STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 11, Special Issue 1, 2023
DOI (Journal): 10.37591/JoPC

http://engineeringjournals.stmjournals.in/index.php/JoPC/index

Research JoPC

Acoustic or Sonic Log Analysis Identifying the Subsurface Geophysical Changes in Hydrocarbon Bearing Zones in Oil and Gas Potential Sedimentary Basins

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Abstract

The introduction of acoustic/sonic logs to oil and gas industry is barely decades old. But, even within such a short span of time it has become an integral part of most of the modern logging programmes. With the recent introduction of acoustic scope pictures, this may even hold a promise of making the old dream of seeing the hydrocarbon in situ come true. In this paper, an attempt has been made to bring out the principles of instrumentation and interpretation and the applications of velocity logs. We have also been attempted to include the most recent developments in this sector. However, because of space limitations they could not be discussed in detail in all aspects. The terms sonic log and acoustic log should be read as synonyms for the velocity logs.

Keywords: Sonic log, hydrocarbons, cycle skipping, resistivity and wave frequency

INTRODUCTION

Since Schlumberger recorded the first well log, there has been a tremendous advancement in this branch and new techniques are being made available to the oil and gas industry. The advancement has been in the direction of greater precision as well as better information that could be made available to the geologist and geophysicist. Log interpretation as other geophysical methods is an identification of all sorts of anomalies [1]. In the early days of logging, the physical property of current flow in the formations adjacent to the bore holes were made. Radioactivity of formation, which is another physical property, was exploited and hence a new family of radioactivity logs followed [2]. These had a distinct advantage over the conventional resistivity logs that they could be recorded even in the cased or gas filled wells. The acoustic properties of the earth's formations are now providing still another family of logs which are being utilized by the oil industry. Velocity logging is primarily an open hold method which competes with electrical logs and may in many cases prove to be superior to any single electrical log [3]. With a simple tool modification this also gives the cement bond quality in cased well whose importance to a production engineer needs no emphasis.

The working principle of sonic logging is not new to a geophysicist as it is like seismic refraction work [4]. It is a recording of the time required for a sound wave to transverse a definite length of formation. The travel times are inversely proportional to the velocity of sound in the formation. The recorded sound waves being the

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Received Date: December 21, 2022
Accepted Date: March 19, 2023
Published Date: June 23, 2023

Citation: R. Giri Prasad, S. Rama Sree, Anil Kumar Thandlam, Y.R.C. Sainarayana. Acoustic or Sonic Log Analysis Identifying the Subsurface Geophysical Changes in Hydrocarbon Bearing Zones in Oil and Gas Potential Sedimentary Basins. Journal of Polymer & Composites. 2023; 11(Special Issue 1): S22–S35.

first arrivals are essentially compressional in nature [5]. The velocity of sound waves in the subsurface formations depends upon the earliest properties of the rock, the property of the formations its fluid content and pressure.

Discussion of Instrumentation

A sonic tool essentially consists of one sound transmitter and one receiver at a fixed distance below it. There are two different types of tools available at present. One employs only one receiver while the other has two receivers. In the case of one receiver system, the distance between the transmitter and the receiver is called the spacing, while in the two-receiver system the spacing is the distance between the two receivers [6]. In the design of the tool the choice of the spacing and the material of the body of the sonde are of very distinct importance [7]. The spacing is so chosen that the refracted wave through the formation reaches the receiver earlier than the direct wave coming through the mud or body of the sonde. If the spacing is too short, it becomes difficult to separate. The compressional wave from the subsequent other types like shear waves. In case of longer spacing, there will be averaging of too much vertical formation interval, resulting in the loss of resolution. The choice of spacing between transmitter and first receiver is controlled by a simple relation:

$$\frac{1\,min}{S} = \sqrt[2]{\frac{1+A}{1-A}}$$

where 1 *min* is the minimum distance between the transmitter and the first receiver, *S* is the stand-off, that is, the distance between the transmitter and the bore hole wall, and *A* is the ratio of the mud velocity to formation velocity. The body of the sonde is made of a low velocity material which delays the reception of the wave coming through the body itself some tens or hundreds of microseconds later than the refracted wave from the formation [8]. With the appropriate circuitry, this time delay renders the receiver insensitive to the waves coming through the body. The transmitter is an electromechanical transducer which produces discrete acoustical pulses 10 to 20 times a second in the frequency range 10 to 20 kilocycles/s. These transmitted pulses are constant in amplitude and duration [9]. The transmitter is designed to act as a point source with waves travelling out from it in all directions with equal intensity. The principle of recording the travel time is as follows: A linear voltage generator is started with each pulse transmission. This generator manufactures a voltage proportional to time. Alternately, with the first measurable energy arriving at the first and then the second receiver, the voltage generated is stored on each of the two suitable capacitors. The difference in voltage between the two capacitors is transferred to the recording galvanometer. The process is continuous. Proper calibration of the recording galvanometer sensitivity, provided there is no cycle skip or noise problems, results in a very accurate time log.

As seen earlier, the transmitter fires about 10 to 20 times a second enabling continuous recording of the log at normal logging speeds. This can be appreciated by a numerical example given below. Suppose the cable is moving at the speed of 2000 meter/hour, which is same as about 6 cm/s. Taking that the transmitter is firing 10 times/s, we record 10 samples for every 6 cm. This results in more or less a continuous record. In well log interpretation, it is highly desirable to know the radius of investigation of the logging sonde. In acoustic well logging the radius of investigation will be determined by the least travel time path for refracted waves leaving the transmitter to arrive at the receivers. One may assume that the wave path very near to the bore hole wall is physically the shortest and hence the path of least travel time. This reasoning might lead one to conclude that the log is influenced only by the rock within a few inches of the bore hole wall. Although this reasoning is not completely unsound it is subject to modification.

The wavelengths of the acoustic energy may be calculated from the relation: $v = V/n$

where v = wavelength, V = velocity through the formation, and n = wave frequency.

In sedimentary rocks, V varies from approximately 5000 to 25000 ft/s. Frequencies used in logging tools now available are from 10 to 20 kilocycles/s. Therefore, wavelength ranges from 0.25 to 2.5 ft.

(1 foot is probably a good average value). Acoustic energy within this range of wavelengths will not be confined to a small region immediately adjacent to the bore hole wall. Experiments made in the laboratory indicate that a thickness of at least 3 wavelengths is necessary to support a compressional wave over an appreciable distance. Then the lateral extent of acoustic waves in velocity logging ranges from 0.75 to 7.5 ft from the bore hole wall, with 3 feet as an average value [10]. This depends mainly on the wavelength of the transmitted energy. The wavelength, in turn, is determined by the frequency of the transmitted wave and its velocity trough formation.

It is pertinent to examine the common instrumental phenomenon known as "cycle skipping". The receiver circuitry is triggered by the first arrival of the sound energy which is above the prefixed bias level. It may sometimes happen that the first arrival is too weak to trigger the receivers. When this happens, the second cycle, which is generally higher in amplitude, will commonly trigger the circuitry. This results in the recording of longer travel times on the log shown in the Figure 1. This is known as "cycle skipping".

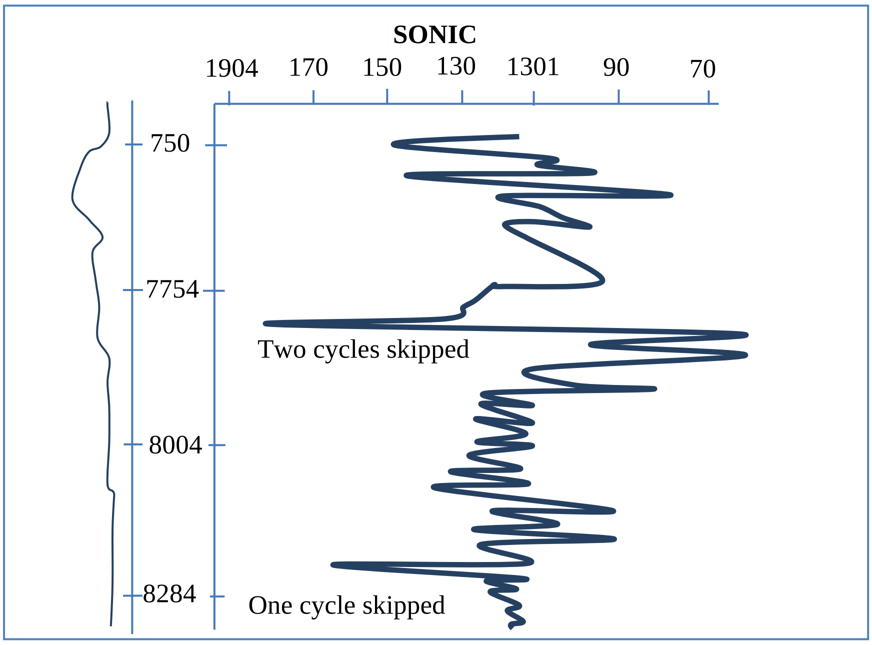

Figure 1. Sonic longer travel times.

In the case of two-receiver system, the receiver nearer the transmitter will trigger on an energy arrival, which, by the time it reaches the farther receiver, will have been so attenuated by the intervening formation that it is unable to trigger that one which is generally triggered by the subsequent energy arrival [11]. This phenomenon of cycle skipping does not hamper the travel time record provided the same arrival triggers both the receivers. There is a likelihood of generating mechanical noise in the receiver because of the drag of the sonde along the bore hole wall [12]. This is overcome by making use of the suitable bumpers attached to the sonde as shown in Figure 2.

Single and Double Receiver Systems

In the single receiver system, the time measurement is made from the initiation of the pulse by the transmitter to the arrival of the acoustical energy at the receiver [13]. The ray path of least time will be ABCD as shown in Figure 3. This can be divided into three segments AB, BC, and CD. AB is the incident ray which gets refracted along the interface at the critical angle Φ, while BC travels through the formation and CD is the emergent ray detected by the receiver. Thus, the total travel time along the refracted path is:

$$t1=\frac{AB}{Vm}+\frac{BC}{Vf}+\frac{CD}{Vm} \tag{1}$$

Vm is the velocity of sound in the drilling fluid, and

Vf is the velocity of Sound in the formation.

As we are interested in the formation velocity (*Vf*), Equation (1) shows that drilling fluid travel times, that is,

$\frac{AB}{Vm}$ and $\frac{CD}{Vm}$ must be accounted for.

Equation (1) is sufficiently accurate when the mud travel times are small. This is possible when the instrument is close to the bore hole wall. Additional corrections are necessary when the distance between the bore hole wall and the instrument is large. This necessity for correcting the mud travel times can be readily eliminated by using a two-receiver system where the difference in arrival times at the second receiver is recorded. This is obvious from the examination of Figure 3.

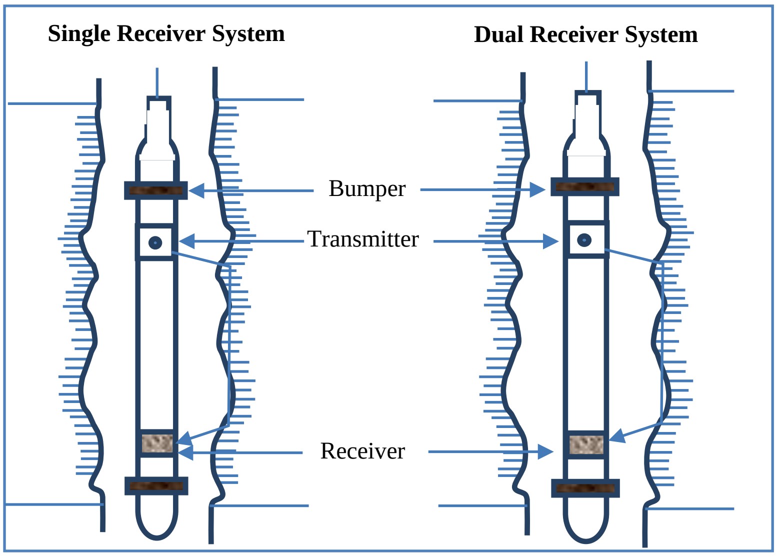

Figure 2. Single and double receivers.

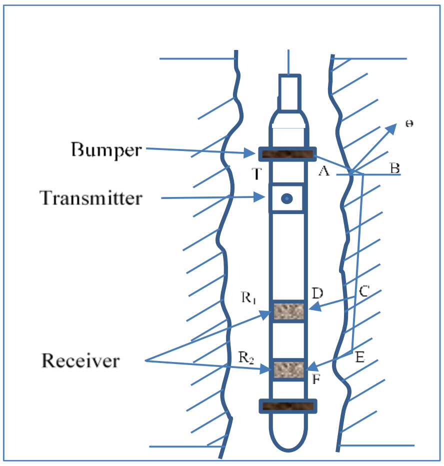

Figure 3. Ray travel paths.

and that to receiver 2 is

$$t2 = \frac{AB}{Vm} + BC + \frac{CE}{Vf} + \frac{EF}{Vm} \quad (2)$$

For sufficiently uniform bore hole against the receiver 1 and 2 and sonde being parallel to the wall, CD = EF. Subtracting Equation (1) from Equation (2) we get:

$\Delta t = t2 - t1 = \frac{CE}{Vf}$ where, CE is nearly equal to the spacing between the receivers hence formation velocity $Vf = \frac{CE}{\Delta t}$

For sufficiently uniform bore hole against the receiver 1 and 2 and sonde being parallel to the wall CD = EF. Subtracting Equation (3) from Equation (4) we get:

$\Delta t = t2 - t1 = \frac{CE}{Vf}$ where, CE is nearly equal to the spacing between the receivers hence formation velocity $Vf = \frac{CE}{\Delta t}$.

The effect on the dual receiver log is shown by the extreme break of the logging trace to the left. It is noted that no corresponding decrease in velocity at this point occurs on the single receiver and therefore we interpret poor or late signal reception at the second portion of the curve, on the dual receiver. This interpretation cannot be made without the signal receiver as a monitor (Figure 4).

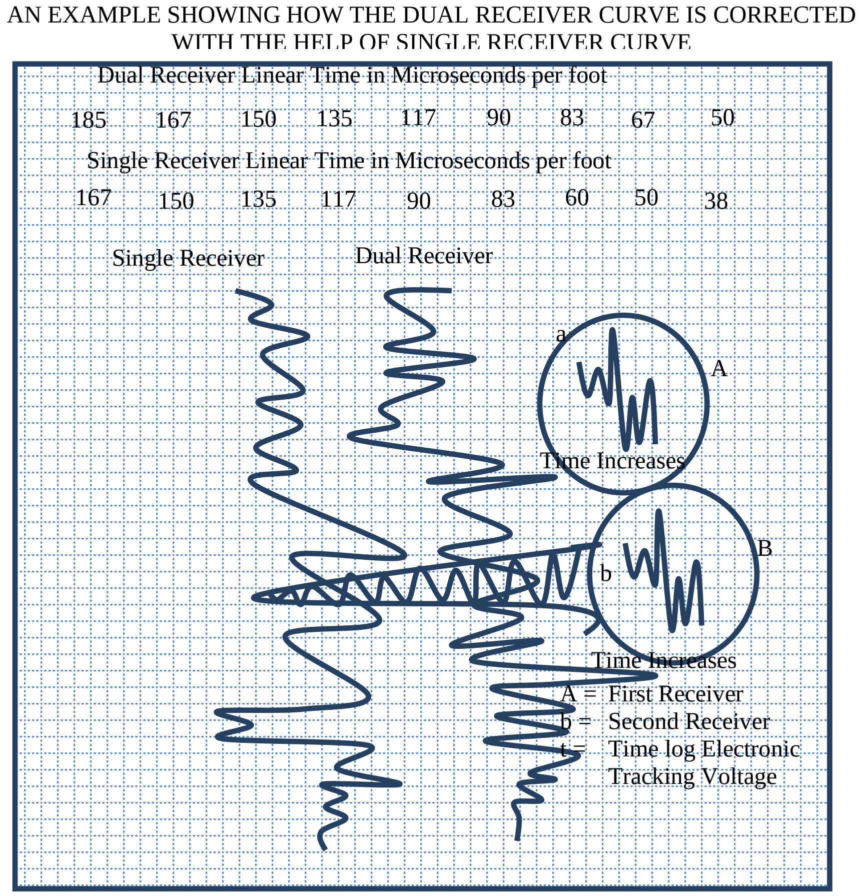

Figure 4. Single and dual receiver curves.

In the case of caved hole, the travel time reading of single receiver sonde is always too great over the entire caved section shown in Figure 5 (single receiver) whereas the reading of the two-receiver sonde is disturbed only at the top and the bottom of a caved section shown in Figure 5 (two receiver). Since the disturbances on the reading are in opposite sense at the top and bottom of the cave, they average out in their effect determination of total travel time through the section.

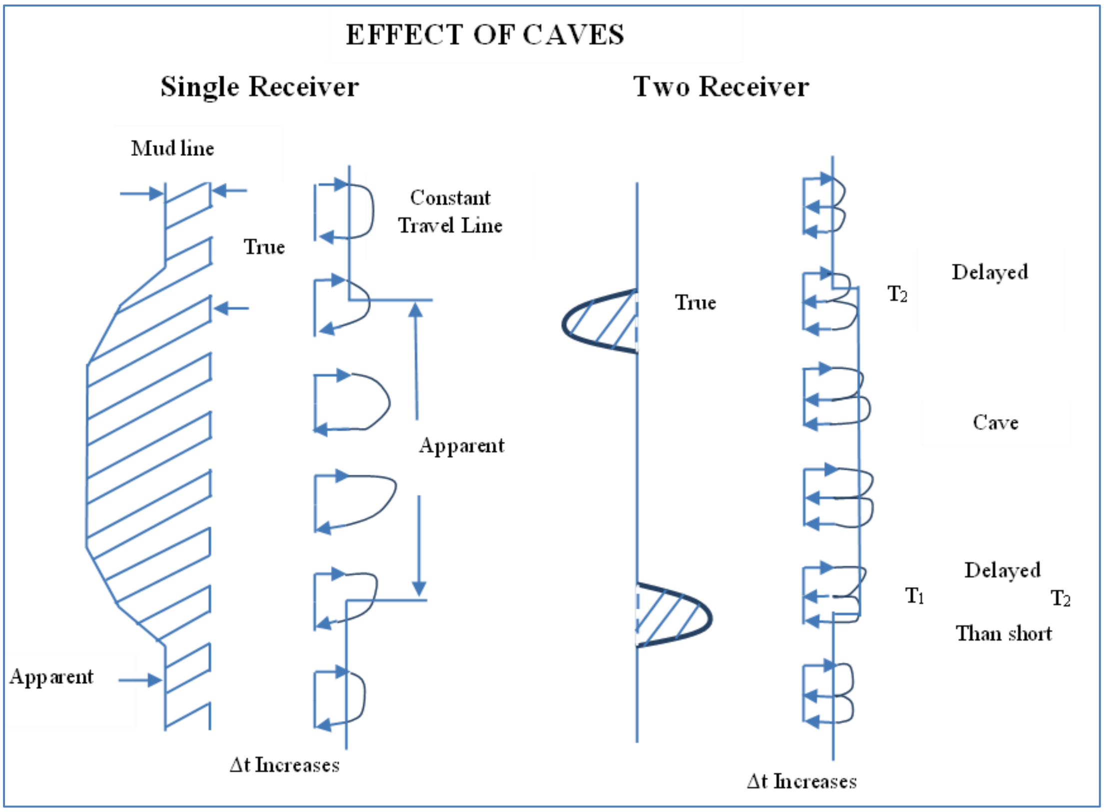

Figure 5. Comparison of single-receiver and two-receiver response in caved hole.

In high attenuation formations, the received signal to noise ratio may be small leading to some spurious recording of the log against such formations. When a noise of sufficient amplitude arrives at the first receiver ahead of the first compressional signal, the circuit is prematurely triggered giving longer time for dual receiver system and shorter time for single receiver system. If the noise triggers the second receiver prematurely, the recorded time is too short. A single receiver time curve when presented in conjunction with the dual time curve will make the noise effect obvious.

Principles of Interpretation

The velocity log data to be of interpretative use, requires the knowledge of the relationship between velocity and rock properties like its porosity, chemical constitution of the constituent grains and the nature of its saturating fluids [14].

For the compact and clean sands formations having uniformly distributed intergranular porosity, a simple relationship between velocity and porosity has been proposed by Wyllie et al.

The relationship is: $\frac{1}{Vlog} = \frac{\emptyset}{V\ liquid} + \frac{1-\emptyset}{V\ Matrix}$ (5)

where, $\emptyset$ is the porosity of the formation.

Since velocity is inversely proportional to time, Equation (5) can be written as

$$\Delta\ t\ \log = \Delta\ t\ \text{liquid} \times \emptyset + \Delta\ t\ \text{matrix}\ (1 - \emptyset) \quad (6)$$

Where

Δt log is the travel time obtained from the log, Δt liquid is the travel time in the interstitial fluid, and Δt matrix is the travel time in the grain material.

The above times are in general measured in microseconds/foot.

Equation (6) holds good only for compact formations having intergranular porosity. So, in case of vugular or fracture porosities the velocity log does not give true value. However, as the velocity log sees more of formation than is available to a core analyst, the values are more reliable than those determined in the laboratory.

If Equation (6) is applied to clean unconsolidated sands, the porosity values obtained are on the higher side. This because as the overburden pressure on the formation decreases there is less of compaction resulting in the decrease of acoustic velocities. The formations whose surroundings shales show delta *t* values of 100 µs, or more are identified as unconsolidated ones, for the purpose of interpretation of acoustic logs.

To determine the porosities of such unconsolidated formations, a compaction correction has to be applied. An empirical relation has been evolved by which we get a good approximate porosity value. The relation is:

$$\Phi v = \Phi c \times \frac{100}{\Delta\, t\, \mathrm{shale}} \times c \qquad (7)$$

where

Φv = porosity given by velocity log using Equation (6)

Φc = porosity given by the core analysis

Δ t shale = travel time in the adjacent shales and

c = compaction correction factor.

This compaction correction factor or variable coefficient for shale compaction generally varies between 0.8 and 1.2. However, in some very shallow formations, this factor may exceed even 1.2.

The presence of shale in sandstones tends to increase the travel time there by giving higher porosities with the use of Equation (4). Hence the correlation for the presence of shale is needed which can be affected using empirical relation,

$Qv = Qv/2 - \alpha$, where α = Precinct Structure Plan (PSP)/Second Structure plan (SSP) as obtained from the SP curve.

The charts supplied by any service company for finding out porosities from interval transit times are constructed by assuming the travel time. The interstitial fluid as water of some definite salinity is shown in Figure 6. It has been observed in some cases that the porosities obtained for clean oil-sands, if multiplied by a factor 0.8 to 0.9 and the porosities for clean gas sands if multiplied by a factor 0.7 tend to be nearer the true value of porosities. However, it is likely that the factors may vary from field to field, and it is desirable to determine them for a particular field.

In shaly formations containing oil, it has been observed that correction for shaliness only should be considered while for shaly gas bearing formations it is preferable to use only the fluid correction factor [15]. In case of fractured formations there is an attenuation of acoustic signal because of multiple reflections at the interfaces of the cracks which lie roughly perpendicular to the direction of propagation of acoustic energy. This results in cycle skipping.

APPLICATIONS

Porosity determinations: the use of velocity log as a porosity tool is rapidly gaining importance because of its more accuracy. As the velocity log is not influenced much by the bore hole conditions; it can be used in almost all types of open holes with a good degree of precision.

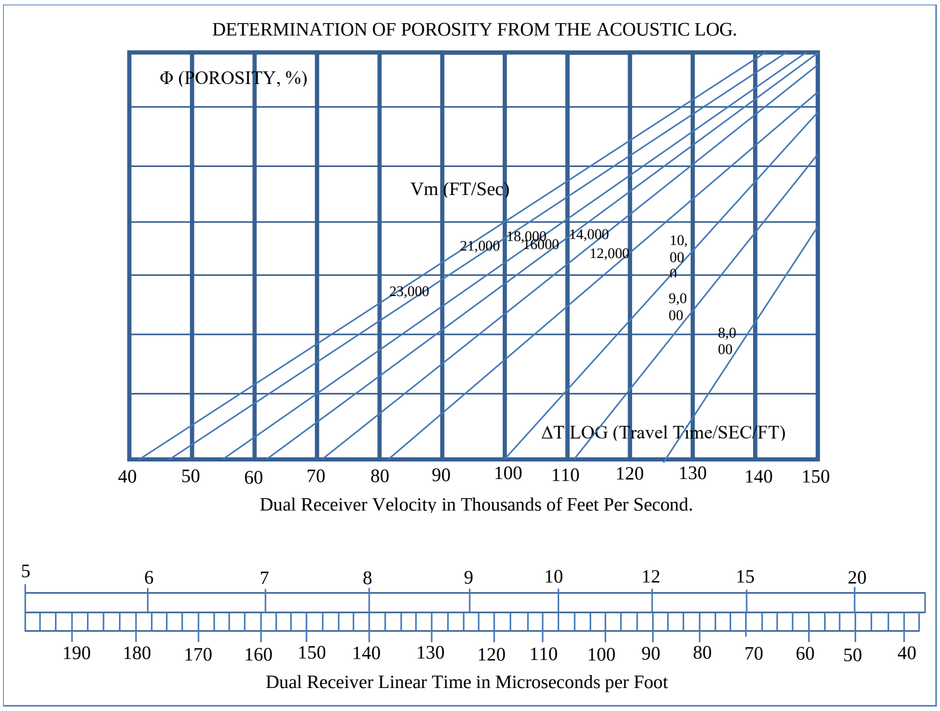

Figure 6. Porosities from interval transit times.

Velocity logs prove to be superior in cases of thick mud cakes more than 0.5 inches as well as shallow invasions less than 4 inches, which limit the usage of Microlog as a porosity tool [16]. In some cases, the porosity values given by the velocity log are superior to neutron porosities for the simple reason, that, the neutron porosity scale is logarithmic in character while for the former it is linear.

Fluid Saturation Determination:

Since water saturation

Sw is given by Sw = $\frac{\sqrt{FRW}}{Rt} - \frac{\sqrt{cxRw}}{\emptyset mxRt}$

It is possible to determine the amount of water saturation in a formation a plot of delta t vs Rt/Rw

Lithological Identification:

Apart from differentiating shale, sand, and limestone layers in the given section a velocity log can be of particular help in identifying coal and lignite beds. These beds exhibit comparatively higher transit times, mostly exceeding 125 µs. Coal generally has higher transit time, high resistivity and specific gravity as shown in Figure 7.

Correlation

Velocity logs provide excellent correction curves with a tremendous amount of detail. In addition to the qualitative picture, the correlation is helped on the quantitative basis for certain types of formations because of their travel time shown in Figure 8.

Detection of Gas Zones

In unconsolidated formations, the interval transit time is slightly more in case of oil-bearing formations than that of water-bearing formations but substantially longer in case of gas-bearing formations [17]. This will give anomalously high porosity values for gas zones, while neutron derived porosities against such formations are on the lower side. Hence a plot of sonic porosity versus neutron porosity can help in identifying the gas bearing zones. In gas bearing formations cycle skipping is also commonly observed on the velocity logs due to high signal attenuation. Figure 9 shows the gas bearing interval between 405 M and 380 M.

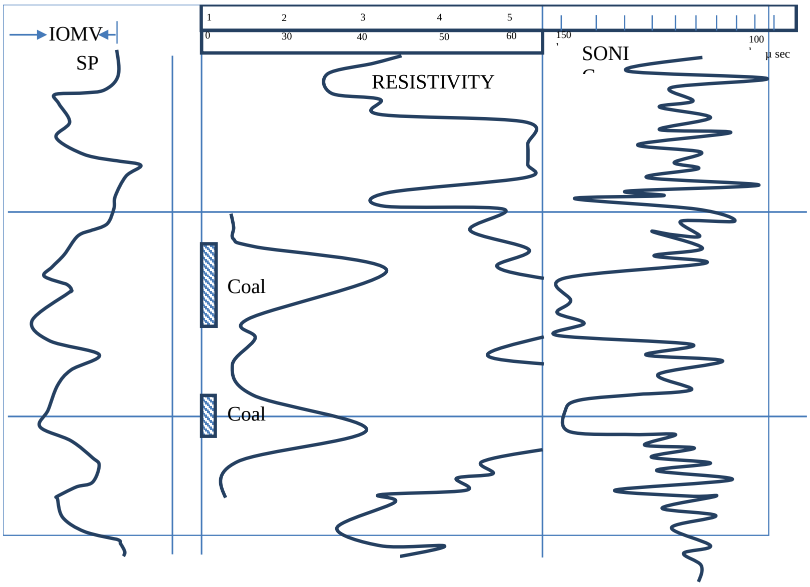

Figure 7. Transit time and resistivity of sonic porosity log.

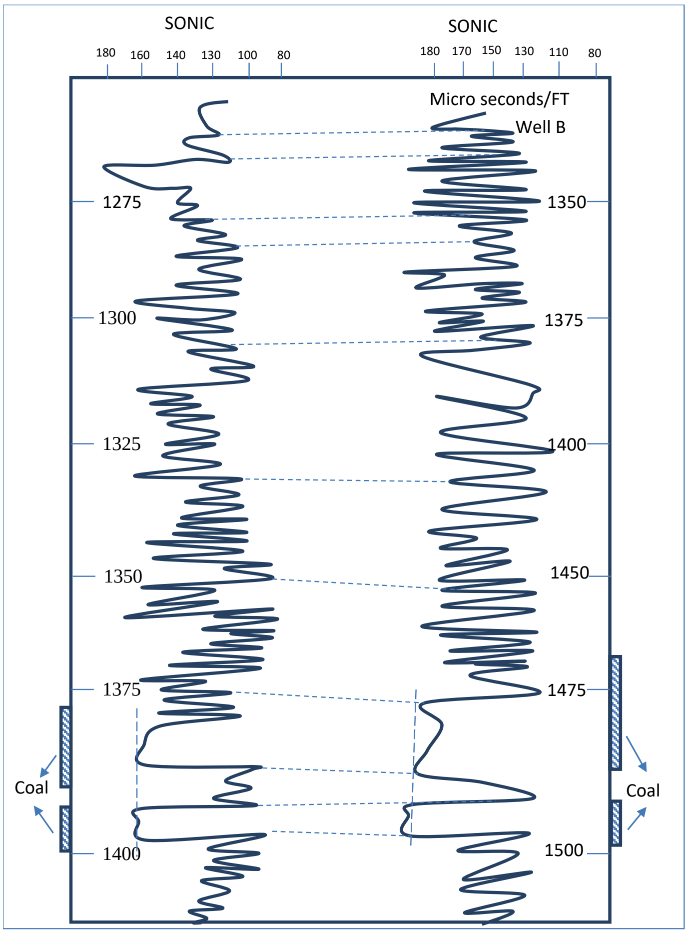

Figure 8. Correlation of sonic log.

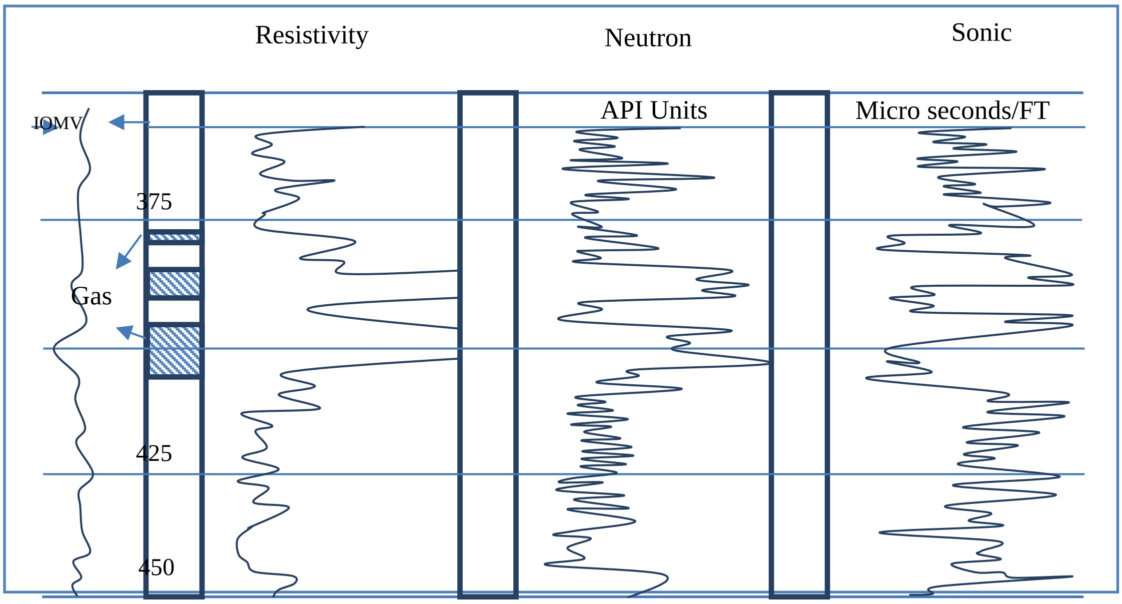

Figure 9. Gas is shown by high resistivity, high neutron, and high ΔT.

Seismic Interpretation

The knowledge of sound velocity in formations is fundamental for the interpretation of seismic surveys. For finding out the average velocities an integrator panel has been introduced [16]. This records the integrated travel times on the left side of the velocity log by pips one millisecond apart. These integrated times can be used for quicker and reliable interpretation of seismic data.

Recent Developments

With a little modification of a velocity tool design, Schlumberger introduced in 1960, a new type of log called a Cement Bond Log which helps in finding out the quality of cementation job in oil and gas wells [18]. The theoretical principle of this log can be demonstrated simply by striking a glass with a knife, which produces a ringing sound, as contrasted to a sound which is heard when the glass held by one hand. It follows that holding the glass with one hand will dampen the sound a noticeable amount. Unbounded and tightly cemented casing responds to sound energy in much the same manner.

In the cement bond log, the time of arrival of an incoming signal as well as its amplitude are recorded. Usually, the sound velocity is greater in the casing than in the formations, and hence the first arrival corresponds to energy propagated along the casing. Solid material in direct contact with the casing impedes the propagated of energy along the casing, accordingly, in a well cemented casing the amplitude measured will be quite low whereas if the casing is not cemented or if no cement is bonded to the casing the amplitude will be high as shown in Figure 10.

Signal Attenuation Transmission Amplitude (SATA) Log

A new type of log called the SATA log has been very recently introduced in the oil industry by Pan Geo Atlas Corporation. Out of the family of acoustic parameters the SATA log records two. They are (i) signal attention as shown by the difference in amplitudes between two receivers and (ii) Transmission amplitude of the received signal and hence the name SATA [19]. The SATA log differs from acoustic velocity logging, by logging the amplitude and attention of the signal rather than the travel time as shown in Figure 11.

Acoustic Scope Pictures

This provides a complete and permanent record of all measurable acoustic parameters arriving at each of the two receivers [17]. This is superior to the conventional velocity log curves wherein only a small portion of the information presented to the scope is utilized; the remainder being wasted.

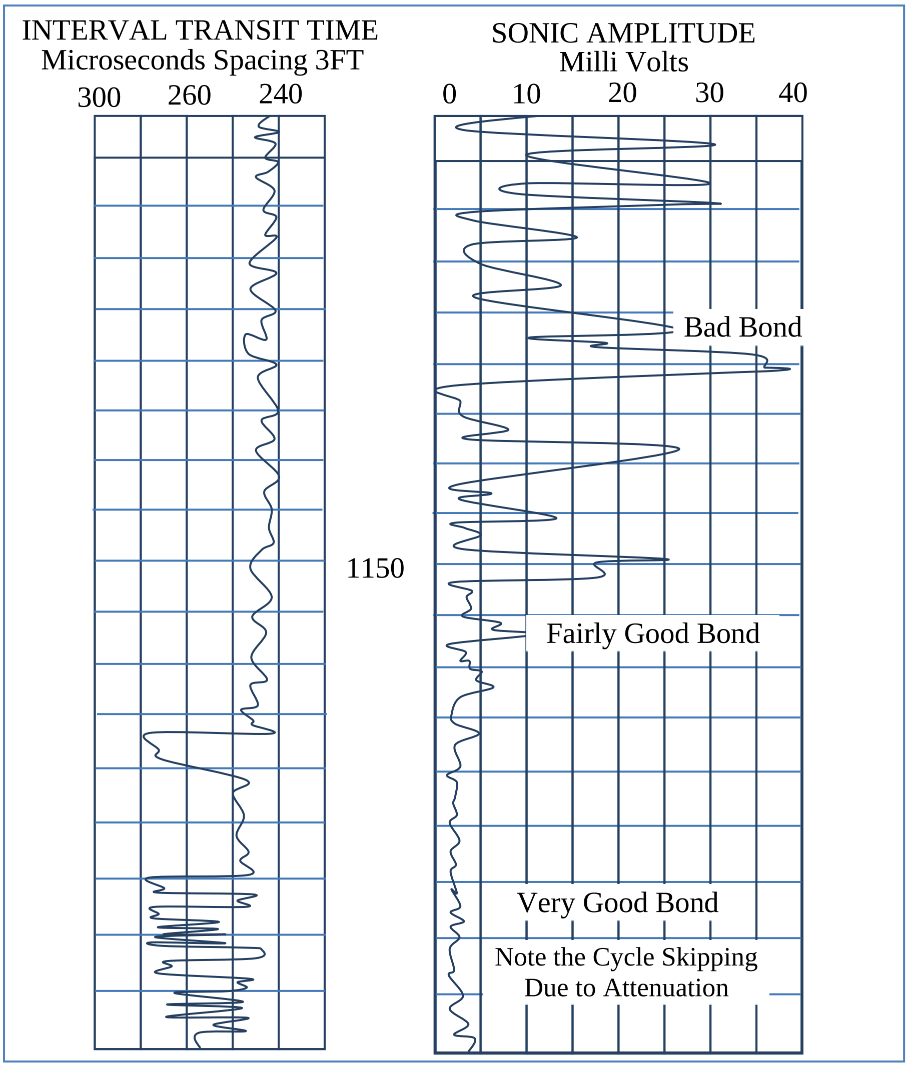

Figure 10. Interval transit time versus sonic amplitude.

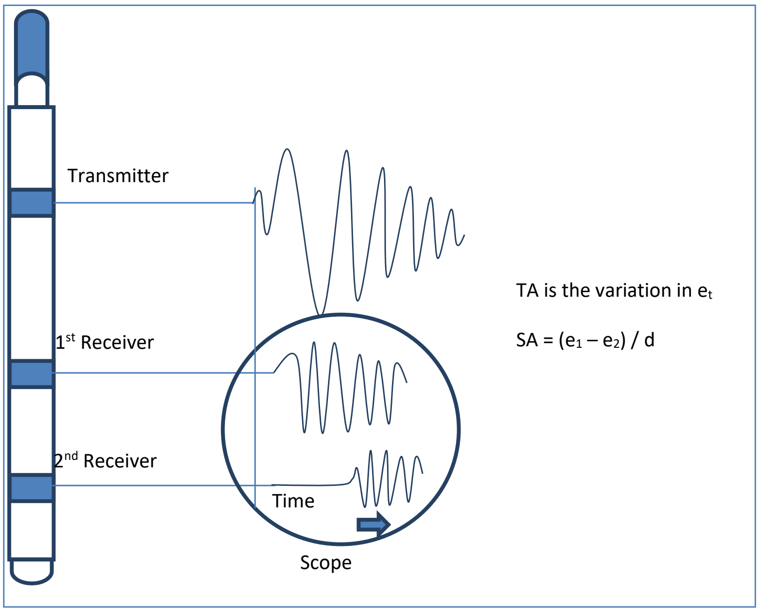

Figure 11. Signal attenuation transmission amplitude (SATA) log.

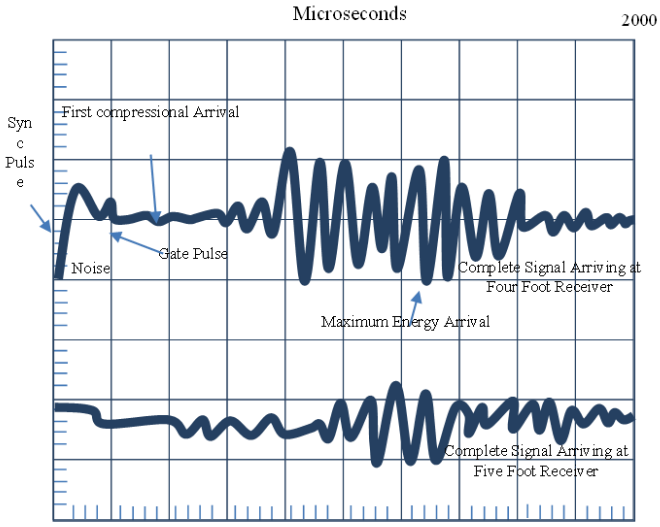

Figure 12. Scope picture.

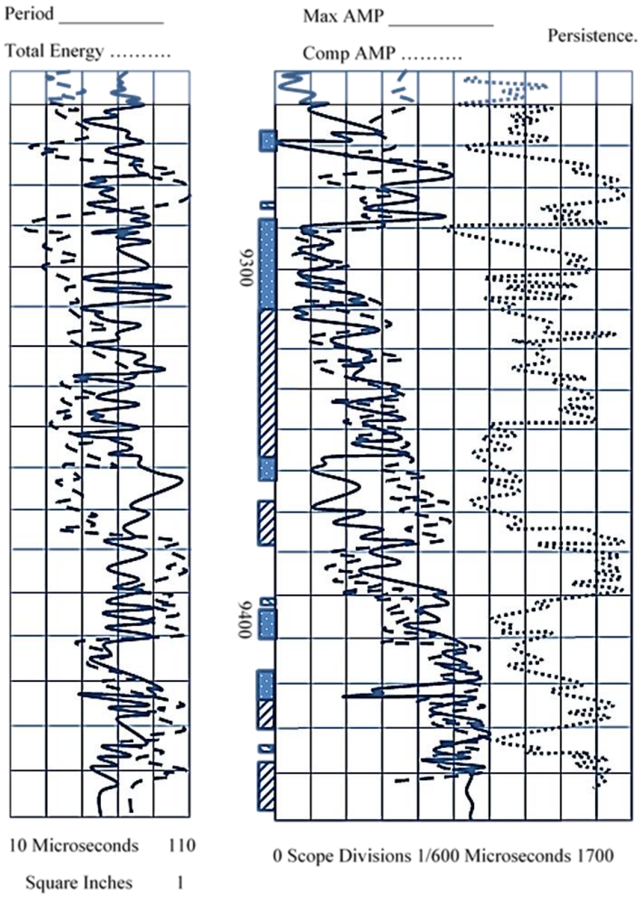

Figure 13. Scope picture result graph.

The scope pictures are a record of received signal frequency, amplitude and velocity and include all variations of these parameters with time at any depth. Continuous direct measurement and plot-out of scope picture data permit the construction of any conceivable acoustic type of log with complete elimination of noise and cycle-skip problems. Figure 12 is an example of a scope picture while Figure 13 shows the plot-out logs of period, total energy, compressional amplitude, maximum amplitude, and persistence as obtained from the scope pictures.

CONCLUSION

Acoustic scope pictures give much additional information than the single conventional velocity log, both in cased and uncased holes. The most important of all, is its ability to directly locate hydrocarbon productive formations in consolidated rock area. Hydrocarbons being more compressible than water, contribute to the reduction of compressional amplitude. A clear relationship between the reduction of compressional amplitude and presence of hydrocarbons has been found. It is therefore believed that the study of acoustic scope pictures and caliper will locate the hydrocarbon-bearing formations.

Permeability to amplitude relations can also exist for most rock types. In high permeability formations, there is a lesser number of grain contacts resulting in greater signal attenuation and the reduced amplitudes. The oil and gas deposits exhibit a more dramatic drop in amplitude. In addition to these, different plot outs can be used for better information regarding rock consolidation, evaluation of non-granular porosity, fracture location etc. in cased holes, the acoustic scope picture supplies the information about cement to casing and cement to formation on bonding, in high- as well as low-velocity formations.

Acknowledgement

We would like to express my gratitude to all those who helped me in different ways in completing this work, directly or indirectly. First and foremost, I would like to express my deep-felt gratitude to our dean of administration, Dr. S. Rama Sree, who provided constant inspiration and guidance throughout the work. In addition, their philosophical guidance has built up momentum inside me.

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