

## **Application of sonic waveform attributes in reservoir studies**

R. GIR

Schlumberger (Malaysia) Sdn Bhd

**Abstract:** Based on the field data of the long spaced sonic tool (LSS\*), and of the digital sonic tool (SDT\*) from several wells, several potential applications have been observed for full waveform sonic logging. The amplitude and phase of the waveform are displayed by combining the signals and their Hilbert transformed signals. From the phase the various wave arrivals, i.e., compressional, shear, etc. can clearly be identified. The amplitude logs are presented in a color VDL form. The features shown in the amplitude VDL are related to the following:

- (1) formation lithology
- (2) gas in the formation
- (3) shale types
- (4) sand strength
- (5) fractures and
- (6) borehole geometry.

Faster formations give weaker compressional wave and stronger shear wave. Shear is usually not detectable in slow formations (soft rocks). The compressional amplitude is significantly weaker in gas zones than in water and oil zones. The hard and soft shales, as well as shale alteration, can all influence the sonic waveforms in predictable ways. It has also been found that the compressional amplitude is stronger in weaker sands. The sand strength observation is in agreement with microfrac tests. The sonic amplitude is also weakened significantly by induced hydraulic fracturing. The correlation between the amplitude and the formation has been found to be very useful in assisting the formation evaluation with other well logging data. In this paper several field examples will be shown and the data explained with borehole acoustic theory.

### **INTRODUCTION**

For the past 20 years, sonic logging has evolved considerably from simple compressional velocity logging using the first break of compressional arrival to using multiple receivers and recording and processing the complete sonic waveform. This trend is driven by the use of shear waves for determining mechanical properties of the formation for sanding or fracing (Coates and Deneo, 1981; Ingram *et al.*, 1972; Newberry *et al.*, 1985), and stoneley waves for fracture identification (Brie *et al.*, 1988; Hornby, 1989), and permeability studies (MEA Review, 1988).

However, very little attention has been given to the use of amplitude information in studying the reservoir rocks.

In this paper, a catalogue of sonic waveforms using examples from different parts of the world will be presented that will illustrate the usefulness of amplitudes of compressional (P) and shear (S) waves and Stoneley and their decay behavior in relation to the following applications, namely:

1. Pore fluid determination
2. Formation strength
3. Formation lithology
4. Fracture identification (induced/natural)
5. Fracture permeability

### **THE EFFECTS OF BOREHOLE ENVIRONMENT ON SONIC WAVEFORM AMPLITUDE**

In borehole sonic waveforms, there are several acoustic wave types that travel from the transmitter to the receivers. The earliest part of the waveforms is the compressional head wave. Trailing the compressional head wave is the shear wave. The shear wave train is actually a combination of the formation shear wave and the guided acoustic modes in the borehole. The guided waves are also called pseudo-Rayleigh waves. In soft rocks, the shear wave is not detectable. In its place there is a borehole fluid wave that follows the compressional head wave. The last portion of the waveforms is a Stoneley wave. The Stoneley wave is particularly significant if the sonic tool emits low frequency acoustic waves. For the signals near 20 kHz, such as the LSS\*, the late arrivals are the acoustic modes that travel near the sound speed of the borehole fluid. In the following, the amplitudes of compressional and shear waves will primarily be discussed.

The amplitude of the compressional and shear arrivals are affected by several borehole environmental factors, including: formation lithology, intrinsic formation acoustic attenuation, formation alteration near the borehole, fluid invasion in a gas zone, and borehole geometry.

#### **Formation Lithology**

In hard rocks, the compressional head wave is weak and the shear/modes can be very strong. The compressional wave is weak because there is a large acoustic impedance contrast between the mud and the formation compressional wave. The shear/modes are strong because the acoustic rays can be totally reflected inside the borehole, making the borehole a wave guide that traps the

acoustic energy. As the formation becomes softer, compressional wave becomes stronger and shear/mode becomes weaker. In the soft rocks, where the formation shear is slower than the guided mode and the shear wave becomes undetectable. A new generation of sonic tool using dipole transducers will be needed to log shear directly in soft rocks.

### **Intrinsic Acoustic Attenuation of the Formation**

In gas reservoirs and in fractured formations, acoustic waves can be quite attenuated in the formation rocks. Results from laboratory experiments of unconsolidated sandstones have indicated that gas in the pore fluid can cause the acoustic attenuation to increase significantly (Winkler and Nur, 1982, Murphy, 1982, 1984). The attenuation (in dB) is equal to  $0.027 f S z / Q$ , where  $f$  is frequency (in kHz),  $S$  is the slowness of the formation wave (in microseconds/ft),  $z$  is the travel distance (in ft) of the sound wave, and  $Q$  is the quality factor that is used to describe attenuation. For example, if the slowness is 80 microseconds/ft, frequency is 20 kHz, and  $Q$  is 20, then the attenuation is about 20 dB if the wave travels a 10 ft distance.

### **Fluid Invasion in Gas Zones**

Low amplitude compressional waves are observed in gas zone. One possible reason for the low amplitude is that there is a fluid invasion into the gas saturated formation. The invaded region has a faster wave speed due to the larger elastic modulus of the invading fluid than that of the gas. With the zone near the borehole wall having a faster wave speed than the virgin formation, the rays will be diverted away from the borehole, causing the compressional wave amplitude to be significantly weaker than usual.

### **Near-Borehole Formation Alteration**

There can be shale alteration due to the chemical reaction between shale and water. Shale alteration forms a soft cylindrical layer near the borehole wall. Stress relief around the borehole in unconsolidated sandstones can also create a cylindrical layer with a slower wave velocity than the virgin formation. With a softer layer near the borehole, the acoustic rays can be re-focused into the borehole, resulting in a stronger formation arrival. This is true even if the acoustic velocity contrast between the altered zone and the virgin formation is only in the order of one percent. Since shale types and sand strength are directly related to the degree and the depth of borehole alteration, the compressional head wave amplitude can be used to distinguish the type of shales and also to indicate the strength of sandstones.

### **Borehole Size, Shape and Conditions**

Borehole fluid wave can be quite strong in large holes. In irregular holes and in holes with cave-ins and other irregularities, the formation arrivals can be less coherent and consequently weaker than normal. Because of these and other environmental effects, one should include other available data from logs, from cores, and from other means in making the waveform interpretation

### **SONIC ATTRIBUTE ANALYSIS (SONATA\*)**

A number of properties of the sonic waveform such as phase, amplitude, frequency and transit times are grouped together in a waveform train. Complex attribute analysis (Taner and Sheriff, 1977) allows a decomposition of the waveform and separates amplitude from angular information. No new information is generated, yet data re-arrangement adds another dimension to the interpretation. Two attributes (Envelope & Phase) are discussed in this paper.

Envelope display gives a measure of instantaneous amplitude and is independent of Phase, and is useful for lithology formation and strength.

Phase on the other hand, is independent of amplitude and is used to identify compressional, shear and stoneley arrivals in gas reservoirs/fractured intervals and washouts. Chevron patterns typically observed in fractured intervals are enhanced in Phase displays.

#### ***A. Application for Fluid Discrimination***

Discrimination of gas sands vs. water sands or oil sands is possible whereas distinguishing oil from water is difficult unless the oil is light. Following criteria are used:

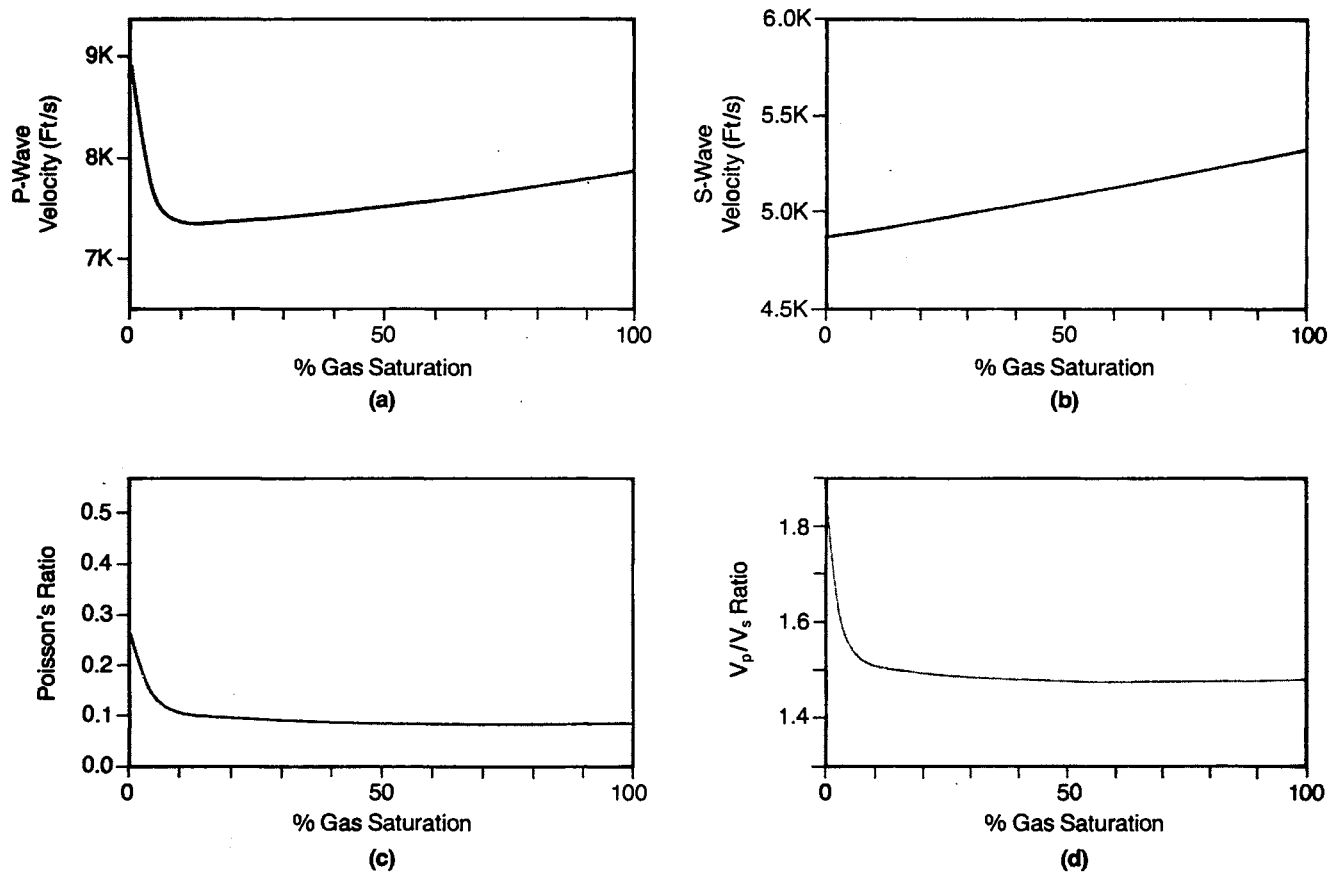
##### **a. VP/VS ratio**

DTc is affected significantly by the presence of gas in its pores. The maximum change occurs between 0-10% gas saturation. Beyond 10% gas saturation, the increase in DTc is insignificant (Figure 1). DTs on the other hand is much less affected by the pore fluid. Therefore, within a given lithologic unit, DTs/DTc is indicative of change in pore fluid (gas). This implies that the presence of gas will be detected even if the water saturation is greater than 90%.

##### **b. Attenuation of P and S Waves**

Amplitude reduction of P and S Waves due to attenuation is dependent upon the percentage of gas saturation. Winkler and Nur, 1982, suggest that S wave attenuation decreases. Winkler and Nur, 1982 suggests that S wave attenuation increases with degree of saturation, reaching a maximum at total saturation. P wave attenuation also increases with saturation at low degrees. P wave attenuation reaches a maximum

## Ostrander

Figure 1: Effect of Gas on  $V_p$  and  $V_s$ .

between 60 to 90 percent water saturation. As saturation continues to increase beyond 90%, P wave attenuation decreases.

### **Example 1 – Sandstone Reservoir (gas vs. water)**

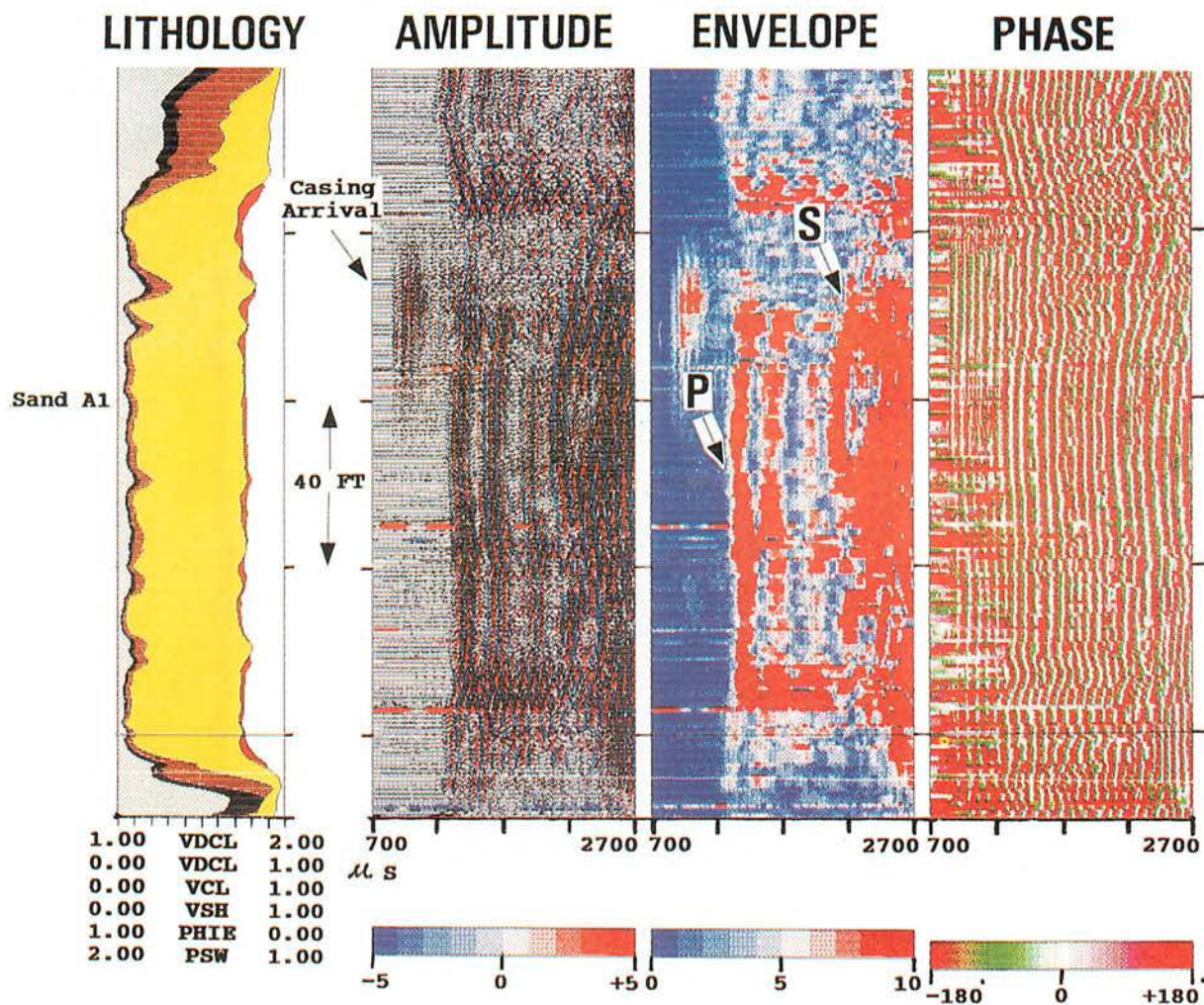
In this example, the array sonic (SDT\*) was run in cased hole. Figures 2a, b, c show the colour VDL (Amplitude, Envelope and Phase) along with a computer processed interpretation (VOLAN\*) based upon several logs. The volumetric breakdown of various components-sand, silt, dry clay, bound water, hydrocarbon, water filled porosity, is shown in different colours-yellow, brown, brown dots, black, red and white respectively. The three main sands A-1, A-2 and A-3 have a different hydrocarbon saturation. Sand A-1 is considered a water wet. The following observations can be made:

1. Presence of hydrocarbon causes strong attenuation of compressional and shear wave arrivals seen in sands A-2 and A-3 (Figure 2b, c). A stronger attenuation of P wave in sand A-3 which has a higher gas saturation is observed. The attenuation seen in the Envelope of sand BI in Figure 2c implies a much higher gas saturation and is one of the producing sands. This is in contradiction with the formation evaluation result showing low gas saturation for this sand. This is most likely the result of high irreducible water saturation in these sands.
2. A strong casing arrival is observed (seen as red colour) coming earlier than the first compressional arrival. This occurs in zones where the cement bond is poor. The hydrocarbon sand A-3 has a poor cement bond on the top and bottom part of the sand. The instantaneous phase display helps in identifying zones of poor cement bond by enhancing the casing arrivals that show constant transit time. Also, P and S wave arrivals in the reservoir sands that are masked by the casing arrival in conventional displays are enhanced in the phase display.

### **Example 2 – Shaly Sand Reservoir (gas/oil/water sands)**

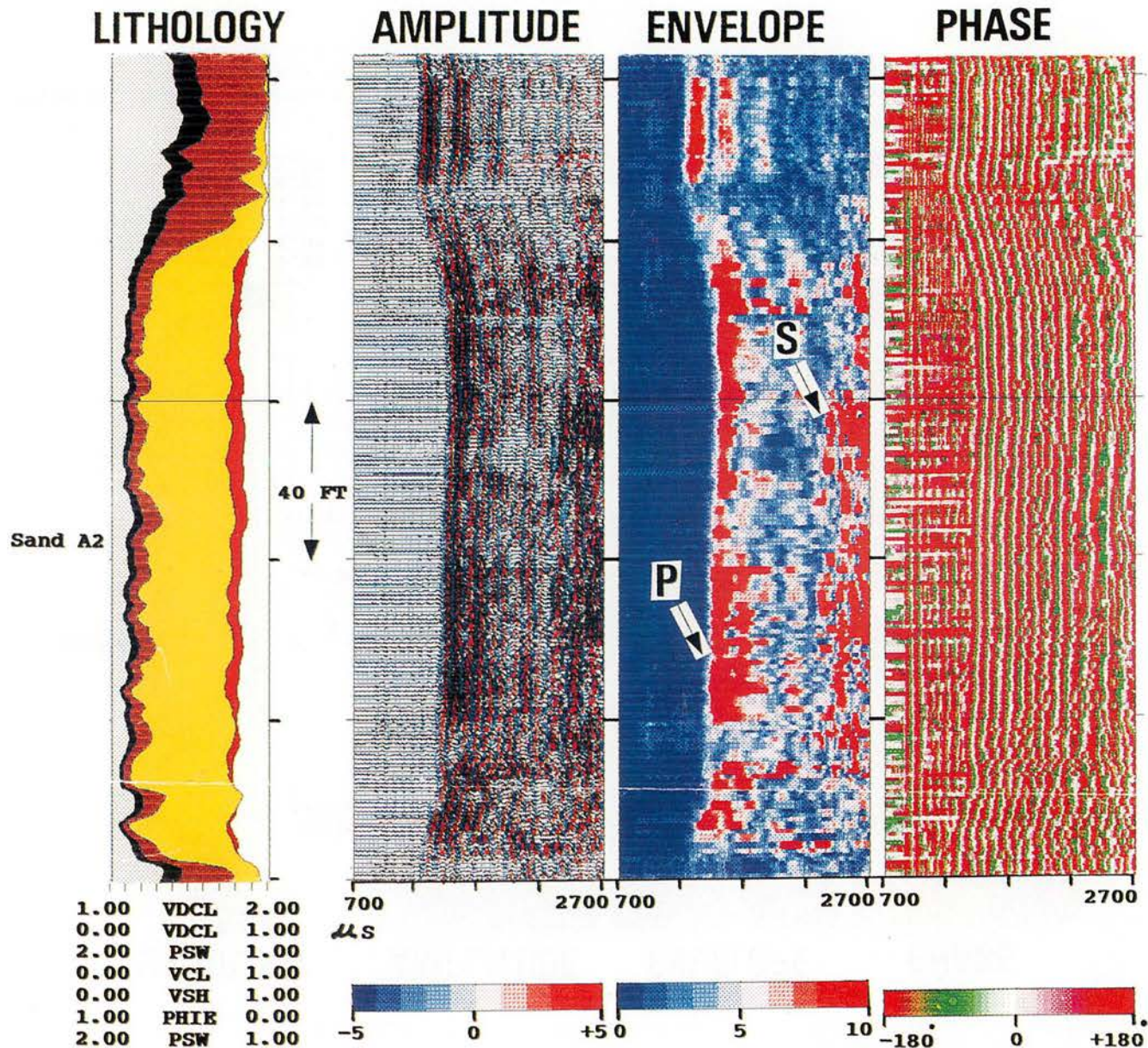
In this field, the sonic waveforms were acquired with long spacing tool in open hole. The formation consists essentially of sands and shales with varying amount of silt and clay and coal streaks. DTc in water bearing sands is typically 80-85 microsec/ft. Shales have a larger DTc of about 95-100 microsec/ft. Figure 3a show a typical signature of a water sand. The DTc is about 80 microsec/ft and Vp/Vs is in the range of 1.7 to 1.75. In Figure 3b, shallower intervals from the same well are displayed. Envelope response of these sands have a longer P wave Envelope (or a slow decay of P wave) indicative of an increase in shaliness.

Figure 3c shows the differences in the Envelope of the P wave within the given sand interval. The caliper appears to be a good indicator for the sand limits. Three zones can be identified based upon amplitude differences. We note DTc in the range of 90-100 microsec/ft. In the lower part, and increasing to 105-110



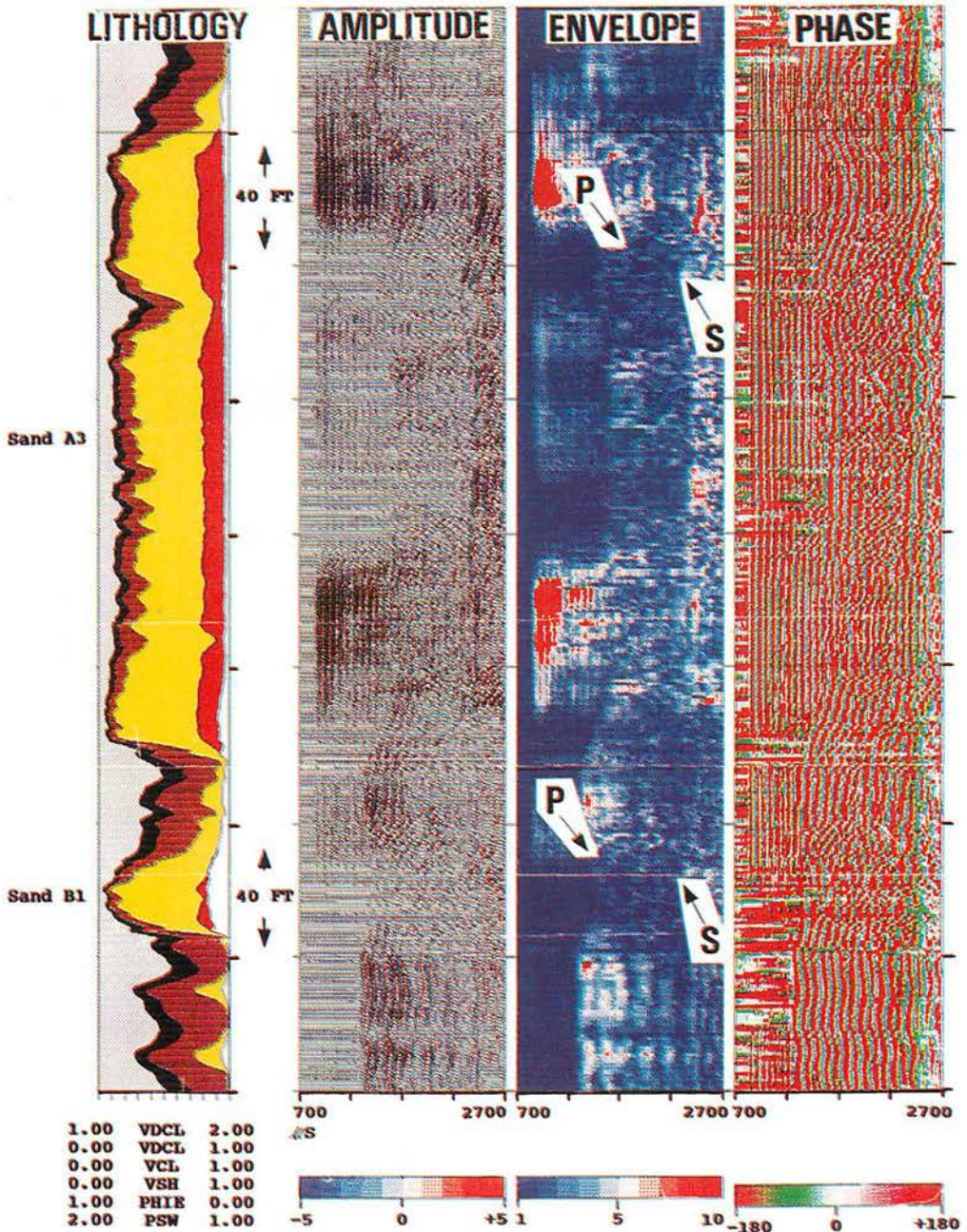
**Figure 2a:** Example of sandstone reservoir with different gas saturations. Notice the increase in attenuation of P and S wave amplitude/Envelopes with increasing percentage of gas. In Figure 2b, a strong reduction of P and S wave amplitude is observed, inspite of casing arrivals.



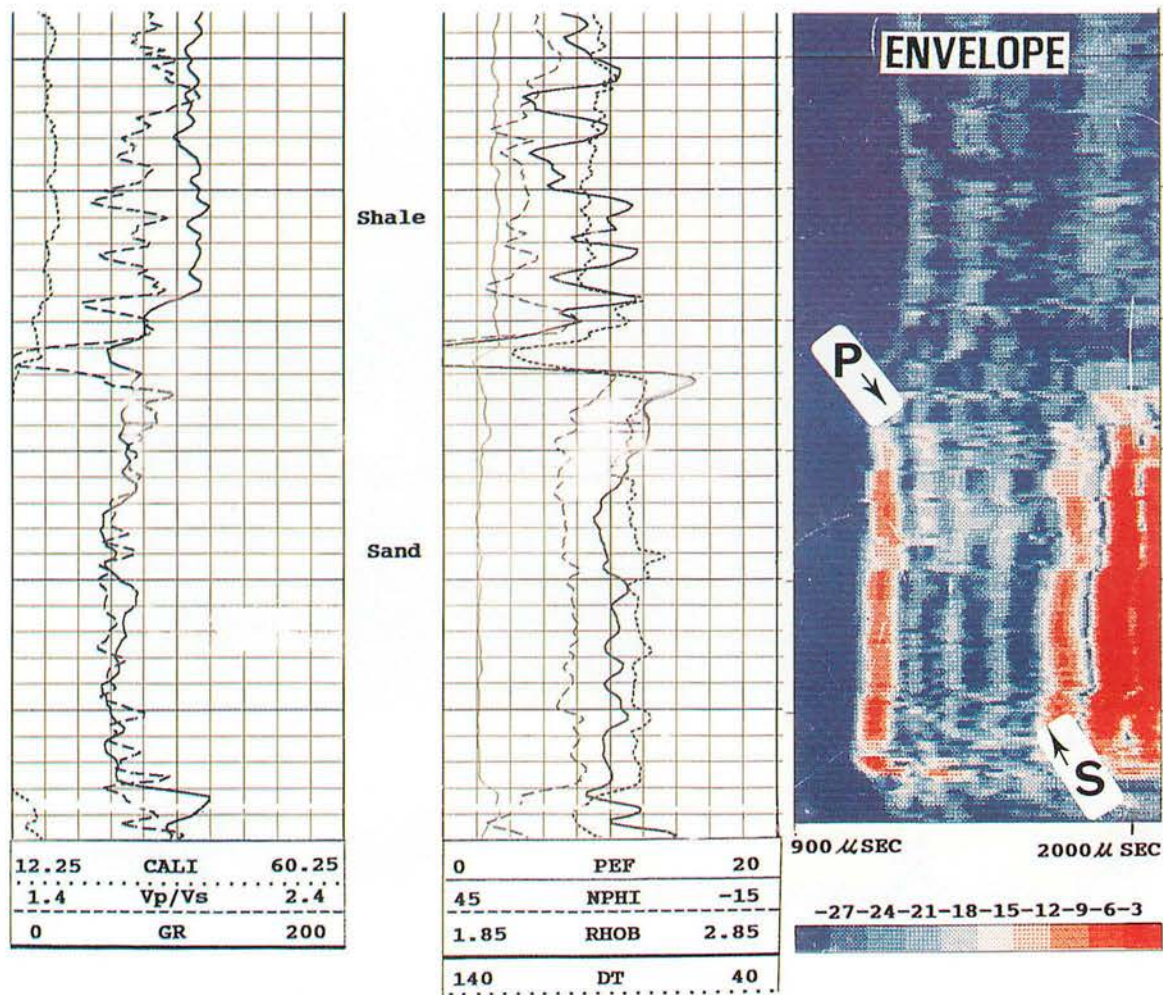


**Figure 2b:** Example of sandstone reservoir with different gas saturations. Notice the increase in attenuation of P and S wave amplitude/Envelopes with increasing percentage of gas. In Figure 2b, a strong reduction of P and S wave amplitude



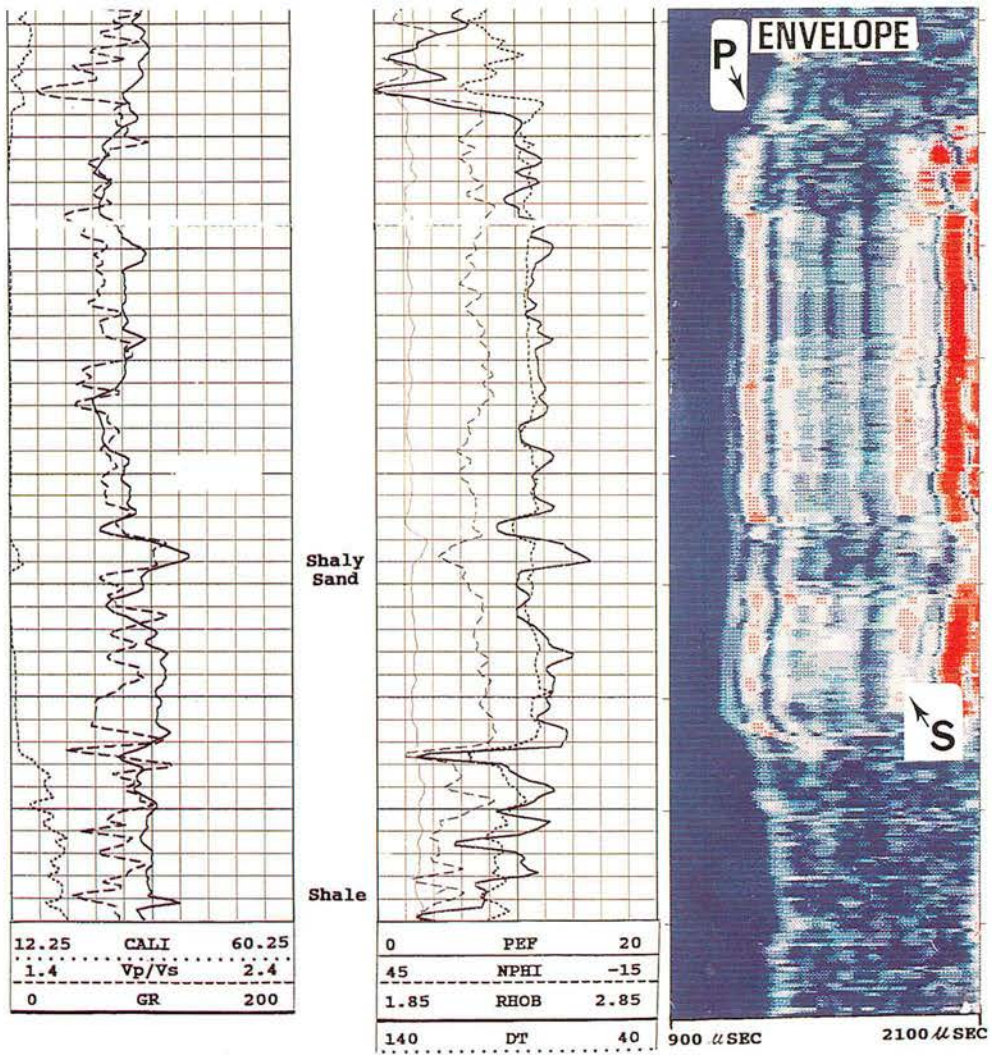


**Figure 2c:** Example of sandstone reservoir with different gas saturations. Notice the increase in attenuation of P and S wave amplitude/Envelopes with increasing percentage of gas. In Figure 2b, a strong reduction of P and S wave amplitude is observed, inspite of casing arrivals.



**Figure 3a:** Typical signature of water sand. The borehole is washed out in shales which explains loss of energy in shales.





**Figure 3b:** Wet shaly-sand. Length of P wave envelope is seen to increase with increase in shaliness compared with Figure 3a.

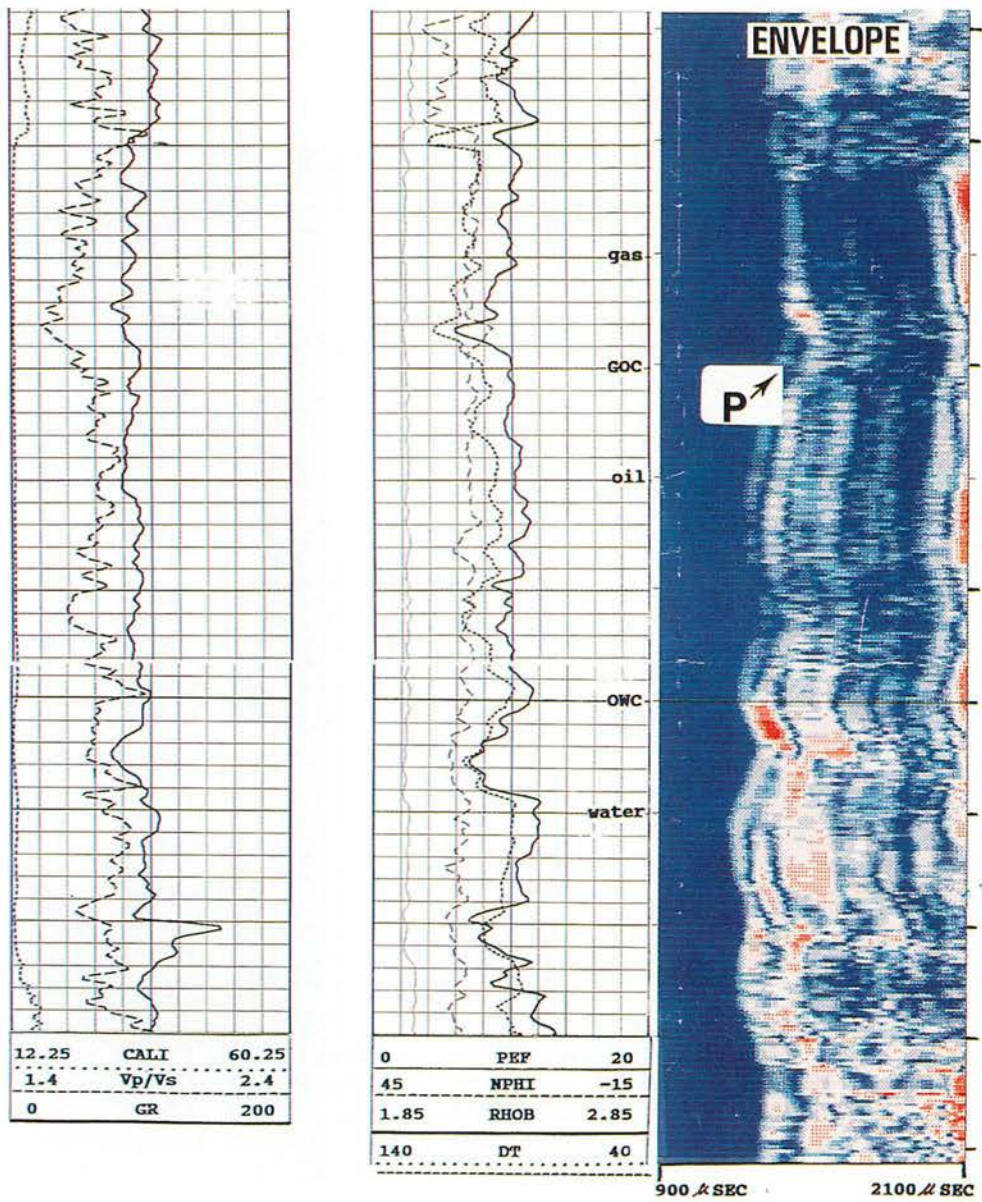


Figure 3c: Shaly-sand reservoir showing difference in P wave envelope between water, oil and gas.

microsec/ft in the upper part of the sand. The Envelope shows strong attenuation of both P and S waves in the top part. Combined with the fact that DTc increases to 110 microsec/ft in this zone suggests a gas cap which is not obvious from neutron and density logs, which do not show any crossover (probably due to shale laminations). These observations were confirmed by Production Tests. The oil/water contact from resistivity log is marked on the Envelope. The differences in Envelope between the water/oil zone is seen because the oil is light (with possibly a high GOR).

**Example 3 – Clean Sandstone Reservoirs ( gas vs. oil)**

In this example, the digital sonic tool acquired the data in open hole. Envelope of different sand intervals along with gamma ray log are shown in Figure 4. Gas clearly shows strong attenuation of compressional arrival, whereas oil and water sands look about the same. This is probably a more typical example as against the one shown in Figure 3 where we differences in oil and water zones were observed because the oil was light

***B. Application of Amplitude Information for Formation Strength***

MECHPRO\*/ROCKPRO\* are traditionally used to quantify the formation strength in terms of sanding i.e. estimation of optimum drawdown to prevent sanding during production. This requires input from various data types (DTC, DTS volume of clay, regional tectonic stress, calibration factor etc.) It is however possible to estimate on a qualitative basis the relative strength of the reservoir sands and any changes in strength within the sand from a study of the P wave Envelope.

Two criteria are used:

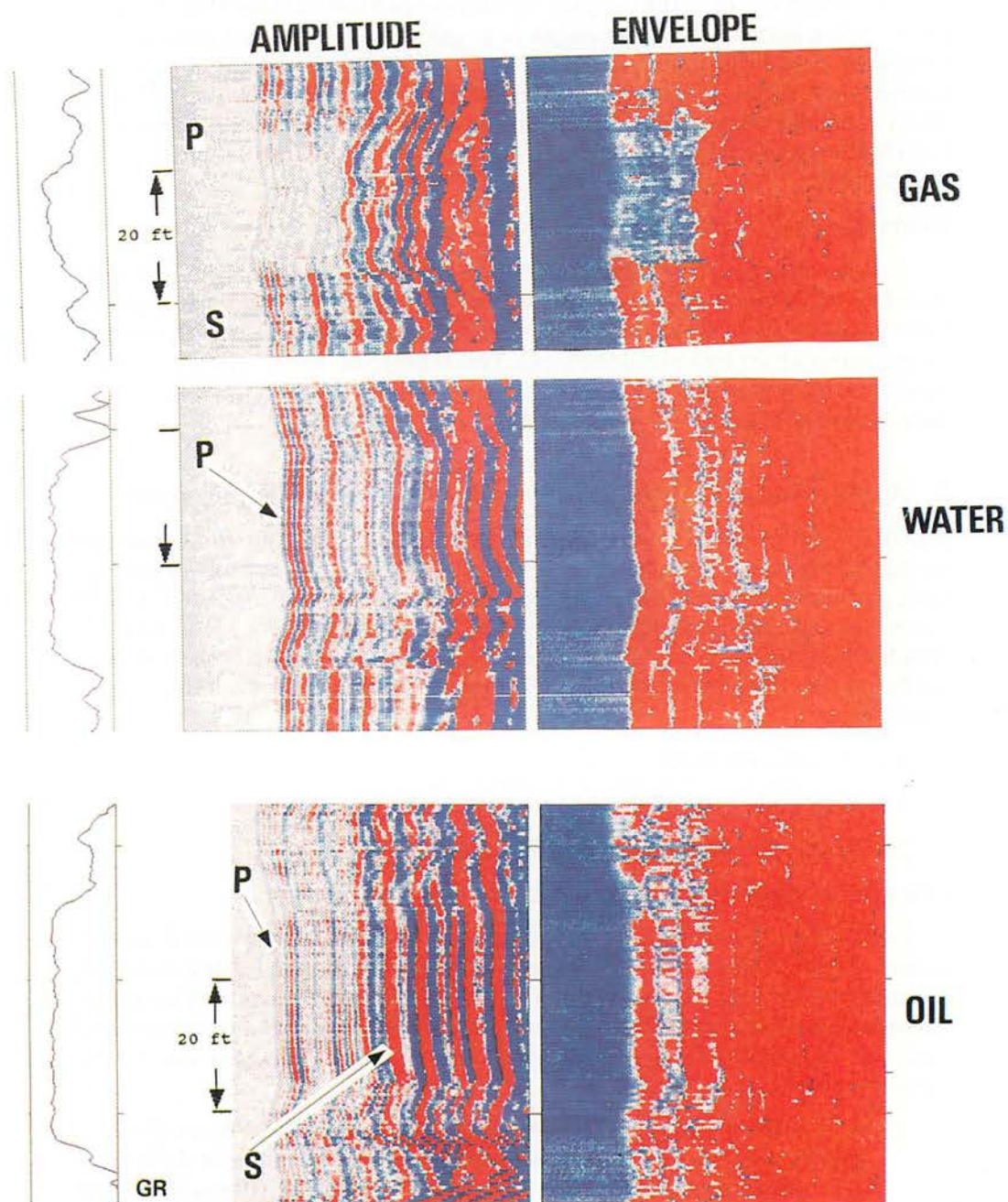
1. Amplitude ratio of shear to compressional wave ( $A_s/A_p$ )
2. Amplitude and length of the P wave Envelope.

**Example 1 – High Porosity Sandstone Reservoir (oil/water)**

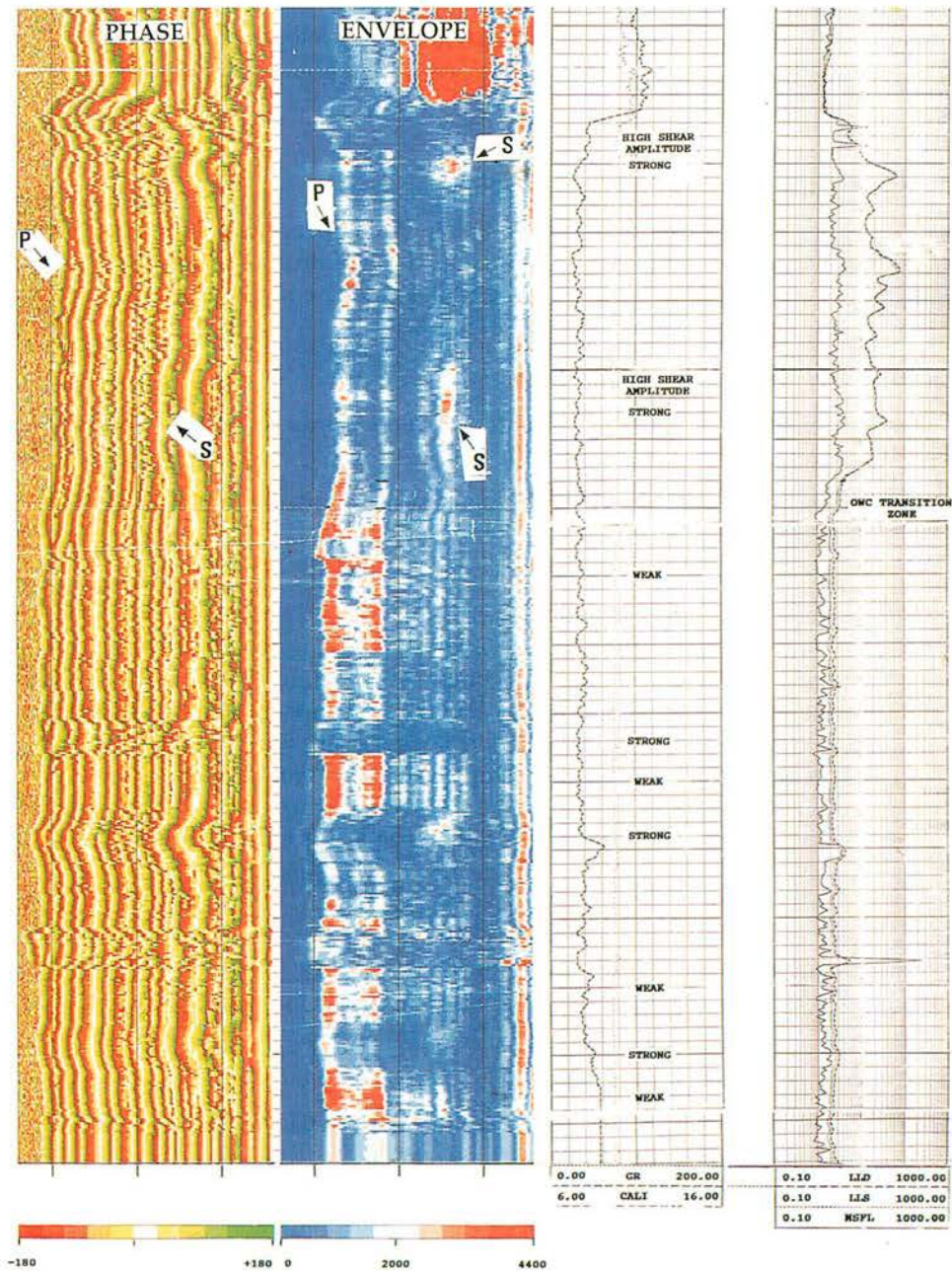
In this field the sands have a high porosity of about 30% and are friable in nature. Figure 5 shows the Envelope display of the pay sand along with GR, resistivity, DTc, DTs,  $V_p/V_s$  ratio. The following observations can be made. Shear waves are generally lower in amplitude as compared to compressional with the exception of some intervals in the pay sand. In this example the following observations are made:

1. Within the hydrocarbon sand, a significant change in  $A_s/A_p$  at different depths, even though the other logs do not indicate any major difference. DTc remains practically the same within the entire hydrocarbon sand interval. Obviously, zones where  $A_s/A_p$  are high indicate a harder sand and therefore should be selected for testing.





**Figure 4:** Examples from sandstone reservoir showing difference in Envelope for gas, oil and water sands. Gas sands are identified by a longer P wave Envelope.



**Figure 5:** Sandstone reservoir showing amplitude differences in the pay section. The stronger zone is identified by higher shear wave amplitude. In the lower part of sand below owe, weak sands are identified by a longer P wave Envelope.

2. Below the oil water contact in the water sand, zones of low strength were identified by their longer P wave Envelope. These zones were selected for Mini-Frac. The zone that had a longer Envelope failed earlier by 750 psi (Figure 6) as compared to the one with a higher  $A_s/A_p$  and a shorter Envelope.

### ***C. Application of Formation Lithology***

In general faster formations give weaker compressional and a stronger shear wave. In soft rocks, shear is usually not detectable if its slowness is greater than mud slowness. The hard and soft shales and the shale alteration can all influence the sonic waveform in predictable waves.

#### **Example 1 – Mixed Lithology**

In this example (Figure 7), the sonic waveform was recorded with the LSS tool. We can make several observations:

1. Zones that have much higher shear wave amplitude as compared to compressional are limestone streaks.
2. Zones marked as shale A and shale B are distinctly different. In the upper shale, there is a long P wave Envelope and no shear wave, whereas in the lower shale the P wave Envelope is shorter and the amplitudes of shear and compressional are comparable. Shale A with a ringing of P waves is observed (i.e., a longer P wave Envelope) is softer than Shale B. Shale A does not support any shear waves, implying that DTs is slower than borehole fluid slowness. Log analysis and core measurements have confirmed that the clay types are different. The upper shale with a higher bound water is Montmorillonite and the lower shale is Kaolinite.
3. The interval shown as sandstone is quite different in waveform character as compared to the lower zone which is a shale
4. Zones where a strong attenuation of energy (deep blue colour) are observed, correspond to high angle ( $>77$  deg.) open fractures confirmed by BHTV and core measurements.

#### **Example 2 – Shale/Silt**

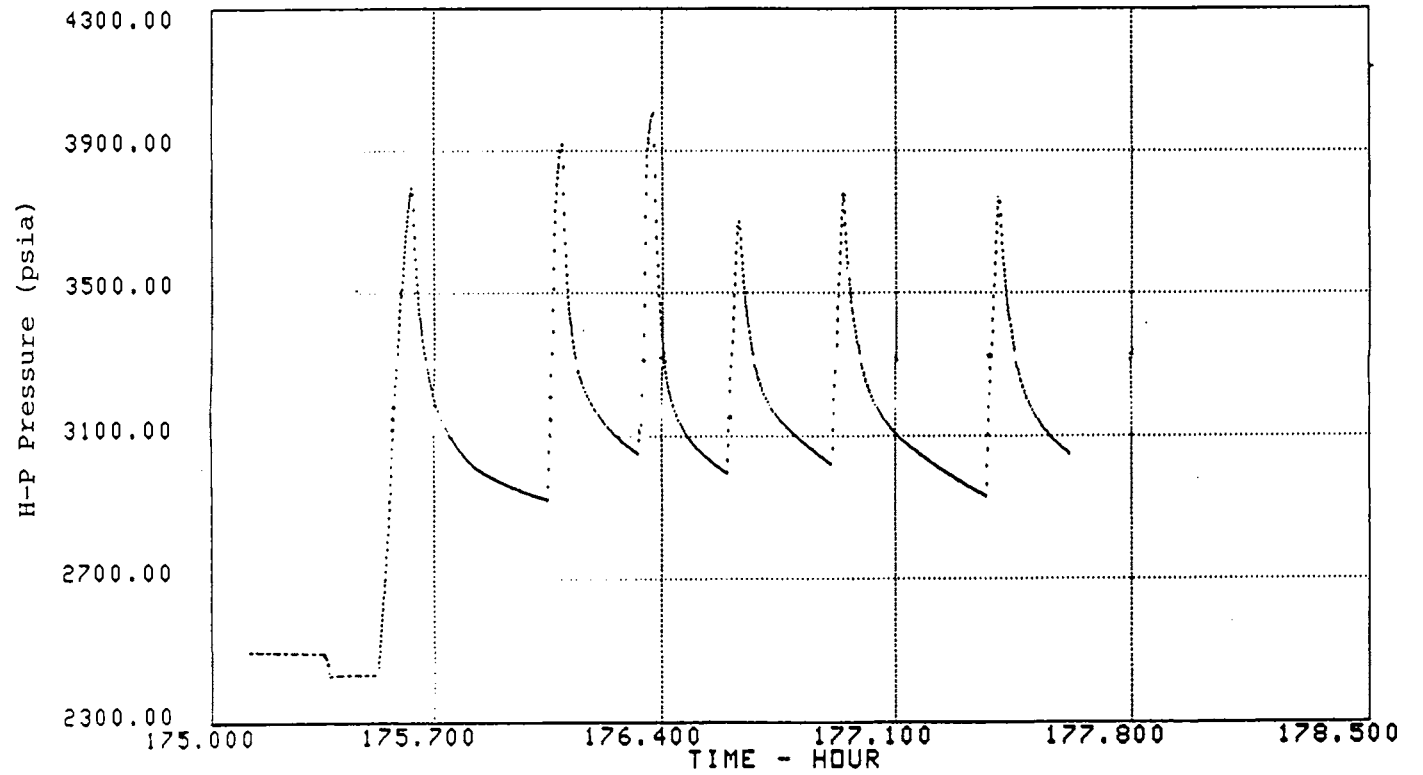
In this example (Figure 8), the Envelope display is presented with a set of logs. Very clearly, the differences in the Envelope within a long shale interval highlight differences within the shale which could be due to different amounts of alteration due to changes in mineralogy/texture.

### ***D. Applications to Fractures (natural)***

Almost all components of sonic waveform are sensitive to fractures. The main effects of fractures on P and S waves are :



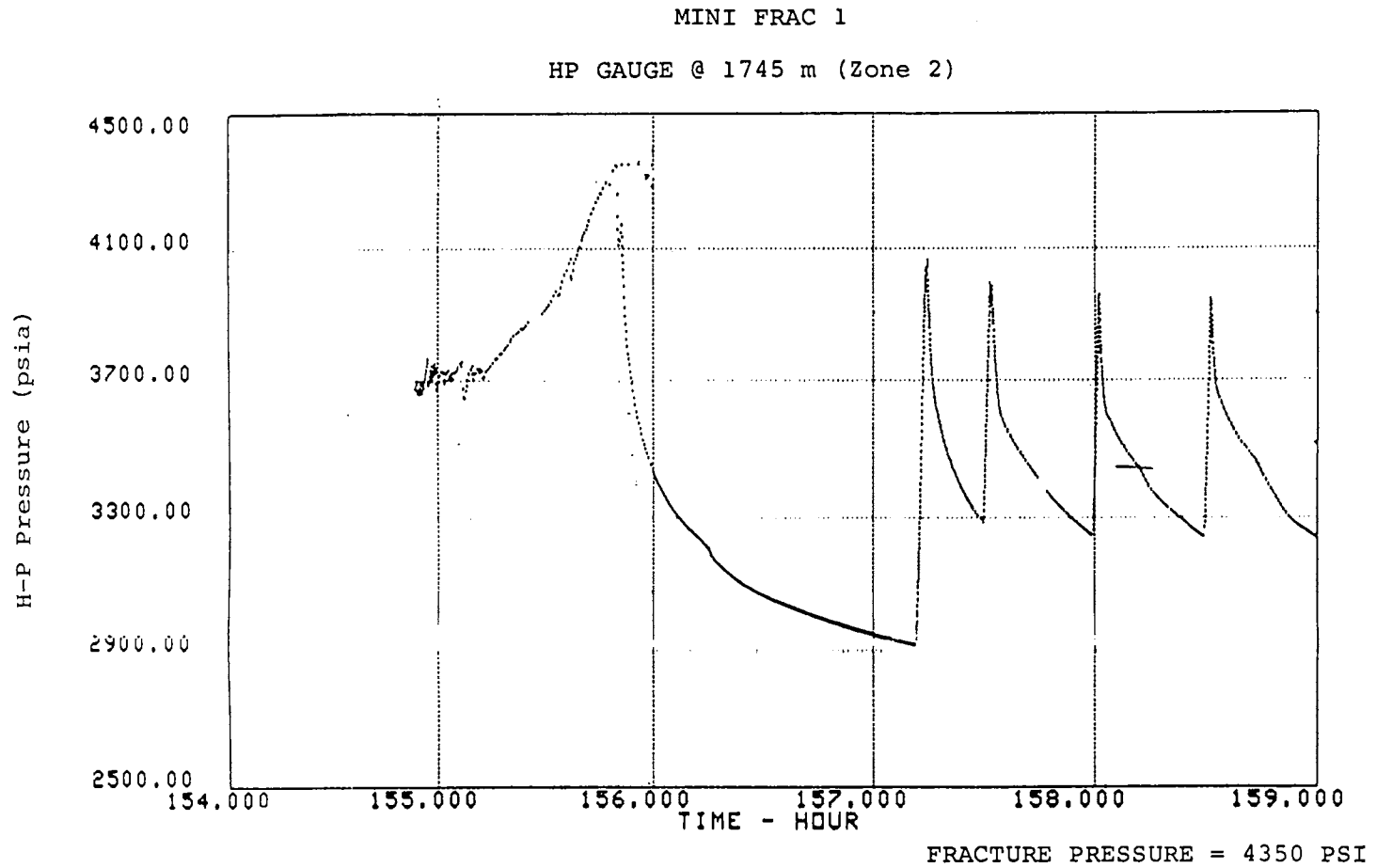
MINI FRAC 2  
HP GAUGE @ 1725 m (Zone 1)



FRACTURE PRESSURE = 3800 PSI

PRESSURE VERSUS TIME

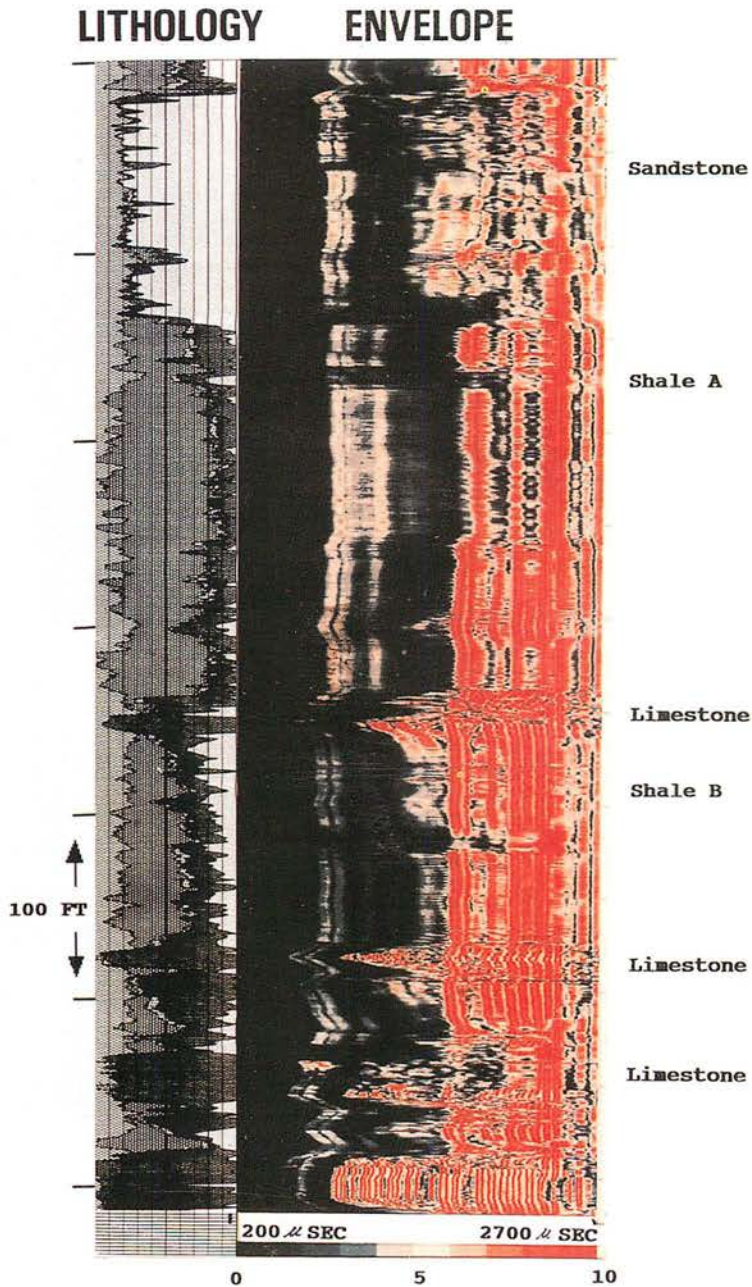
Figure 6a: Mini Frac result



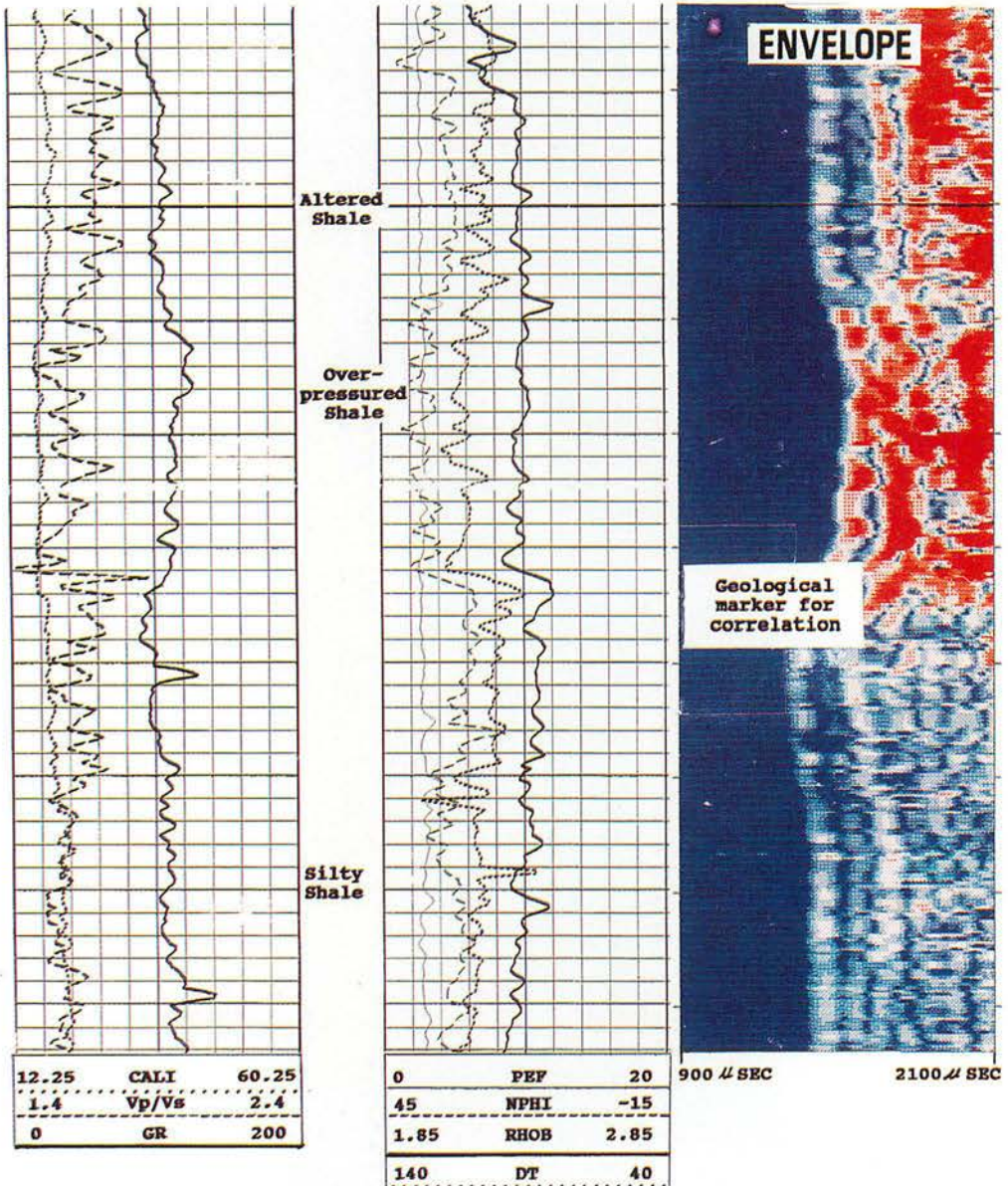
PRESSURE VERSUS TIME

Figure 6b: Mini Frac result





**Figure 7:** Limestone streaks are seen as high  $A_s/A_p$ . Note a marked difference between shale A and shale B in terms of the length of P wave Envelope and shear wave arrival.



**Figure 8:** Envelope of a thick shale section. Zone H shows a higher degree of alteration than zone F. Zone G corresponds to an overpressured shale that stands out as a geological marker on the sonic waveform.

- some delay in the arrivals;
- amplitude reduction of the compressional and /or shear arrivals;
- reflections causing Chevron patterns;
- enhancement of borehole coupling causing spikes.

Fracture indications from P and S waves detect both open and healed fractures.

### **Example 1 – Fractured Basement (Granite) Reservoir**

In this example (Figure 9) the amplitude of the waveform is displaced along with GLOBAL\* results showing formation evaluations. The purple colour represents granite, brown represents weathered diabase, red represents diabase and green represents hydrocarbon (oil). The yellow curve shows a reasonable hole, yet there are several zones where the P and S arrivals are strongly attenuated.

Two main observations can be made on this display :

1. The zones of amplitude reduction of P,S waves are deep formation fractures.
2. The zones where there is no apparent reduction of P and S amplitudes, but a reduction in pseudo Raleigh waves is due to a local phenomenon fractures induced by drilling. It can be seen that the caliper reading shows a kick in these intervals.

The main production in this field is from these natural fractures in the basement.

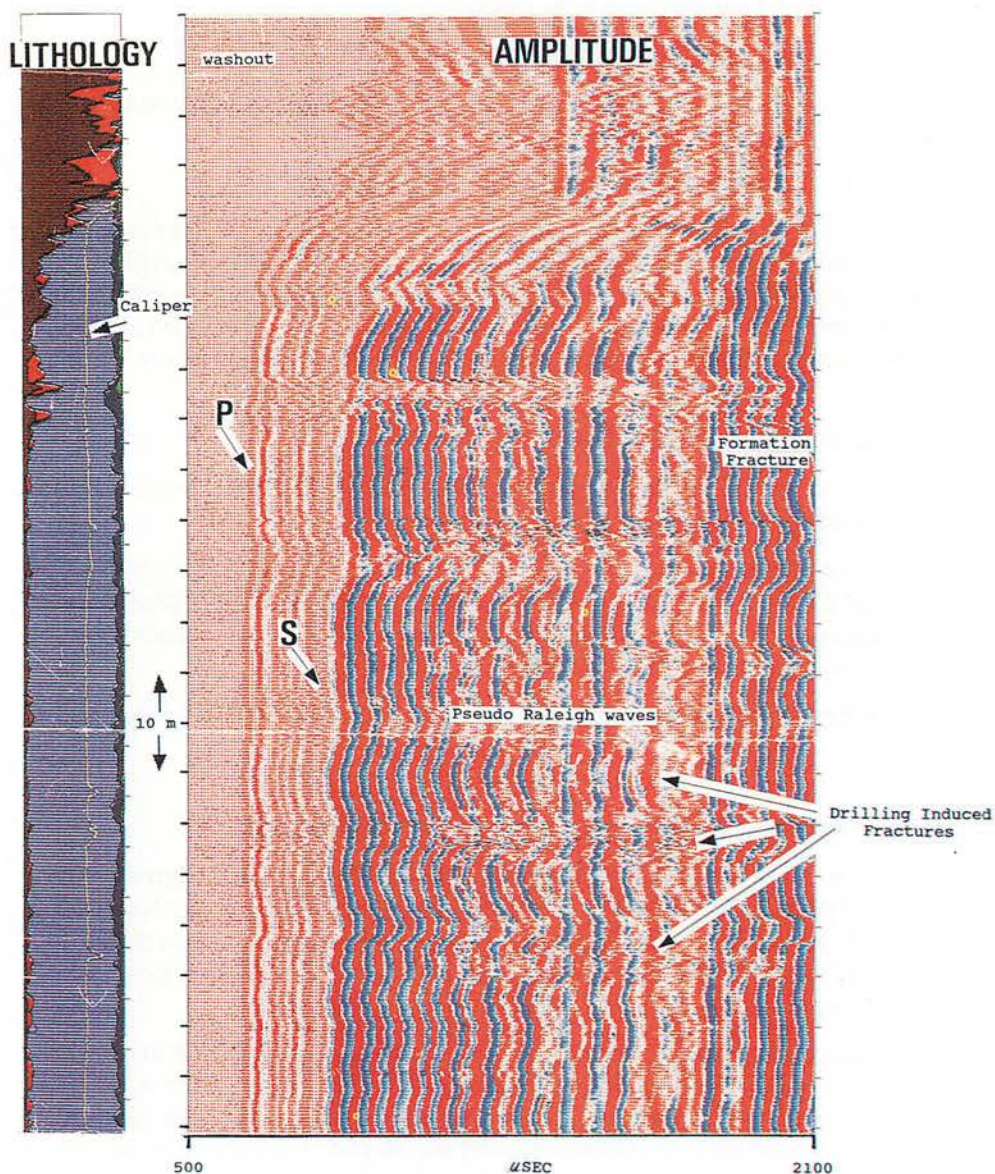
### ***E. Application to Fractures Induced by Hydrofracing***

Fracture height is one of the important parameters in the design of a frac job (Newberry *et al.*, 1985). Sonic waveforms recorded before and after a frac job can be used to determine induced fracture height. Frac-hite parameters can then be adjusted in a given field using the waveform results as a control to predict with reasonable accuracy the fracture height prior to a frac job.

The example shown here is of sonic waveform recorded with LSS in open hole (Figure 10a) before fracing and in cased hole (Figure 10b) after a frac job. Attribute processing enhance effects seen on the raw waveform data. For instance, instantaneous amplitude (Envelope) shows a strong attenuation of compressional (P) and shear (S) energies after fracing. Instantaneous frequency shows a sharp drop in frequencies caused by induced fractures.

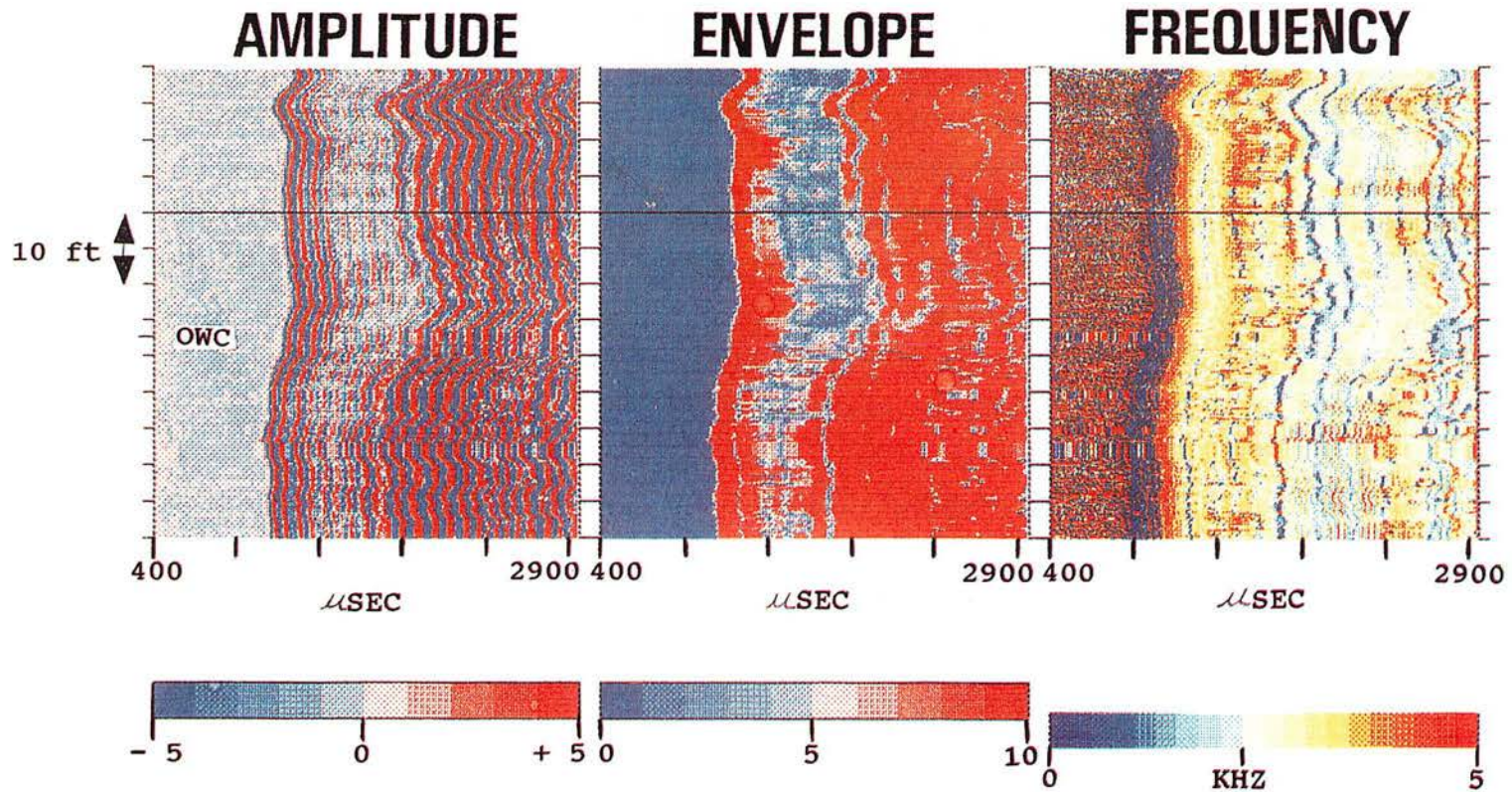
In the example shown, the bottom of the fractured zone reaches below the





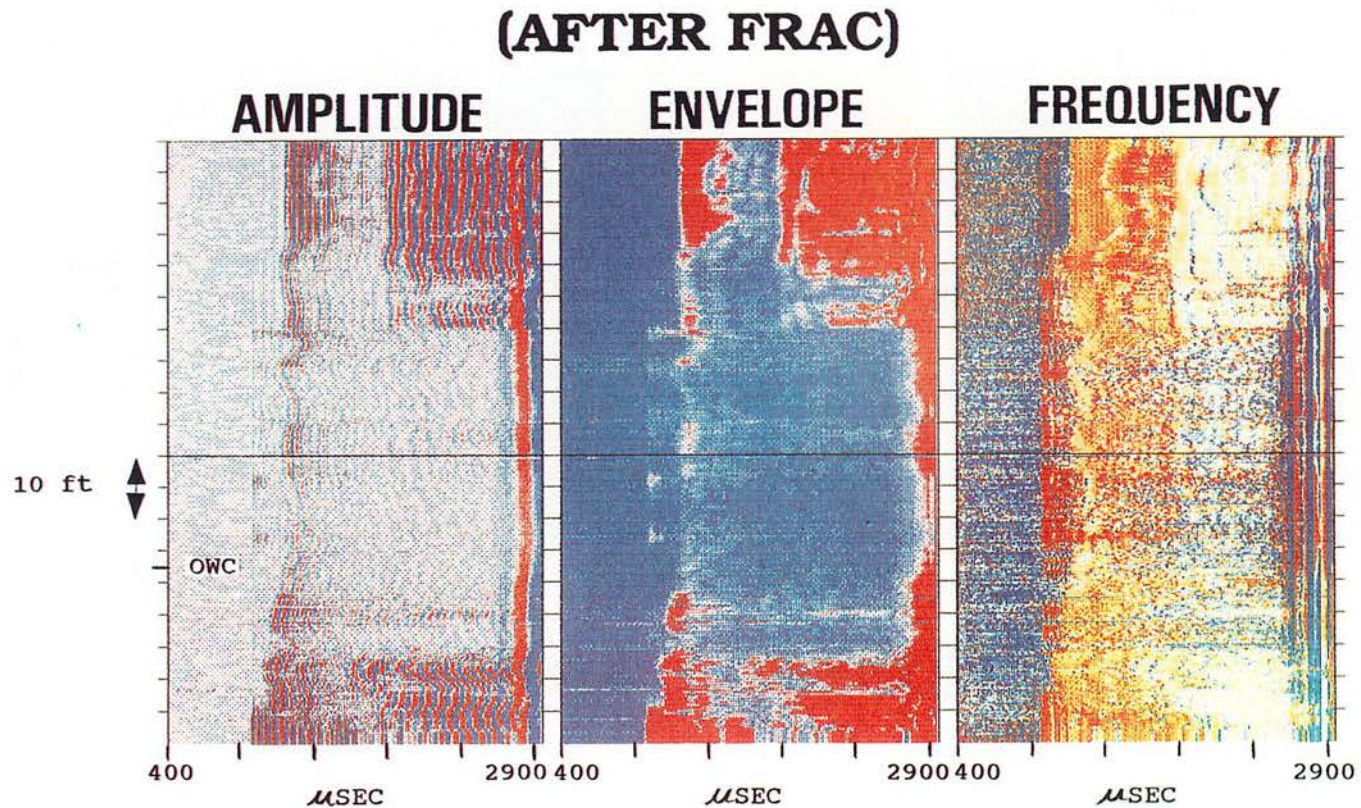
**Figure 9:** Example of fractured Granite Reservoir. Amplitude of sonic waveform showing attenuation of P and S waves amplitude are unaffected but the pseudo-Rayleigh waves show attenuation—could be indicative of drilling induced fractures.

## (BEFORE FRAC)



**Figure 10a:** Example showing amplitude, Envelope and Instantaneous frequency display over a reservoir sand interval before Fracing. Vertical height of the fracture can be verified from the waveforms.





**Figure 10b:** Example showing amplitude, Envelope and Instantaneous frequency display over a reservoir sand interval after Fracing. Vertical height of the fracture can be verified from the waveforms.

oil-water contact. The well produced with 50% water. After recognizing the origin of the water production from sonic waveform analysis, a special operation was conducted with cement injected in the lower part of the reservoir and gel in the upper part. The well now produced clean oil

### ***F. Applications to Fracture Permeability***

Qualitative information about permeability can be obtained from Stoneley waves. Occurring in the 1-5 kHz frequency band, the Stoneley wave propagates along the borehole wall with characteristics of both compressional and shear waves. On encountering an anomaly in the formation, say an open fracture, some of the energy of the pressure wave will be dissipated in and out of the moving fluid in the opening. The wave's transmission time along this path may also increase slightly, and the wave's amplitude could be further reduced by reflections from the fluid/rock interfaces within the crack. These reflected events further complicate the waveform display.

#### **Example 1 – Fractured Carbonate Reservoir Computer Based Formation Evaluation**

In this example (Figure 11a) the phase display is plotted along with lithology interpretation and production logging tool results (PLT) and the Stoneley wave transit time and energy. An increase in DTST combined with a decrease in Stoneley energy 'A' could well indicate zones of increasing permeability. In the zones of high fluid flow into the borehole there is a sharp drop in Stoneley energy and an increase in DT Stoneley- the former is derived from a single receiver, and the latter from the eight receiver array, so there is a difference in vertical 'resolution'. In addition, there is a prominent reflection event in the waveform itself. This waveform, used to derive Stoneley energy, is from the same single receiver and has been filtered to Stoneley frequencies and translated into an instantaneous phase form to highlight the subtle changes in the waveform events.

The lithology results show that the fracture, as indicated by Stoneley analysis, is occurring where a dolomitic zone meets a more porous limestone region. Similarly Stoneley events can be seen next to Production Logging Tool indications of fluid flow into the borehole. Once again, some reflected events may be seen in the waveform. Another way to evaluate the Stoneley results is to compare them with core permeabilities (Figure 11b). This is a different approach to the previous example, as such core measurements are no longer taken in-situ and larger contributors to a formation's permeability-such as fissures and fractures-may not be included.

### **CONCLUSION**

We have described simple criteria for analyzing the Amplitude and Phase information present in a complete sonic waveform train for studying reservoir





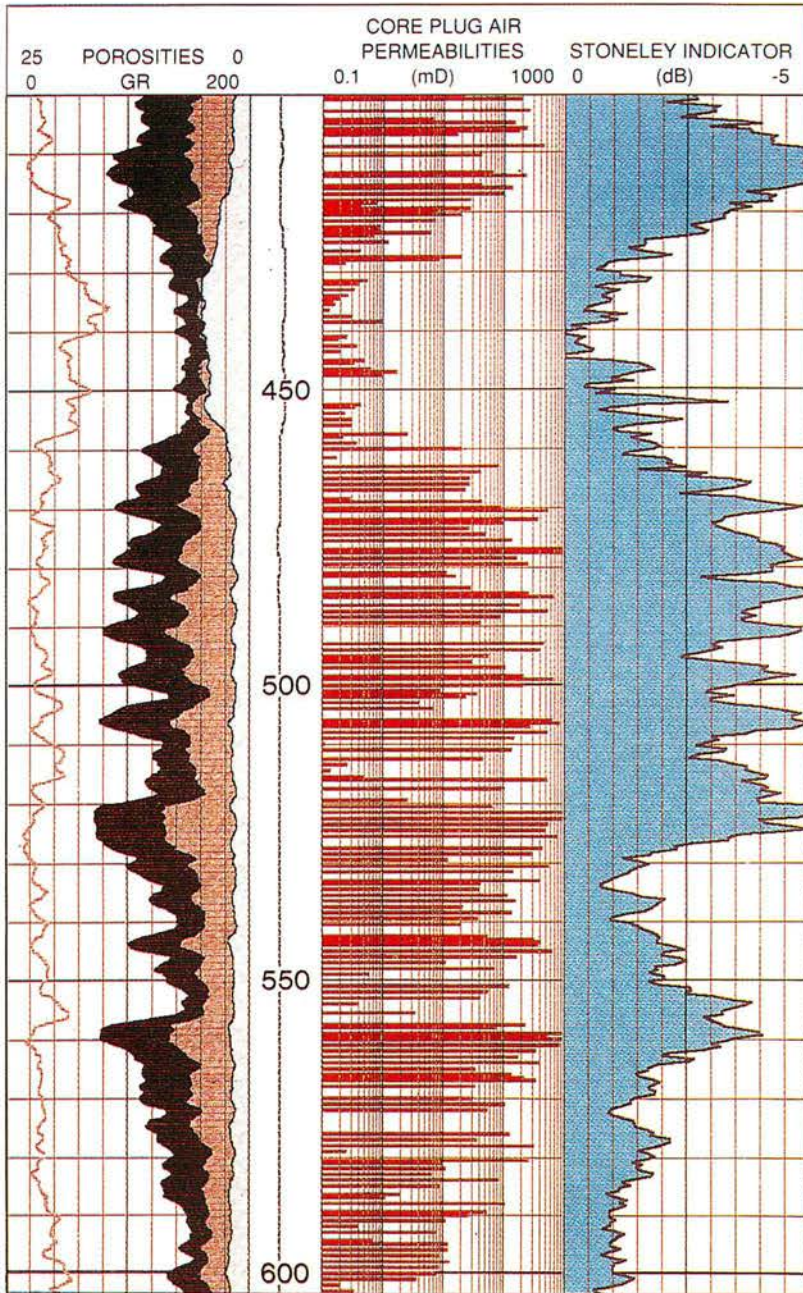


Figure 11b: Comparison of Stoneley energy with permeability measurements from cores.

properties.

Sonic waveforms, when used in synergy with other logging measurement, provide a powerful tool for the geologists, petrophysicists and reservoir engineers.

### ACKNOWLEDGEMENTS

The support of the various oil companies is gratefully acknowledged. I wish to thank B.Felder and C. Poster for providing some of the examples used in this paper.

### REFERENCES

- BRIE, A., HSU, K., ECKERSLEY, C., 1988. Using the Stoneley Normalized Differential Energies for Fractured Reservoir Evaluation, *SPWLA*, 1988
- COATES, G.R., DENEQ, S.A., 1981. Mechanical Properties Program Using Borehole Analysis and Mohr's Circle, 1981
- HORNBY, B. E., 1989. Imaging of Near- Borehole Structure using Full-Waveform Sonic Data, *Geophysics*, 54,6,747-757,1989
- INGRAM, D.S., ANDERSON, R.A., ZANIER, A. M., 1972. Fracture Pressure Gradient Determination from Well Logs, *SPE* 4135,1972
- MEA Review, 1988. *Middle East Well Evaluation Review*, No. 5,1988
- MURPHY, W.F., 1982. Effects of Partial Water Saturation on Attenuation in Massilon Sandstone and Vycor Porous Glass, *J. Acoust. Soc. Am.*, 71, 1458-1468, 1982a
- MURPHY III, WILLIAM F., 1984. Acoustic Measures of Partial Gas Saturation in Tight Sandstones, *J. Geophys. Res.*, 89, B13, 11549-11559,1984
- NEWBERRY, B.A., NELSON, R.F., AHMED, U., 1985. Prediction of Vertical Hydraulic Fracture Migration using Compressional and Shear Wave Slowness, *SPE* 13895,1985
- TANER, M. T., AND SHERIFF, R.E., 1977. Application of Amplitude Frequency and Other Attributes to Stratigraphic and Hydrocarbon Determination, *AAPG Memoir* 26, Seismic Stratigraphy Application to Hydrocarbon Exploration, pp 301-327,1977
- WINKLER, K. W., AND A. NUR, 1979. Pore Fluids and Attenuation in Rocks, *Geophys. Res. Lett.*, 6, 1-4,1979

Manuscript received 10th October 1990