MICROSEISMIC MAPPING OF AN HDR RESERVOIR

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Introduction. Microearthquakes induced by hydraulic fracturing provide considerable information about the flow of fluid through rock. In the Hot Dry Rock (HDR) scheme, two wells are connected by a man-made geothermal reservoir, with cold fluid pumped down one well, and hot fluid produced from the other. The HDR reservoir is created by one or more hydraulic injections into hot, impermeable rock. Microseismicity provides the primary means of characterizing most of the HDR reservoir, which lies outside the limited rock volume interrogated by wellbore logging instruments.

Induced microearthquakes can be used to determine the geometry and location of the prominent fluid flow paths in the reservoir. In addition, the microearthquakes provide information about rock mechanical processes, and about earth stresses within the reservoir.

An HDR reservoir was created at Fenton Hill, New Mexico by a large volume (more than 20,000 m^3) injection, termed the Massive Hydraulic Fracture (MHF), done in December, 1983. Since the MHF, four more large fluid injections have been done at Fenton Hill, and each produced thousands of microearthquakes. We describe here the major results of characterizing that HDR reservoir by analysis of the induced microseismicity from the MHF. The MHF was the largest and single most important fluid injection done to create the reservoir that is currently being further developed and tested.

Microearthquake Locations. The most fundamental information about the induced microearthquakes are their locations. Several studies have shown [Pine and Batchelor, 1984; Majer and Doe, 1986; Fehler, et al, 1987; Dreesen, et al, 1987] that the distribution of microearthquakes encompasses the system of fluid flow paths created by the hydraulic injection. Two techniques have been used for locating the induced microearthquakes: the hodogram (particle motion) method, which requires only a single triaxial instrument, and the arrival time method, which requires a minimum of three instruments. The hodogram method suffers from several problems, the most serious of which appear to be contamination of the particle motions by instrumental effects and inadequate coupling between the instrument and the borehole. Both problems result in unreliable event locations. New instrument designs appear to be needed to obtain more reliable waveform data. Before the MHF, the Los Alamos HDR program used only the hodogram technique for locating induced seismicity.

Enough downhole instrumentation was available during the MHF to locate microearthquakes using arrival times. Although using arrival times requires additional instrumented boreholes, it has yielded event locations that have estimated uncertainties of 30 m or less [House, 1987]. A total of 844 reliable locations were obtained from the MHF [House, 1987]. The locations (see Figure 1) define a volume with dimensions of about 950 m along strike, 850 m down dip, and 150 m in thickness. Subsequent to the MHF, well EE-3 was redrilled through the volume of seismicity and a fluid connection to the other well, EE-2, was successfully established. The substantial improvement in reliability of the arrival times locations compared to the hodogram locations has allowed us to conclude that the predominant fluid flow paths created during the MHF were contained within the distribution of induced earthquakes [Dreesen, et al, 1987].

Our digital data acquisition capabilities have expanded considerably since the MHF. Using MHF data played through the new data acquisition system, we are systematically analyzing all locatable microearthquakes. So far, events from the first half of the MHF have been located. The number of new event locations is more than 10 times the number originally located during the same time period (about 4500 compared to about 400). The new locations are distributed within the volume defined by the original locations, but show some features that are not seen in the original location set.

Three Point Method. Although the overall geometry of the MHF location distribution can be determined from visual inspection, it is much harder to discern more subtle features that may correspond to individual joints or zones that provided prominent fluid paths. Fehler, et al [1987] described a technique to statistically analyze large numbers of earthquake locations and extract the orientations of event planes. This technique is called the three point method. When applied to the MHF seismicity, the three point method identified a total of five distinct event planes (Figure 2) [Fehler, et al, 1987]. Intersections of the planes with wellbores are corroborated by identification of fractured zones from well logs. Moreover, the seismicity planes have provided information about the geometry of the major flow paths within the reservoir [Dreesen, et al, 1987]. If the geometry of those major flow planes had been known before the redrilling of well EE-3, the new trajectory could have been selected to preferentially connect with the most promising paths.

Fault Plane Solutions. In addition to locating them, we can determine the orientations of the surfaces that slipped during the earthquakes. This information also tells us about the joints and fracture system created, and can be used to estimate earth stresses in the reservoir region. The orientations of the slip surfaces are obtained from the nodal planes of fault plane solutions. Fault plane solutions are derived from the pattern of P wave first motions, which may be either up (compressional) or down (dilatational). Two nodal planes separate the first motion quadrants.

We have nearly completed what is intended to be a comprehensive study of fault plane solutions of the larger induced microearthquakes from the MHF. The main differences between this study and a previous one [Kaieda, 1984] is that we are using locations obtained from arrival times at the downhole instruments and obtaining fault plane solutions for individual earthquakes. For this study, we identified events with a large number of first motions. Because the stations are well distributed about the earthquakes, we have been able to obtain well constrained fault plane solutions for about 200 individual earthquakes.

The work is still in progress, but the most interesting results to date have been that all events show both compressional and dilatational first motions. Moreover, all events can be fit by a double-couple type solution. Thus, all the events studied resulted from shear failure; none were purely tensile opening. In addition, the solutions show a large scatter of nodal plane orientations, indicating that joints of many orientations were activated.

Figure 2 shows results of both the fault plane solution study and the three point study. In this figure, the + symbols are the poles to the nodal planes of fault plane solutions, and the letters are the poles to planes determined by the three point method. The fact that poles to both nodal planes for each fault plane solution are plotted complicates a direct comparison between the fault plane solution results and the three point method results. Because only one of the nodal planes represents the slip plane of each earthquake, a comparison of the slip planes with the three point planes would be a more reliable way to compare the results of the two methods. Seismologic information alone does not allow us to distinguish which of the two nodal planes was the slip plane, and therefore we have no way to choose which plane to plot. We expected, however, that nodal planes would cluster around three point planes. Certainly, three point planes D, F, and G are near clusters of nodal planes, but three point planes H and I are not.

Even more surprising is the apparent discrepancy between the stress orientations inferred from fault plane solutions and from wellbore measurements. Fault plane solutions are typically used to estimate stress orientations by associating the bisectors of the compressional and dilatational quadrants (the T and P axes, respectively) with the orientations of the minimum and maximum earth stresses. The association is an oversimplification, in that the true stress orientations can be quite different from those of the T and P axes, but it does provide a rough indication of the stress orientations. The fault plane solutions have shallow dipping P axes that range in azimuth from about NNW to about SSE, with a visual averaging of the P axes orientations at an azimuth of about ESE. In contrast, Barton, et al, [1988], obtained a <u>minimum</u> horizontal stress direction of 119^{o} from televiewer data taken in well EE-3. Thus, the stress orientation estimated from fault plane solutions is completely opposite to that from televiewer data.

We cannot reconcile the fault plane solution results with the televiewer results at present. We tentatively interpret the three point method results as indicating an orientation of the prominent fluid flow paths, while the fault plane solutions indicate the individual joints that were favorably oriented for slip in response to the stress field. In this interpretation, not all of the seismic events occurred within the confines of the prominent flow paths; some may have occurred slightly (a few meters) away from the major fluid paths.

Source Parameters of Induced Earthquakes. In addition to the seismological information discussed so far, the waveforms recorded from the induced seismic events also contain information about the dimensions of the slip surfaces, and the amount of slip during individual seismic events. Fehler and Bame [1985] estimated source parameters of many earthquakes from the MHF. They found earthquake source radii between about 2 and 20 meters, and slip of from 6 to 1000 microns (10^{-6} m) during individual microearthquakes. In addition, Bame and Fehler [1986] identified a different type of earthquake, one that they termed a "long period" earthquake. They associated these very small earthquakes with the fluid flow during the injections. Ferrazzini, et al, [1988] have compared these earthquakes to those observed near volcanoes and have modelled them to obtain their source parameters. Thus, the study of source parameters of the induced microearthquakes provides considerable information about the fluid-rock interaction during an injection.

Where Do We Go From Here?. So far, we have described results of studies that have been largely completed. Yet, there is still much information to be learned about the reservoir. A major unknown is the state of stress in the HDR reservoir. The fault plane solutions can be used to estimate the orientation of stresses. Several recent studies have developed the methodology of inverting fault plane solutions for stress orientations [e.g. Michael, 1987]. This technique has considerable importance for characterizing an HDR reservoir because it should provide information about the state of stress at distances of several to several hundreds of meters from the wellbore. Thus, it should be useful for better understanding how an existing reservoir was created and how it behaved in response to the ambient stresses. Second, it should allow more reliable predictions of how a new reservoir will develop, if we know the stress state and other rock mechanical properties, such as the geometry of pre-existing joints, in the reservoir rock.

We are also developing an automated arrival time (P and S) picking scheme in order to reduce the amount of time needed to manually locate each earthquake. The ability to reliably pick S arrivals is crucial in using an automated picking and locating scheme for Fenton Hill data, because we have so few stations. Automated arrival time picking will give us the "on-line" analysis ability that has long been a goal. Such capability will considerably reduce the time between occurrence of events and availability of information about the events, and should be of great usefulness during creation of a new HDR reservoir.

Finally, although we have so far discussed microseismic studies only in the context of developing and characterizing an HDR reservoir, these studies would also be useful for determining results of the hydraulic fracturing operations done by the oil and gas industry. There are serious objections to the need for multiple monitoring wells to implement the arrival times locational method. Nevertheless, there have been successful studies that used the hodogram locational technique with data from a single triaxial instrument in injection wells [e.g. Sarda, et al, 1988].

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Figures

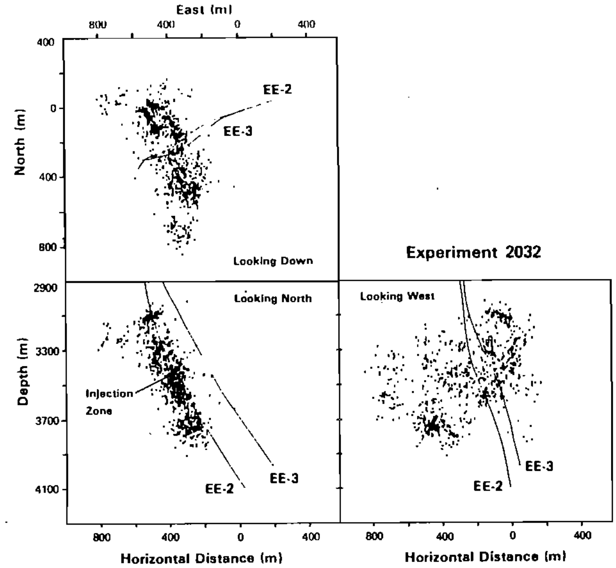

Figure 1. Three orthogonal views of the reliable microearthquake locations from the MHF. Top left is a map view, bottom views are vertical cross sections looking North (left) and West (right).

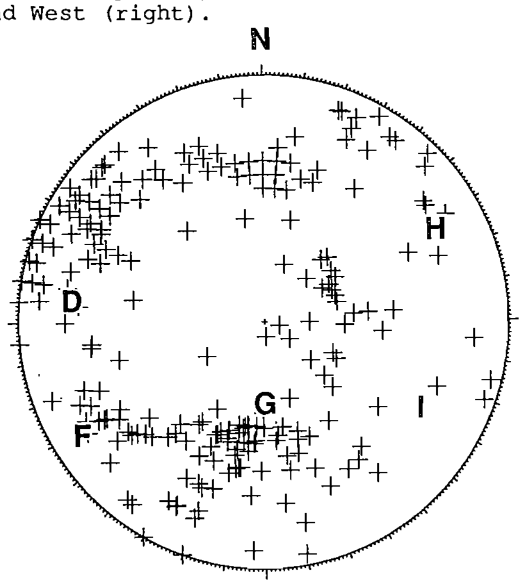

Figure 2. Plot of MHF data: crosses are poles to nodal planes of fault plane solutions; letters D, F, G, H, and I are poles to planes determined by the three point method [Fehler, et al, 1987]. Note that three point planes D, F, and G lie near edges of clusters of poles nodal planes.