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RECENT RESULTS: LOS ALAMOS HOT-DRY-ROCK PROJECT

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ABSTRACT

A new deeper reservoir is presently being investigated at the Laboratory's Fenton Hill Hot Dry Rock (HDR) site. The region surrounding the lower of two inclined boreholes, directionally-drilled to about 4 km in hot crystalline rock, has been pressurized in a sequence of injection tests. Based primarily on the measurements made by two close-in microseismic detectors, two similar volumetric reservoir regions have been developed by massive hydraulic fracturing, but with no significant hydraulic communication with the upper borehole as yet.

INTRODUCTION

Since June of 1982 -- including a 10-week furlough period -- the Los Alamos National Laboratory has been attempting to connect two deep inclined boreholes in hot granitic rock by means of massive hydraulic fracturing. As of this writing (November 1982), we have yet to be successful in making a connection, although close-in microseismic data have revealed the probable causes of our difficulties. Renewed fracturing operations early next year, guided by a careful assessment of recent pumping and seismic data, hopefully will result in a significant number of fracture connections, and a very large thermal reservoir.

The setting for these experiments, beneath the Jemez Mountains of northern New Mexico, is depicted in the sectional view of Figure 1. The Fenton Hill Hot Dry Rock (HDR) Geothermal Site is located several kilometers west of the Valles Caldera, in a region of low apparent structural complexity, but of high volcanic-associated heat flow. The trajectories of our two new wellbores -- EE-2 and EE-3 -- are shown in the plan and sectional views of Figures 2 and 3. The lower openhole portions of these two near-parallel directionally-drilled boreholes are inclined 35° from the vertical, and were drilled to the east, approximately parallel to the direction of the least principal earth stress.

BRIEF DESCRIPTION OF FRACTURING EXPERIMENTS

A series of three large-scale pumping experiments have been performed in the lower portion of the new -- Phase II -- reservoir region, at injection rates up to about 90 ℓ/s. After cementing in a scab liner about 150 m above the bottom of EE-2 for wellbore isolation, the openhole interval (at a mean depth of 4310 m) was pressurized in three successively larger injection tests of 500, 3000 and 4900 m^3 respectively. Despite these relatively large volumes of injected water, we failed to achieve hydraulic communication with the upper borehole (EE-3) for reasons discussed below.

Following these tests, the EE-2 wellbore was sanded up to within about 150 m of the casing shoe, providing an isolated openhole interval in the upper portion of the Phase II reservoir region. Two injection tests of 900 and 3200 m^3 have recently been performed in this upper region, with only a slight indication of hydraulic communication so far. Because of the nature of the fractured reservoir being developed, it now appears that significantly larger volumes of injected water will be required to achieve the desired level of communication.

FRACTURE GEOMETRY INFERRED FROM CLOSE-IN MICROSEISMIC DATA

Extensive downhole measurements of the locations of microseismic events generated by the hydraulic fracturing process have been made during all of the injection tests. The microseismic event locations were primarily determined from signals received by a three-axis oriented high-temperature geophone sonde at a depth of 2950 m in EE-1 (the injection borehole for the previous shallower Phase I HDR reservoir at Fenton Hill). Also, for the more recent injection experiments, a series of detonator shots were made deep in EE-3 prior to pumping. This was done to provide both a redundant geophone package orientation, and a relative sensitivity calibration of the geophones (the sensitivity of the vertical geophone as compared to that of the two horizontal geophones, which is needed for accurate particle motion determinations). For most of the injection tests, a newly-developed three-axis oriented high-temperature accelerometer sonde was also positioned in the EE-3 borehole adjacent to the pressurized interval in EE-2 (following the detonator shots). Although the accelerometer tool is still under development, it has generally provided accurate $V_s - V_p$ time differences for the microseismic events, significantly reducing location errors associated with the analysis of the geophone-measured signals.

The microseismic event locations associated with the pumping experiments performed in the lower part of the Phase II reservoir suggest that three distinct -- but parallel -- fracture zones, inclined about 45° from the vertical, were opened (hydraulically fractured). These fracture zones strike roughly north-south, dip towards the west, and appear to extend upwards and to the east away from EE-3. Thus, these upward-extending fracture zones may have all missed -- passed below -- the bottom of EE-3, explaining the lack of hydraulic communication. Figure 4 shows, in both plan and elevation views, the seismic data for one 50-minute time interval during the last (4900 m^3) injection test. The steeply-dipping seismic feature apparent in the elevation view of Figure 4, which persisted for about 5 hours, is one of three roughly parallel zones that were developed during this sequence of pumping tests in the deeper part of the Phase II reservoir.

The microseismic event locations associated with the pressurization of the upper part of the Phase II reservoir exhibit a more volumetric character than those associated with the lower part of the reservoir. Figure 5 shows the microseismic pattern for the last two hours of EE-2 pressurization during the second (3200 m^3) injection test in the upper part of the reservoir.* In both the plan and elevation views, the microseismic event locations appear to be fairly uniformly distributed around the openhole section of EE-2, having not yet reached EE-3 as shown in the elevation view. A rough ($\sim R^2$) scaling based on the microseismic event location data shown in the elevation view of Figure 5 suggests that a total injected volume of about 13,000 m^3 (3.4 x 10^6 gallons) would be required to extend the active seismic boundary -- growing radially outwards from EE-2 -- to the vicinity of the EE-3 wellbore.

If the volumetric interpretation of the seismically-active region surrounding EE-2 is correct, this would imply that we have already hydraulically activated 37 million cubic meters of hot crystalline rock in the upper part of the Phase II reservoir. A statistical analysis of the microseismic data from the first pumping test indicates that this fractured volume is formed by the intersections of

*In Figure 5, the smaller letters "T" and "B" represent the top and bottom of the openhole interval.

two -- and probably three -- joint sets. The major set strikes N10W and dips about 60° to the west, while the sub-major set strikes N35E and dips very steeply ($\sim$80°) to the west. The minor set (at least seismically) is vertical and strikes somewhat east of north.

DIFFERENCES BETWEEN THE TWO FENTON HILL HDR RESERVOIRS

The Phase II reservoir appears to differ from the previous -- and somewhat shallower -- Phase I reservoir in two distinct ways. First, the Phase I reservoir was formed mainly by a parallel set of near-vertical fractures, whereas the Phase II reservoir appears to be much more volumetric in nature, and is controlled by the principal set of 60° west-dipping fractures. Second, the Phase II reservoir exhibits a very marked volcanic association when compared with the Phase I reservoir. We have been surprised by both the large amounts of dissolved CO_2 encountered in the connate pore -- or fracture (?) -- fluids in the Phase II reservoir, and the lesser amounts of associated H_2S. This dominant inclined fracture system that appears to truncate the older near-vertical joint sets, in combination with typical volcanically-derived dissolved gasses, strongly suggests that the Phase II reservoir has a significant volcanic association that was not exhibited by the Phase I reservoir.

In a sense, our Fenton Hill site has allowed us to investigate two significantly different HDR regimes: one of relatively simple structure typical of the Basin-and-Range Province, and the other more typical of volcanically active regions.

PRESSURE/FLOW DATA AND EARTH STRESS IMPLICATIONS

The most significant feature of the Phase II reservoir, from the pressure/flow standpoint, has been the much higher fracture opening stress levels when compared to the Phase I reservoir. However, if one accepts that we are primarily opening inclined joints in the Phase II reservoir as compared to vertical joints in the overlying Phase I reservoir, then the significant increase in fracture closure stress as inferred from fluid injection pressure levels is more easily explained.

For the lower part of the Phase II reservoir at a mean depth of 4300 m, the effective fracture closure stress obtained from four instantaneous shutin pressure (ISIP) measurements during the final (4900 m^3) injection test was 805 bars (11,680 psi), corresponding to a 376 bar (5450 psi) surface pressure. If one linearly extrapolates the measured Phase I value for the least principal earth stress* to the lower part of the Phase II reservoir and

*S_3 = 358.5 bars (5200 psi) at 2700 m in the Phase I reservoir.

uses the overburden stress as the maximum principal stress (S_1), the measured fracture closure stress of 805 bars would correspond to an inclined fracture zone dipping 49° to the west, in good agreement with the seismic data shown in Figure 4.

The pressure/flow behavior of the upper part of the Phase II reservoir is much more anomalous, as shown by the ISIP data of Table I.

The shutin pressure data for the upper part of the reservoir during the second injection test (Expt. 2020) show a steady rise in the ISIP with time, and therefore with total injected volume. Surprisingly, about half way through Expt. 2020, the ISIP (surface) had exceeded the average measured ISIP value for the lower part of the Phase II reservoir. Even more anomalous is the very significant 70 bar (1000 psi) increase in the ISIP between the end of the first injection test (after a total injection of 905 m^3), and early during the second injection test (after having injected only 114 m^3).

Although our understanding of these ISIP data is still not complete, one fact is clear. We have produced a bounded volumetric reservoir in the upper region. It would appear that we are inflating a contained region with limited outflow, and activating progressively higher-closure-stress joints within the pressurized region as the static inflation pressure slowly rises: a very foreign concept among the experts on hydraulic fracturing in the petroleum industry.

Table I

ISIP Summary for Upper Phase II Reservoir

Experiment Number	ISIP, Surface bars (psi)	Flow Rate ℓ/s (BPM)	Cumulative Flow m^3 (gallons)
2018	293 (4250)	33.4 (12.6)	905 (239,000)
[EE-2 vented between experiments]			
2020	339 (4910)	5.0 (1.9)	117 (31,000)
2020	363 (5270)	12.5 (4.7)	114 (30,000)
2020	371 (5380)	25.1 (9.5)	170 (45,000)
2020	367 (5330)	42.1 (15.9)	254 (67,000)
2020	395 (5730)	90 (34)	1840 (486,000)
2020	401 (5820)	82 (31)	3200 (844,000)

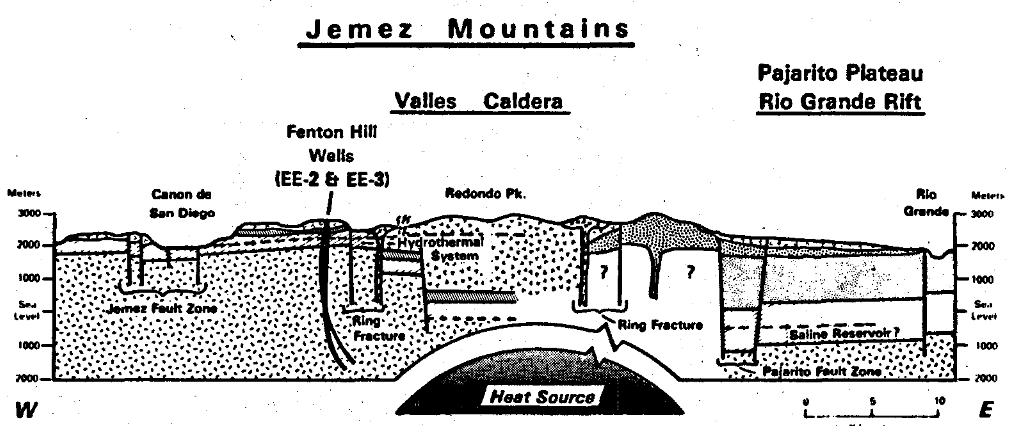

Figure 1. Setting for the Fenton Hill Hot Dry Rock Project.

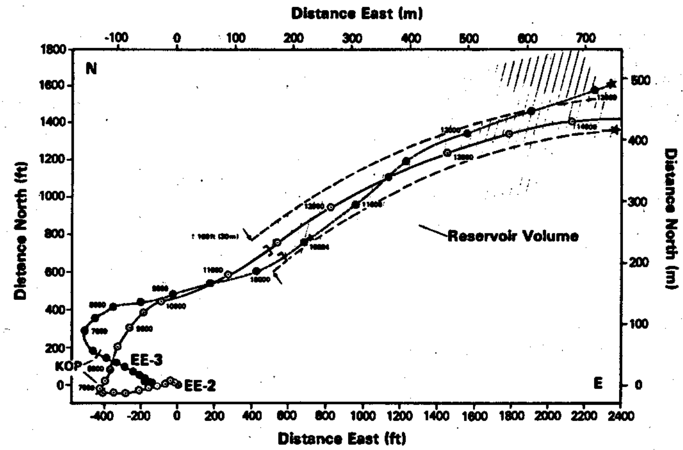

Figure 2. Plan view of Holes EE-2 and EE-3.

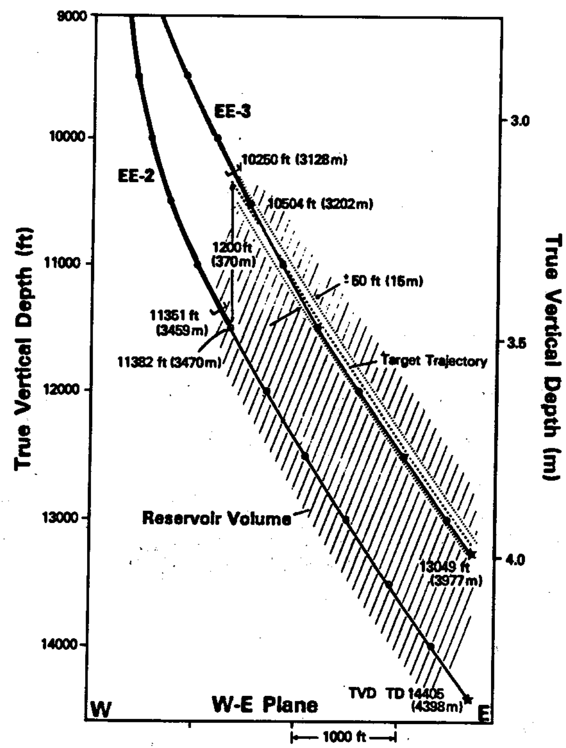

Figure 3. Section view of the openhole portions of EE-2 and EE-3.

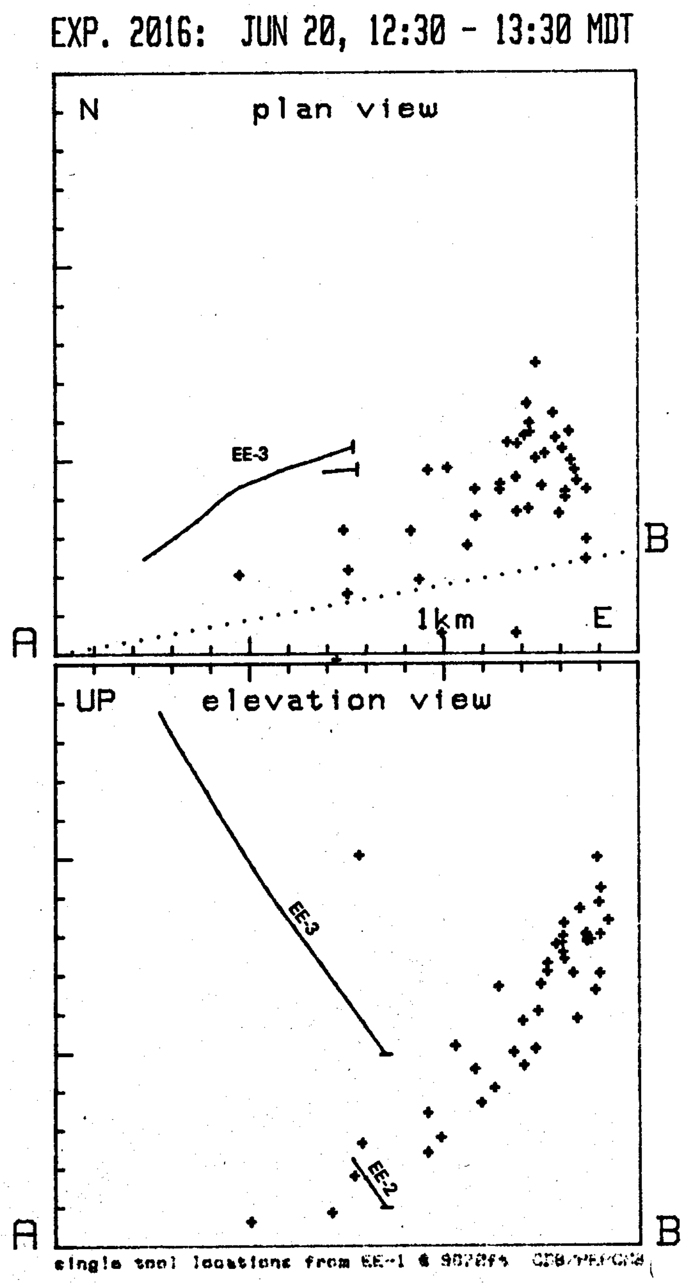

Figure 4. Hypocenters of microseismic events typical of the time between 10:00 and 15:00 when seismicity occurred along a narrow inclined region in the deeper part of the Phase II reservoir.

EXP. 2020   05:00 - 07:00

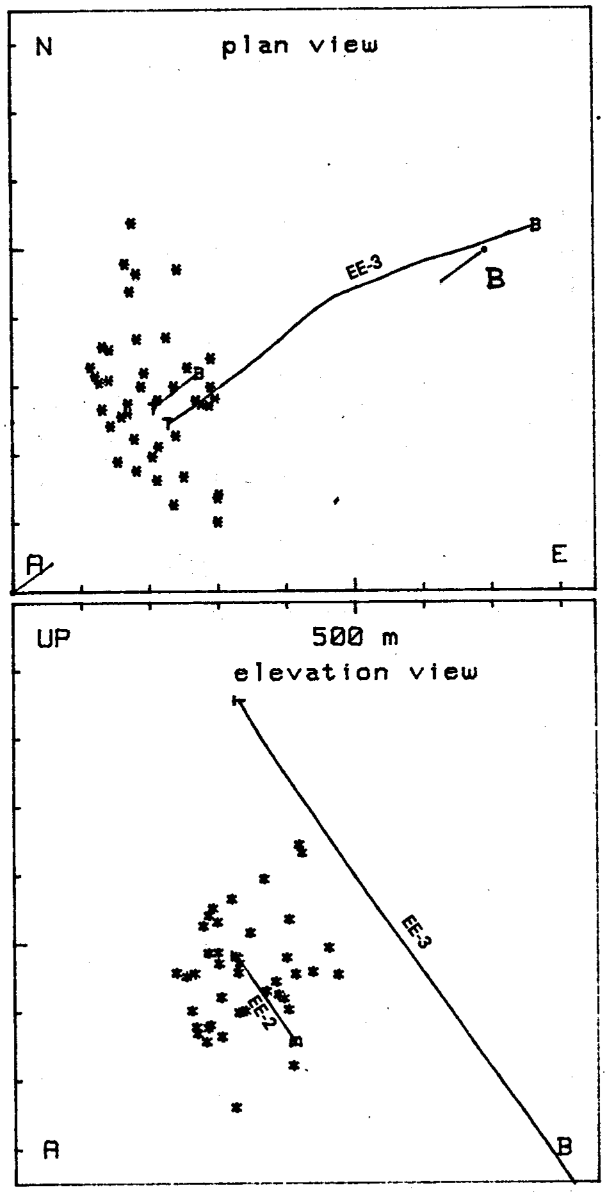

Figure 5. Microseismic event locations during the last two hours of injection into the upper part of the Phase II reservoir.