The matching procedure is finished when the "best" match to the measured data is achieved. Preliminary results obtained from the prediction runs show that after injecting 3500 t/h of brine for 5 years, the temperature and pressure changes around the injection areas are not significant.

RECOMMENDATIONS

If a program of brine injection similar to those proposed in Scenarios II to IV is carried out in CP1, it is recommended that a temperature and pressure monitoring program be established using observation wells around the injection areas. Data collected from the observation wells should be used as feedback to the simulation model. The model could be a useful tool to detect and/or to predict trouble zones in the field. We consider that the analyses of the data from the observation wells and the simulation model will be a very useful in the design of the large-scale brine injection operations planned for Cerro Prieto.

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Slit-Island Fractal Analysis of Single Fracture Aperture Patterns

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B. L. Cox and J. S. Y. Wang

The character of fracture openings (apertures) is often one of the primary factors controlling fluid flow in the fracture. In particular, the shape, distribution, and connectivity of contact areas and flow channels can affect the relative permeability of wetting and nonwetting fluid phases in unsaturated systems. We used three methods of fractal analysis (the slit-island, the divider, and the variogram) as well as statistical and geostatistical analysis to characterize the geometry of measured fracture apertures obtained from two fractured rock specimens (Cox and Wang, 1993). One of these is a fracture in a granitic rock of homogeneous lithology; the other is a fracture in a specimen obtained from a highly altered fault zone containing striations and slickensides.

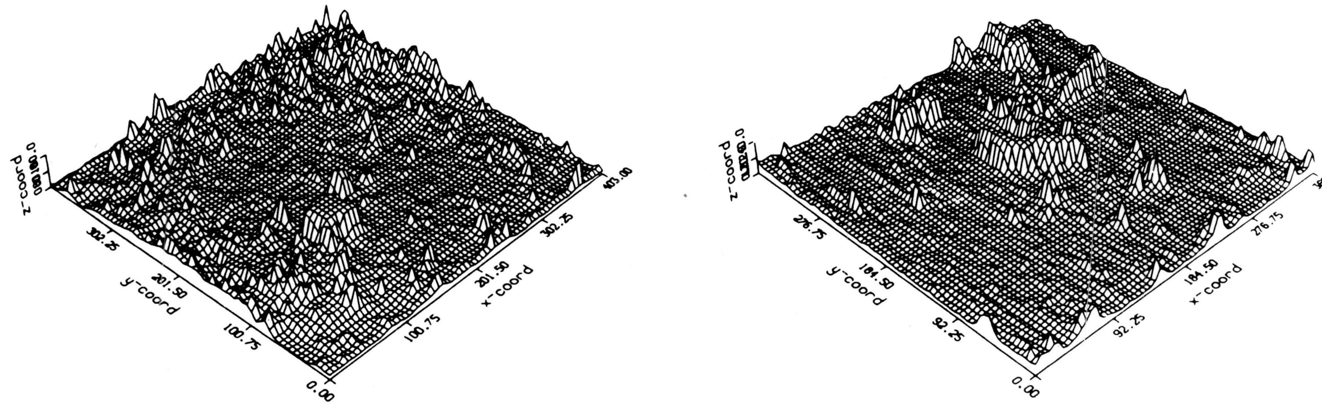
FRACTURE APERTURE DATA

Fracture aperture measurements of a fractured rock specimen sampled from a fault near Dixie Valley, Nevada, were obtained by three nondestructive fracture measurement techniques. The fracture aperture pattern was measured by profilometry (Power, 1989), by light transmission through translucent silicone casts (Cox et al., 1990), and by light transmission through dyed fluid in epoxy replicas of the rock (Persoff and Pruess, 1993). We examined the Dixie Valley fracture aperture as measured by the dyed-fluid method (Persoff and Pruess, 1993) and compared its aperture topography with that of a fracture in a specimen of Stripa granite (Persoff et al., 1991) measured by the same technique. Using this same approach, we compared the variability of the three Dixie Valley data sets measured by different techniques with the aim of distinguishing intrinsic features from experimental artifacts.

FRACTAL ANALYSIS BY THE SLIT-ISLAND METHOD

Fractal geometry offers an approach to geometric description of irregular geometric patterns (Mandelbrot, 1982). The fractal dimension of topographic surfaces measures the rate of change in the total length of contours or profiles as a function of the rate of change of a measurement interval. The fractal analysis of surfaces can be approached by at least seven different measurement methods (Cox and Wang, 1992), including the divider, variogram, and slit-island methods.

The slit-island method was first introduced by Mandelbrot et al. (1984), who used it to determine the fractal dimension of steel fractures. We applied this technique numerically to topographic surfaces (Figure 1) of



STRIPA FRACTURE

Min = 0.0 μm
Max = 110.06 μm
Mean = 37.00 μm
Standard Deviation = 21.28 μm
Covariance = 0.58
Skewness = 1.01
Kurtosis = 0.95
N = 152,943

DIXIE VALLEY FRACTURE

Min = 0.0 μm
Max = 152.90 μm
Mean = 41.95 μm
Standard Deviation = 20.92 μm
Covariance = 0.50
Skewness = 1.84
Kurtosis = 5.05
N = 128,014

Figure 1. Surface plots of Stripa and Dixie Valley fractures. [XBL 935-805]

data measurements (aperture thickness) by selecting several cutoffs, thereby creating surface contours that divided the surface into two kinds of shapes, positive (islands) and negative (water). We measured both the perimeter and the area of each island and made a log-log plot of the measurements, with the perimeter on the x axis and the area on the y axis. If the measurements form a straight line, this implies a self-similarity to the scaling of the population, and the slope can be used to determine the fractal dimension D, where $D = 2/\text{slope}$.

The log-log plots of the cutoffs of the two fractures all form straight lines, with least-squares correlation coefficients greater than 0.9. Cutoffs for each fracture are displayed in Figure 2, where the white areas represent aperture openings larger than the cutoffs and the dark areas represent aperture openings smaller than the cutoffs. (These cutoffs are referred to as "indicator maps" in the geostatistics literature; Isaaks and Srivastava, 1989.) The results of the fractal analyses for the cutoffs are shown in Table 1.

DISCUSSION

Both the fractal analyses and the statistics of the two fractures show that they have similar means, standard deviations, and fractal dimensions (Figure 1). The variograms show that there is evident anisotropy in the Dixie Valley fracture (Cox and Wang, 1993). However, the cutoff patterns for the two fractures look very different (Figure 2). The Stripa fracture shows a somewhat radial pattern of shapes, whereas the Dixie Valley fracture shows shapes that are extended in the sliding direction. These two very different patterns might have very different consequences for fluid flow. We could test the hypothesis that these patterns have significantly different effects on fluid flow by both numerical and physical experiments.

The concept of a cutoff pattern can be applied to aperture distributions to determine the possibility of different phase occupancy (Cox et al., 1990; Pruess and Tsang, 1990). A coarse average of a region of one of the fracture aperture distributions for the Dixie Valley rock specimen was previously analyzed for relative permeability (Cox et al., 1990). The analysis suggested that in small fractures with numerous asperity contacts, contiguous liquid flow paths exist even at small values of liquid saturation with strong capillary suction conditions. Cutoff patterns obtained from these two fractures could be used to test models (both computer and laboratory) for faulted versus radial patterns. If variability in the geometry of these otherwise similar fracture patterns does not result in a very different fluid flow regime, then a stochastic model might be adequate.

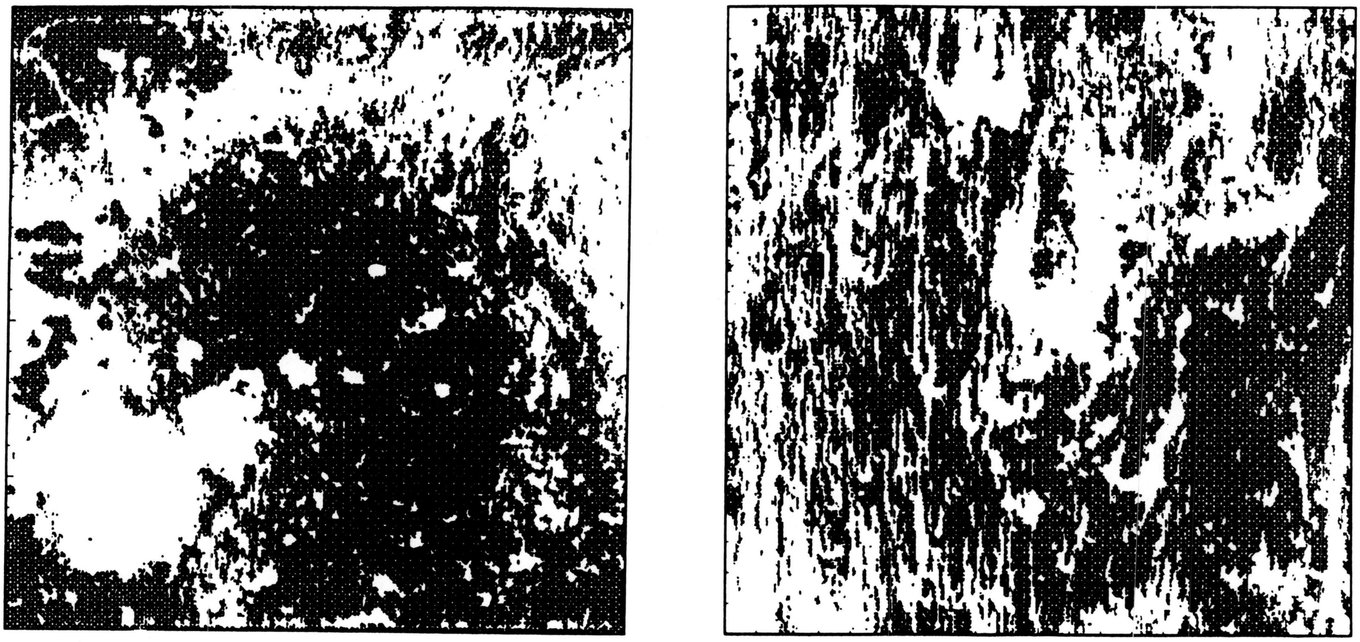


Figure 2. Cutoffs (indicator maps) for Stripa and Dixie Valley fractures. Apertures greater than 50 μm are shown in white. [XBL 935-806]

CONCLUSIONS

1. The fractal dimensions, means, and standard deviations for the Stripa and Dixie Valley apertures measured with the dyed-fluid technique are very similar. The slit-island and profile fractal dimensions were practically identical, whereas the variogram fractal dimensions were much higher (Cox and Wang, 1993). High variogram fractal dimensions were also observed in a literature review of fractal surface measurement techniques (Cox and Wang, 1992).
2. The cutoff patterns were distinctly different and were not similar to typical stochastic patterns. The Stripa cutoffs showed a radial pattern, and the Dixie Valley cutoffs showed patterns elongated in the sliding direction.
3. The cutoff patterns (or "indicator maps") could be used in flow models (Cox et al., 1990; Pruess and Tsang, 1990) to determine if the pattern would make a difference in the fluid flow characteristics. These predictions could then be tested by comparing flow visualization laboratory experiments in the two different fracture replicas (Persoff and Pruess, 1993).

Table 1. Slit-island analyses.

Name	Cutoff	No.Is.	Area%	Totalperimeter	Slope	*D*
Stripa	27.	536	36	25,890	1.52	1.31
Stripa	37.	791	55	27,790	1.54	1.30
Stripa	50.	919	72	26,470	1.51	1.33
Stripa	(37.)	(653)	(45)	(27,790)	(1.49)	(1.34)
Dix Val	30.	383	28	29,970	1.44	1.39
Dix Val	40.	698	53	33,280	1.43	1.40
Dix Val	50.	897	71	26,040	1.47	1.36
Dix Val	(40.)	(598)	(47)	(33,280)	(1.44)	(1.39)

Notes: Cutoff is in micrometers. No.Is. are islands greater than cutoffs (except for those in parentheses). Percent area is area with apertures greater than cutoff. Total perimeter is in grid units (grid spacing approximately 0.2 micrometers). Slope is from plot of log-log area versus perimeter. *D* is the fractal dimension from the slit-island slope. Cutoffs in parentheses are for the inverse analysis (i.e., islands are apertures less than the cutoff).

4. The slit-island fractal analysis indicates a higher fractal dimension and a higher total perimeter for the Dixie Valley fracture. In the absence of information about anisotropy or connectedness, the higher fractal dimension might indicate greater resistance to flow. However, visual inspection of the cutoff patterns suggests that the anisotropy of the Dixie Valley fracture patterns would be more important for flow properties than the fractal dimension of the total perimeter of the contacts. The fractal dimension is only one piece of information about the pattern geometry and does not indicate connectedness or anisotropy.

ACKNOWLEDGMENT

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LBL/Industry Heterogeneous Reservoir Performance Definition Project: The Conoco Site

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The Earth Sciences Division at Lawrence Berkeley Laboratory (LBL) is conducting interdisciplinary projects for characterizing heterogeneous reservoirs. As part of this work, a number of hydrologic and seismic field experiments were performed during 1992. With these experiments, we hope to develop equipment, field techniques, and interpretational methods that will improve geophysical imaging and hydrologic definition of reservoir rock. Our experiment at a Conoco Inc. test facility is one of two experiments being conducted to apply this approach to a fractured reservoir. Further information on the background of the interdisciplinary approach and a description of work in a porous reservoir site is given in Doughty et al. (1992).

We are currently in the initial stages of studies at the Conoco well test site in Kay County, Oklahoma, which penetrates a fractured groundwater reservoir consisting of limestones and shales. This site has been previously studied, and many of the hydrologic and seismic properties are

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