EVALUATION OF THE FENTON HILL HOT DRY ROCK GEOTHERMAL RESERVOIR

PART III. RESERVOIR CHARACTERIZATION USING ACOUSTIC TECHNIQUES

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Introduction

The success in establishing flow between wells at Fenton Hill is due in part to the development of crude acoustic measurement techniques which enabled targeting of a hydraulically fractured rock volume for the final directional drilling of the production well.[4,5,6] Our purpose here is to review subsequent efforts to detect pressurized hydraulic fractures in the Fenton Hill reservoir that are based on the acquisition of data using commercially available acoustic logging tools and signal processing techniques developed at LASL. Only the dual-well measurements made with these tools will be discussed. In the application of these methods at Fenton Hill, results of the earlier work have been substantiated and more detailed information regarding fractures in the reservoir has been obtained.

The Fenton Hill Reservoir

The downhole arrangement at Fenton Hill is shown in Fig. III-1. Energy Extraction Well No. 1 (EE-1) and Granite Test Well No. 2 (second redrilled section, GT-2B) are the injection and production wells respectively. GT-2B terminates at 2.7 km (8882 ft) and EE-1 at 3.0 km (10,000 ft) at a greater depth than represented in the figure. Both wells penetrate basement rocks at approximately 0.7 km (2400 ft) and terminate in granodiorite. Four fractures in GT-2B account for 90% of production. In order of decreasing flow, the fractures are located at 2.64 km (8665 ft) (35%, 2.70 km (8857 ft) (24%), 2.67 km (8750 ft) (19%) and 2.69 km (8815 ft) (12%). GT-2B is cased to 2.60 km (8541 ft). The bottom casing in EE-1 is at 2.92 km (9578 ft), but 90% of the flow moves behind casing from 2.92 km to 2.76 km (9053 ft) where it enters the reservoir through a hydraulic fracture. Water then moves vertically 64 m (210 ft) before the lowest entry point in GT-2B is reached. Several other fractures over the depth interval 2.1-2.9 km (7000 to 9600 ft) accept water on pressurization of the injection well, but these account for only a small percentage of the injection into the reservoir. Because of the depth of the reservoir, the major fractures are believed to be always vertical or nearly so.

Logging Tools and Acquisition of Data

Two acoustic logging systems, one for use in each well, were provided under subcontract for this work by Dresser Atlas, Dresser Industries, Inc. One system is that used by Dresser Atlas in providing their Acoustilog logging service. The second system is a modified version of the first with the principal difference being the use of a more powerful transmitter. The bandpass of the detected signals transmitted between wells was 12 kHz ± 2 kHz. A signal repetition rate of 5 signals/second and a logging rate of 0.1 m/s (20 ft/min) was used when either tool was in operation.

The sequence of transmitter and receiver movements for the dual-well measurements is illustrated in Fig. III-1 and is as follows. With the receiver in fixed position in GT-2, the transmitter in EE-1 was moved from an inclination of 45° above the receiver to 45° below it. Next, the receiver was moved in the same manner. This sequence was followed until the depth interval of interest was logged. A staggered sequence was followed in logging upwards. The entire sequence of operations was conducted twice: first, when the wells and reservoir fracture system were at a hydrostatic or unpressurized condition and subsequently when reservoir pressure was elevated to values approaching that believed necessary to part fracture faces.

Direct ray paths of the signals transmitted between wells traversed slant distances up to 46 m (150 ft) and horizontal distances as short as 15 m (48 ft). Volume elements as small as 16 cm^3 in the region between wells were traversed by at least two signals having direct ray paths of different incidence in both unpressurized and pressurized conditions.

Results

An interesting picture of the Fenton Hill experiment emerges when recent analyses of the waveform of signals transmitted between wells is viewed in terms of the acoustic attenuation in the reservoir. Such a study is greatly facilitated using Power logs and Equi-Power logs (NEP logs) of the kind reviewed in references 7 and 8. The recent work shows that characteristic acoustic waveforms identified using the NEP representation can be used to simply describe the extent and nature of the reservoir. Each waveform finds representation over large vertical dimensions in the reservoir under hydrostatic conditions. The significance of each of the waveforms is not understood in detail: reasonable hypotheses can be advanced which are constrained by the changes in attenuation that were observed on pressurization of the reservoir.

The signals transmitted between wells have been found to have one of three distinctive waveforms. Figure III-2 shows the waveforms which we have designated as S, P, or D type, depending on the relationship between the peak amplitude of the compressional wave arrival and the peak amplitude of the shear wave arrival. The S-type exhibits a strong S-wave arrival whereas in the P-type for comparable P-wave amplitudes, the amplitude of the shear wave is severely attenuated or not observed within reasonable limits to its appropriate arrival time. The D-type shows an emergent P-wave onset and peak P-wave amplitudes comparable to that observed anywhere in the signal coda.

The Power logs for signals transmitted between wells is given in Fig. 111-3. The logs are subdivided in segments according to receiver position. With increasing depth the horizontal distance between wells decreases. The logs are not corrected for geometric spreading. This correction however is independent of pressure conditions in the reservoir.

Shown in the Power log is a general increase in attenuation on reservoir pressurization with depth below 2.67 km (8450 ft). A marked discontinuity in attenuation is noted in the center of both unpressurized and pressurized sections of the 2.63 km (8642 ft) segment. On pressurization, attenuation changes by a factor of 10 greater throughout the sections below the discontinuity than above it. We call the discontinuity the top of the primary attenuator in the reservoir. The discontinuity is well within the bounds of the granodiorite section of the reservoir. A primary attenuator is probably not one but perhaps the several mega-fractures which formed the primary flow paths prior to the 1000-hr heat extraction experiment. The producing fractures all intersect GT-2B below this depth.

Of special interest is the 2.7 km (8850 ft) section. The magnitude of the attenuation increases with depth throughout the shallower sections in both pressurized and unpressurized reservoir conditions even though wellbore distances have closed from 37 to 21 m (120 to 70 ft). In the 2.7 km (8850 ft) section the magnitude of the attenuation is reduced by a factor of nearly 100. The increase in attenuation with pressurization however is large -- a factor of 1000. This section of the reservoir is unique in other respects which cannot be discussed here.

The spatial distribution of the waveforms transmitted through the reservoir is shown in Fig. III-4 as the variously colored areas. Also indicated are the locations of the injection point in EE-1, the production points in GT-2 and the top of the primary attenuator.

Now take the liberty of associating the P- and D-type signals with two different fractured regions even though the nature of these systems has not been thus far established. In the unpressurized system an S-type region caps the reservoir, a P-type region dominates, and small wedges of each type including D, are found in the lower section of the reservoir. On pressurizing the system the S-type cap region transforms to a P-type and the mixed types of the lower part convert to D-type. One can reasonably assume that prior to hydraulic stimulation, the reservoir consisted of entirely S-type regions, the red lithology in Fig. 111-4. Clearly the waveform types, their spatial distribution in the reservoir, and the changes in waveform effected by pressurization are of global significance in understanding the reservoir. Changes in signal type occur even above the contact, a region quite removed from the injection and production fractures. A communitivity of waveform modification appears to exist, such that on pressurization of S-type regions are converted to P-type, and P-type in turn are converted to D-type. There can be little disagreement that the S-type rock supports shearing stresses of the magnitude associated with high frequency acoustic signals. Further, in the absence of fractures, shear phases will not vanish with pressurization. Our observations indicate to the contrary that within the reservoir under investigation the only S-type region observed in the reservoir converted to P-type on pressurization. Shearing stresses were not transmitted hence fractures are present in the S-type region. The fractures must however have sufficient contact area in the unpressurized state so that loss of shear waves by scattering or back reflection does not occur.

Because P-type regions do not transmit shear waves, it may imply that these regions contain mega-fractures which have single or multiple single parted surface areas exceeding several acoustic signal wavelengths in one dimension. One anticipates that only regions containing mega-fractures pressurized above the least confining stress should be P-type. Somewhat unexpected is that this condition is met locally in the reservoir without pressurization. Indeed one is led to the conclusion that the fractures do exist which have mismatched parted surfaces caused by relative displacements or chemical dissolution resulting in a self-propped condition.

The existence of P-type regions and the absence of a clear transition between S and P is an apparent contradiction. Components of shearing stress (shear waves) normal to parted fracture surfaces should propagate through the fracture even though that component parallel to the fracture surfaces is reflected. The arrival of a shear phase through P rock should be observed but in fact is not. A solution to this dilemma has not been found.

Several observations provide information regarding the nature of D-type regions. Most of the reservoir when pressurized is D-type. A wedge of D-type bounded successively by P- and S-type regions, exists in the reservoir at hydrostatic pressure. Compressional waves transmitted through D-type regions are not minimum phase, rather they are emergent. Obvious shear wave arrivals are absent. The section of the reservoir exhibiting conversion to D-type on pressurization shows high relative attenuation. By inference D-type regions may contain, in addition to parallel striking mega-fractures, conjugate mega-fractures, or numerous fractures with sufficiently small parted areas so that transmitted compressional and shear waves are scattered.

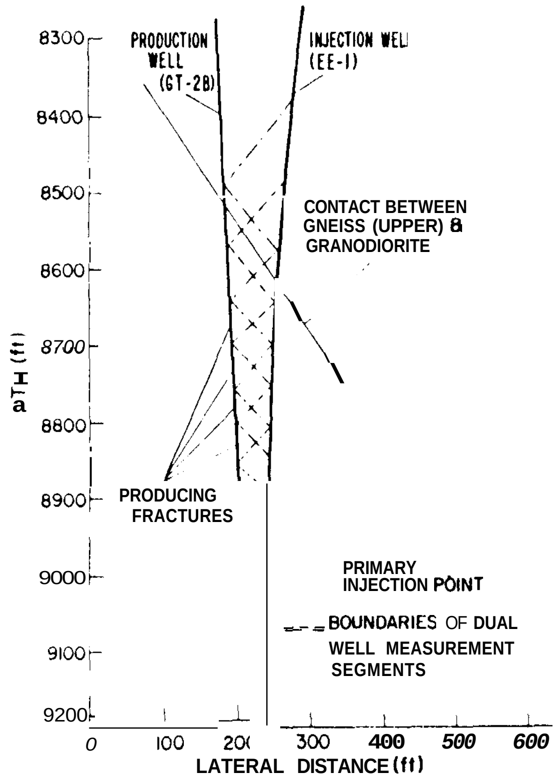

Figure III-1. Logged sections of the Fenton Hill man-made geothermal reservoir.

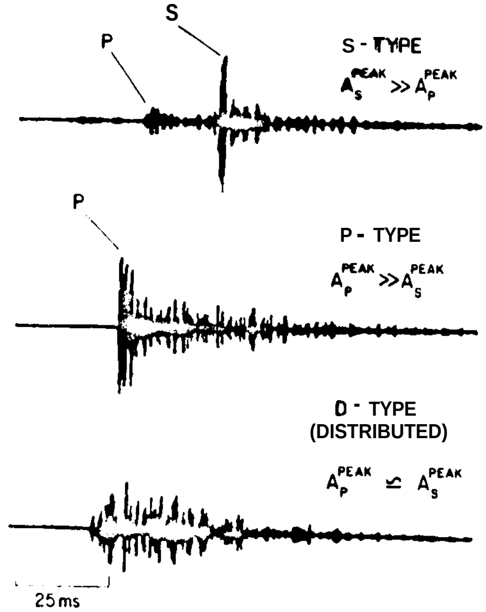

Figure III-2. S-, P-, and D-type waveforms.

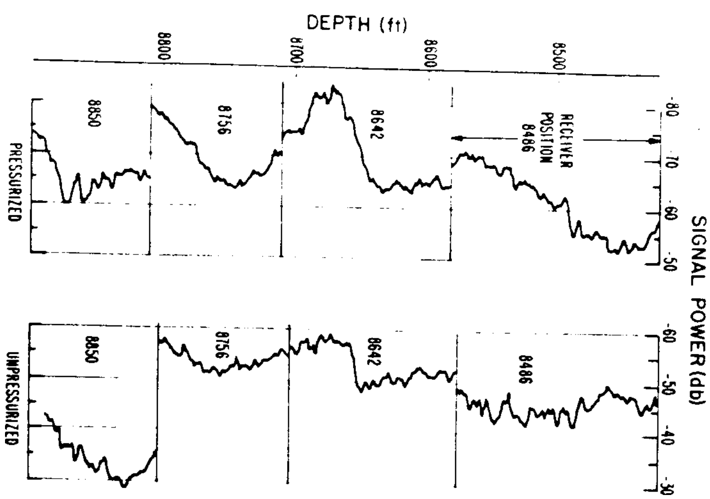

Figure 111-3. Power Logs - dual well.

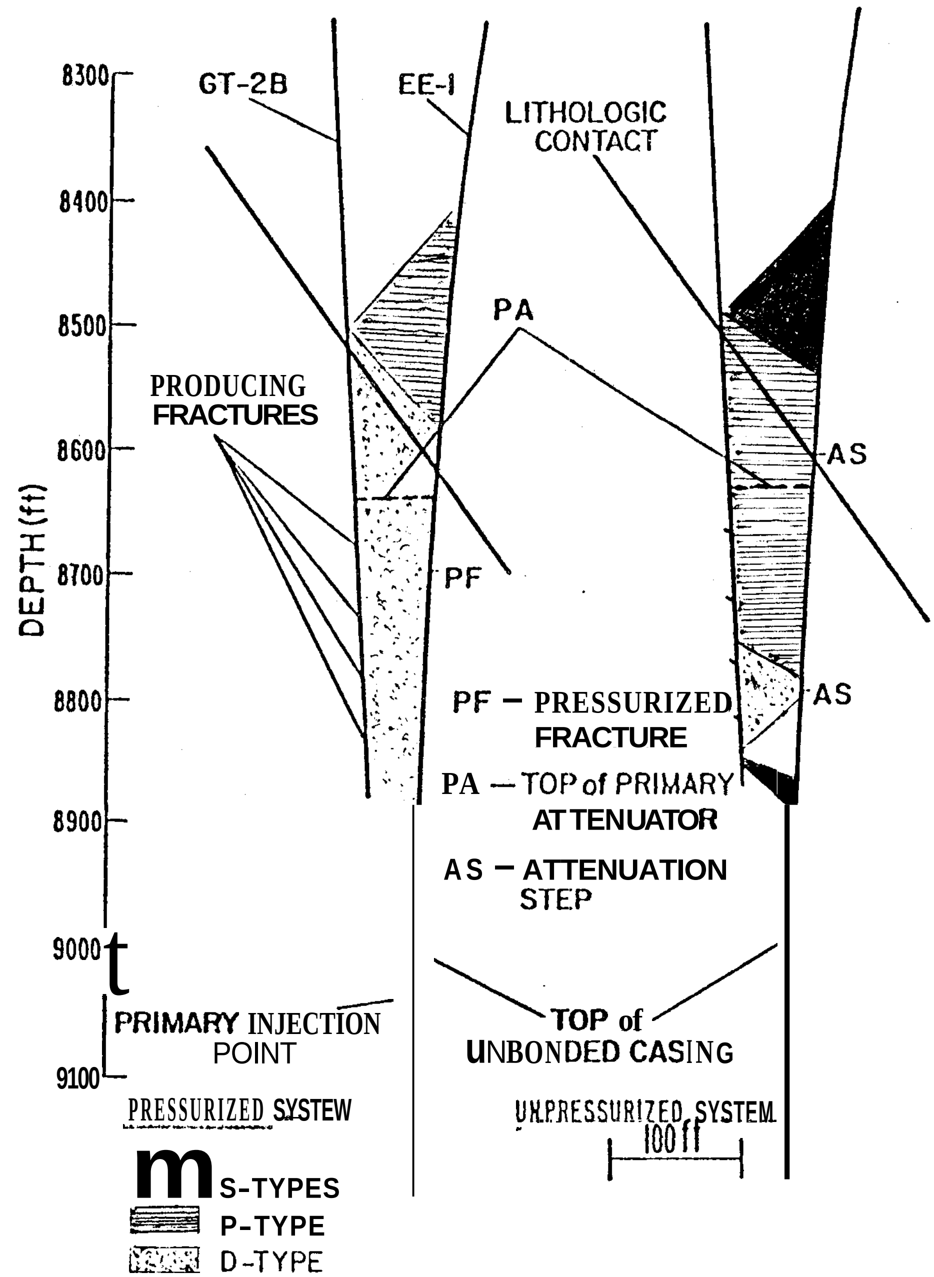

Figure 111-4. Spatial relationship between region of high relative attenuation and characteristic waveform.

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