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A NEW METHOD FOR DETERMINING DOMINANT FLUID FLOW PATHS DURING HYDRAULIC FRACTURING

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ABSTRACT

Although hydraulic fracturing is a method that has been applied for many years to increase fracture permeability of reservoirs, there is no direct way other than drilling additional boreholes to determine where the injected fluid has gone and thus what direction fractures have propagated. Information about fluid flow paths is important for designing subsequent fracturing operations for nearby wells or for choosing a trajectory for a second well to drill through the fracture system, and thus create a hot dry rock geothermal energy reservoir. I have developed a method for determining the orientations and locations of fractures along which fluid flows during hydraulic fracturing. The method is based on accurate determination of the locations of microseismic events, or microearthquakes, that accompany the hydraulic injection. The method has been applied to data collected during a massive hydraulic fracturing experiment carried out as part of the hot dry rock project. Planes with five different orientations were found in the data. The planes determined using the method intersect the injection borehole and a second, nearby borehole, in regions where other data indicate that fractures are present.

INTRODUCTION

During the past 12 years we have been monitoring seismicity associated with hydraulic fracturing in granitic rock (Albright and Hanold, 1976). The monitoring was initially carried out for environmental assessment but was later deemed to provide useful information about where the fluid had penetrated into the rock. This work has been carried out with the implicit assumption that the seismicity is a direct result of the fluid pressure on the rock and thus is an indication of where the fluid has penetrated in the formation (Murphy and Fehler, 1986). We have asserted that the fluid penetrates the formation along pre-existing fractures in the rock that open in response to the fluid pressure interacting with the in situ stress field (Murphy and Fehler, 1986). We have justified our assertion with the observation that the zone in which seismicity occurs is diffuse, that this observation cannot be explained by systematic errors in locations of the microearthquakes, and hence cannot be explained by a single tensile fracture. Until now we have had no method for determining where individual fractures exist in the formation. I now present results of applying a method, called the three point method, for determining orientations and locations of planes defined by locations of microearthquakes in a reservoir. The method is described in detail in the open literature (Fehler, et al., 1987) so only a brief sketch will be given here.

METHOD

The method is an extension to three dimensions of a procedure outlined by Lutz (1986) for finding lineaments in two-dimensional surfical geological data. The method is based on the observation that every combination of three microearthquake locations defines a plane. I begin by calculating the strike and dip of the plane made out of every possible combination of three microearthquake locations within a data set from a single hydraulic fracturing experiment. One intuitive way to find the orientation of any plane along which the microearthquakes may have occurred would be to separate all of the planes defined by combinations of three locations into bins corresponding to ranges of similar orientations, and to then identify which bin has the largest number of planes. However, this technique would produce a biased result due to the shape of the region in which the microearthquakes occur. This bias was discussed for the two-dimensional case by Lutz (1986). The bias caused by the shape of the region in which the microearthquakes fall can be eliminated by normalizing the number of combinations in each bin by the number of combinations in each bin found for synthetic sets of location data. These synthetic locations are uniformly but randomly distributed throughout the zone in which the actual microearthquakes were found to occur. In this way, an unbiased estimate of the orientation of planes along which microearthquakes fall is obtained and, by comparison with many sets of synthetic locations, a statistical estimate of the reliability of the result can be made.

To determine the location of the plane, we count how many times, Tj, that a given microearthquake, j, combines with other microearthquakes to form planes with the preferred orientation. The earthquakes that have the largest value of Tj are those that fall along the plane. By plotting the locations of these events, we find the location of the plane defined by the data.

The method can be successively applied to a given dataset to find planes of differing orientations and locations. By removing those earthquakes that were found to define the primary plane, we eliminate the preference for that orientation in a subsequent application. In this manner further planes can be obtained from the data.

The method has been extensively tested on synthetic data. In a typical test, synthetic locations that fall along a pre-determined plane were generated and supplemented with points that fall randomly but uniformly in a zone surrounding the plane. The three point method was applied and the plane located. The points that fell along the plane were subsequently perturbed away from the plane to represent errors in microearthquake locations. The ability of the three point method to locate the plane in the presence of this locational noise was then investigated to determine how much error could be added to the locations that originally fell along the plane before the method was unable to resolve the plane. Figure 1 shows an

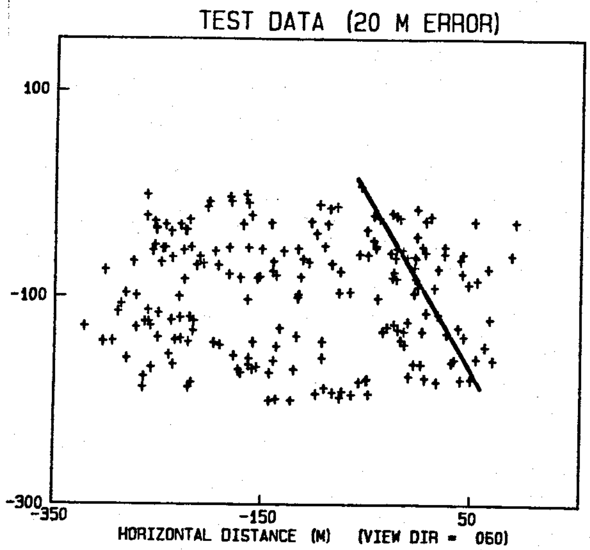

Figure 1. Test data for three point method. Line connects points along plane.

example of such a test. The test data consist of 200 synthetic locations that fall inside a box of dimensions 200 by 200 by 400 m, with the long axis oriented north-south. Twenty five of the locations were placed along a plane and subsequently perturbed in random directions by an average of 20 m to represent errors in locations. The locations are drawn in vertical cross section oriented perpendicular to the strike of the plane so that the line represents the location of the plane defined by the unperturbed data. The method was successful in determining the location of the plane in these data.

RESULTS

I have applied the three point method to a suite of microearthquakes that accompanied a massive hydraulic fracturing operation in granitic rock (Hot Dry Rock experiment 2032). This operation was carried out in an attempt to create a fluid path between the injection wellbore and a second, nearby wellbore. A total of 21,600 m^3 of water were injected into a 20 m long section of wellbore at an average rate of .1 m^3/sec (Dreesen and Nicholson, 1985). A total of 844 microearthquakes were located and used in the analysis. The events were located using travel times to several subsurface seismic stations located in boreholes surrounding the injection borehole (House, 1987). The precision in the locations is estimated to be 20 m. A total of five planar orientations along which seismic events occurred were found by the method. The first plane found, shown in Figure 2, contains 130 microearthquakes. This plane intersects the

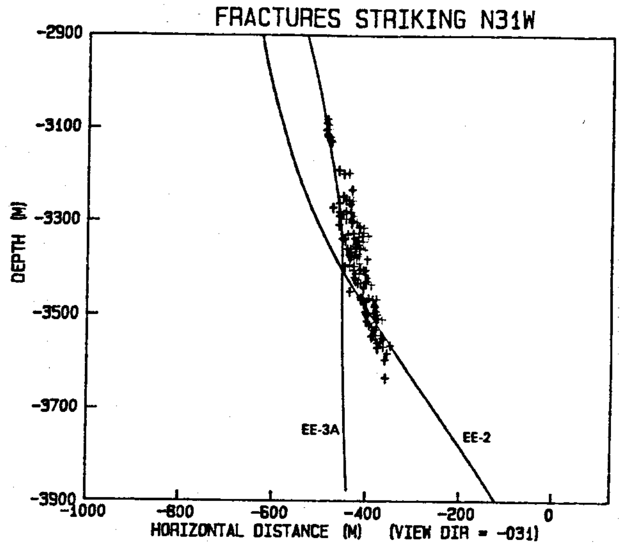

Figure 2. Vertical cross section showing locations found along primary plane. Location of wellbores EE-2 (injection) and EE-3a (drilled after injection) are shown. Data are projected onto a vertical cross section oriented perpendicular to the primary plane so that the plane appears as a line.

injection wellbore, labeled EE-2, in a location where several major fluid flow exits were identified from temperature logs taken during experiments carried out prior to the hydraulic fracturing operation. The second plane, shown in Figure 3, intersects a borehole that was drilled after the hydraulic fracturing. The point where this fracture intersects the wellbore was identified as a fracture zone by analysis of drill cuttings (Levy, written communication). Further evidence for the existence of a fractured reservoir is the fact that a flow path exists between two wells and energy has been extracted by flowing water along this path (Hendron, 1987).

To test the application of the method to the real data, a set of synthetic data were generated. These data consisted of 130 events located along a plane in the same location as the primary plane determined from the real data as shown in Figure 2. An additional 714 events were distributed randomly but uniformly inside the zone of seismicity determined for the experiment (House, 1987). The three point method was applied and successfully located the plane. The locations of events along the plane were then perturbed off the plane in random directions to simulate locational errors. I found that the perturbations could average as much as 60 m and the method could still successfully locate the plane. Since we estimate that the locational precision is 20 m for our data set (House, 1987), the results of application of the method are considered reliable for the current

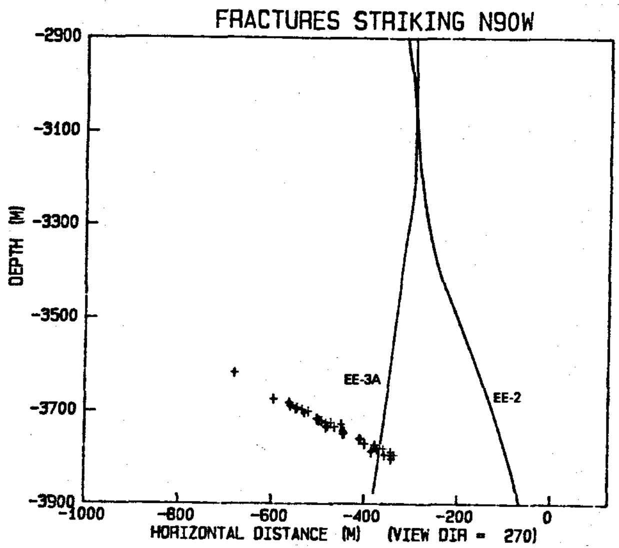

Figure 3. Vertical cross section showing locations along secondary plane.

dataset. Figure 4 shows the perturbed synthetic locations that fall along the plane in the same vertical cross section used to show the events found along the plane in Figure 2. In this case, the locations have been perturbed by an average of 20 m from their original locations along a perfect plane. It is interesting to note that the apparent width of the plane defined by these synthetic locations is nearly the same as that for the plane defined by the real data. The agreement between the apparent widths of the planes for the actual data and synthetic dataset with 20 m error further confirms that our estimate of 20 m precision in microearthquake locations determined by our location method is reliable.

INTERPRETATION

We interpret the planes found by the three point method to be flow paths along which the water flowed into the rock. These fractures are most likely pre-existing joints which shear in response to changes in effective stress caused by the fluid pressure acting against the present in situ stress field. The above method of locating fractures during hydraulic fracturing thus locates those fractures which are most likely to be flow paths given the current state of stress. It should be

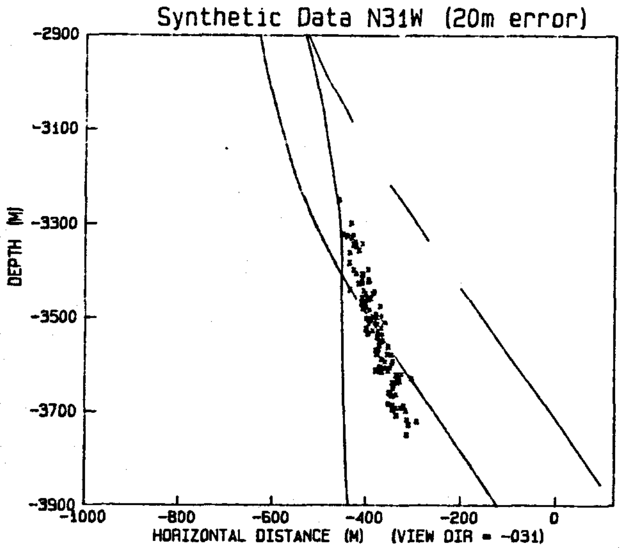

Figure 4. Vertical cross section showing locations of synthetic microearthquake locations that were generated to test the three point method. The data originally fell along a perfect plane but were subsequently perturbed off the plane by an average of 20 m to represent locatonal errors.

noted that not all of the planes found are directly connected to the injection wellbore. Presumably some of these planes are fractures that have connections to the injection wellbore through fractures which are too small to be detected seismically.

PRESENT STATUS AND FUTURE WORK

The method has been successfully applied to data collected during the largest massive hydraulic fracturing experiment carried out by the Hot Dry Rock program. I am currently in the process of applying the method to data collected during injections carried out during the EE-3a redrilling phase during which time the present HDR reservoir was established. These more recent data are most important since they define the fracture system through which water flows between the two wellbores drilled into the reservoir. A complete understanding of these fractures is important for reservoir modeling and for improved understanding of the seismicity accompanying hydraulic fracturing. In addition, by determining the orientations of fractures along which slip occurs, we will gain some insight into the in situ stress field since the orientations of fractures that slip are controlled by the current stress field.

This method will be important in future Hot Dry Rock development projects since it provides the capability to determine locations of fractures created during hydraulic injections. A typical scenario for building a HDR system would thus be to drill one hole to completion, fracture it, locate the seismicity and interpret it with the three point method to find locations of fractures. A second well could then be drilled to intersect a fracture thus creating the flow path between the two wellbores. An additional application would occur in a mature HDR system where fractures could be identified from seismicity accompanying heat extraction. By identifying these fractures, new wellbores could be drilled or one of the existing holes sidetracked to optimize the system based on current knowledge of the fracture system.

CONCLUSIONS

The three point method has been successfully applied to a microearthquake location data set collected during a massive hydraulic fracturing operation. Planes with five differing orientations were found by the method. The first two planes were found to intersect wellbores in locations where other data indicate the presence of fracture zones. This method thus provides a powerful framework for interpretation of microearthquake data collected during hydraulic fracturing operations, and provides locations of flow paths along which water flowed during the injection.

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