ACOUSTIC METHODS FOR DETECTING WATER-FILLED FRACTURES USING COMMERCIAL LOGGING TOOLS

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ABSTRACT

The Los Alamos Scientific Laboratory Hot Dry Rock Geothermal Energy Development Project, under the Department of Energy and in cooperation with Dresser Atlas, has conducted single- and dual-well acoustic measurements to detect fractures in the artificial geothermal reservoir at the Fenton Hill New Mexico experimental site. The measurements were made using modified Dresser Atlas logging tools.

Signals traversed distances of from 48 to 150 feet between two wells. Signals intersecting hydraulic fractures in the reservoir under both hydrostatic and pressurized conditions were simultaneously detected in both wells. Upon reservoir pressurization, signals along many ray paths were severely attenuated throughout their entire coda. In addition obvious shear wave arrivals were notably absent. The signals were processed to obtain Full-Wave Acoustic, Power, and Normalized Equi-Power Logs. Analysis of these logs identified the effective "top" of a region of hydraulically activated fractures and fractures intersecting the injection well behind casing.

INTRODUCTION

Los Alamos Scientific Laboratory (LASL) under Department of Energy sponsorship, in support of the Hot Dry Rock Geothermal Energy Development Program has examined special applications of commercially available acoustic logging tools in detecting pressurized hydraulic fractures. A man-made geothermal reservoir has been produced at a demonstration site, Fenton Hill, in North Central New Mexico, by drilling a well into hot relatively impermeable basement rocks, by making large surface area hydraulic fractures, and by drilling a second well to intercept the fractures. Heat extraction is accomplished through a closed-loop circulation system. Water pumped into the pressurized injection well passes through

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hot rock between wells via the hydraulic fractures to the production well. Flow from the production well moves through a heat exchanger; the cooled water is reinjected. Numerous discussions of the LASL Hot Dry Rock concept and demonstration appear in the literature (1-4) so that a further discussion of them is not necessary. The success in establishing flow between wells 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.(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. Both dual- and single-well measurement methods are 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 Figure 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 8882 ft* and EE-1 at 10,000 ft, at a greater depth than represented in the figure. Both wells penetrate basement rocks at approximately 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 8665 (35%), 8857 (24%), 8750 (19%) and 8815 ft (12%). GT-2B is cased to 8541 ft. The bottom casing in EE-1 is at 9578 ft, but 90% of the flow moves behind casing from 9578 to 9053 ft where it enters the reservoir through a hydraulic fracture. Water then moves vertically 210 ft before the lowest entry point in GT-2B is reached. Several other fractures over the depth interval 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. Two transmitter-receiver pairs of cylindrical piezoelectric transducers with 2 in. diameters separated by intervals 2 to 4 ft

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*All depths cited in this paper are measured from a datum plane whose elevation is 8700 ft above mean sea level.

along their axis comprise one full system. We refer to the system as the 2 in. tool. In this work one receiver and both transmitters were disconnected; only one receiver continued to be operated. The other system consists of one 3-5/8 in. diameter transmitter acoustically isolated and separated from a 2 in. diameter receiver by 12 ft. Both transmitter and receiver were used. This second system we refer to as the 3-5/8 in tool. The band pass of the detected signals was effectively ± 2 kHz centered at 6.5 kHz for the 3-5/8 in. tool and 12 kHz for the 2 in. tool. Both tools are rated for high-temperature performance. During the course of our work each tool operated successfully at temperatures up to 180°C for periods in excess of 3 hours. A signal repetition rate of 5 signals/second and a logging rate of 20 ft/min was used when either tool was in use. Detected signals were recorded uphole by an analogue system. Signals were digitized and processed for analysis using a 5451B Hewlett Packard Fourier Analyzer System.

The sequence of transmitter and receiver positions for the single- and dual-well measurements is also shown in Figure 1. In dual-well configurations the 3-5/8 in. tool, a transmitter-receiver pair, logged EE-1; the 2 in. tool, a single receiver, logged GT-2B. With the receiver fixed in position, the 3-5/8 in. tool 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 was at a hydrostatic or unpressurized condition and subsequently when reservoir pressure was elevated to values approaching that believed necessary to open fracture faces.

Direct ray paths of signals detected in GT-2B traversed slant distances up to 150 ft and horizontal distances as short as 48 ft. Movements of the 2 in. tool in the open hole section of GT-2B were inherently more noisy than movements of either tool within casing. Only data collected while the 3-5/8 in. tool moved are reviewed here. Signals simultaneously detected in both wells during the dual-well movement sequence and signals detected when the section between 8886 and 9280 ft was independently logged with the 3-5/8 in. tool, comprise much of the data base for our work. A total of 360 ft of GT-2B and 800 ft of EE-1 was logged.

The organization of measurements provided for redundant means of detecting pressurized fractures and measuring bulk rock properties in the reservoir. Volume elements as small as 1 cu. in. 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.

DETECTION OF FRACTURES ON RESERVOIR PRESSURIZATION

In principle, any pressurized fracture which cuts direct transmission paths between wells attenuates acoustic signals, and consequently can be detected. Similarly, a fracture intersecting a well may also be detected by signal attenuation where a transmitter and receiver in a logging tool straddle the fracture. In the simplest case attenuation results from the partition of acoustic energy at a water-fracture interface into transmitted and reflected components -- the transmitted signal thus is attenuated with respect to the incident signal.(7) Figure 2a illustrates attenuation of signals transmitted between wells. By knowing combinations of transmitter-receiver positions where attenuation is observed, the location of the top of a single fracture or the shape of a multiply fractured zone can be determined. For a fracture that intersects either well and is vertical the determination of its orientation follows. Fractures cutting transmission paths between wells also reflect signals which may be detected by a receiver in the transmitter well.

A pressurized fracture not cutting transmission paths reflects signals which may be detected by a receiver in either well. Compressional and shear waves may be generated by incidence of either compressional or shear waves on a pressurized fracture. Figure 2b illustrates shear wave generation at a fracture by compressional wave incidence. For each transmitter and receiver position and for a fixed sound velocity the only possible points of reflection at a fracture surface have the common property that the sum of incident- and reflected-wave travel-distances determined by the arrival time of the reflection at the receiver is a constant. The locus of such points in space is an ellipsoid with transmitter and receiver positions serving as foci. In the special cases where the incident wave and detected reflection are both shear or compressional waves, the reflecting fracture must be tangent to the ellipsoid. If a reflection has been detected at several non-coplanar transmitter-receiver positions the location and orientation of the fracture can be determined. Although methods based on the detection of reflections from pressurized fractures appear feasible thus far we have not identified specific reflections for this type of analysis.

RESULTS

Different analytical methods were applied to the acoustic data in order to obtain logs reviewed here. Often an important characteristic of one log may have a counterpart in another. For the sake of brevity rather than completeness only that log in which the characteristic finds its principal expression will be discussed.

Full-Wave Acoustic Logs

Full-Wave - dual well. The general form of signals transmitted between wells is shown in Figures 3a and b. These particular logs were run over the same depth interval. The distance between transmitter and receiver positions varied from 70 to 120 ft. The signals shown in Fig. 3a are complicated by electrical cross talk from the receiver in the transmitter tool. This cross talk was reduced during the pressurized runs by increasing the amplification of the receiver signal before it entered the surface transmission line.

The first and second acoustic arrivals to the 2 in. tool are compressional and shear waves propagating along the most direct ray path between the transmitter and receiver. At minimum travel time the 2 in. and the 3-5/8 in. tools are closest together and positioned at nearly equivalent depths. This log shows the combined effects of the radiation pattern of the transmitter and the variation in receiver sensitivity with signal arrival inclination. The effect is seen best in the S-wave arrival. As the inclination between transmitter and receiver positions increases to $\pm$ 45°, S-wave signal strength increases.

Taken together these logs shown the differences resulting from pressurization of fractures. The gain of the log taken under pressurized conditions is four times that of the companion log taken when the system was unpressurized. On system pressurization a general reduction in signal strength occurs and obvious shear wave arrivals are lost. These phenomena were observed in previous work where signals from detonations, traveling ray paths known to intersect pressurized fractures, were similarly modified.[5]

Determinations of acoustic propagation velocities using these logs are generally not precise enough to identify changes of less than 5%. However, in at least one region, the P-wave velocity was ∿8% lower in the pressurized system than in the unpressurized system; it is believed that this difference is real. With refinements in tool design and measurement techniques the precision can probably be increased to $\pm$ 1%. This means that borehole separation distances can be measured to the same precision.

<u>Full-Wave - single well</u>. Figure 4 shows signal traces as a function of depth obtained with the 3-5/8 in. tool. Only general features of the log are important for the purposes of our discussion.

Below 8950 ft one sees successively compressive wave first arrivals through steel, longer signal length containing high-amplitude waves, and late-arriving reflections from casing collars arriving from below. Each of these phenomena, on visual inspection alone, indicates weak to negligible cement bonding of the casing to rock. Although not shown here, reflections from collars arriving as late as 25 ms were detected. Poor cement bonding in this section of the well was identified previous to the acoustic measurements in cement bond, radioiodine tracer studies and temperature logs.

In this log the absence of a collar signal arriving from above is striking. Physically irrespective of whether the acoustic tool is moving toward or away from a collar, reflections should occur. The collar signals propagate at velocities dependent on the pressurization of the system. In the unpressurized system the propagation velocity is 6.5 ft/ms; in the pressurized system 7.9 ft/ms. A low-amplitude collar signal with a propagation velocity of 14.1 ft/ms is observed in the pressurized system. The ratio between the two implies that the slower moving signal is a shear (perhaps torsional) wave. Whatever the cause of the loss of collar signals traveling to the receiver from above, it seems reasonable that the geometry of the tool in the casing is involved.

SIGNAL POWER LOGS

The principal effect that pressurized fractures have on signal propagation is attenuation. Power logs, giving in our case signal power over a 25 ms time interval vs depth, provide a useful means for displaying attenuation measurements. An advantage of power logs is that they are highly reproducible. Two separate logs taken over the same depth interval under the same reservoir conditions are indistinguishable. This is illustrated in Figure 6 by the power log run in the pressurized system and an overlain second log in the depth interval identified as a repeat section. The major disadvantage results from the fact that power involves integral measurements; the spatial information contained in the arrival times of wavelets is lost, and the attenuation along specific ray paths is indeterminant. Nonetheless, attenuation measured using this approach is dominated by effects along the shortest ray paths.

Power Log - dual well. The power log derived from signals transmitted between wells is given in Figure 5. The log is subdivided in segments according to receiver position. With increasing depth the horizontal distance between wells decreases. The logs are not corrected for geometric spreading although such a correction would clarify certain features in the logs. This correction however is independent of pressure conditions in the reservoir.

The measured difference in signal power on pressurization increases continuously from -10 db above 8500 ft to an approximate mean value of -30 db below this depth. Locally in the segments that have receiver positions at 8642 and 8850 ft differences in power increase to -60 db. The change above 8500 ft is comparable to the loss in output power of the transmitter (see Power Logs - single well). After applying a -10 db correction to the power log taken in the pressurized system, one sees that within measurement error no change in power occurs above 8500 ft. This depth then marks the effective top of the fractured reservoir.

Overall power losses due to pressurization are greatest in the 8850 ft segment. Although the distances between transmitter and receiver are shortest here, this segment encompasses the region closest to the injection point of cold water into the reservoir which may contain a high density of microfractures. The absolute power level was much higher in this region, for reasons which are not understood. The high power level may be related to the lower sound velocity observed in this region which provides a focussing mechanism. A discontinuity in attenuation is evident in the 8642 ft segment at the 8660 ft transmitter depth. The discontinuity may be correlated with one of two similar discontinuities or step changes identified in the single well power logs which may be related to lithologic changes. Locally below this depth absorption increases markedly on pressurization.

Power Log - single well. The power logs derived from data acquired with the 3-5/8 in. tool in EE-1 are given in Figure 6. The log taken in the unpressurized system shows two step-changes in power at 8600 and 8800 ft, respectively, separating rather uniform power levels in the depth interval between 8500 and 9800 ft. The step change at 8600 ft occurs near a contact bectween granitic gneiss (upper) and granodiorite lithologies which had been previously identified from gamma logs and cores. By coincidence, also near this depth the casing diameter reduces from 8-5/8 in. to 7-5/8 in. Since the step change is not apparent on the log taken in the pressurized reservoir, it is not likely to be related to the change in casing diameter. Below 8900 ft the formation is multiply fractured. Below 9000 ft the casing is completely unbonded to the rock. Also below 9000 ft an absolute difference in power level of approximately -10 db between logs taken in the pressurized and unpressurized systems can be observed. This difference can be attributed to a reduction in output power at the transmitter caused by pressurization. In the unbonded sections of casing little if any signal is dissipated to the reservoir.

Above 9000 ft the cement bond is substantially better but not complete because some water does move up the casing annulus and into fractures throughout the interval logged. The log taken in the pressurized system above 9000 ft indicates the presence of water. Because the internal pressure of the casing forces better acoustic coupling between casing and rock, less signal power is contained in the well. The general increase in signal power from 9000 to 8500 ft probably is related to the pressure gradient in the annulus. As the pressure of the annulus water decreases, coupling improves.

That part of signal power returning to the well again shows the attenuating effect of pressurized fractures. For example, the minima in power at 8700 and 8800 ft have correlative anomalous depressions on temperature logs indicating water is injected through fractures into the reservoir at these points.

<u>Normalized Equi-Power Logs (NEP Logs) - single well</u>. The loss in temporal information in the power logs can be recovered in a NEP Log. Figure 7 shows details of the logs. In preparing an NEP Log the contribution to full power as a function of time is calculated. Percentage increments to full power, in our case increments of 10%, are plotted in the NEP Log as a function of time and depth. Delayed rise to full power at one depth relative to another indicates that signals contributing to full power have traveled greater distances.

The Equi-Power logs taken in EE-1 are given in Figure 8. The log taken with the system unpressurized shows clearly power delays above 8600 ft associated with the change in lithology. Fully 50% of the contribution to the full power of signals traveling above this depth arrives after 3.5 ms, whereas throughout the lower section 90% of the contribution generally arrives before 2.5 ms. The effect of the unbonded casing below 9000 ft is to substantially delay the rise to full power. The appearance of the NEP Log in the unbonded section is relatively unaffected by pressure. The principal effect of system pressurization above is again to delay the rise to full power. NEP lines become much more erratic probably indicating that the rock has become more heterogenous in terms of acoustic properties.

SUMMARY

Advances have been made in developing techniques based on single- and dual-well acoustic attentuation measurements. These techniques utilize commercially available acoustic logging tools singly or in combination in multiple-well configurations. Full Wave, Power, and NEP presentation of these data are helpful in characterizing fractured regions in basement rock.

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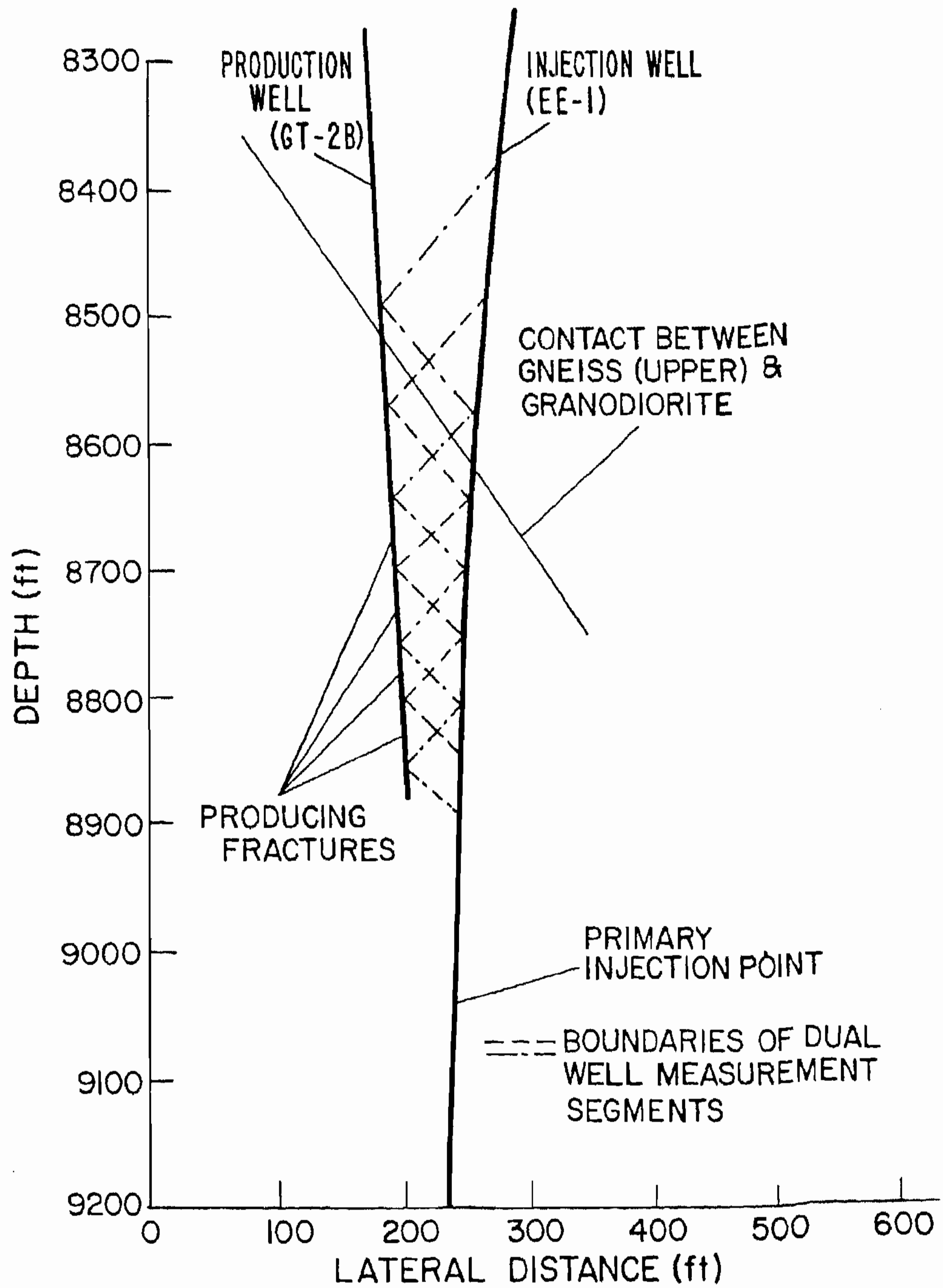

Figure 1 Logged sections of the Fenton Hill man-made geothermal reservoir.

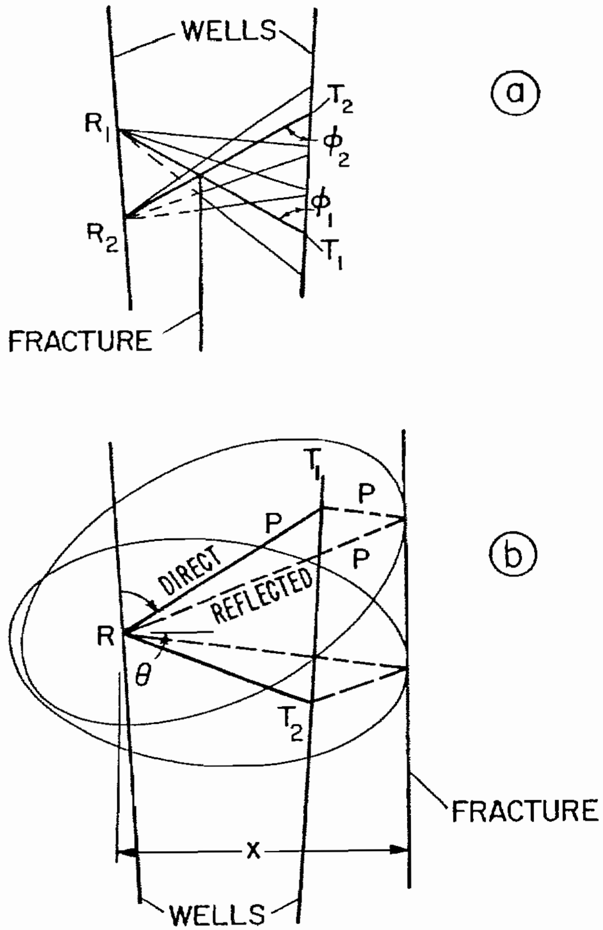

Figure 2 Detection of pressurized fractures by (a) acoustic attenuation and (b) by reflection.

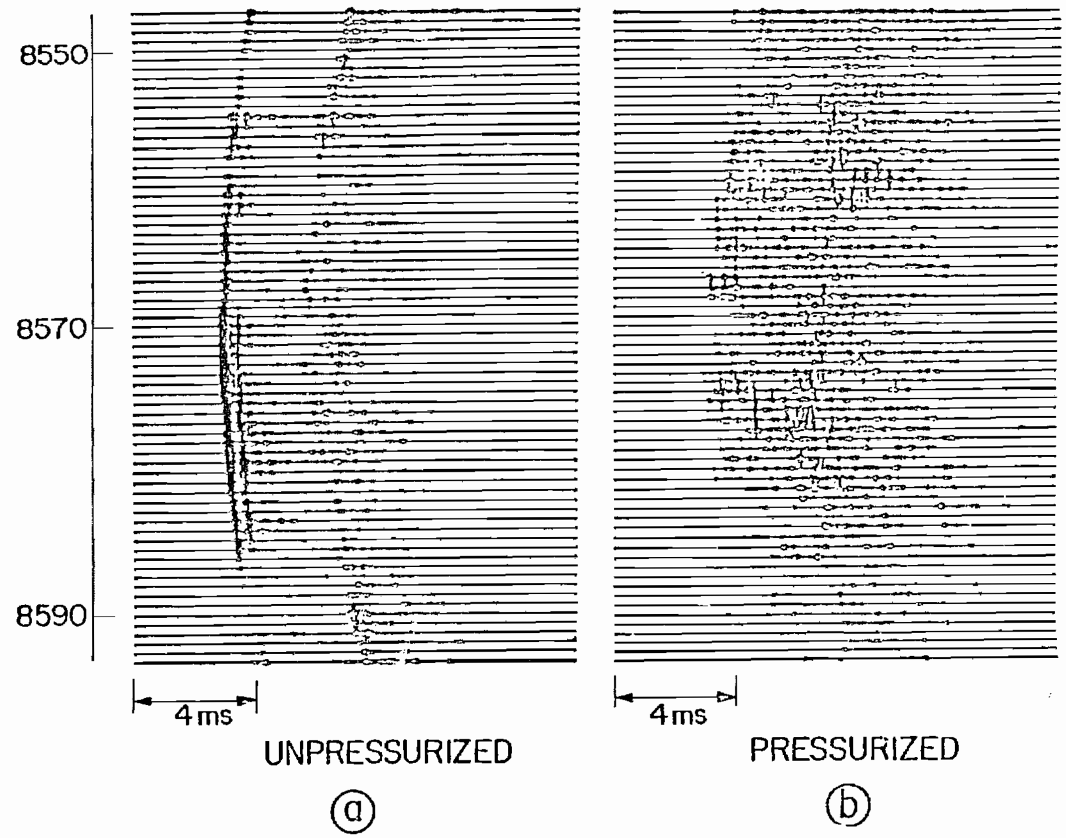

Figure 3 Full-Wave Acoustic Logs - dual well.

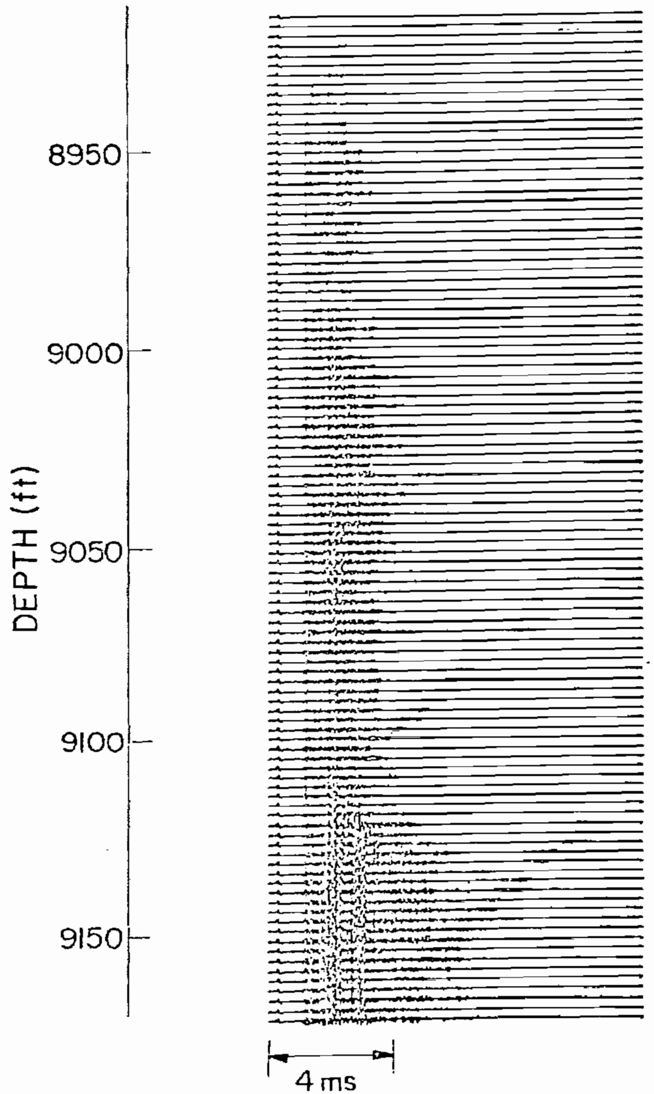

Figure 4 Full-Wave Acoustic Logs - single well.

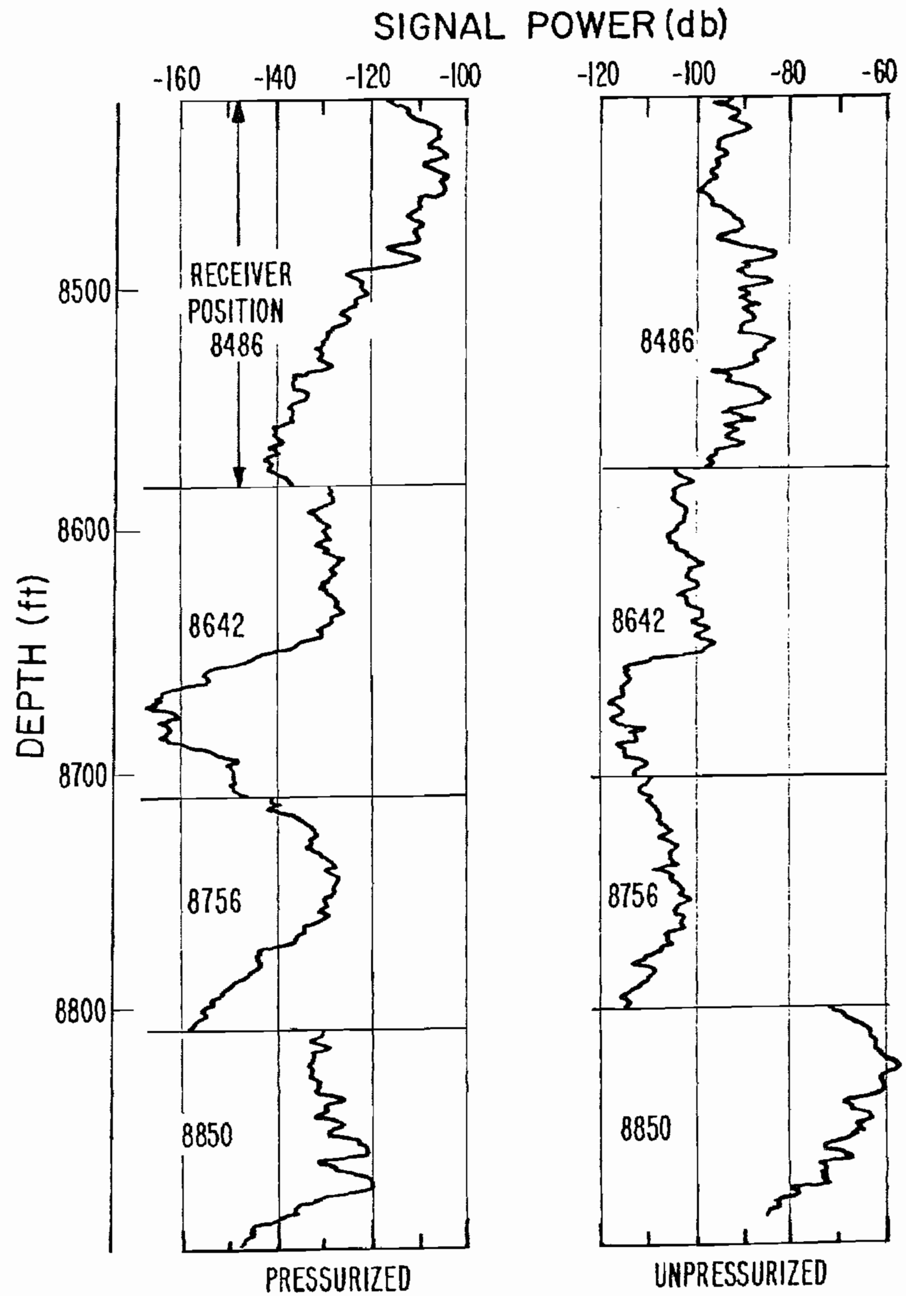

Figure 5 Power Logs - dual well.

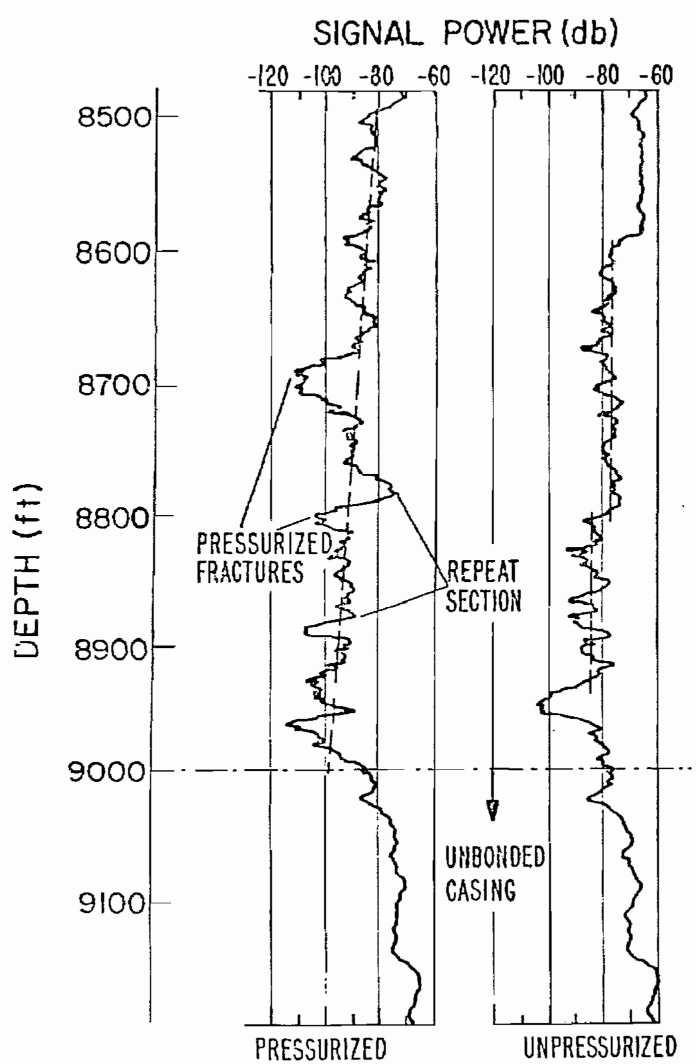

Figure 6 Power Logs - single well.

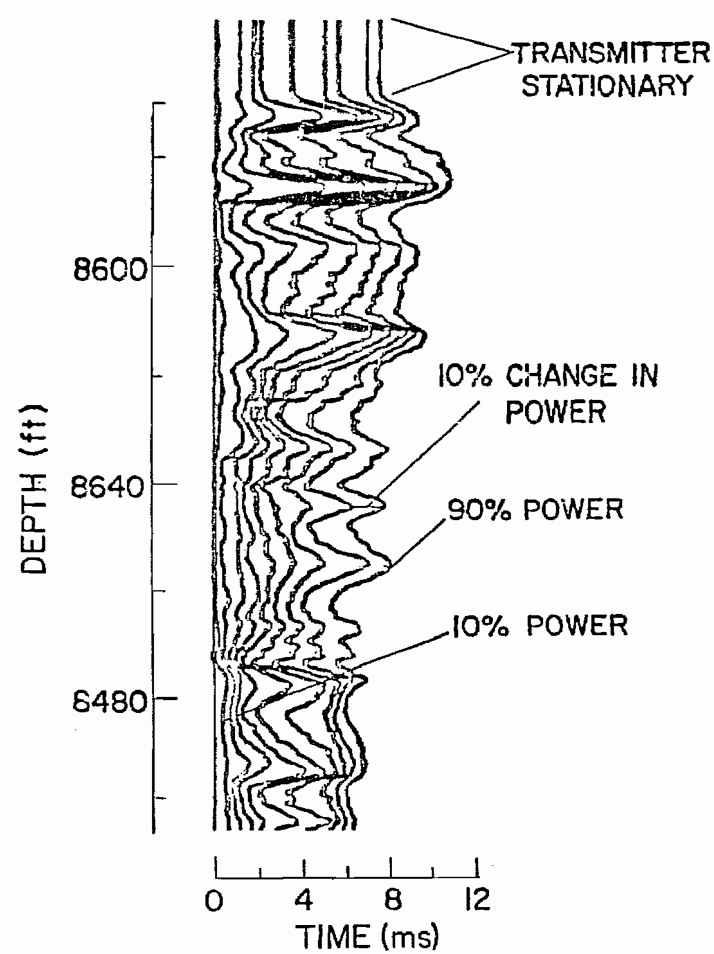

Figure 7 Normalized Equi-Power Log (NEP Log) - example.

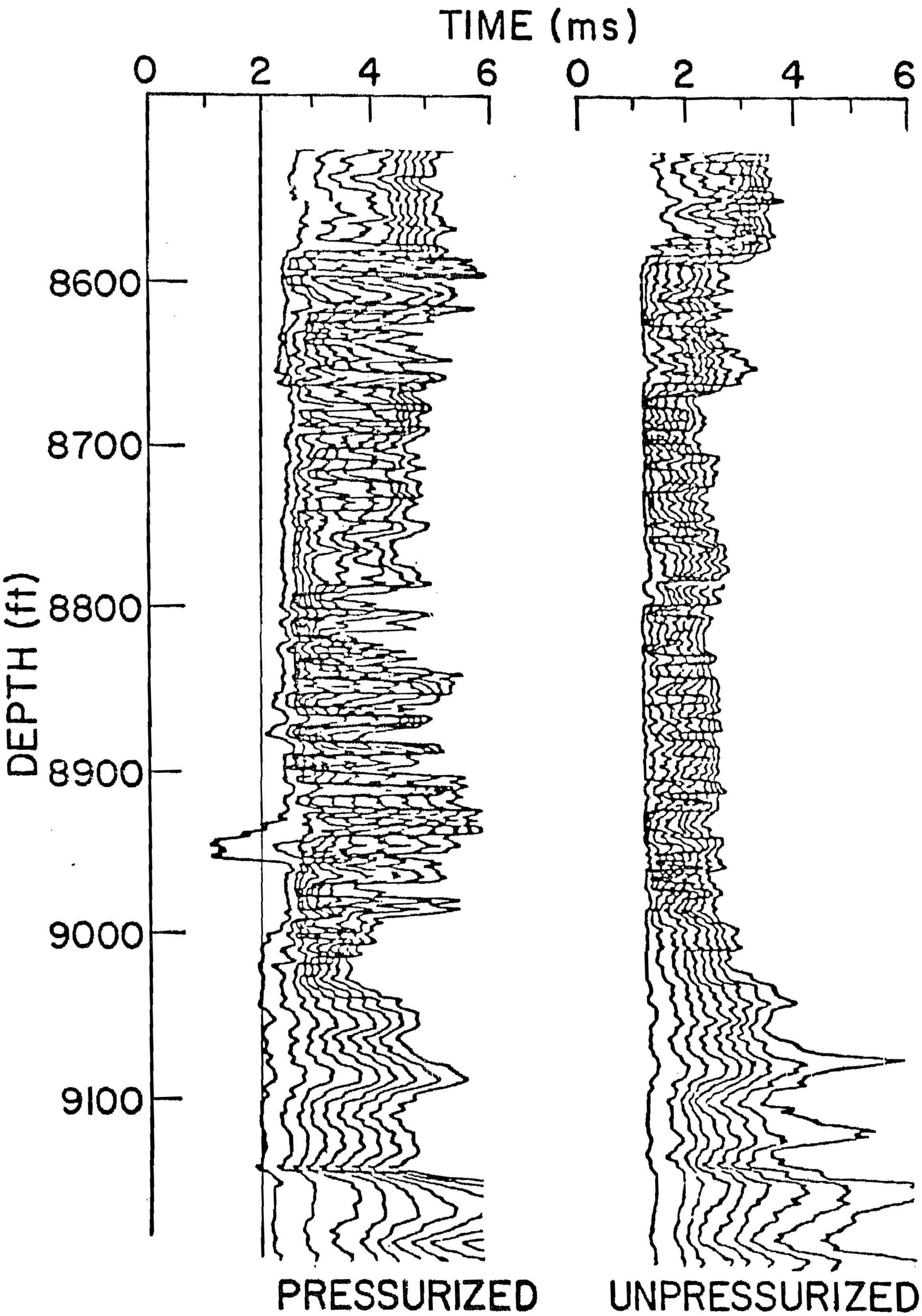

Figure 8 NEP Log - single well.