FRACTURE IDENTIFICATION USING CONTEMPORARY ACOUSTIC TOOLS IN THE PERMIAN BASIN

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ABSTRACT
The contemporary acoustic logging tools can be used to identify both naturally occurring and hydraulically induced fracture systems. These tools and the related concepts are applicable in both the open hole and cased hole environments. The advantages of running these acoustic tools are to identify, visualize, and quantify the intensity of the fracturing in addition to deriving the directional orientation of the fracture system.

INTRODUCTION

Fractures play an important part in the hydrocarbon potential of a reservoir. The identification of naturally occurring fractures provides the basis for evaluating the porosity and permeability necessary to the production and flow of hydrocarbons. The identification of hydraulically induced fractures indicate whether the stimulation techniques were effective. This application is used for new well completion and the evaluation of re-entry potentials when considering whether a zone is depleted of hydrocarbons or whether the original "frac-job" has closed. The modern acoustic tools that image the borehole and measure the acoustic properties of the formation provide the solution to the above problems. The concepts that apply to the open hole well bore environment for identifying fracture systems apply also to the cased hole environments. These features of the tools and techniques of the identification of fracture systems produce a method of formation evaluation unequaled by any other tools or techniques.

CONCEPT

In a non-fractured acoustically homogeneous formation there is a straight flow path for the transmission and reception of an acoustic signal in the well bore (Figure 1). In a fractured formation either natural or induced the fracture planes deflect and disperse the acoustic energy which results in the attenuation of the reflected acoustic signal or waveform (Figure 2).

ACOUSTIC IMAGING

A borehole imaging tool is the best way to visualize fractures in the open hole. A borehole imaging tool such as the HLS Circumferential Acoustic Scanning Tool (CAST) records the amplitude and travel time of acoustic energy arrivals and presents these measurements as raster scan images in varying (16) shades of gray (Figure 3). The amplitude images are light gray in high energy acoustic reflections and darker grays in low acoustic energy reflections. Travel time images are light gray for high energy reflection and dark gray in low energy returns. Since fractures cause attenuation in the reflected acoustic signal, fractured zones would appear as dark grays on the amplitude record. If the fracture is "open" at the borehole, a dark gray would appear on the travel time record. Also included on the CAST display is a directional reference with respect to magnetic north so that the borehole image may be oriented.

Figure 4 shows a CAST amplitude image of a Strawn limestone in Eddy County which has high angle naturally occurring fractures (dark gray images) intersecting the borehole. The format shows the flat, two dimensional plan from 7282 feet to 7314 feet. The CAST on the right shows a three dimensional perspective from an orientation of 270 degrees.

ACOUSTIC WAVEFORMS

Waveform logs such as the Full Wave Sonic Log display the acoustic waveform and show the measurements associated with the waveform properties (Figure 5).

The visual record of the acoustic waveform in a non-fractured formation will show constant amplitudes on each arriving waveset. In a fractured formation the visual record of the wave train will appear erratic near the fractured zones. The reason for the erratic appearance in the arrivals is that the fracture planes disrupt the path of the transmission and reflection of the acoustic arrivals. The wavefronts arrive in different cycles and phase angles because of the disruption which results in the overall destruction of the normal amplitude of the waves. The greater the intensity of the fracturing, the greater the magnitude of attenuation and the smaller the amplitude of the wave arrivals.

ACOUSTIC PROPERTIES

In this study, the measured properties of the acoustic waveform that reflect fractured formations are related to attenuation and travel time anomalies. The measured properties are presented on three subset logs of the Full Wave Sonic Log. The Gain I curve on the waveform plot is proportional to the formation attenuation of the shear wave. The greater the intensity of fracturing the larger the Gain I value, and the larger the attenuation in the shear region (Figure 6 and Figure 7).

The Quality Log shows two indicators for fracture identification (Figure 8). The ARAT curve measures the ratio of the amplitude of the shear wave to the amplitude of the compressional wave. The reduction in the acoustic energy of the shear wave in a fracture zone is much greater than the loss of energy in the compressional wave. Therefore, the greater the intensity of the fracturing, the larger the attenuation value in the shear region, and the lower the ARAT (amplitude ratio) value.

A second curve on the Quality Log is the STDS curve, a mnemonic for the standard deviation of the shear wave travel time. The shear travel time is computed from the average of the travel time for each of the receiver pairs (1-2, 2-3, 3-4). The STDS curve is the standard deviation for the average shear travel time for each sampled interval. In an acoustically homogeneous formation, the three travel time measurements will be equal in value. Under the circumstances there would be no deviation about the average shear travel time. However, in a fractured zone, disruption of the shear waves will result in different travel times for each receiver pair which will compute a high standard deviation about the average shear travel time.

FRACTURE INTENSITY LOG

The Fracture Intensity Log displays the ratio of STDS to the shear travel time for each sampled depth (Figure 9). This ratio shows the fracture activity or intensity is greatest when the ratio is highest. Figures 10, 11 and 12 are photographs of a conventional core from a Wolfcamp limestone. The limestone core shows vertical fractures that are partially filled with silica. The Fracture Intensity Log shows an area of medium fracture intensity corresponding to the core depth. The zones with the highest fracture intensity were not recovered during the coring process. The conventional logs show only a 2 percent cross plot porosity value over this interval.

NATURAL FRACTURE SYSTEMS - OPEN HOLE - STONELEY WAVE

The identification of fractures can be achieved by focusing on the Stoneley wave characteristics. Stoneley waves are propagated along the interface of the borehole and formation. The Stoneley wave energy diminishes where fractures intersect the borehole. The greater the intensity of fracturing, the greater the attenuation of the Stoneley waveform. The Delta T Stoneley Log combines the measured properties of the amplitude, attenuation, and the travel time of the Stoneley wave for each sampled interval. The amplitude curve and the travel time curve are normalized and then made to overlay in non-fractured zones. In a fractured zone the two curves will diverge with a slight increase in the Stoneley travel time value and the Stoneley amplitude decreasing in magnitude or value. The Stoneley attenuation value will increase in a fractured interval. The greater the divergence between the amplitude and travel time, the greater the magnitude of fracturing.

This example of an Ellenburger well shows how fractures are interpreted to be "open" or "closed" at the well bore. Figure 13 shows the Full Wave Sonic - Quality Log over a portion of the Ellenburger. The high values in the SDTS (standard deviation of the shear wave travel time) and the low values in the ARAT (Amplitude Ratio curve) in the interval from X450 to X550 suggest a zone of intense fracturing. Notice that the compressional wave properties in Track 3 show little deviation in the fractured zone. Figure 14 is a display of the Delta T Stoneley Log over the same interval in the subject well. The greatest divergence in the amplitude vs. travel time curve in track 2 occurs at X450. Also, notice, the attenuation and frequency change in the Stoneley waveform plot at X450.

Figure 15 is a CAST display for the subject well over the zone of interest. This display shows high angle (75^o to 80^o) fracture planes intersecting the borehole and dipping to the north. The Travel Time track shows the fractures to be "open" in the zone at X450 because of the surface irregularities. Figure 16 at X500 has the Amplitude Track revealing the presence of fracturing, however the Travel Time display indicates the fractures to be closed at this depth. This example shows that

- vertical fractures affect the shear wave much more intensely than the vertical fractures affect the compressional wave, and

- Stoneley wave reflect the permeable fractures that intersect the borehole but not necessarily those fractures that are less permeable, closed or occurring away from the borehole interface.

NATURAL FRACTURE SYSTEMS - A COMPARISON OF OPEN AND CASED HOLE MEASUREMENTS

This example illustrates that the techniques for identifying natural fractures in the open hole also apply to identifying natural fractures in the cased hole. Figure 17 is the Waveform Plot for the subject well, an Ellenburger test in Midland County. The attenuation of the acoustic wave arrivals and the Gain 1 increase at X358 to X378 and X424 to X442 indicate the zone to be heavily fractured. Figure 18 is the waveform plot of the subject well in the cased hole. The same characteristics of waveform attenuation and the Gain 1 increase indicate natural fractures at X354 to X374 and X420 to X438.

Figure 19 and Figure 20 are the Quality Logs for the subject well in the open and cased hole. Notice that the STDS curve appears as an anomalous value at the depths of interest in both the open and cased hole.

Figure 21 and Figure 22 are the Delta T Stoneley Logs for the subject well. Figure 21 is the open hole interval that shows that the Stoneley wave amplitude decreases with respect to the Stoneley travel time in the zones of interest. However, the cased hole log for the zone of interest shows the fractures to be much more extensive. This apparent fracturing from the cased hole example is due to a channel rather than a natural fracture system.

INDUCED FRACTURE SYSTEM - OPEN HOLE - CAST

This example shows how hydraulically induced fractures appear on the CAST display. The subject well was drilled into the Queen sandstone in Andrews County. Figure 23 is an open hole porosity log. Figure 24 - Figure 28 shows the comparison between the "before frac" CAST and the "after frac" CAST. The fracture was hydraulically induced with water to determine the direction the "real" hydraulic fracture, with proppant and gel, would propagate. The CAST display on the left is the "before frac" and shows only bedding fractures. The "after frac" CAST display of the amplitude track shows the induced fracture bisecting the well in a northeast to southwest direction.

Figures 29 - Figure 32 display the CAST log from the actual "after frac" job which was hydraulically fractured. Notice that in the zone from 4802' to 4812', the zone of highest porosity, the hydraulically induced fracture appears to widen to the southwest.

INDUCED FRACTURE SYSTEM - OPEN HOLE - FULL WAVE SONIC LOG

This example shows how hydraulically induced fractures affect the Full Wave Sonic Log. The subject well was drilled into the Queen Sandstone in Andrews County. Figure 33 is the open hole porosity log showing the Gamma, Dual Spaced Neutron, and Spectral Density. After the open hole logs were run, casing was set down to 4900' and the well was fractured in the open hole interval from 4900' to 4980'. Figure 34 shows the compressional and shear travel times for the open hole "before frac", DTS-OH, DTS-CH and the open hole "after frac", labelled DTS-CH, DTC-CH. The compressional travel times show very little variation in values between the two runs. There are some minor increases in the shear travel time in the "after frac" survey. The increase in the "after frac" shear travel time is due to the attenuation of the first shear arrivals and the actual "picks" for the travel time occur on the second and third arrivals.

Figure 35 is a Tracer Scan Log from the subject well showing the distribution of the "tagged" proppant and gel. The proppant was tagged with Iridium 192 and the gel was tagged with Scandium 46. Figure 36 is the Delta T Stoneley Log for the subject well. A comparison of both the Tracer Scan and Stoneley Log show that the formation is fractured from T.D. to 4905'. Above 4905', the Tracer Scan Log shows a formation and borehole component, however, the Stoneley Log shows no further vertical extent of the hydraulic fracture.

INDUCED FRACTURE SYSTEMS - CASED HOLE - FULL WAVE SONIC

This example shows how the acoustic waveform plot was used to evaluate the extent of hydraulically induced features in the cased hole. The subject well was drilled 15 years ago in Edwards County. The producing zones are the Canyon sands. Prior to running the Full Wave Sonic Logs, the well was on a pump and making 20 Mcfd and 25 Bwpd. Figure 37 is the open hole porosity log for the subject well. Figure 38 is the Waveform Plot for the zone of interest. The acoustic waves are plotted every 3 inches of the well bore. The wave arrivals coming in at 600 microseconds appear to be casing arrivals caused by the effects of perforating and fracturing creating a channel about the interval. The absence of a shear and Stoneley in the sand (X548 to X570) is a good indication the sand has been adequately fractured. There appears to be no growth of the fracture into the above sand zone (X458 to X520). Figure 39 is the upper zone of interest from X196 to X242. Figure 40 shows the waveform plot for the zone X196 to X242. There appears to be no attenuation in the Shear or Stoneley region. This well was re-perforated in the zone X220 to X240 and X458 to X520 in 2 stages and is currently producing in excess of 100 Mcf.

LITHOLOGY EFFECTS

Figure 38 is an excellent example of the way shales effect the Full Wave Sonic. Shales attenuate the Shear and Stoneley wave on a monopole source acoustic tool making the distinction between a shale zone and fractured zone impossible. The newest tools, di-pole source acoustic tool propagate a shear wave in shale zones thus making an interpretation on fracturing much more definitive.

SUMMARY

1) The CAST image of the borehole can display the fractures and the orientations but the acoustic waveform and measured acoustic properties must be used to evaluate the intensity of the fracturing.

2) Near vertical fracturing affects only the shear wave amplitude. Horizontal features such as vugs and styolites affect both the shear and compressional amplitude.

3) Hydraulically induced fractures do not alter the acoustic travel times but these induced fractures do affect the amplitude of the shear wave

4) Excluding some miracle, there must be Stoneley wave anomalies in the apparent zone of fracturing for the well to produce any formation fluids.

REFERENCES

Aguilera, Roberto; Naturally Fractured Reservoirs, Petroleum Publishing Company, 1980.

Paillet, F.L., Chuen, H.C.; Acoustic Waves in Boreholes, CRC Press, 1991.

Walker, T., Kessler C.; "Detection of Natural Fractures with Well Logs", Halliburton Logging Services, internal publication, 1983.

Walker, T.; Basic Acoustics & Fracture Finder/Micro-Seismogram Logs, Halliburton Logging Services, internal publication, 1975.

NON-FRACTURED FORMATION

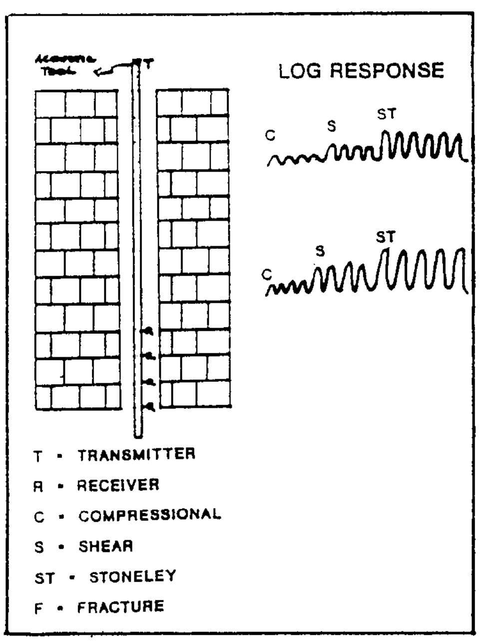

Figure 1 - Acoustic signal in non-fractured formation

FRACTURED FORMATION

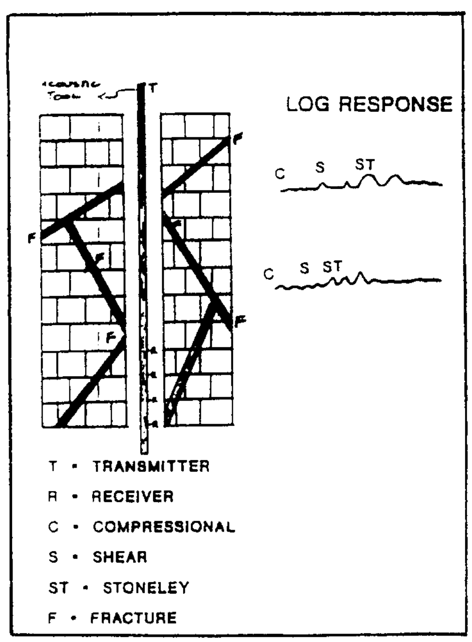

Figure 2 - Acoustic signal in fractured formation

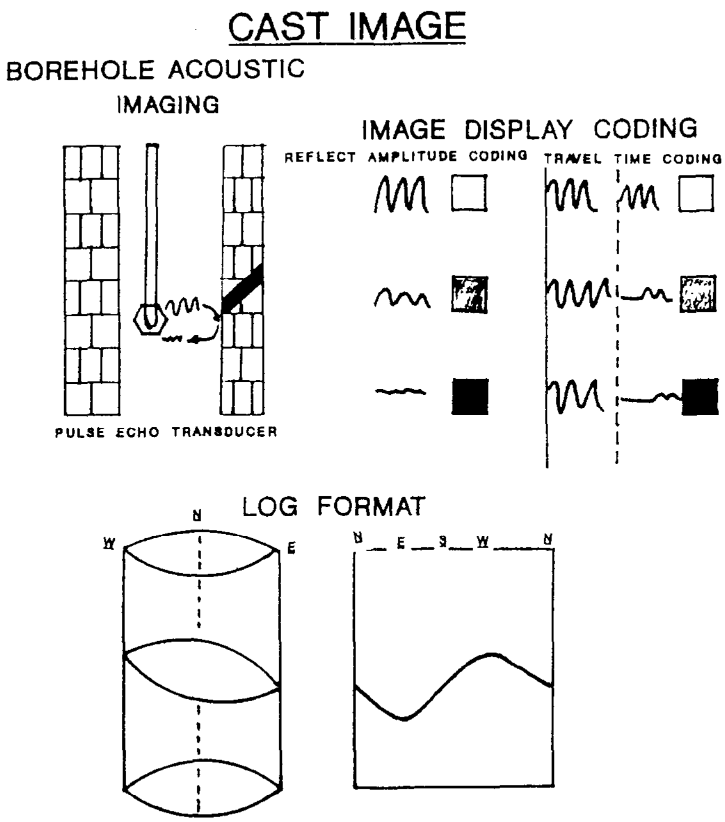

Figure 3 - Borehole televiewer

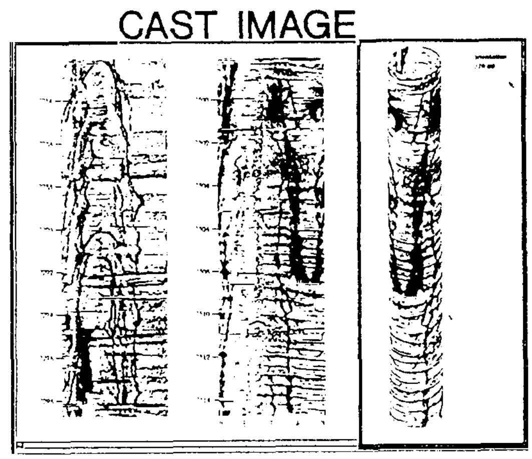

Figure 4 - CAST image

ACOUSTIC WAVEFORMS

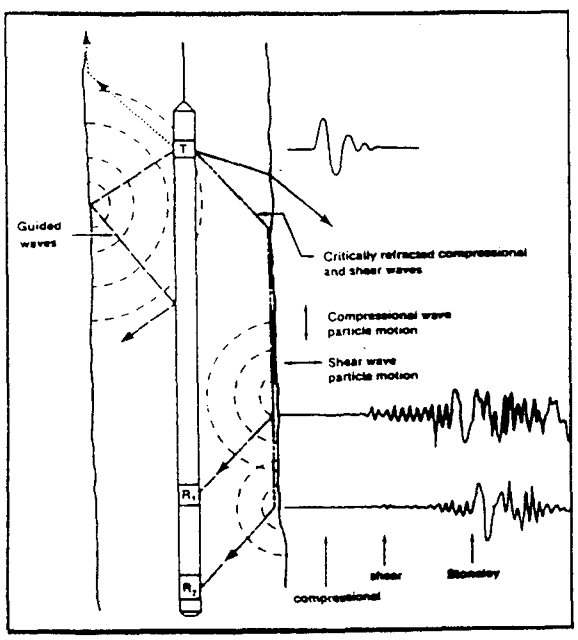

Figure 5 - Compressive, shear and Stoneley wave

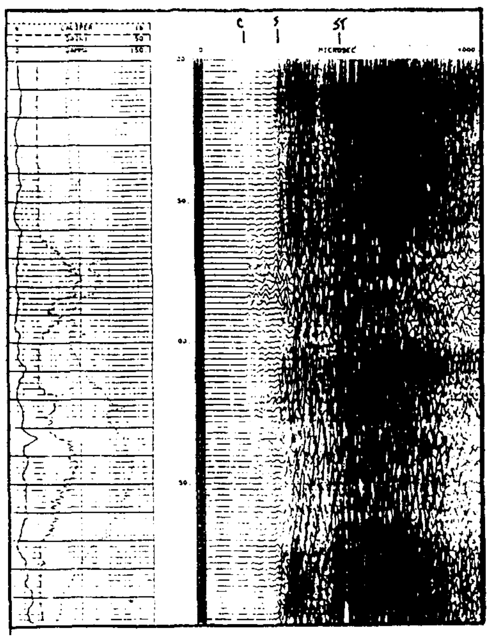

Figure 6 - Waveform plot

ACOUSTIC PROPERTIES

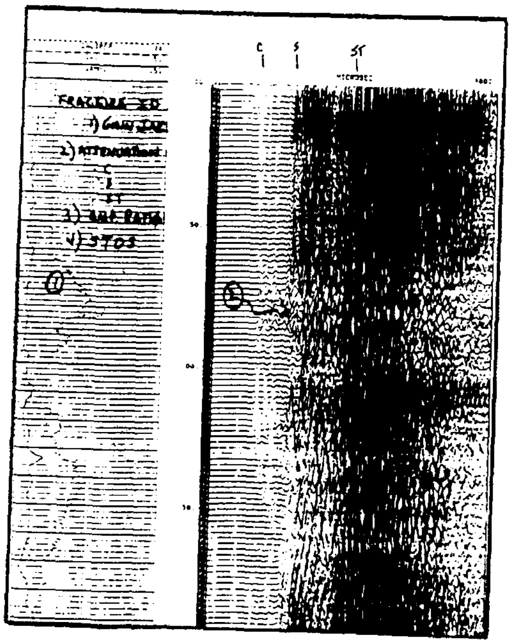

Figure 7 - Waveform plot and fracture indicators

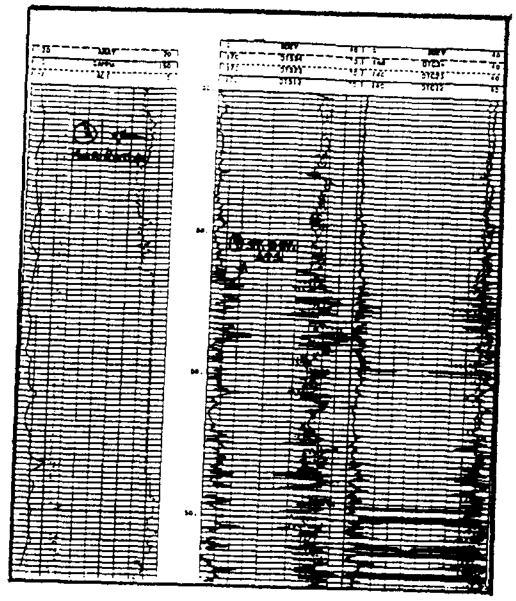

Figure 8 - Quality Log and fracture indicators

FRACTURE INTENSITY LOG

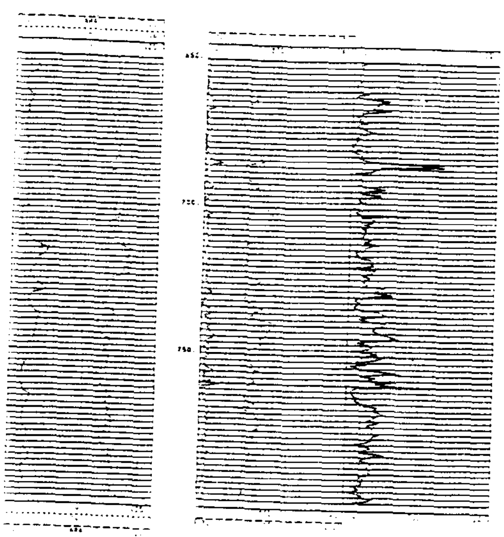

Figure 9 - Fracture intensity log

Figure 10 - Core section 683

FRACTURE INTENSITY LOG

Figure 11 - Core section 684

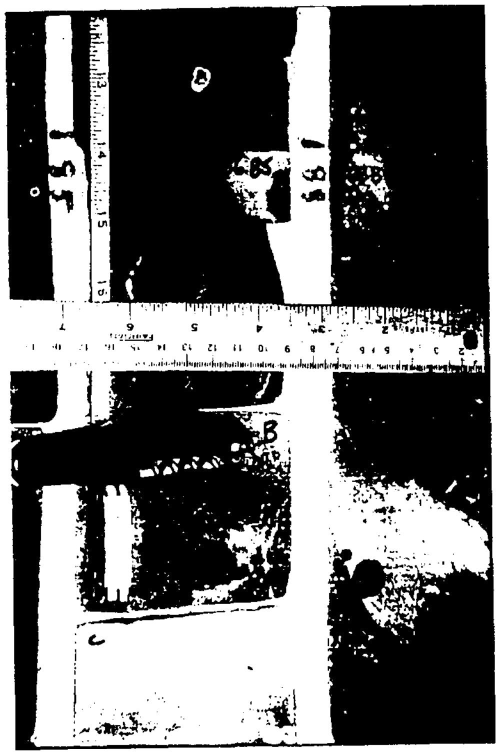

Figure 12 - Core section 685

NATURAL FRACTURE SYSTEMS - STONELEY WAVES

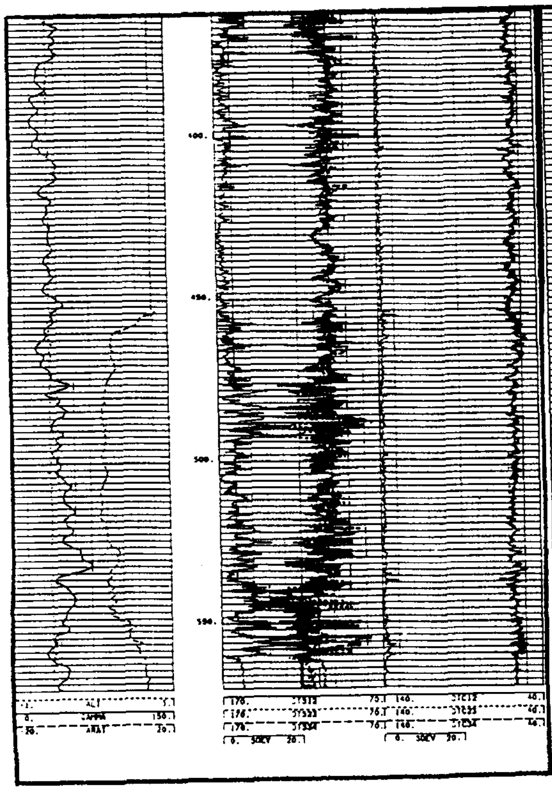

Figure 13 - Quality Log and fracture indicators

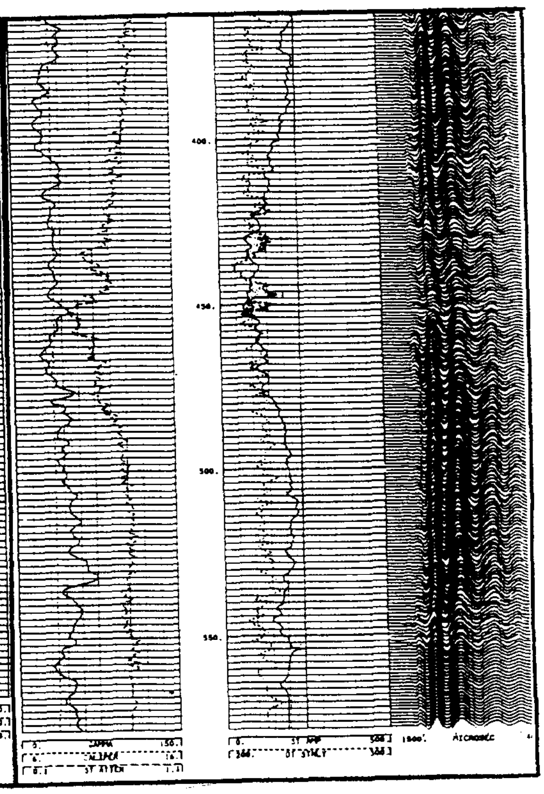

Figure 14 - Delta-T Stoneley Log

NATURAL FRACTURE SYSTEMS - STONELEY WAVES

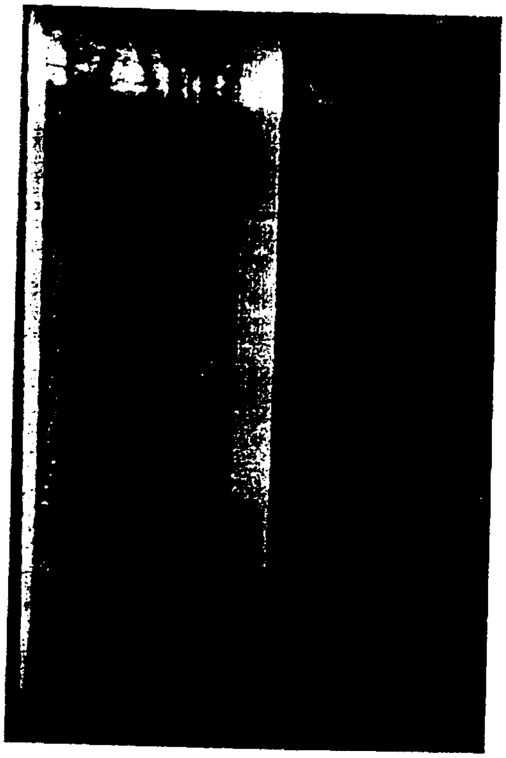

Figure 15 - CAST image and open fractures

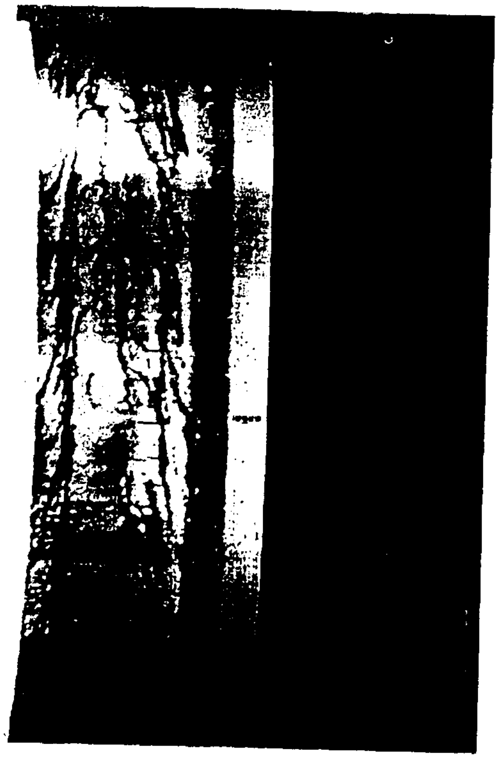

Figure 16 - CAST image and healed fractures

NATURAL FRACTURE SYSTEMS - OPEN VS. CASED HOLE

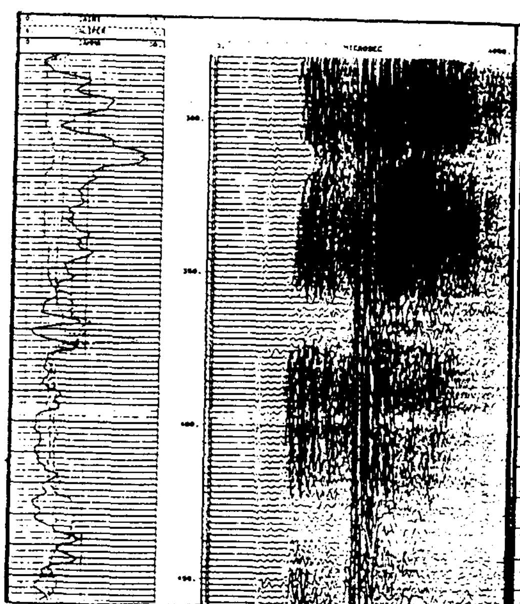

Figure 17 - Waveform plot - open hole

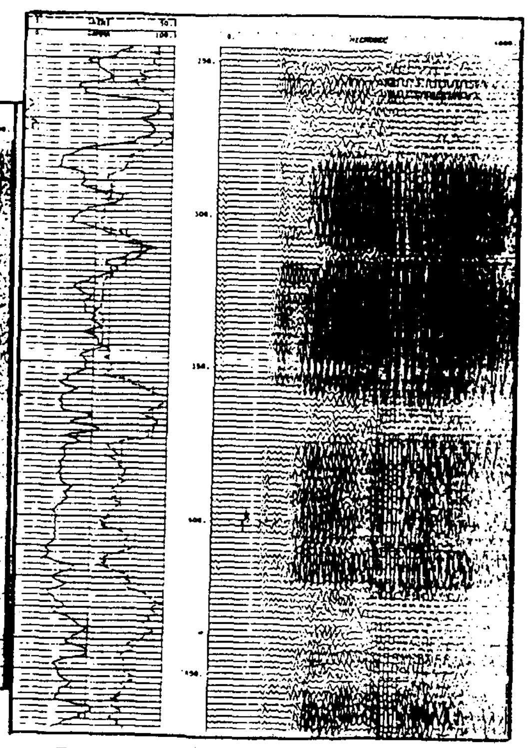

Figure 18 - Waveform plot - cased hole

NATURAL FRACTURE SYSTEMS - OPEN VS. CASED HOLE

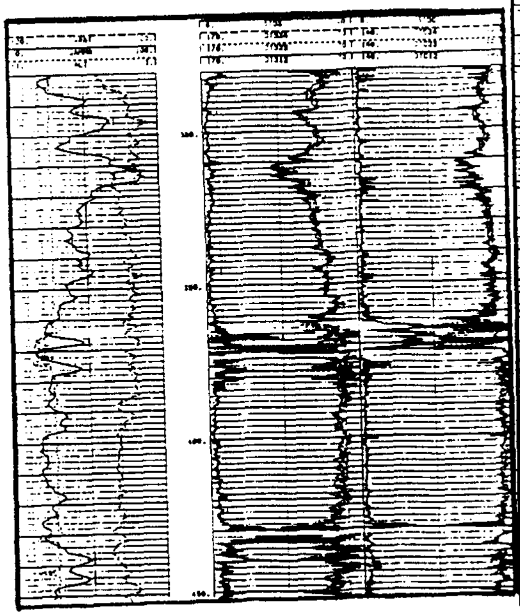

Figure 19 - Quality Log - open hole

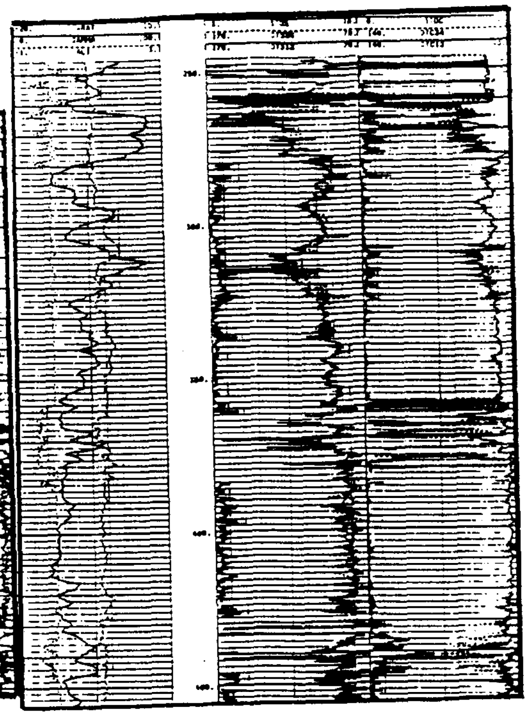

Figure 20 - Quality Log - cased hole

NATURAL FRACTURE SYSTEMS - OPEN VS. CASED HOLE

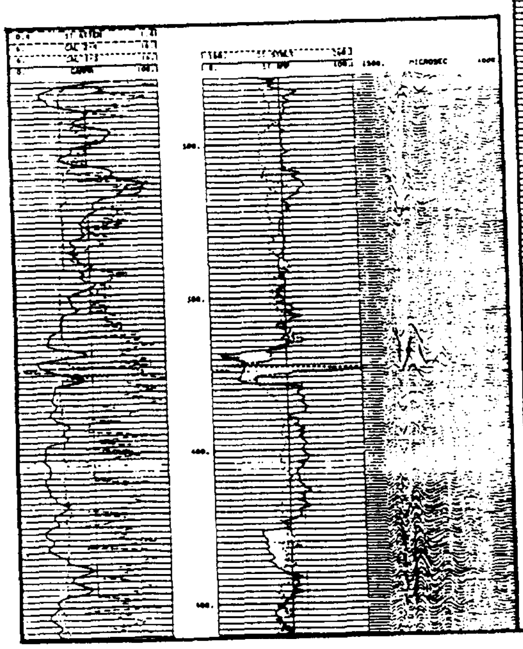

Figure 21 - Delta T Stoneley - open hole

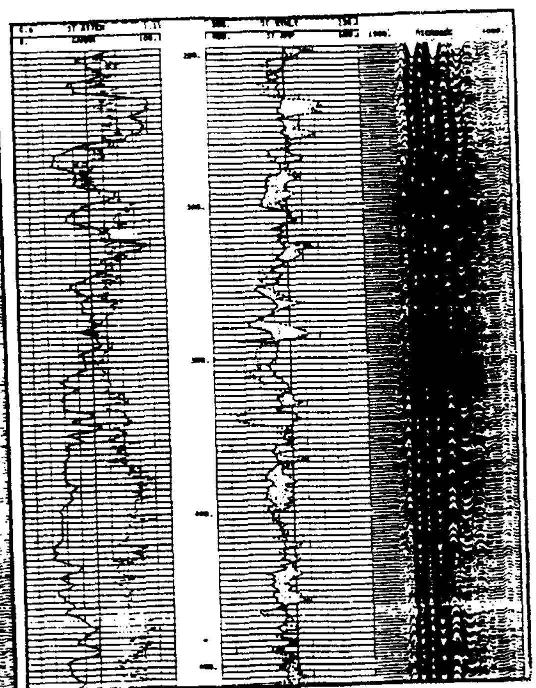

Figure 22 - Delta T Stoneley - cased hole

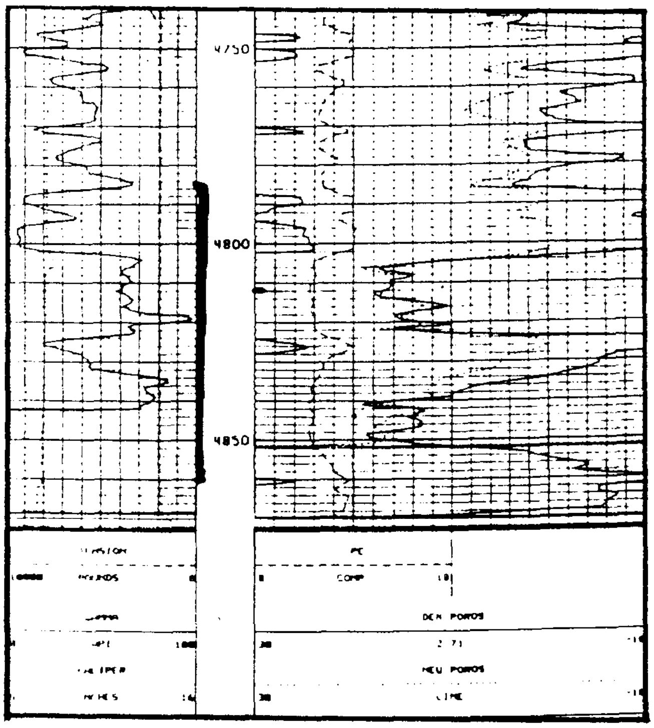

Figure 23 - Porosity log - induced fractures

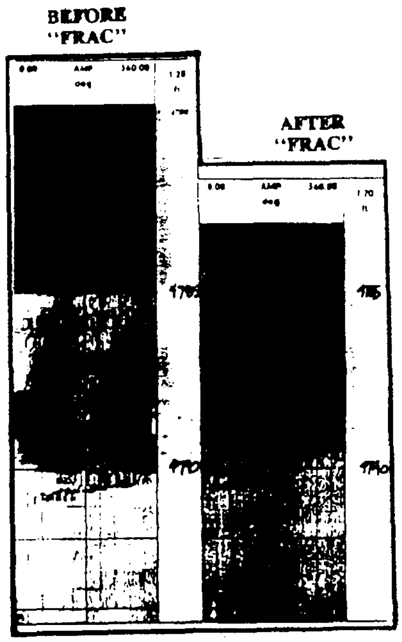

Figure 24 - CAST image - before/after water

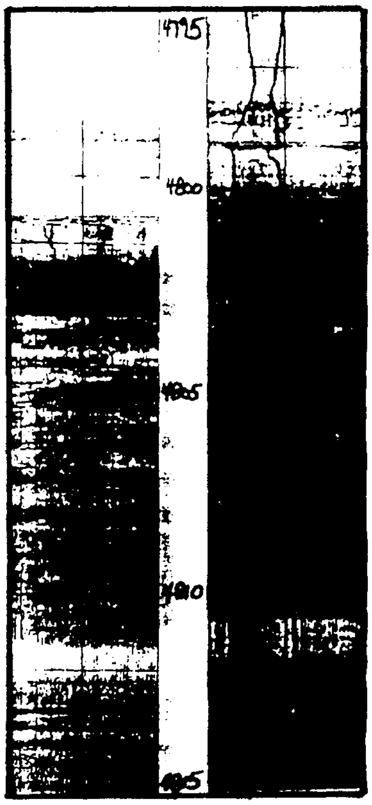

Figure 25 - CAST image - before/after water

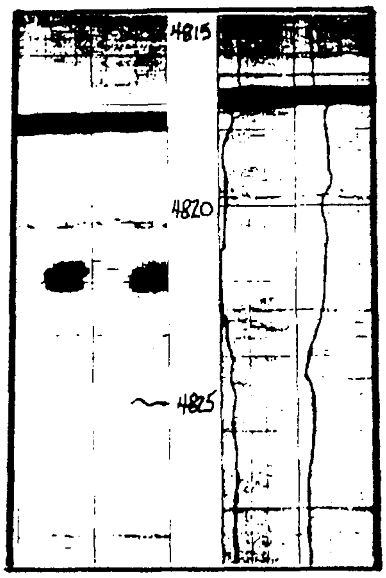

Figure 26 - CAST image - before/after water

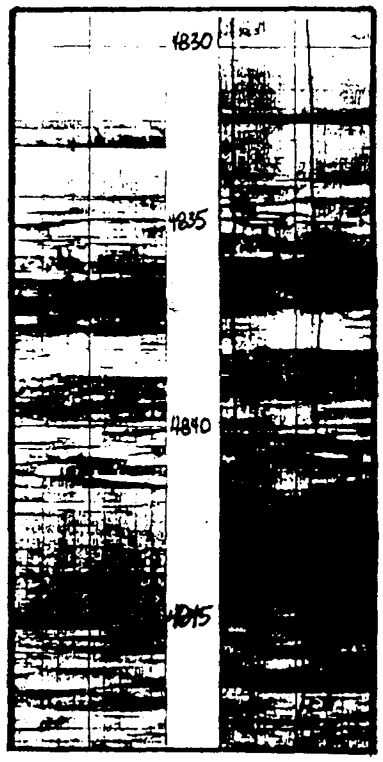

Figure 27 - CAST image - before/after water

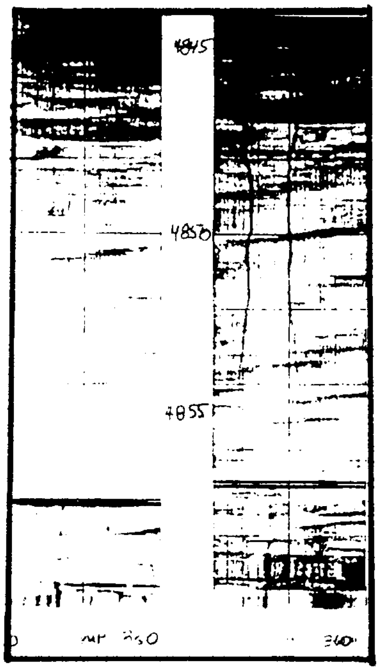

Figure 28 - CAST image -
before/after water

Figure 29 - CAST image -
after frac

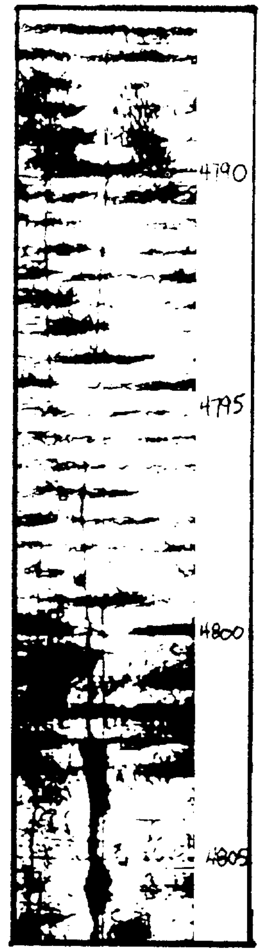

Figure 30 - CAST image

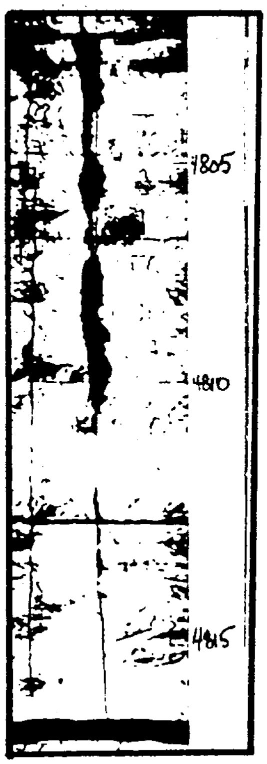

Figure 31 - CAST image -
after frac

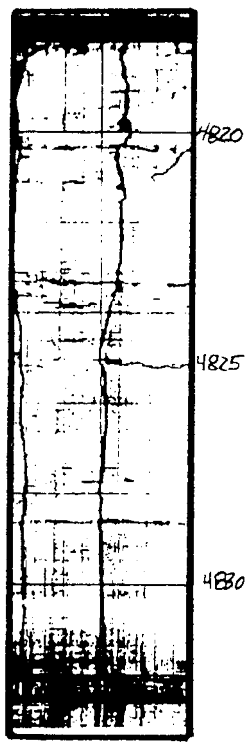

Figure 32 - CAST image -
after frac

INDUCED FRACTURE SYSTEMS - OPEN HOLE FWS

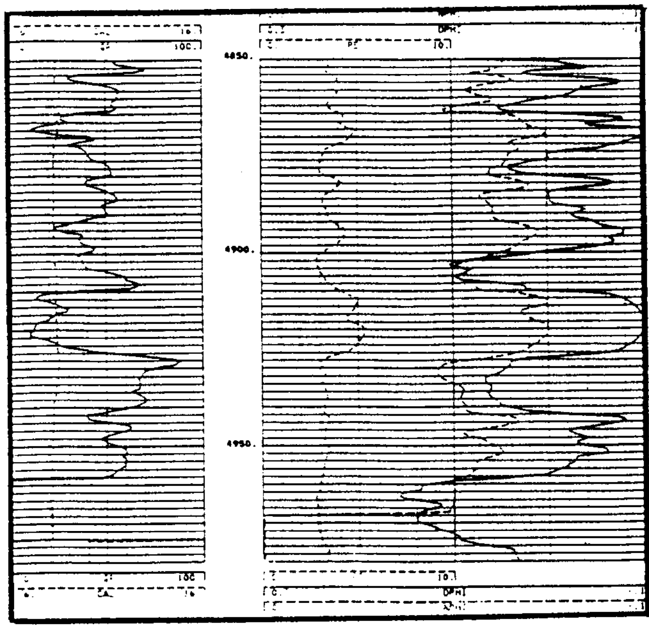

Figure 33 - Porosity log - open hole

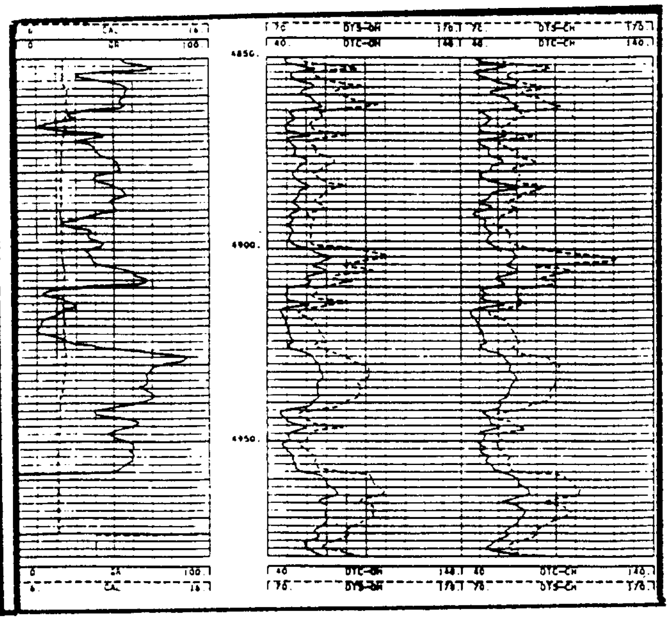

Figure 34 - Comparison of before (OH) and after (CH)

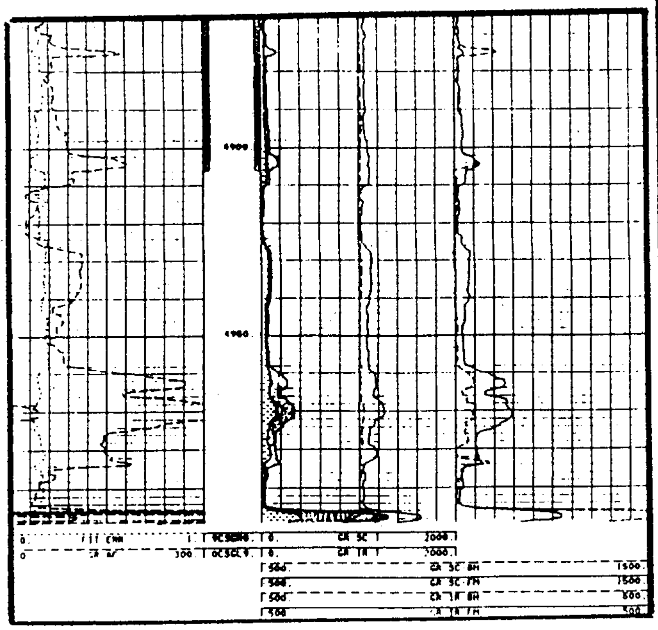

Figure 35 - Tracer Scan Log

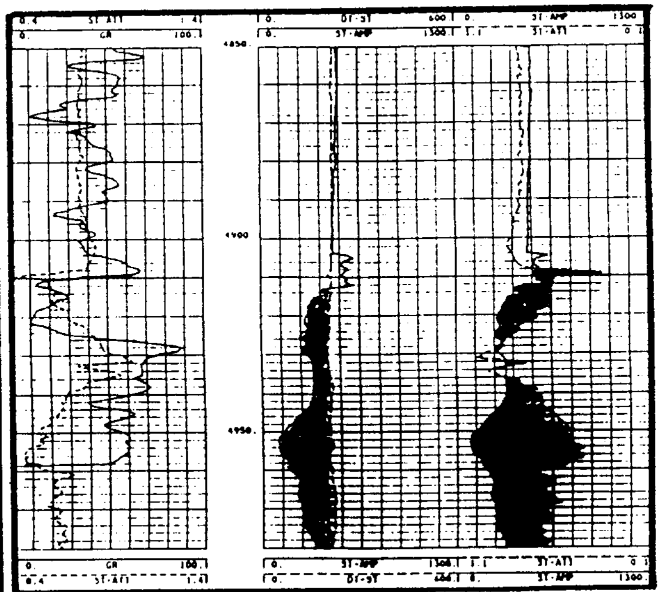

Figure 36 - Delta T Stoneley

INDUCED FRACTURE SYSTEMS - CASED HOLE FWS

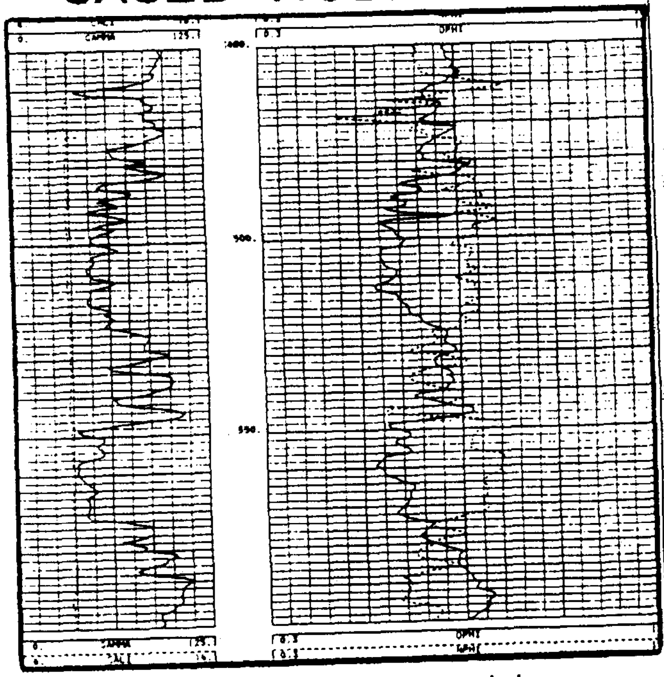

Figure 37 - Porosity log - open hole

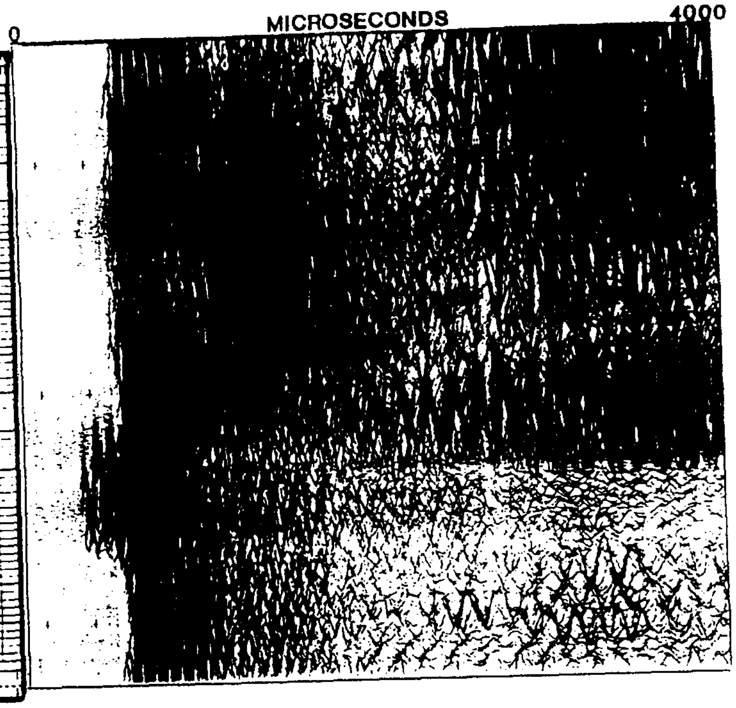

Figure 38 - Waveform plot - cased hole

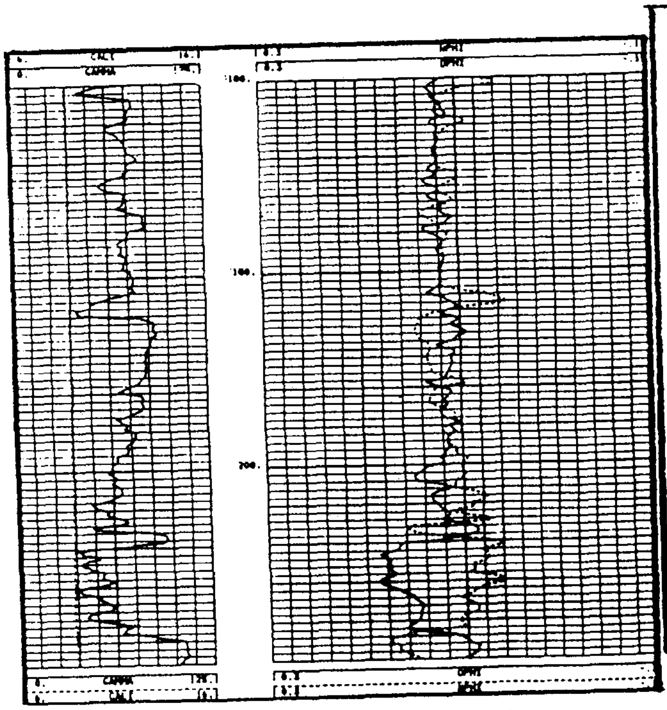

Figure 39 - Porosity log - open hole

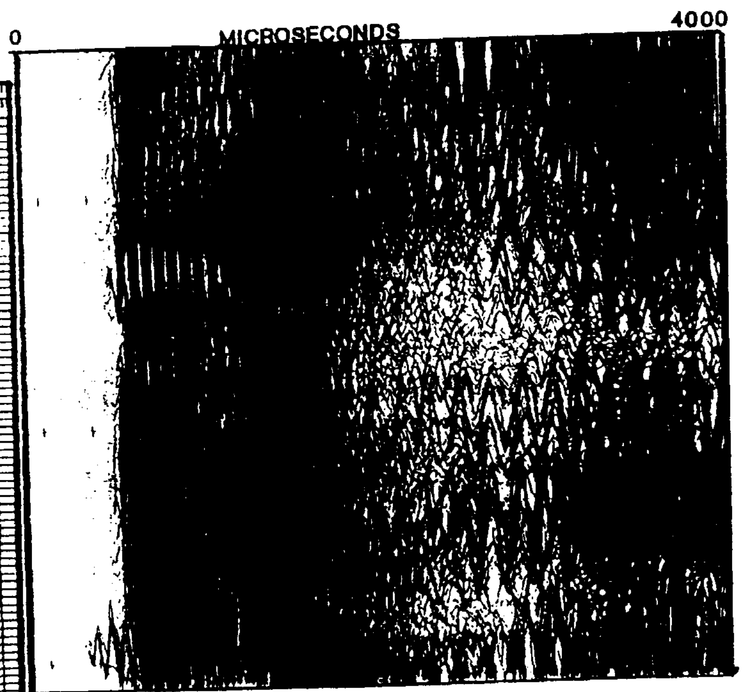

Figure 40 - Waveform plot - cased hole