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

We wish to thank Dr. Peter Persoff for the aperture data sets.

## REFERENCES

Cox, B.L., and Wang, J.S.Y., 1992. Fractal surfaces: Measurement and applications in the earth sciences. Accepted by Fractals (LBL-31737).

Cox, B.L., and Wang, J.S.Y., 1993. Single fracture aperture patterns: Characterization by slit-island fractal analysis. Presented at the International High Level Radioactive Waste Management Conference, Las Vegas, Nevada, April 26–30, 1993 (LBL-33660).

Cox, B.L., Pruess, K., and Persoff, P., 1990. A casting and imaging technique for determining void geometry and relative permeability behavior of a single fracture specimen. *In* Proceedings, 15th Workshop on Geothermal Reservoir Engineering, Stanford University, p. 173–178.

Isaaks, E.H., and Srivastava, R.M., 1989. An Introduction to Applied Geostatistics. Oxford University Press, New York, p. 80–89.

Mandelbrot, B.B., 1982. The Fractal Geometry of Nature. W.H. Freeman, New York.

Mandelbrot, B.B., Passoja, D.E., and Paullay, A.J., 1984. Fractal character of fracture surfaces of metals. Nature, v. 308, p. 721–722.

Persoff, P., and Pruess, K., 1993. Flow visualization and relative permeability measurement in a rough-walled fracture. Presented at the International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, April 26–30, 1993 (LBL-33447).

Persoff, P., Pruess, K., and Myer, L., 1991. Two-phase flow visualization and relative permeability measurement in transparent replicas of rough-walled rock fractures. Presented at the 16th Workshop on Geothermal Reservoir Engineering, Stanford, California, January 23–25, 1991 (LBL-30161).

Power, W.L., 1989. Roughness of natural fault surfaces: Implications for friction and deformation in fault zones. Ph.D. dissertation, Brown University, U.M.I. # 9002277, p. 101–141.

Pruess, K., and Tsang, Y.W., 1990. On two-phase relative permeability and capillary pressure in rough-walled rock fractures. Water Resour. Res., v. 26, no. 9, p. 1915–1926 (LBL–27449).

6818

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

*T. M. Daley, E. L. Majer, J. C. S. Long, K. Hestir, P. D'Onfro,* W. D. Rizer,* and J. H. Queen**

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

* Conoco Inc., Exploration Research and Services, Ponca City, Oklahoma.

understood (e.g., Queen and Rizer, 1990, Lines et al., 1992). Because of these previous studies, we can test new concepts while developing a more refined understanding of this site. To improve and refine our field techniques, test current analysis methods, and work toward an improved description of reservoir properties, separate hydrologic and seismic field experiments have been carried out at this site. The results of these separate experiments will eventually be integrated.

In the initial seismic experiment, five cross-well surveys were recorded in the shallow groundwater wells (GW-1 through GW-5 in Figure 1). The surveys were done with fairly coarse sampling of the subsurface because of field problems. A lightning strike was apparently responsible for the breakdown of two out of six recording channels, and the remaining four channels were found to be out of calibration upon our return to LBL. Nonetheless, we feel the acquired data represent the frequency response and signal-to-noise ratios that we can expect upon returning for more detailed surveys in 1993.

Each of the five seismic cross-hole surveys used a separate pair of wells, with the seismic source in one well and a string of seismic receivers in the second well. The data were acquired at depths between 50 and 110 feet, covering the Fort Riley formation, a limestone with thin interbedded shales. The seismic data were acquired with LBL's high-frequency seismic imaging system (Daley and Majer, 1992). The eight seismic receivers were recorded four at a time at 6-ft spacing for each of 60 source points spaced 2 ft apart. The distance between wells was approximately 150 ft. Figure 2 shows an example of the data acquired in the groundwater wells. A Fourier transform of these shallow data (Figure 3) shows that energy above 10,000 Hz is being transmitted between wells. Since the velocities are above 10,000 ft/sec, we can potentially expect a resolution of one foot, although the data acquisition was not designed to take advantage of this resolution. Now that the potential resolution is known, future work will use smaller spacing between source locations and receiver locations.

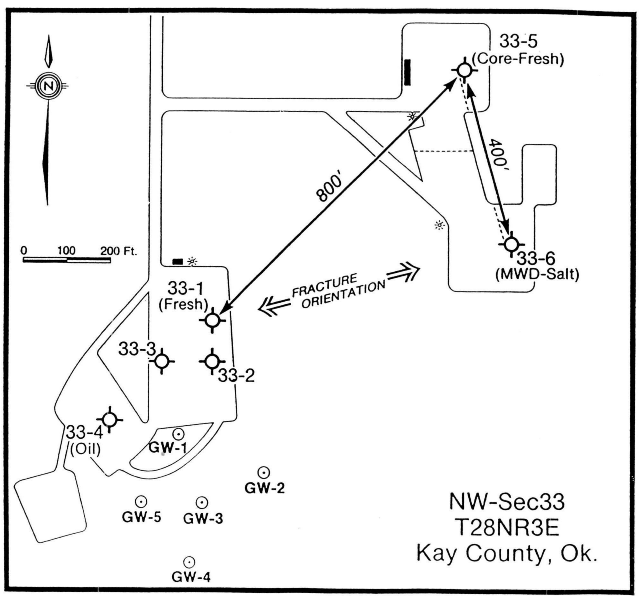


**Figure 1.** Layout map of Conoco Inc. borehole test facility. The field tests were conducted in wells GW-1 through GW-5. [XBL 934-489]

The seismic data can be analyzed for velocity, velocity anisotropy, attenuation, and other attributes that can characterize the fracture content. However, we feel that many wave-propagation effects may be caused by the thin bedding of sedimentary layers. Among the observed effects in the seismic recordings are oscillatory channel waves, apparently caused by the thin high-velocity layers. These channel waves, which were previously reported at this site (Lines et al., 1992) could prove a valuable tool for understanding the details of seismic propagation, including separating the effects of fractures from the effects of thin layering.

In the hydrologic experiments, a series of interference tests were conducted in the GW holes. The interference data will be used in fiscal 1993 as a basis for developing a hydrologic model of the site. Hydrologic inversion methods will be used to identify fracture flow paths. Several techniques are under investigation. In each of these a conceptual model will be optimized such that the well tests simulated by the model will match the observations taken in the field. Two methods are under consideration at this time. The first method is based on representing the fracture network as an "attractor." The attractor is determined using a simple iterative mathematical process called iterated function systems (ifs), which can be used to determine a complex heterogeneous field of permeability (Doughty et al., 1992). The parameters of the ifs are optimized until a case is found that matches the well test data. Such a process results in the determination of a fractal model for the reservoir. The second method is based on using the outcrop information to infer the genetic history of the rock. Then a heuristic process is defined that will "grow" fractures the same way. A series of these generated fracture systems are examined until one is found that matches the well test data. Either of these techniques can be conditioned with geophysical information. To the extent that geophysics indicates the orientation or density of the fractures, the inversion can be constrained to produce models that also have these properties. The second step in the inversion process will be to design and accomplish conditioning with geophysical information.

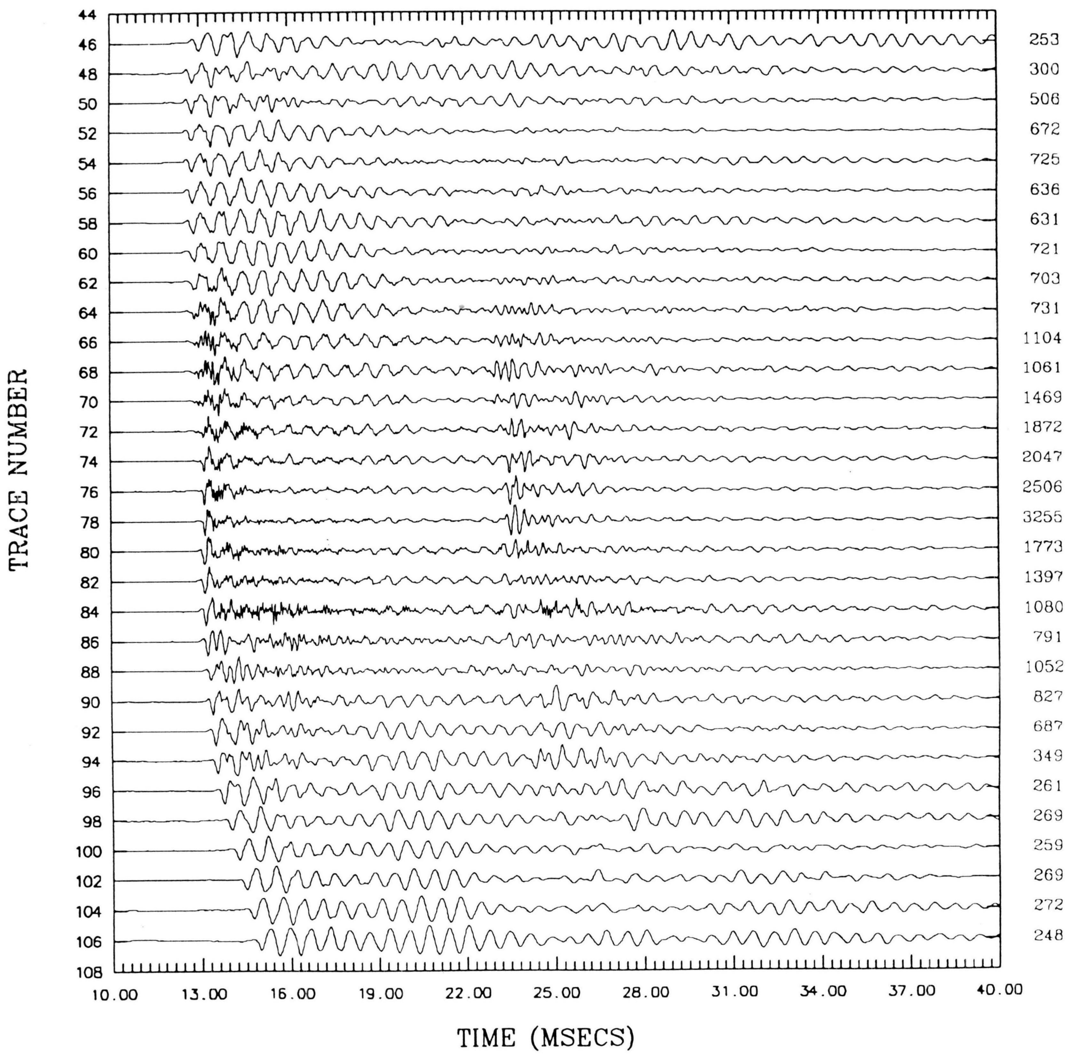


**Figure 2.** Cross-borehole seismic data. Each trace is a single source-receiver pair. The source was in well GW-3 from depths of 45 through 106 feet. The receiver was fixed at 72 feet in well GW-2. The first *P*-wave arrival is seen at about 13 msec. A later arrival at about 24 msec is probably a shear wave. The oscillatory arrivals (e.g., traces 96–106) are probably channel waves. [XBL 935-607]

The first well tests were carried out in July and August of 1992. Simple pumping tests were designed that would perturb each well in succession and monitor the other four. Thus each test would produce five records of drawdown. Testing conditions were extremely difficult. The tests were planned for this time period because it is usually a period of dry weather. Unfortunately, this turned out to be one of the wettest years in recent history. Consequently, the water levels in the wells were fluctuating over many centimeters within periods of hours. The horizontal permeability of the formation was low enough that these fluctuations completely masked the signal from the pumping well. In addition, the pumping rates had to be maintained at a very low level (0.5 gal/min) in order to avoid drawing the wells down below the formation. This constraint effectively reduced the size of the signal such that it was impossible to conduct controlled tests until the rain stopped.

During some eight weeks in the field, the rain held off for two periods long enough to obtain two good interference tests, one from well GW-5 and one from well GW-2. The first test was conducted at a relatively constant pumping rate. It was not possible to hold the rate constant for the second test, but the pumping rate was measured regularly. Plans for fiscal 1993 include analysis of our data as described above, collection of more detailed seismic data, and beginning to integrate the hydrologic and geophysical data.

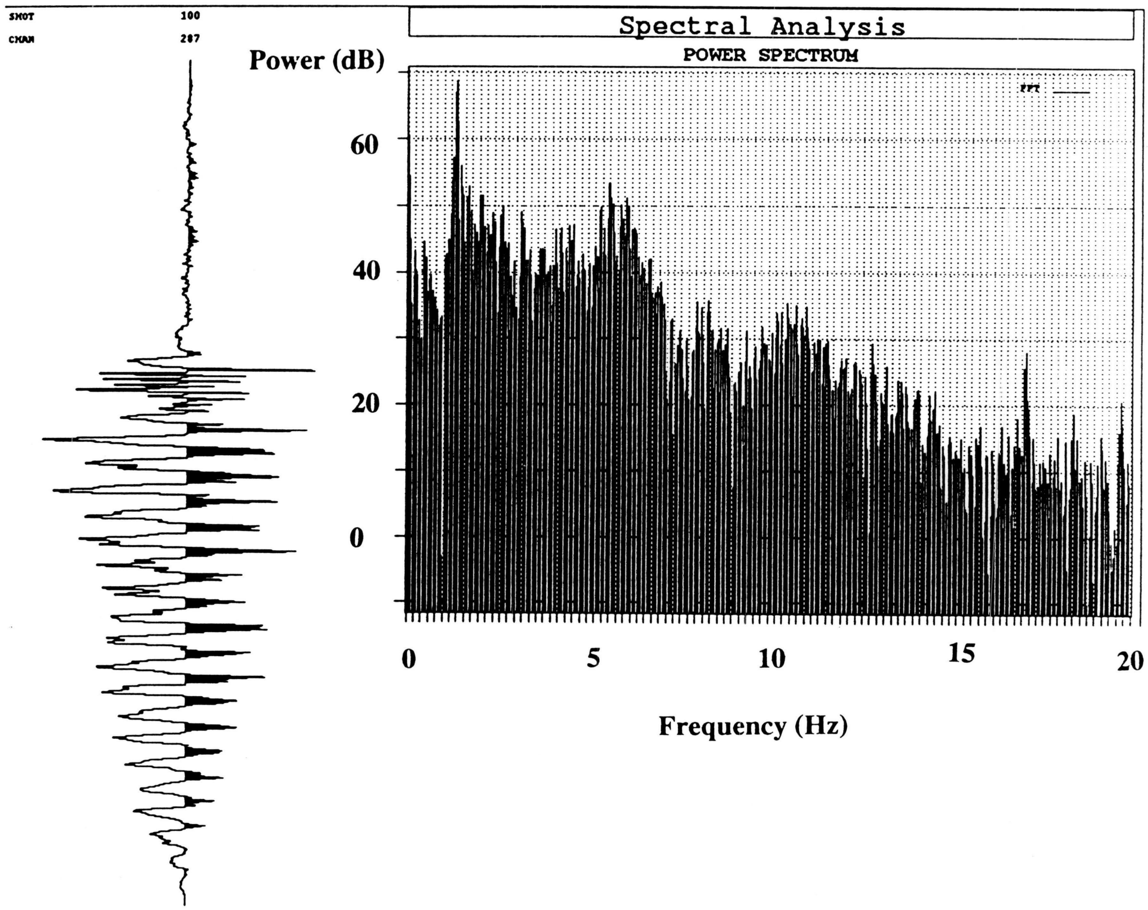


**Figure 3.** Frequency content of one representative seismic data trace. The trace is shown on the left. The background noise level is about 10 dB. The signal level is seen to exceed 30 dB for most frequencies up to 10,000 Hz. [XBL 935-808]

## REFERENCES

Daley, T.M., and Majer, E.L., 1992. Applications of the LBL high-frequency seismic imaging system. *In this Annual Report.*

Doughty, C., Daley, T.M., Long, J.C.S., and Majer, E.L., 1992. LBL/Industry heterogeneous reservoir performance definition project: The BP Gypsy Site. *In this Annual Report.*

Lines, L.R., Kelly, K.R., and Queen, J.H., 1992. Channel waves in cross-borehole data. Geophysics, v. 5, p. 1–9.

Queen, J.H., and Rizer, W.D., 1990. An integrated study of seismic anisotropy and the natural fracture system at the Conoco Borehole Test Facility, Kay County, Oklahoma. J. Geophys. Res., v. 95, p. 11255–11273.