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ROCK FAILURE DURING MASSIVE HYDRAULIC STIMULATION OF THE BACA LOCATION GEOTHERMAL RESERVOIR

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ABSTRACT

The analyses of microearthquake signals occurring during hydraulic stimulation provide an estimate of the size and location of the fractures thus produced. We report studies of microearthquakes occurring during two large ($>10^3 m^3$) hydraulic stimulations of the hydrothermal reservoir at the Baca Location in the Jemez Mountains of Northeastern New Mexico. Both stimulations consisted of water, viscosity enhancer, and proppant. The microearthquake event rate was low but variable throughout most of the treatment. Rock failure as indicated by the distribution of the microearthquakes' foci appeared restricted to a nearly vertical NE striking zone. This orientation is in good agreement with the local earth stresses inferred from geological considerations. The second stimulation which occurred in a neighboring well was similar to the first except for a larger injected volume. The lateral extent of the detected fracture system was 600 m in both stimulations.

INTRODUCTION

Determining the orientation and size of hydraulic fractures produced by hydraulic stimulation of geothermal wells remains an important unsolved problem in geothermal engineering. This paper describes a technique for using the location of very small (magnitude -5 to -2) microearthquakes that often accompany hydraulic stimulation experiments in geothermal wells. Since these events, which are induced by a localized zone of high pore pressure, occur in a narrow band about the hydraulic fracture, their locations can be used to infer the fracture size and orientation.

Microearthquake observation techniques were originally developed to locate hydraulic fractures in low permeability, low porosity crystalline rocks for Los Alamos National Laboratory Hot Dry Rock Geothermal Project (Albright and Hanold, 1976). However, in this paper, we describe experiments that successfully used microearthquake signals to locate hydraulic fractures produced during stimulations of hydrothermal wells on the Union Geothermal Baca lease in NE New Mexico.

PHYSICAL SETTING

The Baca Geothermal lease is located in the Jemez Mountains, a well known Miocene to Quaternary volcanic center in Northwestern New Mexico. Volcanic activity here culminated in the formation of the Valles Caldera 1.1 Myr ago (Smith and Bailey, 1980). The two wells (Baca No. 23 and No. 20), which were stimulated during this program are located in Redondo Creek valley, a prominent graben structure slightly northwest of Mt. Redondo, the resurgent dome.

The graben structure is filled with 1200-1800 m of tuff which is underlain by 300-600 m of andesite. All of the tuff has been hydrothermally altered resulting in quite low matrix permeabilities (<1 md). The upper part of the tuff is highly silicified forming a nearly impermeable caprock for the reservoir. Figure 1 shows a generalized stratigraphy. Because of the low permeability production is from fractures principally in the lower 300 m of the tuff. Formation temperatures in this zone can be as high as 260°C (Dondanville, 1978).

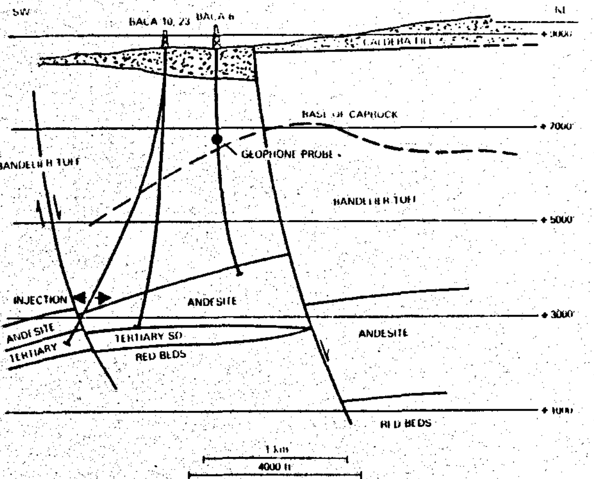

Figure 1. Lithology near Union's Baca Well No. 23. Well No. 6, our observation well and Well No. 10 in which vertical seismic profile measurements were made.

When locating these events we assumed that the P wave velocity was 5.3 km/s. This value came from a preliminary analysis of a vertical seismic profile, measured in cooperation with Union Geothermal Co. in well No. 10, which is within a few meters of well No. 23. During this survey 10 explosive charges were fired in 10 m boreholes located approximately 100 m from the well to avoid generating tube waves.

Our analysis of this survey suggests two layers, the upper one having a velocity of 3.9 km/s (12,900 ft/s) and the lower one having a velocity of 5.3 km/s (17,300 ft/s). The interface between the two layers is at 610 m (2000 ft) depth in well No. 10. As shown in Fig. 1 this depth correlates with the base of the caprock in well No. 10 so the 5.3 km/s layer represents the saturated tuff and the 3.9 km/s layer represents the dry caprock.

INSTRUMENTATION

The microearthquakes were recorded using a removable three-component geophone package (Albright and Pearson, 1982) which we lowered down a shut-in geothermal well to a depth of 305 m during the first experiment and 1000 m during the second. This downhole system allows us to record events within a few hundred meters of the source and avoid the excessive attenuation in the overburden which would be expected, if detection by surface instruments were attempted. Good coupling between the rock and the geophone package is ensured by extending the retractable arm, which locks the package in the well.

EVENTS

An example of the microearthquake signals detected during each stimulation is shown in Fig. 2. The records usually show two clear arrivals, the first of which is the compressional (P) wave and the second is the shear (S) wave. These characteristics allowed us to distinguish between microseismic signals and electronic noise. In practice, surface pumping noise was not a problem because the geophone was located more than 300 m below the surface in a shut-in well.

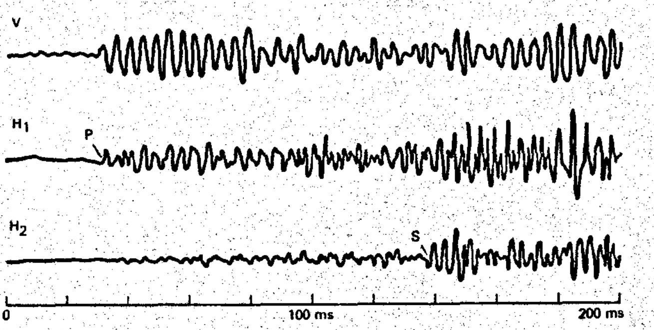

Figure 2. Microearthquake signal from the Baca No. 23 stimulation.

These events have magnitudes ranging between -5 and -3, approximately four orders of magnitude smaller in energy than earthquakes which would be noticed or felt on the surface. The magnitudes were estimated using the signal duration or coda length method described by Real and Teng (1973). In calculating the magnitude we used an empirical relation between magnitude and duration developed by Newton et al. (1976) for the Jemez region.

The direction and distance to microearthquake foci were determined using P-wave onset polarization and the S- and P-wave arrival time difference, respectively (Albright and Pearson, 1982).

Because the orientation of microearthquake radiation patterns is not known a priori, there are two possible locations for the origin of the microearthquake. By design, during the hydraulic fracturing experiments the geophone tool was stationed substantially above the stimulated reservoir volume. Thus, one can assume that the event locations can be properly placed below the geophone station.

The first measurements were conducted during a hydraulic stimulation of Baca Well No. 23. 1300 m^3 water, viscosity enhancer, and proppant were injected at up to 0.20 m^3/s (76 bpm). Microearthquake signals were detected within 18 min after the start of pumping. The event rate was low but variable throughout most of the treatment. Bursts of activity, which included the largest events detected occurred both after injecting 120 m^3 of untreated water and after having pumped 140 m^3 of the proppant schedule. No change in event rate was observed on injection of the viscosity-enhancing gel. Figure 3 shows the rate of energy release during this experiment. The first cluster of events, labeled A in Figure 3, represent a natural earthquake which occurred 1.5 hr before the hydraulic stimulation. Fortunately this swarm died out before the beginning of pumping.

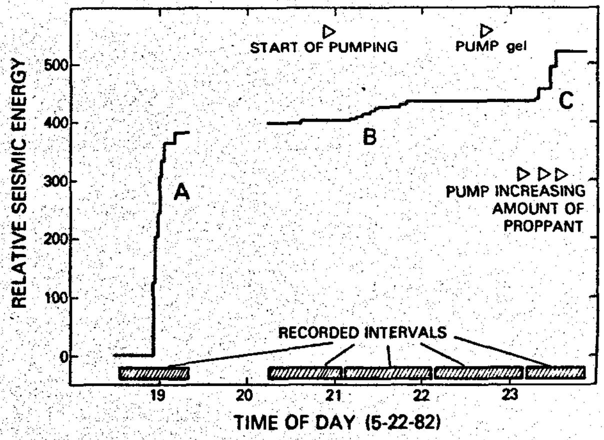

Figure 3. Seismic energy release as a function of time for the Baca No. 23 stimulation. Focal energies are plotted on a scale normalized to the smallest detectable event of $M_L \sim -5$.

The second stimulation, which occurred in Baca Well No. 20, a well 2 km up Redondo Creek from Baca Well No. 23, was similar to the first except for a larger injected volume of both water and proppant as well as a higher injection rate. During this experiment most of the activity occurred within one hour after the start of pumping. There was no burst of activity similar to C in Figure 3 at the start of the proppant schedule.

EVENT LOCATIONS

During the first experiment rock failure appeared restricted to a nearly vertical NE striking zone approximately 600 m in length. This orientation is roughly perpendicular to the least principal horizontal earth stress as inferred from geological findings and regional earthquake fault-plane solutions (Aldrich and Laughlin, 1982).

Most events clustered in a narrow band 100 m high near the injection point which may represent the main fracture opened during this experiment. However, three events occurred as much as 400 m higher, suggesting hydraulic communication over that great a distance in the reservoir. Figure 4 shows the event locations both in plan view and projected to a plane close to the probable fractured zone. The injection zone in the stimulated well falls slightly off the fracture plane in the plan view projection but this is probably caused by small errors in determining the orientation of the geophone package in the wellbore.

During the second stimulation (see Figure 5) the resulting fracture was somewhat larger, nearly 400 m high and almost 600 m long. An equipment failure prevented us from determining the orientation of our geophone package in the wellbore so we were not able to measure the strike of this fracture.

During both experiments the seismic zones were approximately 150 m thick. Some but not all of this thickness is due to errors in our location technique (Pearson, 1981). Albright and Pearson (1982) show that the events are caused by shear

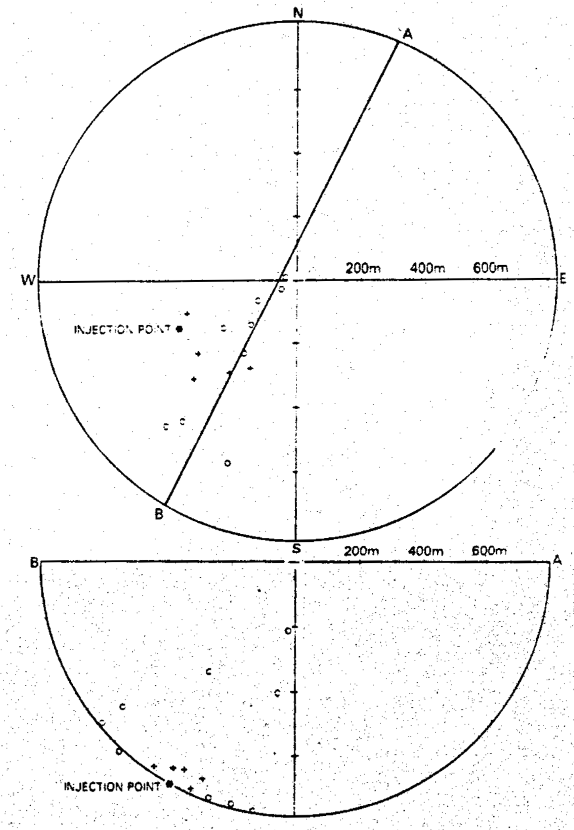

Figure 4. Location of microearthquakes that occurred during the stimulation of Baca Well No. 23 — plan view (upper) and projection to the vertical AB plane. Crosses indicate positive first motions, circles indicate negative first motions. The coordinate origin is the geophone location and the injection point is indicated by an asterisk.

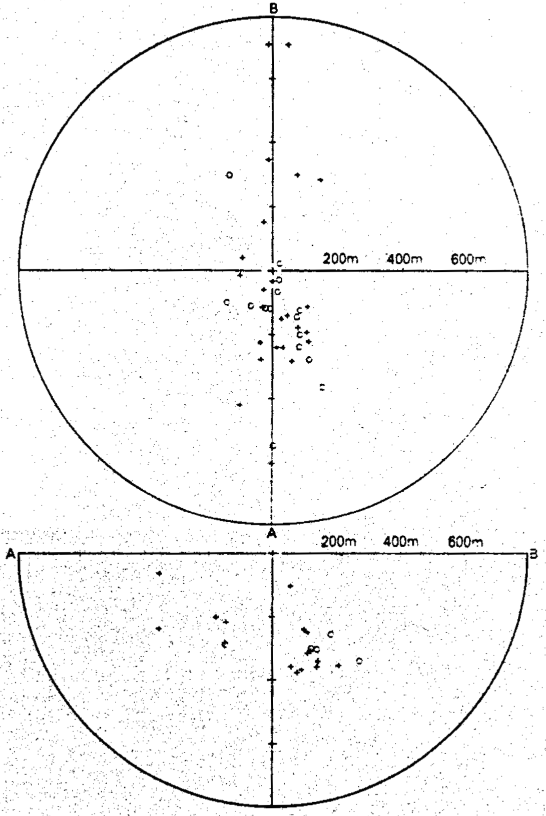

Figure 5. Location of microearthquakes that occurred during the stimulation of Baca Well No. 20 — plan view (upper) and projection to the vertical AB plane. Crosses indicate positive first motions, circles indicate negative first motions. The coordinate origin is the geophone location.

failure on secondary joints and fractures that intersect the main hydraulic fracture. Failure thus occurs in a potentially wide zone where leak-off has locally increased the pore water pressure.

CONCLUSION

Both stimulation experiments turned unproductive wells into producers (Verity and Morris, 1981). Large fractures or fracture zones with dimensions on the order of several hundred meters opened up during the hydraulic stimulation. Since part of the fractured rock may have low hydraulic conductivity, the effective area accessible during production may be smaller.

The results of these measurements suggest that microearthquake observation methods are a potentially useful technique for evaluating hydraulic stimulations of wells in other geothermal fields. However for this technique to work, reservoir rock must transmit both the P- and S-waves without excessive attenuation. In many geothermal reservoirs, particularly if unconsolidated sand or partially saturated rock is present, this may not be possible (Nur et al., 1980).

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