unit length τ. The relationship between the number of these intervals *Ns* and unit length τ is defined by:

$$Ns=Cs\ \tau^{-Ds} \qquad (3)$$

where, *Cs* is a constant and *Ds* is a fractal dimension of the spatial distribution of fractures observed in core.

- Plot *Ns* as the function of τ on a log–log graph and read off the fractal dimension from the straight line portion of the graph.

Figure 7 shows the results of the analysis by this method of 3,512 veins and 172 drusy open fractures in the cores taken from Well–18. The vein data are shown as solid circles and the drusy open fracture data by open circles. The fractal dimension *Ds* of the veins is 0.39 and the fractal dimension *Ds* of the drusy open fracture is 0.21. The higher fractal dimensions of the drusy open fractures reflects their more heterogeneous distribution compared to the veins since spatial heterogeneity increases as fractal dimension decreases. There is a possibility that the difference in fractal dimensions is caused by the different development process of these fractures.

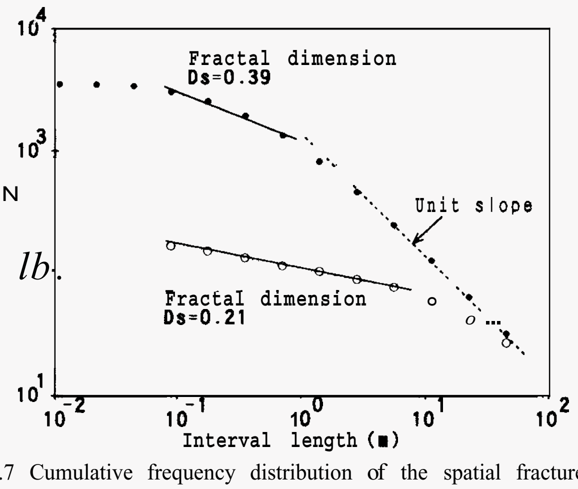


Fig.7 Cumulative frequency distribution of the spatial fracture distribution. N = number of intervals in which fractures are found. Solid circles – veins: open circles – drusy open fractures.

The distance between pairs of neighboring fractures was analyzed. Figure 8 shows the relationship between the cumulative number and the distance between two neighboring open drusy open fractures a log–linear graph. The relationship is approximately exponential over most ranges except in smaller distances. This distribution is similar to that expected from a branching Poisson model, which indicates that fractures tend to cluster around certain points. A good correspondence is seen in Fig.4 which shows the veins and drusy open fractures concentrated at certain intervals.

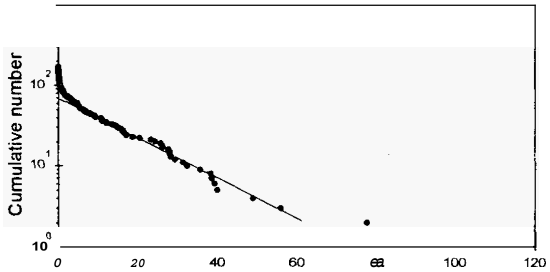


Fig.8 Cumulative frequency distribution of the distance between neighboring drusy open fractures. (Note: log–linear plot)

3.4 Variation of Fractal Dimension with Depth

It has been shown that the frequency distribution of vein thickness, open fracture widths and the spatial distribution of fractures can be described by fractal distributions. The spatial fracture distribution is heterogeneous, and the different fractal dimensions for different types of fracture reflect the different development processes. In this section, the variation of fracture spatial and width fractal dimensions are examined as a function of depth in the reservoir. Figure 9 shows the frequency, spatial distribution fractal dimension, *Us,* and the fracture width fractal dimension, *Dw,* for vein and drusy open fractures in each 100m interval of Well–18. The average of *Us* of the veins is 0.42.
The average of *Dw* of the veins is 1.14. The average of *Dw* of the drusy open fractures is 0.97. The characteristics of the depth distributions of the fractal dimensions shown in Fig.9 are as follows: *Dw* of the veins is larger than 0.8 at depths shallower than 1,250m and about 1.0 at depth greater than 1,250m. Most of the *Ds* of the veins are larger than 0.4. Every fractal dimension has a peak at around 950m depth corresponding to a major fracture and large losses of circulating drilling fluid.
These results suggest that the variation of fractal dimension with depth indicate the characteristics of the fracture and permeability distribution.

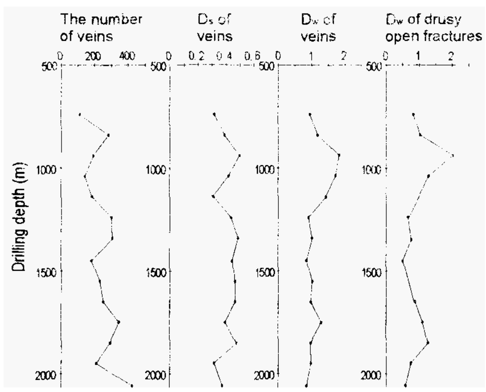


Fig.9 Number of the veins, the fractal dimension of the spatial fracture distribution *(Us),* the fractal dimension of the vein thickness (*Dw*) and the fractal dimension of the width of drusy open fractures (*Dw*) in each 100m interval of **Well–18**

4. EXAMINATION OF FRACTURES IN A GEOTHERMAL RESERVOIR USMG LOST CIRCULATION DATA

In the previous sections, the results of the fractal analyses of fractures in a geothermal field using the cores obtained from a well were described. In this section, some fractal characteristics of fractures in a whole reservoir are examined using lost circulation from the drilling of many wells.
Lost circulation occurs when the well encounter permeable fractures during drilling and is recognized by a decrease in the quantity of returned drilling mud. The rate of the lost circulation is determined by many factors such as the fracture permeability, the specific gravity of the mud, the viscosity of the mud and the reservoir pressure. The reservoir pressure within the Kakkonda geothermai reservoir is hydrostatic in the steady state (Hanano et ai., 1990) and the specific gravity of the drilling mud is almost the same because the same kind of mud is used for drilling. Thus, the rate of losr circulation depends chiefly on the frcture permeability which means that it is possible to estimate the distribution of fracture permeability using lost circulation data.

4.1 Lost Circulation Data from the Kakkonda Geothermal Field

About 800 lost circulation events from the Kakkonda geothermal field were used for fractal analysis. The data quality is good, selected from lost circulation records of more than 50 production and reinjection wells. The lost circulation rate is measured by manual recording of the circulation mud tank fluid level. Very small lost circulation are below the resolution of this method and are not recorded. Also, if the fluid loss rate exceeds the capacity of the mud pumps then the true rate can not be measured. The range over which fluid loss rate can be confidently measured lies between $3 \times 10^{-4} \sim 3 \times 10^{-2}\ m^3/s$.

1.2 Fractal Analysis of Lost Circulation Rate

Figure 10 shows 752 lost circulation rate data from the Kakkonda geothermal field plotted as cumulative frequency on a log–log graph. Over the rang for which the estimate of lost circulation rate can be confidenrly made, the relationship is linear indicating a fractal distribution which cao be expressed as follows:

$$N l \quad C l \, Q^{D l} \tag{4}$$

where Q is the lost circulation rate, Nl is the cumulative number, Dl is a fractal dimension and Cl is a constant. In this investigation, the fractal dimension Dl is 0.41 between $1 \times 10^{-3} \sim 2 \times 10^{-2}\ m^3/s$

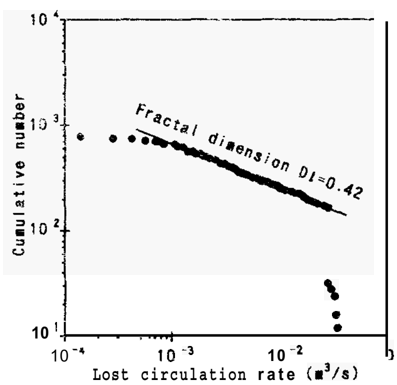


Fig.10 Cumulative frequency distribution of lost circulation rates from wells drilled in the Kakkonda geothermal field.

Figure 11 shows the fractal distributions of the lost circulation rate for sections of the reservoir shallower than sea level, between sea level and −700m S.L. and deeper than −700m **S.L.** The fractal dimensions are 0.38, 0.47 and 0.72, respectively. The fractal dimension changes remarkably at −700m S.L. **This** indicates that the proportion of large lost circulation events is greater in the reservoir shallower than −700 m S.L. than it is at greater depth. The Kakkonda hydrothermal system was found to consist of *two* reservoirs, one below the other, with a boundary between −600m S.L. and −1,000m S.L. The difference in fractal dimension indicates the different character of each of these reservoirs.

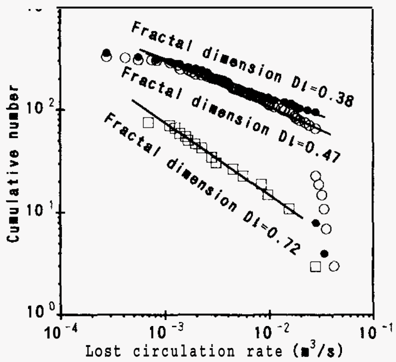


Fig.11 Cumulative frequency distribution of the lost circulation rates from different depth horizons in the Kakkonda geothermal field. Solid circles − above sea level; open circles − sea level to −700m below S.L; open squares − deeper than −700m below S.L.

Figure 12 shows the regional variation of fractal dimensions *Dl* within the Kakkonda geothermal field. The *Dl* values shown in the figure are for each of the regions I − V enclosed by the dotted lines from depth shallower than −700 m S.L. The values of *Dl* in regions Ⅲ and Ⅳ are less than 0.4 and less than the others. This indicates a relatively greater proportion of large lost circulation events in regions Ⅲ and Ⅳ. The distribution of the fractal dimension corresponds to the distribution of the productivity index of the production wells (Sato, 1982). This shows that the variation in fractal dimension follows the distribution of fracture permeability in the Kakkonda geothermal reservoir.

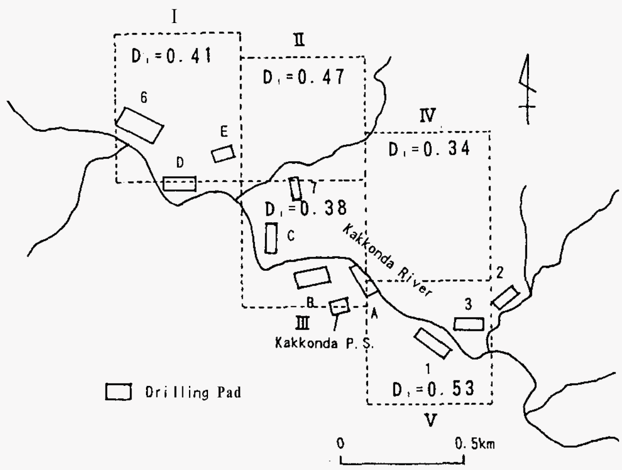


Fig.12 Areal distribution of the fractal dimension of the rate **of** lost circulation events, *Dl*

4.3 Fractal Analysis **of** Spatial Distribution **of** Fractures Using Lost Circulation Data

The spatial distribution of permeable fractures indicated by lost circulation events was examined, using Cantors Dust method outlined in section 3.3.

Figure 13 shows an example of the fractal analysis using data from Well−18 which contained a total of 24 lost circulation events. The fractal dimension, *Ds,* is almost the **same** as value of 0.21 found for drusy open fractures. This suggests that the spatial distribution of permeable fractures indicated by lost circulation is the same as that of open fractures identified in the core. Thus, it appears better **to** use open fracture data alone to characterize the reservoir permeability rather than all fractures and veins.

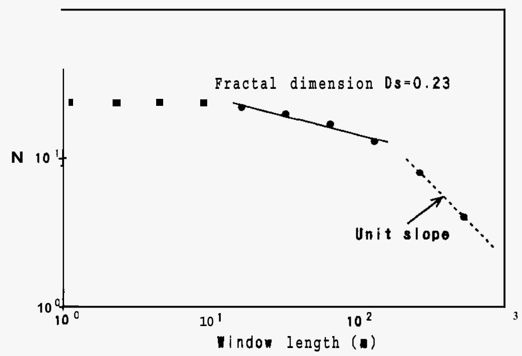


Fig.13 Fractal analysis by Cantors Dust method of the spatial distribution of permeable fractures revealed by lost circulation events in Well−18. N = number of intervals in which lost circulation events are found.

The areal distribution of the fractal dimensions ***Ds,*** was examined using lost circulation data from most wells. ***Ds*** varied between 0.2 and 0.6 with an average of 0.46 with wide variation from well to well. However, there was a tendency **for** fractal dimensions in regions Ⅲ and Ⅳ (as defied in Fig.12) to be greater than the others. This shows a tendency for a more homogeneous distribution of fractures in these regions.

5. DISCUSSION

It has been shown above that fracture fill thickness, fracture width and the spatial fracture distribution in the Kakkonda geothermal field can be described by fractals. However, there remain some practical problems concerning data sampling and interpretation before fractals can be used to characterize the geometry of the permeable fractures in geothermal reservoirs. **These** problems are now considered.

Fracture permeability distributions in geothermal reservoirs are functions of fracture size, density and the connectivity. These factors relate to measured fractal dimensions as follows: Reservoir in which the fractal dimension *Dw* is small, will be more permeable because the reservoir contains a greater proportion of comparatively bigger fractures. The permeability structure of reservoirs in which the fractal dimension *Ds* is large will be more homogeneous because the spatial distribution of the fracture **is** more homogeneous. The fracture connectivity will go up as the fracture density becomes higher and the fracture length becomes increases because fractures then more rapidly connect with each other. The effect of the fracture length distribution on permeability was investigated by Watanabe and

Takahashi (1993). The fractal analysis of the fractures in the Kakkonda geothermal field show good correspondence with these considerations, with the exception of fracture length which could not be measured.

When simulating reservoir performance using a fractals, the accuracy of the fractal dimensions used is critically important. In geothermal fields, the fractal data are chiefly derived from geothermal well drilling. Therefore, there is a fear that the fractal dimensions derived from such limited field data might not accurately reflect the character of the reservoir. An important task for the future, is to establish accurate methods for estimating the fractal dimensions on which reservoir evaluations can be based.

6. CONCLUSIONS

Fracture data from cores taken from Well–18 and lost circulation data from all wells in the Kakkonda geothermal field were examined for fractal distributions. The study showed:
(1) The distribution of vein thickness and the open fracture width are fractal as is the spatial distribution of fractures themselves. The fractal dimensions vary with the fracture type and location within the field. This indicates differences in the time of fracture formation and in the fracture formation process. It also indicates the character of the distribution of the fractures and permeable **zones** in the geothermal reservoir. Furthermore, the distribution of inter–fracture distances is similar to that expected from the branching Poisson model.

(2) Both the lost circulation rate and their spatial distribution are fractal. The fractal dimensions vary with region in the field and with depth. The variation indicates the distribution of fracture permeability in the geothermal reservoir.

Acknowledgments

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