STUDY EFFECTS OF GEOPRESSURED-GEOTHERMAL SUBSURFACE
ENVIRONMENT ON ELASTIC PROPERTIES OF TEXAS GULF
COAST SANDSTONES AND SHALES USING WELL LOGS,
CORE DATA, AND VELOCITY SURVEYS

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Abstract

Relations between porosity and permeability for the Pleasant Bayou wells were determined from conventional core data. Porosities from the time average equations required compaction correction factors of 1.9 in hydro pressured sandstones and 1.0 in geopressured sandstones. Best average permeabilities in the geopressured zone were found in the primary production interval 14,687 to 14,716 ft (4,477 to 4,485 m). Average density gradients were 2.106×10^{-3} and 2.688×10^{-3} (gm/cm³)/100 ft in sandstones and shales respectively.

Compressional (P-wave) and shear (S-wave) velocities from the long-spaced sonic log and bulk densities from the formation density log were used to compute in-situ elastic moduli, Poisson's ratio, V_p/V_s , and bulk compressibility in two intervals of deep geopressured sandstone and shale in No. 2 Pleasant Bayou. Most computed values of these parameters seem reasonable.

Improved accuracy of travel times from the long-spaced sonic log should permit more accurate depth-to-time correlation with seismic data. However, wave theory from Biot (1956) and Geertsma (1961) predicts dispersion at well log frequencies that may introduce velocity errors of 1.5 to 3.6 percent in sandstones with high porosity and permeability.

High reflection coefficients at interfaces between shales and brine-saturated sandstones indicate that seismic reflection methods may be able to detect high quality reservoirs with enhanced dissolution porosity in deep Tertiary sandstones.

Introduction

The General Crude Oil/Department of Energy No. 1 and No. 2 Pleasant Bayou wells are located in the Brazoria Fairway within the Austin Bayou Prospect described by Bebout, Loucks, and Gregory (1978). The wells are located in a synclinal area between Chocolate Bayou field on the northeast and Danbury dome on the southwest.

The No. 1 Pleasant Bayou, drilled to a total depth of 15,675 ft (4,778 m), was abandoned as a production well because of drilling problems. The upper portion of the well was recompleted as a water-injection well. The No. 2 Pleasant Bayou, located about 500 ft (152 m) southeast of No. 1 Pleasant Bayou, was completed as a geothermal production well at a total depth of 16,500 ft (5,029 m).

This report describes certain relationships between formation parameters based on well log measurements, conventional core measurements, and elastic wave theory. The organization and content of the report follows the list of revised project tasks that is attached for convenient reference (Appendix B).

Relationships are established between conventional core porosity and permeability versus depth and between core porosity and porosity derived from acoustilogs. Average bulk density trends versus depth are shown for

sandstones and shales, and relationships between bulk density and velocity are discussed.

Elastic moduli of deep Frio geopressured sandstones and shales are computed where both compressional (P-wave) and shear (S-wave) velocities can be picked from sonic waveforms recorded digitally by the long-spaced sonic logging (LSSL) system. A separate report (by R. G. Anderson) explaining P-wave and S-wave transit time picks from waveforms recorded in a deep geopressured zone is attached (Appendix C). A report (by Core Laboratories, Inc.) listing P-wave and S-wave velocity data for cores from selected cored intervals is also attached (Appendix D).

The amount of velocity dispersion that can be expected at well logging frequencies in the Pleasant Bayou wells is estimated from theoretical concepts. Dry gas-saturated rock (skeleton) velocity and bulk compressibility, required for evaluation of dispersion, were determined for Pleasant Bayou sandstones from theoretical relations (Appendix A). These dry rock parameters were also used to determine reflection coefficients at shale/gas sandstone/brine sandstone interfaces.

Porosity and Permeability (Task C.1a)

Porosities measured on conventional cores recovered from sandstone intervals in No. 1 and No. 2 Pleasant Bayou range from 37.8 percent in the depth interval 4,343 to 4,344 ft to less than 3 percent in dense, shaly sandstones below 14,000 ft. Mean values of porosity from conventional core data for the Pleasant Bayou wells range from 32.7 to 13.3 percent in the hydropressured zone and from 17.6 to 13.2 percent in the geopressured zone (fig. 1). Mean core porosity was 16.5 percent in the

production interval 14,644, to 14,704 ft (4,463 to 4,482 m). An average curve for porosity versus depth, based on mean values, is extrapolated to 40 percent at the surface (fig. 1) to agree with properties of average Gulf Coast sands (Gregory, 1977). Porosity values from the average curve are used later in this report to calculate bulk density, dry skeleton velocity, and bulk compressibility. In the shallow portion of the Pleasant Bayou well, primary porosity is observed to decrease rapidly with depth because of compaction, cementation, and diagenetic processes that reduce the original intergranular porosity. Below a depth of 10,000 ft (3,048 m) primary porosity is less than 2 percent (Loucks, 1980), but total average porosity is greater than 15 percent. Secondary porosity created by diagenetic processes, such as dissolution porosity from leaching of carbonate, feldspar, and other soluble material, reverses the trend of porosity reduction with depth and accounts for most of the porosity observed in the deep Pleasant Bayou sandstone aquifers. The porosity of many major hydrocarbon reservoirs is not original intergranular porosity which escaped destruction but, rather, is almost totally secondary (Hayes, 1979).

Good permeability can be expected in sandstone reservoirs with only dissolution porosity if the dissolved material is abundant and forms interconnected pore channels. Excellent reservoirs develop where carbonate cement has been dissolved to form secondary intergranular porosity (Schmidt and McDonald, 1979; Pittman, 1979; Loucks, Richmann, and Milliken, 1980).

Horizontal air permeabilities measured at atmospheric pressure on cores from No. 1 Pleasant Bayou range from less than 0.1 to 1,041 md for conventional cores (fig. 2). The highest permeability was found in the depth interval 14,759 to 14,760 ft (4,498.5 to 4,498.8 m). Two sidewall

cores from depths of less than 3,400 ft (1,036 m) had permeabilities of more than 1,000 md. In No. 2 Pleasant Bayou, permeabilities ranged from less than 0.1 to 729 md (fig. 3). The best average permeabilities were found in fluvial channel deposits in the depth interval 14,687 to 14,716 ft (4,477 to 4,485 m) where the range was 0.07 to 515 md and the mean was 175 md. The average permeability determined from production flow tests is in good agreement with the mean permeability from core measurements (fig. 4). The range of permeabilities in depositional sequence F in the depth interval 15,615 to 15,670 ft (4,759 to 4,766 m) was 0.02 to 729 md and the average of 23 core measurements was 54 md. Lowest permeability occurs in associated muddy delta plain and interdistributary facies (Loucks, Richmann, and Milliken, 1980).

Porosities estimated from the time average equation (Wyllie, Gregory, and Gardner, 1956), using transit times from conventional acoustic logs, require a compaction correction factor of 1.9 to give reasonably good agreement with core data (fig. 5) at depths above 7,000 ft (2,134 m). No compaction correction is needed below 7,000 ft, including the geopressured sandstones (Gregory and Backus, 1980).

Formation Density (Task C.1b)

Bulk density ρ was calculated for brine-saturated conventional sandstone cores from No. 1 and No. 2 Pleasant Bayou (fig. 6 and table 1) using the relation,

$$\rho = (1 - \phi)\rho_f + \phi\rho_g \quad (1)$$

Grain density ρ_g and fractional porosity ϕ were obtained from core measurements. Brine density ρ_f was determined by taking into account the average

salinity of formation water as a function of depth (table 1). The brine density values in table 1 do not take into account the temperature and pressure effects discussed by Barker (1972), and these effects may be significant for some applications. Mean densities range from 2.17 to 2.43 gm/cm³ above 7,000 ft (2,134 m) and from 2.37 to 2.53 gm/cm³ in geopressured sandstones below 7,000 ft. Agreement between densities calculated from equation (1) and densities from neutron and formation density log (FDC) is satisfactory (fig. 7 and table 1). The density gradient is shown to be 2.106×10^{-3} (gm/cm³)/100 ft for sandstones.

Shale bulk density versus depth (fig. 8 and table 2) was derived from the FDC logs run in No. 1 and No. 2 Pleasant Bayou. A limited amount of density data from core measurements is also given. The density gradient for shales is 2.688×10^{-3} (gm/cm³)/100 ft.

The relation between bulk density ρ and acoustic velocity V (fig. 9 and table 1) for most of the higher velocity sandstones in No. 1 and No. 2 Pleasant Bayou is in good agreement with the empirical relation,

$$\rho = 0.23V^{0.25}. \quad (2)$$

Equation (2) is based on density and velocity data collected for different sedimentary rock types from a wide range of basins, geologic ages, and depths (Gardner, Gardner, and Gregory, 1974). Hence, it is not surprising that some data from the Pleasant Bayou wells do not agree very well with the curve derived from equation (2). The density values for shale (fig. 9 and table 2) obtained from the FDC log, in particular, are anomalously high in No. 2 Pleasant Bayou. Data from figure 9 are superimposed on the density plot (fig. 10) from Gardner, Gardner, and Gregory, 1974.

In-Situ Waveform Velocity Data,
No. 2 Pleasant Bayou (Task C.1c)

P-wave and S-wave velocities, used later in this report for computing elastic moduli, were derived from the long-spaced sonic log (LSSL). The LSSL system with digitized sonic waveforms was developed by well log service companies to give a greater depth of investigation into formations adjacent to the borehole and to provide waveforms that can be analyzed to give additional information that cannot be obtained from conventional borehole-compensated acoustic logs.

The LSSL sonde contains two transmitters and two receivers that provide four channels for recording transit times for 8, 10, and 12 ft spacings (fig. 11). The most striking feature of the sonic waveforms recorded with this logging tool is the variability in amplitude of the P-wave arrival. Some of the observed variations are caused by the position of the tool in the borehole as observed in a section of the Anahuac shale in No. 2 Pleasant Bayou (fig. 12). As the tool approaches the center of the hole, all direct refraction paths come into focus and the amplitude is greatly increased. The effect is recognized by the merging of two main P-wave arrivals associated with the near and far borehole walls. Large amplitude variations also appear to be associated with lithology. High amplitudes are observed in clean sand, but shales have moderate and variable amplitude. A four-channel P-wave aligned plot (fig. 13) shows details of the two main P-wave arrivals in the Anahuac shale within the depth intervals indicated in figure 12. A single channel P-wave aligned plot (fig. 14) illustrates good discrimination between arrivals, but no shear waves can be detected visually. Caliper logs show that the borehole has an almost constant

diameter through the shale, and the SP log is almost flat. The separation observed between resistivity curves from focused and deep induction logs indicates that some alteration of shale has occurred near the borehole. There is negligible difference between the 8 to 10 ft and 10 to 12 ft transit times in the interval, suggesting that an 8 ft spacing is adequate to investigate the unaltered zone.

Large differences are observed in the acoustilog transit times for No. 1 and No. 2 Pleasant Bayou (fig. 15) in the depth interval 7,010 to 7,200 ft (2,137 to 2,195 m). There are some obvious cycle skips in the No. 2 Pleasant Bayou log, i.e., at 7,020 ft. The acoustilog for No. 1 Pleasant Bayou is substantially different in form and absolute value, but agreement is acceptable in the sand layer below 7,150 ft (2,179 m). Differences between the acoustilogs and the LSSL (fig. 15) illustrate the problem of running a conventional BHC acoustic log with automatic picking of first arrivals in a large diameter hole (17.5 inch bit diameter) in Tertiary clastic sediments. The acoustilogs are believed to be in substantial error in this interval (Gregory and Backus, 1980).

Sonic waveform data in deep geopressured zones were obtained in a smaller hole (8.5 inch bit diameter). Shear wave transit times are, in general, less than the mud transit time and can be measured directly in sandstones. In shales, the shear arrival is not obvious but might be extracted by P-wave reduction processing. S-wave arrivals can be identified in several of the four-channel sonic waveform displays (fig. 16) recorded in the depositional sequence below 16,000 ft (4,877 m). In general, the S-wave events are stronger and more easily identified when shorter spacings are used, i.e., 8 and 10 ft spacings (fig. 16) and 3 and 5 ft spacings. A "pseudo-Rayleigh wave" arrives with a slightly

lower velocity immediately following the S-wave. P-wave and S-wave transit times and V_p/V_s values obtained from the waveforms in these deep geopressed sandstones seem reasonable.

Methods for extracting P-wave velocities from LSSL waveforms in the deepest 500 ft (152 m) and S-wave velocities from waveforms in the depth interval from 16,118 to 16,176 ft (4,913 to 4,930 m) of No. 2 Pleasant Bayou are given in Appendix C.

Core Velocity Data, No. 1 Pleasant Bayou

P-wave and S-wave velocities were measured as a function of pressure (0 to 10,000 psi) on 20 cores saturated with brine (45,000 ppm NaCl). Cores were taken from cored intervals of the No. 1 Pleasant Bayou in the depth range from 10,223 to 15,583 ft (3,116 to 4,750 m). Measurements were also made on these cores to determine porosity, vertical permeability, dry bulk density, and wet bulk density. Results of these measurements* and examples of acoustic waveforms with P-wave and S-wave transit time picks are given in Appendix D.

Velocity data were plotted versus effective pressure ΔP for some of the cores, where ΔP is defined as the difference between overburden pressure and pore fluid pressure (fig. 17). Pore fluid pressure in the cores remained at atmospheric pressure while external (overburden) pressure was varied. P-wave velocity V_p at values of ΔP corresponding to the mud weight equivalent pressure at core depths agree reasonably well in some cases with conventional BHC acoustilog velocity (fig. 17). Transit times for core

*Core measurements were made by Core Laboratories, Inc., Dallas, Texas.

no. 12 seem anomalously high and agreement with the log velocity is poor. It should be pointed out, of course, that comparisons between single core velocities and acoustilog velocities are not valid because of the difference in sample sizes involved. Originally, it was hoped that core velocities would provide spot checks for values of V_p and V_s obtained from LSSL waveforms. However, physical characteristics of sand/shale sequences in the Frio Formation are extremely variable with depth. Any comparison between single core velocities and conventional BHC sonic logs or LSSL are not very meaningful unless continuous core velocity data can be averaged over the intervals measured by the log. Insufficient core velocity data are available for valid comparisons with velocity logs.

No V_s data from well logs are available for the cored intervals represented in figure 17. Progress in determining V_s from the LSSL has been slower than expected. Only two short intervals in the deep geopressed zone (14,665 to 14,697 and 16,118 to 16,176 ft) have been processed by hand picking of S-wave transit times. Values of V_s determined for the shallow interval above are believed to be more reliable than those picked in the deeper interval. Additional work is planned for extracting S-wave transit times from LSSL waveforms when P-wave reduction processing methods are developed.

P-Wave Reflectivity (Task C.1d)

The effect of the type of pore fluid contained in sandstone on the reflection coefficient R for a shale-sandstone sequence has been determined for typical recent sediments in a Gulf Coast area (fig. 18). The velocity and density data for shale and water-saturated sandstone was

derived from well logs. The effect of gas and oil on the acoustic impedance of the sandstone was computed from the theory of Biot (1956) as explained by Gregory (1977). Note that R becomes essentially independent of the type of pore fluid at considerable depths but the differences may still be of practical significance for seismic interpretation. No information is available about fluid pressures in the formations considered in figure 18, thus the effect of geopressures on R cannot be determined in this example.

A similar approach was taken to evaluate R for Tertiary sediments in the Pleasant Bayou wells, where

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} . \quad (3)$$

R was determined for sediment sequences (shale/gas-saturated sandstone/brine-saturated sandstone/shale) as a function of depth (fig. 19 and table 3). Values of velocity V_p (table 3) for brine-saturated sandstones and shales were obtained from conventional acoustilogs. Bulk density ρ_b for brine-saturated sandstones and shales are average values based on well log and core data shown by curves in figures 7 and 8. Velocity $\bar{V}_p$ for gas-saturated (dry) sandstones was calculated (equation A5) from theoretical relations described in Appendix A.

Typically, there is little contrast in acoustic impedance between shales and brine-saturated sandstones above the Anahuac shale in the hydro pressured zone as indicated by low average values of R (fig. 19). In this interval, seismic reflections are related primarily to calcite-cemented zones. The reflection coefficient is fairly large in some of these localized high velocity zones, i.e., at about 7,000 ft (2,134 m). It was found that conventional acoustilogs in the Pleasant Bayou wells

measured erroneously high transit times in these high velocity zones (Gregory and Backus, 1980). Further work may prove that more accurate reflectivity data can be obtained when transit times are measured by a long-spaced sonic log or by vertical seismic profiling within the well.

Below the Anahuac shale in the deep geopressed zone, there is generally greater contrast in acoustic impedance between shales and brine-saturated sandstones. Values of R average about -0.08 , although larger values below 14,500 ft (4,420 m) may be associated with enhanced dissolution porosity.

Acoustic impedance contrasts are large between shale and gas-saturated sandstones and between gas-saturated and brine-saturated sandstones in the hydro pressured zone (fig. 19 and table 3). There is considerable scatter in values of R , but if average values from the curves are realistic, sandstones containing gas should give strong seismic reflections. In the geopressed zone, there is much less contrast in acoustic impedance when gas is present. It is interesting that the reflectivity of the gas/brine interface in sandstones is larger than that of the shale/gas-saturated sandstone interface in the geopressed zone above 14,500 ft (4,420 m). Below 14,500 ft, the reflectivity of the shale/gas-saturated sandstone increases and R exceeds $+0.1$ in some zones.

Overall, there is considerable similarity between comparable curves in figures 18 and 19, but significant differences exist. Average reflectivity of the gas-saturated sandstone/shale interface for average Miocene sediments (fig. 18, curve no. 1) is greater in the geopressed zone than the gas-saturated sandstone/shale interface in the Miocene-Oligocene sediments in Brazoria County (fig. 19, curve no. 1). It is not possible to determine if this difference in reflectivity is related to geopressures,

since no subsurface pressure data is available for figure 18. In general, however, deep Miocene sediments of the Gulf Coast area are geopressured to some extent.

A comparison of curve 3 (fig. 19) with curve 4 (fig. 18) shows that the reflectivity of the brine-saturated sandstone/shale interface in the Pleasant Bayou wells is smaller in the hydro pressured zone and larger in the geopressured zone. This could be interpreted to mean that larger acoustic impedance contrasts between shales and sandstones can be expected in geopressured Miocene-Oligocene sediments than in geopressured Miocene sediments in the Gulf Coast area.

Influence of Frequency on Velocity (Task C.1e)

Good agreement is usually observed between transit times from seismic reflection surveys and well velocity surveys (check-shot times), but these results commonly disagree with sonic logs and synthetic seismograms. These observations indicate that conventional sonic logs do not measure seismic velocities and are likely to give erroneous time-depth relationships. This is unfortunate since the continuous velocity sonic log was developed primarily to provide time-to-depth conversion and to associate specific seismic events with corresponding physical changes in formation properties that are recorded by sonic, density, and other well logs.

There are several reasons for discrepancies between sonic log velocities and seismic velocities. The sample of rock investigated by the sonic log may not be typical of the sample measured by seismic methods. Problems associated with technical limitations of conventional BHC sonic logs with automatic picking of first arrivals in large boreholes or in

holes with large variations in diameter have been reduced by using a long-spaced sonic log (LSSL) with sonde spacings of 8 to 10 ft and 10 to 12 ft (Gregory and Backus, 1980). Use of the LSSL usually eliminates erroneously low sonic velocities, and the intervals showing erroneously high sonic velocity can be recognized easily and corrections can be made (Thomas, 1978). Alteration of shales near the borehole has little effect on velocities from the LSSL.

The improved accuracy of travel times from the LSSL should permit accurate depth-to-time correlations with seismic data unless dispersion is found to have a large effect. The frequency spectrum of pulses transmitted by sonic logs is about 10 KHz compared to about 10 to 100 Hz for seismic pulses. If dispersion is significant, the pulse with the higher frequency will travel faster. We will look for evidence of dispersion at sonic log frequencies based on the criteria discussed below.

Theoretical Wave Velocities

Geertsma and Smit (1961), following the theoretical concepts developed by Biot (1956) and Gassmann (1951), derived expressions for the velocity V of waves that are normally used in seismic, well logging, and laboratory measurements; that is,

$$V^2 = \frac{V_{\infty}^4 + V_0^4 \left(\frac{\omega_c}{\omega} \right)^2}{V_{\infty}^2 + V_0^2 \left(\frac{\omega_c}{\omega} \right)^2}, \quad (4)$$

where V_0 = Theoretical wave velocity (cm/sec) at zero frequency;
 V_{∞} = Wave velocity (cm/sec) for an infinitely large frequency;
 ω = Angular frequency; and
 ω_c = Characteristic angular frequency.

Hence for zero frequency

$$V_o^2 = \left[\left(\frac{\beta}{c_r} + \frac{4}{3} \bar{G}_b \right) + \frac{(1 - \beta)^2}{(1 - \phi - \beta)c_r + \phi c_f} \right] \frac{1}{\rho_b}, \quad (5)$$

where c_r = Rock matrix compressibility (quartz in sandstones),
cm²/dyne

c_f = Pore fluid compressibility = $\rho_f V_f^2$, cm²/dyne

β = $c_r / \bar{c}_b$

$\bar{c}_b$ = Dry rock bulk compressibility, cm²/dyne

= $1/(\bar{\rho}_b \bar{V}_p^2 - 4/3 \bar{G}_b) = 1/\bar{k}$

$\bar{G}_b$ = Shear modulus of dry bulk rock, dynes/cm²

= $\bar{V}_s^2 \bar{\rho}_b = \frac{3(1 - 2\bar{\nu})}{2\bar{C}_b(1 + \bar{\nu})}$

ϕ = Fractional porosity

ρ_b = Bulk density of fluid-saturated rock, gm/cm³

$\bar{\nu}$ = Poisson's ratio of dry bulk rock

$\bar{k}$ = Dry rock bulk modulus, dynes/cm²

and for infinite frequency

$$V_\infty^2 = \left[\left(\frac{\beta}{c_r} + \frac{4}{3} \bar{G}_b \right) + \frac{\beta\phi/\kappa\rho_f + (1 - \beta)(1 - \beta - 2\phi/\kappa)}{(1 - \phi - \beta)c_r + \phi c_f} \right] \frac{1}{\rho_b \left(1 - \frac{\rho_f \phi}{\rho_b \kappa} \right)}, \quad (6)$$

where ρ_f is the pore-fluid density, and κ is the mass coupling factor between the pore fluid and sandstone grains. For $\kappa = 1$, no coupling exists, and for $\kappa = \infty$, there is perfect coupling. For the case of perfect coupling, equation (6) reduces to the equation for zero frequency and the wave velocity is independent of frequency. The frequency number is

$$\frac{\omega}{\omega_c} = \frac{K' \rho_b \omega}{\mu} \left(\frac{\rho_b \rho_c - \rho_f^2}{\rho_b^2} \right), \quad (7)$$

where $\omega = 2\pi f$; f = frequency, Hz

μ = Fluid viscosity, poise

K' = Permeability of rock, cm^2

$$\rho_c = \kappa \left(\frac{\rho_f}{\phi} \right) \quad (8)$$

$$\omega_c = \frac{\mu}{K' \rho_b} \left(\frac{\rho_b^2}{\rho_b \rho_c - \rho_f^2} \right). \quad (9)$$

Since the theory predicts that wave velocity depends on frequency, it is important to know the extent of this dependence on frequencies used in seismic, sonic well logging, and laboratory measurements. The general wave equations of Biot are valid only if fluid flow, induced by relative volume changes between the pore fluid and the pore volume of the rock, takes place in the range of viscous flow according to Darcy's law, i.e., at a Reynolds number less than one (Muskat, 1949). The frequency number, ω/ω_c , represents the ratio of inertia and viscous forces and may be considered the Reynolds number of vibrating motion. Equation (4) predicts the presence of a dispersion zone at values of ω/ω_c which lie between 0.1 and 5.0. The wave velocity is almost independent of frequency when ω/ω_c is less than 0.1 or greater than 5.0. The location of the dispersion zone for water-saturated sandstones is shown in a plot of ω , and frequency as a function of porosity with permeability also shown as a parameter (fig. 20). The dispersion zone for frequencies (10 to 30 KHz) used in sonic well logging includes sandstones with porosities that are greater than about 18 percent. For laboratory frequencies (0.2 to 1.1 MHz), the dispersion zone narrows to a porosity range varying from 10 to 24 percent at 0.2 MHz, and 6 to 17 percent at 1.0 MHz. The low frequencies used in seismic work completely avoid the dispersion zone. The amount of dispersion that may

be encountered at frequencies used in well logging depends on the numerical differences between V_0 and V_∞ . These differences will be computed and compared with measured values. Zwikker and Kosten (1949) determined a theoretical value of 3 for κ , and this was one of the values used in our calculations. Geertsma (1961) estimates that differences between V_0 and V_∞ for reasonable values of κ will generally be less than 10 percent for sedimentary rocks. He further points out that the validity of the theory is limited by the condition that the wavelength should be larger than the grain diameter.

Application to Sandstones, Pleasant Bayou Wells

Theoretical wave velocities V_0 and V_∞ were computed for sandstones versus depth in the Pleasant Bayou wells after skeleton (dry rock) parameters $\bar{K}$, $\bar{C}_b$, $\bar{G}_b$, and $\bar{V}_p$ were evaluated by the method described in Appendix A. Values of these parameters for sandstones versus depth are tabulated in table A1, and formation brine properties are given in table A2. Comparison of acoustilog velocity V_p with gas-saturated (dry rock) velocity $\bar{V}_p$ (fig. 21) shows that the type of pore fluid has a large effect in the hydro pressured zone above 7,500 ft (2,286 m) and relatively little effect in the geopressured zone below 10,000 ft (3,048 m).

Theoretical dilatational wave velocities at zero frequency V_0 are smaller than those for infinitely large frequency V_∞ (fig. 22 and table 4). These velocity differences vary from 1 to more than 5 percent in the hydro pressured zone and from 1 to 3.25 percent in the geopressured zone depending on the value of mass coupling factor κ (fig. 23). For $\kappa = 3$, velocity differences decrease from 3.6 percent at 2,000 ft (610 m) to 1.5 percent at 7,000 ft (2,134 m) in the hydro pressured zone and average

about 2 percent in the geopressured zone. The large decrease in velocity difference observed between 6,000 and 7,000 ft (1,829 and 2,134 m) is related to the sharp reduction in average porosity shown in figure 1.

For hydropressured sandstones, a dispersive zone is predicted by equation (7) for sonic well log frequencies (10 to 30 KHz) when average permeability exceeds a certain value (fig. 24). These critical permeability values associated with dispersion are frequency-dependent. Dispersion at the low end of the frequency spectrum requires a higher permeability than at the high end of the spectrum. Since the average permeability increases as depth decreases, the curve for a frequency of 30 KHz enters the dispersion zone deeper in the hydropressured section than the curves for lower frequencies. Dispersion is not indicated in the geopressured sandstones except in a thin zone at an average depth of 11,860 ft (3,615 m) where anomalously high permeability was encountered.

Elastic Moduli (Task C.1f)

The dynamic elastic moduli of earth materials are calculated by assuming that rocks are homogeneous, isotropic, elastic media. Parameters required for the computations are P-wave velocity V_p , S-wave velocity V_s , and bulk density ρ_b . These parameters are used to compute bulk modulus K , Young's modulus E , rigidity modulus μ , Poisson's ratio ν , and bulk compressibility β from the relations

$$K = \rho_b (V_p^2 - 4/3 V_s^2), \quad (10)$$

$$E = \frac{(9\rho_b V_s^2 R_2^2)}{(3R_2^2 + 1)}, \quad (11)$$

where $R_2^2 = K/(\rho_b V_s^2),$

$$\mu = \rho_b V_s^2, \text{ and} \quad (12)$$

$$\nu = \frac{1}{2} \left[\frac{(R_1 - 2)}{(R_1 - 1)} \right], \quad (13)$$

where $R_1 = (V_p/V_s)^2$, and

$$\beta = 1/K. \quad (14)$$

Elastic moduli and bulk compressibility data derived from laboratory velocity and density measurements of samples of several types of sedimentary rocks (fig. 25) under a confining pressure of 5,000 psi (34.4×10^3 kPa) vary substantially as a function of porosity and type of pore fluid (Gregory, 1976). The suite of 20 samples contained sandstones and carbonates ranging in porosity from 4.5 to 41.0 percent and in age from Pliocene to Early Devonian. Only one of these samples, however, came from deep Miocene sandstones from the Gulf Coast area. The moduli decrease as porosity increases and increase as pressure increases. Liquid pore fluids (water or oil) increase the moduli and gas decreases the moduli (fig. 25). Poisson's ratio tends to increase as porosity increases but may increase, remain constant, or decrease as a function of pressure. Distinctly different values of Poisson's ratio obtained for samples with high porosity (fig. 25) indicate potential diagnostic value for distinguishing between gas and water-saturated rocks. Dramatic increases in bulk compressibility are observed for rocks with porosities above 25 percent.

When both P-wave and S-wave velocity information is available from field or laboratory measurements, the ratio V_p/V_s may indicate whether formations are consolidated or unconsolidated and if water or gas is present. Ratios greater than 2.0 are characteristic of water-saturated

unconsolidated sands, and values less than 2.0 indicate either a well-consolidated rock or the presence of gas in an unconsolidated sand (Gardner and Harris, 1968). A plot of V_p/V_s versus porosity (fig. 26) shows the range and limits of the ratio for the 20 rock samples, discussed above, when saturated with water and gas and under confining pressures up to 10,000 psi (68.9×10^3 kPa).

Points plotted in the illustration (fig. 26) are the V_p/V_s values obtained from in-situ measurements in deep geopressed Frio sandstones using the long-spaced sonic logging system in No. 2 Pleasant Bayou, Brazoria County, Texas. It is significant that the in-situ values fall within the range of V_p/V_s ratios determined from laboratory measurements made at ultrasonic frequencies on small hand samples of sedimentary rocks with widely different geological ages and depositional environments.

P-wave and S-wave transit times have been picked from sonic waveform displays recorded by the LSSL for the primary production zone in No. 2 Pleasant Bayou (Gregory and Backus, 1980). These velocities and bulk density data from the formation density log were used to compute in-situ bulk compressibility β , Poisson's ratio ν , and V_p/V_s ratios (table 5), and these data were plotted versus depth (fig. 27).

Transit time picks for P-wave and S-wave arrivals from waveforms digitized by the LSSL system seem reasonable in the primary production interval 14,644 to 14,704 ft (4,463 to 4,482 m). Computed in-situ bulk compressibilities in this depth interval range from 2.79×10^{-7} to 5.53×10^{-7} psi⁻¹ (4.05×10^{-12} to 8.02×10^{-12} cm²/dyne), and average 3.73×10^{-7} psi⁻¹ (5.41×10^{-12} cm²/dyne). Average values for V_p/V_s and Poisson's ratio are 1.67 and 0.220 respectively.

Shales and shaly sandstones in the depth interval 16,136 to 16,176 ft (4,918 to 4,930 m) have average values of V_p/V_s and Poisson's ratio of 1.75 and 0.253 respectively. Measured and computed parameters are plotted versus depth (figs. 28 and 29) and tabulated versus depth (tables 6 and 7). The average bulk compressibility of this shaly zone was $3.43 \times 10^{-7} \text{ psi}^{-1}$ ($4.97 \times 10^{-12} \text{ cm}^2/\text{dyne}$). Inspection of waveforms indicates that S-wave transit times may have been picked at an event which occurs somewhat later in time than the first arrival of the S-wave.

Correlation of Geophysical Measurements with Reservoir Quality (Task C.1h)

High quality sandstone reservoirs suitable for production of large volumes of geothermal water develop under favorable subsurface conditions that are controlled by a complex relationship between depositional environment, mineral composition, and diagenetic events commonly dominated by compaction, cementation, and leaching (fig. 30). Porosity and permeability are controlled largely by diagenetic history. Potentially favorable areas for high quality reservoirs in the lower Tertiary stratigraphic section along the Texas Gulf Coast have been recognized (fig. 31) from an extensive study of sandstone mineralogical composition and consolidation sequence (Loucks, Dodge, and Galloway, 1979). The most important practical impact of sandstone diagenesis on final reservoir quality is the loss or preservation of primary porosity and the creation of secondary porosity. Primary porosity decreases with time and depth of burial through compaction and cementation. Secondary porosity is created by leaching of soluble material and may increase with depth. Loucks, Dodge, and Galloway (1979) show that secondary porosity is the dominant form of

porosity in moderate and deep Tertiary sandstones in the Texas Gulf Coast (fig. 32) and attempt to correlate interval transit time from sonic logs with rock consolidation history. The effort to relate transit time to the development of secondary leached porosity was complicated because the top of geopressure appeared to coincide with the zone of leached porosity. Both geopressure and secondary dissolution porosity tend to increase interval transit time, and it is difficult to separate one effect from the other.

Secondary dissolution porosity is also found to be dominant in the geopressured zone of the Pleasant Bayou wells (Loucks, Richmann, and Milliken, 1980). The average trend of conventional BHC acoustilog velocity with depth (fig. 33) indicates the presence of an enhanced dissolution porosity zone below 13,300 ft (4,054 m). The conventional BHC acoustilog velocities are reasonably reliable in the geopressured zone but, in general, are erroneously low in the hydro pressured zone above the Anahuac shale (Gregory and Backus, 1980). The erroneously low acoustilog velocities are responsible, in part, for the poor agreement with the time average velocity in the lower portion of the hydro pressured zone (fig. 33). Normally, good agreement is obtained between reliable sonic log velocities and time average velocities at depths where sands become reasonably well-consolidated by cementation processes as illustrated by Miocene sands in offshore Louisiana (fig. 34). Velocities of Miocene-Oligocene geopressured sandstones in the Pleasant Bayou wells (plotted in fig. 34) are higher than those of Miocene sandstones because porosities are lower in the older sandstones.

Acoustic impedance values are lower than the normal trend for Pleasant Bayou geopressured sandstones below 13,300 ft (4,054 m) and

possibly indicate the presence of high quality reservoirs with enhanced dissolution porosity (fig. 35). This does not mean, of course, that adequate permeability exists throughout this high porosity zone to provide the high rates of water flow required for producing economically viable geothermal energy. It is known, however, that the depth interval 14,644 to 14,704 ft (4,463 to 4,482 m) has both high porosity and high permeability and is capable of producing water at high flow rates. This high quality reservoir is a medium-grained sandstone that was deposited in a traction load fluvial channel and has good dip and strike continuity (Loucks, Richmann, and Milliken, 1980). Possibly, it is beyond the present state-of-the-art of geophysical methods to locate fluvial channel sandstone reservoirs that have high permeability as well as high porosity. It does seem possible, however, that seismic reflection methods can locate zones of enhanced dissolution porosity as indicated by high reflection coefficients (fig. 19, curve 3) encountered at interfaces between brine-saturated sandstone and shale at depths below 14,500 ft (4,420 m).

Summary and Conclusions

Task C.1a

Mean values of porosity from conventional core data range from 32.7 to 13.3 percent in the hydro pressured zone and from 17.6 to 13.2 percent in the geopressured zone. Below a depth of 10,000 ft (3,048 m), primary porosity is less than 2 percent, but total average porosity is greater than 15 percent. A compaction correction factor of 1.9 was required to give satisfactory agreement between porosity from the time average equation and core porosity in hydro pressured sandstones. No compaction

correction was needed in geopressured sandstones. Best average permeabilities were found in fluvial channel deposits at depths from 14,687 to 14,716 ft (4,477 to 4,485 m), where the range was 0.07 to 515 md and the mean was 175 md. In this interval, the average permeability from production flow tests was in good agreement with mean permeability from core measurements.

Task C.1b

Agreement between bulk densities calculated from core data and those derived from neutron and formation density logs is satisfactory. Bulk density gradients in the Pleasant Bayou wells are 2.106×10^{-3} (gm/cm³)/100 ft for shales. The relation between bulk density and acoustic velocity data is in good agreement with equation (2) for high velocity sandstones, but agreement is only fair for sandstones with lower velocities.

Task C.1c

Digital long-spaced sonic log waveform data is shown to be of value in the geologic environment found in the Pleasant Bayou geothermal-geopressured test wells. It is shown that reasonable P-wave transit times are provided by waveform data. In general, conventional BHC acoustilog data in the hydro pressured zone above the Anahuac shale is significantly in error. Transit times in good quality sandstones below 7,000 ft (2,134 m) are measured with reasonable reliability by all acoustic logging tools. Waveform data illustrate large coupling-related amplitude variations due to lithology and tool geometry.

A limited amount of S-wave velocity data and related elastic parameters is given for deep, good quality geopressured sandstones and shaly sandstones. In general, S-wave events are stronger and more easily

identified when shorter spacings are used. Additional work with S-wave extraction methods is planned.

Task C.1d

Typically, acoustic impedance contrasts between shales and brine-saturated sandstones are small in the hydro pressured zone and larger in the geopressured zone. The presence of gas in these sandstones gives high contrasts in acoustic impedance at interfaces with shale and brine-saturated sandstone in the hydro pressured zone and lower contrasts in the geopressured zone.

Task C.1e

The improved accuracy of travel times from the long-spaced sonic log over that of the conventional BHC acoustilog should permit more accurate depth-to-time correlation with seismic data. However, wave theory predicts that dispersion at well log frequencies may introduce errors of 1.5 to 3.6 percent (for a mass coupling factor of 3.0) in sandstones with high porosity and permeability.

Task C.1f

Values of V_p/V_s obtained from waveforms recorded by the LSSL in deep geopressured Frio sandstone fall within the range of V_p/V_s ratios determined from laboratory measurements made on different types of sedimentary rock samples under simulated subsurface conditions at ultrasonic frequencies. Average values of V_p/V_s and Poisson's ratio in good quality geopressured sandstones in the primary production interval are 1.67 and 0.220 compared to 1.75 and 0.253 for shaly sandstones located deeper in the section. Average bulk compressibilities were higher in the good quality sandstones than in shaly sandstones.

Task C.1h

The presence of high quality reservoirs with enhanced dissolution porosity is indicated by acoustic impedance values that are lower than the normal trend for deep geopressured sandstones. High reflection coefficients at interfaces between shale and brine-saturated sandstone at depths below 14,500 ft (4,420 m) indicate that these zones of enhanced leached porosity might be detected by seismic reflection methods.

Acknowledgments

P-wave and S-wave transit times from long-spaced sonic log waveforms were analyzed (Appendix C) by Richard G. Anderson, graduate student in the Geological Sciences Department, The University of Texas at Austin. Mr. Anderson was supervised in this work by Dr. Milo M. Backus, the Wallace E. Pratt Professor of Geophysics in the Department of Geological Sciences, The University of Texas at Austin.

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Table 1

Bulk Density of Brine-Saturated Sandstone from Core Data and
From Neutron and Formation Density Logs,
Pleasant Bayou Wells, Brazoria County, Texas

	Depth		Mean Core Porosity Percent	Mean Grain Density* (Core) gm/cm ³	Average Brine Density gm/cm ³	Average Brine# Salinity ppm NaCl	Mean Bulk Density** gm/cm ³	Neutron Log Density gm/cm ³	FDC Log Density gm/cm ³	Density Calcu- lated## gm/cm ³	Velocity Acoustilog ft/sec
	Feet	Meters									
29	1,500	PB#1 457	35.6	-	1.01	25,000	2.07	2.20	-	-	-
	2,000	610	34.2	-	1.01	30,000	2.09	2.18	-	2.10	6,993
	2,500	762	32.6	-	1.01	35,000	2.12	2.18	-	2.08	6,667
	3,000	914	31.2	-	1.01	40,000	2.14	2.21	-	2.15	7,576
	3,500	1,067	29.9	-	1.02	50,000	2.16	2.17	-	2.10	6,944
	4,000	1,219	28.5	-	1.04	60,000	2.19	2.22	-	2.19	8,264
	4,300	1,311	28.2	2.62*	1.06	72,000	2.18	2.26	-	2.17	7,874
	5,000	1,524	26.4	-	1.06	83,000	2.23	2.17	-	2.16	7,752
	5,500	1,676	25.0	-	1.06	83,000	2.25	2.25	-	2.21	8,475
	6,000	1,829	23.7	-	1.06	83,000	2.27	2.27	-	2.22	8,696
	6,700	2,042	13.3	2.64*	1.06	83,000	2.43	2.29	-	2.25	9,091
	7,000	2,134	13.5	-	1.06	83,000	2.44	2.38	-	2.25	9,174
	10,200	3,109	14.1	2.68*	1.02	28,000	2.45	-	-	2.40	11,765
	10,500	3,200	14.3	-	1.02	30,000	2.42	-	-	2.38	11,364
	11,000	3,353	16.4	-	1.02	31,000	2.38	-	-	2.42	12,196
	11,750	3,581	16.9	2.66*	1.02	37,000	2.38	-	-	2.40	11,909
	12,000	3,658	17.8	-	1.03	42,000	2.36	-	-	2.44	12,658
	12,500	3,810	17.4	-	1.04	50,000	2.37	-	-	2.44	12,658
	13,000	3,962	17.1	-	1.04	57,000	2.37	-	-	2.47	13,334
	13,500	4,115	16.8	-	1.05	67,000	2.38	-	-	2.42	12,346
	14,050	4,282	16.2	2.68*	1.06	76,000	2.42	-	-	2.46	12,987
	14,750	PB#2 4,496	16.6	2.67*	1.07	96,000	2.40	-	2.41	2.49	13,699
	15,150	4,618	8.0	2.66*	1.08	108,000	2.53	-	2.44	2.48	13,518
	15,500	4,724	9.6	2.66*	1.09	120,000	2.51	-	2.51	2.52	14,815
	15,650	4,770	13.2	2.65*	1.09	120,000	2.44	-	2.51	2.53	14,706
	16,300	4,968	12.9	-	1.09	120,000	2.45	-	2.53	2.52	14,493

*Grain density from core data at these depths; grain density assumed to be 2.65 at other depths.

**Calculated from equation 1.

#From Gregory and Backus, 1980 (table 4).

##Calculated from equation 2, using velocity data from BHC acoustilog.

Table 2

Bulk Density of Shales, Pleasant Bayou Wells, Brazoria County, Texas

Depth			Density Calculated*	FDC Density	Core Density	Porosity		Velocity Acoustilog
Feet		Meters				Calculated**	FDC Log	
			gm/cm ³	gm/cm ³	gm/cm ³	percent	percent	ft/sec
1,500	PB#1	457	-	2.11	-	-	34.4	-
2,000		610	2.04	2.18	-	38.9	29.9	6,173
2,500		762	2.06	2.17	-	37.6	30.6	6,452
3,000		914	2.09	2.25	-	35.7	25.5	6,757
3,500		1,067	2.18	2.27	-	29.9	24.2	8,065
4,000		1,219	2.18	2.23	-	29.9	26.8	8,130
4,500		1,372	2.13	2.29	-	33.1	22.9	7,407
5,000		1,524	2.24	2.30	-	26.1	22.3	8,929
5,500		1,676	2.26	2.33	-	24.8	20.4	9,345
6,000		1,829	2.15	2.27	-	31.8	24.2	7,576
6,500		1,981	2.18	2.24	-	29.9	26.1	8,130
7,000		2,134	2.18	2.20	-	29.9	28.7	8,065
7,500		2,286	2.25	2.38	-	25.5	17.2	9,175
8,000		2,438	2.20	2.31	-	28.7	21.2	8,403
8,400		2,560	2.10	2.33	-	35.0	20.4	6,897
9,000		2,743	2.20	-	-	28.7	-	8,333
9,500		2,896	2.05	-	-	38.2	-	6,329
10,000		3,048	2.22	-	-	27.4	-	8,696
10,500		3,200	2.32	-	-	21.0	-	10,365
11,000		3,353	2.26	-	-	24.8	-	9,259
11,750		3,581	2.31	-	2.54	21.7	-	10,101
12,000		3,658	2.29	-	-	22.9	-	9,901
12,500		3,810	2.32	-	2.53	21.0	-	10,309
13,000		3,962	2.47	-	-	11.5	-	13,333
13,500		4,115	2.43	-	-	14.0	-	12,500
14,050		4,267	2.30	-	2.46	22.3	-	10,000
14,500	PB#2	4,420	2.38	2.51	-	17.2	8.9	11,494
15,150		4,618	2.40	2.54	2.49	15.9	7.0	11,765
15,500		4,724	2.43	2.57	2.53	14.0	5.1	12,500
16,000		4,877	2.40	2.57	-	15.9	5.1	11,905
16,500		5,029	2.45	2.57	-	12.7	5.1	12,821

*Calculated from equation 2.

**Calculated from equation 1, grain density assumed to be 2.65 gm/cm³, density of water in shale assumed to be 1.07 gm/cm³.

P-Wave Velocities, Bulk Densities, and Reflection Coefficients for Tertiary Sediments,
Pleasant Bayou Wells, Brazoria County, Texas

PB Well No.	Depth		Shale		Sandstone (Gas)		Sandstone (Brine)		R Sh/SS _g	R SS _g /SS _b	R SS _b /Sh
	Feet	Meters	V _p ft/sec	ρ _b gm/cm ³	V _p ft/sec	ρ _b gm/cm ³	V _p ft/sec	ρ _b gm/cm ³			
1 31	1,715	523	6,181	2.17	4,090	1.72	6,494	2.18	-.312	.336	-.027
	1,770	539	6,254	2.17	5,030	1.72	6,944	2.19	-.221	.275	-.057
	1,895	578	6,351	2.18	3,690	1.73	6,369	2.19	-.369	.372	-.004
	1,944	593	6,231	2.18	3,850	1.74	6,452	2.19	-.339	.357	-.020
	2,055	626	6,729	2.18	4,960	1.74	6,993	2.19	-.259	.279	-.022
	2,100	640	7,048	2.18	3,820	1.75	6,494	2.19	-.394	.360	.039
	2,160	658	6,431	2.18	4,700	1.75	6,897	2.19	-.260	.295	-.037
	2,226	678	7,911	2.19	3,920	1.76	6,579	2.19	-.430	.352	.092
	2,246	685	6,971	2.19	4,860	1.76	6,993	2.20	-.282	.285	-.004
	2,278	694	6,459	2.19	4,120	1.76	6,667	2.20	-.322	.338	-.018
	2,367	721	7,195	2.19	4,370	1.77	6,803	2.20	-.341	.319	.026
	2,402	732	8,194	2.19	4,540	1.78	6,897	2.20	-.379	.305	.084
	2,435	742	7,433	2.19	3,990	1.78	6,667	2.20	-.392	.348	.052
	2,656	810	6,797	2.20	5,530	1.79	7,463	2.20	-.203	.248	-.047
	2,690	820	6,516	2.20	4,980	1.80	7,194	2.20	-.231	.277	-.049
	2,810	856	7,123	2.20	4,520	1.80	6,993	2.21	-.316	.310	.007
	2,834	864	7,166	2.20	3,740	1.81	6,667	2.21	-.401	.370	.034
	2,900	884	6,830	2.20	4,760	1.81	7,143	2.21	-.271	.294	-.025
	3,065	934	6,585	2.21	5,570	1.82	7,576	2.21	-.179	.246	-.070
	3,175	967	7,143	2.21	5,200	1.83	7,407	2.22	-.248	.267	-.020
	3,225	983	7,146	2.21	4,410	1.84	7,042	2.22	-.321	.317	.005
	3,310	1,009	7,055	2.22	4,180	1.84	6,993	2.22	-.341	.337	.004
	3,462	1,055	8,098	2.22	4,570	1.85	7,194	2.22	-.360	.308	.059
	3,490	1,064	8,232	2.22	3,940	1.86	6,944	2.22	-.428	.356	.085
	3,596	1,096	6,921	2.22	4,260	1.87	6,135	2.22	-.317	.262	.060
	3,654	1,114	6,993	2.22	4,910	1.87	7,407	2.23	-.257	.285	-.031
	3,688	1,124	7,171	2.23	5,240	1.87	7,576	2.23	-.240	.266	-.027
	3,770	1,149	8,402	2.23	6,370	1.88	8,197	2.23	-.220	.208	.012

Table 3

(continued)

PB Well No.	Depth		Shale		Sandstone (Gas)		Sandstone (Brine)		R	R	R
	Feet	Meters	V _p ft/sec	ρ _b gm/cm ³	V _p ft/sec	ρ _b gm/cm ³	V _p ft/sec	ρ _b gm/cm ³	Sh/SS _g	SS _g /SS _b	SS _b /Sh
1	3,812	1,162	7,813	2.23	7,700	1.88	9,009	2.23	-.092	.162	-.071
	3,935	1,199	7,175	2.23	6,650	1.89	8,403	2.23	-.120	.197	-.079
	3,955	1,205	7,736	2.23	8,580	1.89	9,615	2.23	-.031	.139	-.108
	3,980	1,213	8,234	2.23	6,340	1.89	8,264	2.23	-.210	.212	-.002
	4,054	1,236	7,303	2.23	5,460	1.89	7,813	2.23	-.224	.256	-.034
	4,078	1,243	7,764	2.24	6,450	1.90	8,333	2.24	-.173	.207	-.035
	4,118	1,255	7,483	2.24	4,220	1.90	7,246	2.24	-.353	.339	.016
	4,230	1,289	7,525	2.24	3,910	1.91	7,143	2.24	-.386	.364	.026
	4,275	1,303	7,790	2.24	4,590	1.91	7,463	2.24	-.331	.312	.021
	4,331	1,320	7,941	2.25	5,420	1.91	7,874	2.24	-.266	.260	.006
	4,385	1,337	7,693	2.25	4,380	1.92	7,407	2.24	-.346	.259	.021
	4,425	1,349	7,576	2.25	5,750	1.92	8,065	2.24	-.214	.241	-.029
	4,445	1,355	7,491	2.25	4,610	1.92	7,519	2.24	-.311	.311	.0004
	4,525	1,379	7,520	2.25	6,570	1.92	8,547	2.24	-.146	.206	-.062
	4,575	1,394	7,605	2.25	5,680	1.93	8,065	2.25	-.219	.247	-.029
	4,630	1,411	7,722	2.25	5,510	1.93	8,000	2.25	-.241	.257	-.018
	4,685	1,428	7,463	2.25	3,020	1.93	6,993	2.25	-.485	.459	.033
	4,725	1,440	8,118	2.25	6,380	1.94	8,475	2.25	-.192	.213	-.022
	4,754	1,449	8,811	2.25	5,060	1.94	7,813	2.25	-.338	.283	.060
	4,782	1,458	8,490	2.25	6,230	1.94	8,403	2.25	-.225	.220	.005
	5,148	1,569	6,970	2.26	4,750	1.96	7,752	2.26	-.257	.306	-.053
	5,277	1,608	7,578	2.27	5,220	1.97	8,000	2.26	-.252	.275	-.025
	5,375	1,638	8,930	2.27	5,860	1.98	8,333	2.26	-.272	.238	.037
	5,410	1,649	8,971	2.27	5,290	1.98	8,065	2.26	-.321	.270	.055
	5,555	1,693	9,098	2.28	6,080	1.99	8,475	2.27	-.263	.228	.038
	5,594	1,705	8,299	2.28	5,240	1.99	8,065	2.27	-.289	.274	.016
	5,763	1,757	7,669	2.28	2,680	2.00	7,143	2.27	-.531	.503	.038
	5,833	1,778	8,851	2.28	4,820	2.01	7,937	2.27	-.351	.301	.057
	5,950	1,814	7,971	2.29	4,350	2.01	7,751	2.28	-.352	.338	.016
	5,985	1,824	8,659	2.29	4,790	2.01	7,937	2.28	-.346	.305	.046

(continued)

PB Well No.	Depth		Shale		Sandstone (Gas)		Sandstone (Brine)		R Sh/SS _g	R SS _g /SS _b	R SS _b /Sh
	Feet	Meters	V _p ft/sec	ρ _b gm/cm ³	V _p ft/sec	ρ _b gm/cm ³	V _p ft/sec	ρ _b gm/cm ³			
1	6,095	1,858	7,634	2.29	6,290	2.02	8,696	2.28	-.158	.219	-.063
	6,135	1,870	8,392	2.29	7,140	2.02	9,174	2.28	-.139	.184	-.042
	6,155	1,876	9,352	2.29	6,120	2.02	8,621	2.28	-.268	.228	.043
	6,195	1,888	9,477	2.29	6,230	2.03	8,696	2.28	-.264	.221	.045
	6,242	1,903	9,622	2.29	6,810	2.05	9,091	2.28	-.224	.195	.031
	6,272	1,912	9,853	2.29	6,420	2.06	8,929	2.28	-.261	.212	.051
	6,324	1,928	8,197	2.30	6,410	2.09	9,009	2.28	-.176	.217	-.043
	6,365	1,940	8,164	2.30	5,800	2.10	8,772	2.28	-.213	.243	-.032
	6,408	1,953	8,265	2.30	5,200	2.12	8,547	2.29	-.266	.279	-.015
	6,445	1,964	8,232	2.30	5,200	2.14	8,621	2.29	-.260	.279	-.021
33	6,470	1,972	8,065	2.30	4,980	2.15	8,584	2.29	-.268	.295	-.029
	6,518	1,987	8,065	2.30	5,700	2.17	9,009	2.29	-.200	.250	-.053
	6,610	2,015	8,490	2.30	4,890	2.21	8,850	2.29	-.287	.304	-.019
	6,665	2,031	8,773	2.30	11,800	2.24	12,987	2.29	.134	.059	-.192
	6,722	2,049	9,783	2.31	4,790	2.26	9,091	2.29	-.352	.316	.041
	6,757	2,060	10,102	2.31	4,130	2.28	8,929	2.29	-.425	.369	.066
	6,840	2,085	10,155	2.31	11,900	2.29	13,333	2.29	.075	.057	-.131
	6,885	2,099	9,742	2.31	4,110	2.29	9,009	2.30	-.410	.375	.041
	6,936	2,114	8,299	2.31	3,870	2.29	8,929	2.30	-.368	.397	-.034
	6,995	2,132	8,475	2.31	4,790	2.29	9,259	2.30	-.377	.412	-.042
	7,020	2,140	8,475	2.31	4,570	2.29	9,174	2.30	-.303	.337	-.037
	7,056	2,151	9,732	2.32	10,700	2.29	12,500	2.30	.041	.080	-.120
	7,085	2,160	9,959	2.32	11,000	2.29	12,658	2.30	.043	.072	-.115
	7,170	2,185	8,630	2.32	5,230	2.29	9,434	2.30	-.251	.289	-.040
	7,494	2,284	8,894	2.33	4,840	2.29	9,259	2.31	-.303	.317	-.016
	10,236	3,120	9,175	2.44	10,100	2.28	11,765	2.37	.014	.095	-.109
	10,275	3,132	9,680	2.44	10,300	2.28	11,905	2.37	-.003	.092	-.089
	10,475	3,193	9,710	2.44	9,500	2.28	11,364	2.37	-.045	.109	-.064
	10,525	3,208	9,619	2.44	9,660	2.26	11,364	2.37	-.036	.105	-.069
	10,754	3,278	9,710	2.44	12,700	2.24	13,334	2.38	.091	.055	-.145

Table 3

(continued)

PB Well No.	Depth		Shale		Sandstone (Gas)		Sandstone (Brine)		R Sh/SS _g	R SS _g /SS _b	R SS _b /Sh
	Feet	Meters	V _p ft/sec	ρ _b gm/cm ³	V _p ft/sec	ρ _b gm/cm ³	V _p ft/sec	ρ _b gm/cm ³			
1	10,840	3,303	10,696	2.44	11,200	2.22	12,196	2.38	-.024	.077	-.053
	11,367	3,465	10,004	2.44	11,600	2.20	12,346	2.39	.022	.072	-.095
	11,450	3,490	10,754	2.44	12,200	2.19	12,820	2.39	.009	.068	-.077
	11,480	3,499	10,696	2.44	12,100	2.19	12,658	2.40	.008	.068	-.076
	11,764	3,586	10,000	2.44	11,000	2.19	11,909	2.40	-.006	.085	-.079
	11,812	3,600	10,000	2.44	11,700	2.18	12,346	2.40	.022	-.075	-.097
	11,850	3,612	9,852	2.44	11,900	2.18	12,500	2.40	.038	.073	-.110
	12,030	3,667	9,864	2.45	12,100	2.18	12,658	2.41	.044	.073	-.116
	12,372	3,771	10,279	2.46	12,100	2.18	12,658	2.41	.021	.073	-.094
	12,685	3,866	10,669	2.47	13,300	2.19	13,518	2.42	.050	.058	-.108
	12,730	3,880	11,500	2.47	13,500	2.19	13,699	2.42	.020	.057	-.077
	12,764	3,890	11,629	2.47	12,100	2.19	12,658	2.42	-.040	.072	-.032
	12,864	3,921	10,263	2.47	13,800	2.19	13,889	2.43	.088	.055	-.142
	12,889	3,929	11,126	2.47	12,600	2.19	12,987	2.43	.002	.067	-.069
	12,925	3,940	11,419	2.47	12,300	2.19	12,820	2.43	-.023	.073	-.050
	13,012	3,966	10,479	2.47	13,000	2.20	13,334	2.43	.050	.062	-.112
	13,035	3,973	10,696	2.47	12,300	2.20	12,820	2.43	.012	.070	-.082
	13,320	4,060	10,696	2.48	12,100	2.20	12,658	2.44	.002	.074	-.076
	13,392	4,082	10,418	2.48	12,300	2.20	12,820	2.44	.023	.072	-.095
	13,498	4,114	10,209	2.49	11,600	2.20	12,346	2.44	.002	.083	-.085
	13,583	4,140	10,209	2.49	12,000	2.21	12,658	2.44	.021	.076	-.097
	13,710	4,179	11,287	2.49	13,000	2.21	13,334	2.44	.011	.062	-.073
	14,060	4,285	10,418	2.50	11,800	2.22	12,500	2.45	.003	.078	-.081
	14,104	4,299	10,205	2.50	10,700	2.22	11,765	2.45	-.036	.096	-.061
	14,410	4,392	10,259	2.51	11,500	2.23	12,346	2.46	-.002	.084	-.082
	14,498	4,419	10,312	2.51	11,700	2.23	12,500	2.46	-.004	.090	-.086
	14,670	4,471	10,474	2.52	11,200	2.24	12,196	2.46	-.025	.089	-.064
	14,718	4,486	10,875	2.52	11,700	2.24	12,500	2.47	-.022	.082	-.060
	14,684	4,476	10,698	2.52	12,300	2.24	12,987	2.46	.011	.074	-.085
	14,858	4,529	10,819	2.52	13,400	2.25	13,699	2.47	.050	.0058	-.108

(continued)

PB Well No.	Depth		Shale		Sandstone (Gas)		Sandstone (Brine)		R Sh/SS _g	R SS _g /SS _b	R SS _b /Sh	
	Feet	Meters	V _p	ρ _b	V _p	ρ _b	V _p	ρ _b				
			ft/sec	gm/cm ³	ft/sec	gm/cm ³	ft/sec	gm/cm ³				
35	2	14,878	4,535	10,640	2.52	12,300	2.25	12,987	2.47	.016	.073	-.089
		14,960	4,560	10,638	2.53	12,600	2.25	13,158	2.47	.026	.068	-.094
		15,000	4,572	10,582	2.53	12,300	2.26	12,987	2.47	.019	.071	-.090
		15,027	4,580	10,640	2.53	13,800	2.26	14,058	2.47	.073	.054	-.127
		15,125	4,610	12,274	2.53	13,000	2.26	13,518	2.47	-.028	.064	-.036
		15,200	4,633	11,513	2.53	15,600	2.26	15,385	2.48	.095	.039	-.134
		15,382	4,688	10,777	2.54	15,300	2.26	15,152	2.48	.116	.041	-.157
		15,404	4,695	11,294	2.54	13,800	2.27	14,085	2.48	.044	.054	-.098
		15,432	4,704	11,236	2.54	14,400	2.27	14,493	2.48	.068	.047	-.115
		15,565	4,744	10,444	2.54	14,800	2.28	14,815	2.48	.120	.041	-.161
		15,620	4,761	10,786	2.54	15,500	2.28	15,385	2.49	.127	.039	-.166
		15,642	4,768	12,048	2.54	12,800	2.28	13,333	2.49	-.024	.065	-.041
		15,675	4,778	12,048	2.55	14,600	2.28	14,706	2.49	.040	.048	-.088
		15,723	4,792	12,500	2.55	14,000	2.28	14,286	2.49	.001	.054	-.055
		15,770	4,807	12,122	2.55	12,000	2.28	12,821	2.49	-.061	.077	-.016
		15,950	4,862	11,697	2.55	12,700	2.29	13,333	2.49	-.013	.066	-.053
		16,000	4,877	11,767	2.55	15,100	2.29	15,152	2.49	.071	.043	-.114
		16,050	4,892	11,697	2.56	15,400	2.30	15,385	2.49	.084	.039	-.123
		16,130	4,916	11,987	2.56	14,600	2.30	14,706	2.50	.045	.045	-.090
		16,190	4,935	12,056	2.56	13,400	2.30	13,889	2.50	-.001	.060	-.059
		16,215	4,942	11,565	2.56	13,400	2.30	13,889	2.50	.020	.060	-.080
		16,295	4,967	11,838	2.56	14,200	2.31	14,493	2.50	.040	.049	-.089
		16,355	4,985	11,561	2.56	13,900	2.31	14,286	2.50	.041	.053	-.094
		16,410	5,002	12,427	2.56	14,800	2.31	14,925	2.50	.036	.044	-.080
		16,430	5,008	12,143	2.56	13,600	2.31	14,085	2.50	.005	.057	-.062

Table 4

Calculated Parameters Showing Influence of Well Log Frequency
on Velocity of Sandstones, Pleasant Bayou Wells,
Brazoria County, Texas

(Plane dilatational wave velocity V , equation (4); wave velocity at zero frequency V_0 , equation (5); wave velocity at infinite frequency V_∞ , equation (6); angular frequency, $\omega = 2\pi f$, $f = 20$ KHz; characteristic angular frequency ω_c , equation (7); mass coupling factor, $\kappa = 3.0$; well log velocity, $V_p \approx V_0$)

Depth		V_0	V_∞	V	ω_c	ω/ω_c
Feet	Meters	ft/sec	ft/sec	ft/sec	Hz	
1,715	523	6,447	6,690	6,568	131,800	.9534
1,770	539	6,899	7,160	7,025	136,700	.9193
1,895	578	6,325	6,563	6,429	149,100	.8428
1,944	593	6,415	6,655	6,516	153,800	.8171
2,055	626	6,964	7,222	7,064	165,900	.7575
2,100	640	6,467	6,706	6,557	168,500	.7458
2,160	658	6,875	7,128	6,966	176,100	.7136
2,226	678	6,559	6,799	6,641	183,300	.6856
2,246	685	6,969	7,225	7,056	183,500	.6848
2,278	694	6,645	6,888	6,725	186,900	.6724
2,367	721	6,784	7,031	6,859	199,000	.6315
2,402	732	6,882	7,131	6,946	223,700	.5618
2,435	742	6,655	6,894	6,723	207,900	.6044
2,656	810	7,471	7,736	7,533	238,100	.5278
2,690	820	7,198	7,452	7,255	243,300	.5165
2,810	856	7,009	7,256	7,058	264,200	.4756
2,834	864	6,686	6,921	6,731	268,900	.4673
2,900	884	7,147	7,397	7,192	281,000	.4472
3,065	934	7,597	7,860	7,638	305,600	.4112
3,172	967	7,428	7,683	7,428	327,700	.3835
3,225	983	7,062	7,310	7,099	334,000	.3762
3,310	1,009	7,024	7,259	7,053	350,900	.3581
3,462	1,055	7,226	7,465	7,250	388,900	.3231
3,490	1,064	6,979	7,209	7,002	389,200	.3229
3,596	1,096	6,185	6,385	6,203	416,800	.3015
3,654	1,114	7,442	7,686	7,462	433,000	.2902
3,688	1,124	7,612	7,861	7,632	443,200	.2835
3,770	1,149	8,234	8,499	8,254	457,200	.2749
3,812	1,162	9,042	9,335	9,063	472,700	.2658
3,935	1,199	8,443	8,711	8,459	511,100	.2459
3,955	1,205	9,646	9,955	9,665	517,800	.2427
3,980	1,213	8,306	8,566	8,322	516,600	.2433
4,054	1,236	7,864	8,109	7,877	542,500	.2316

Table 4
(continued)

Depth		V_o	V_∞	V	ω_c	ω/ω_c
Feet	Meters	ft/sec	ft/sec	ft/sec	Hz	
4,078	1,243	8,380	8,644	8,394	550,300	.2284
4,118	1,255	7,301	7,526	7,312	569,200	.2208
4,230	1,289	7,209	7,425	7,219	600,200	.2094
4,275	1,303	7,529	7,756	7,539	623,700	.2015
4,331	1,320	7,939	8,179	7,987	261,700	.4802
4,385	1,337	7,483	7,706	7,491	666,900	.1884
4,425	1,349	8,127	8,372	8,135	688,400	.1825
4,445	1,355	7,591	7,813	7,599	690,500	.1820
4,525	1,379	8,613	8,872	8,621	713,400	.1761
4,575	1,394	8,138	8,379	8,146	727,300	.1728
4,630	1,411	8,077	8,315	8,084	752,200	.1671
4,685	1,428	7,089	7,290	7,094	782,300	.1606
4,725	1,440	8,549	8,802	8,556	793,600	.1583
4,754	1,449	7,898	8,127	7,904	802,600	.1566
4,782	1,458	8,479	8,728	8,485	810,000	.1551
5,148	1,569	7,854	8,075	7,877	1,008,000	.1247
5,277	1,608	8,104	8,331	8,107	1,092,000	.1151
5,375	1,638	8,434	8,671	8,437	1,164,000	.1080
5,410	1,649	8,173	8,399	8,176	1,189,000	.1057
5,555	1,693	8,574	8,813	8,576	1,285,000	.0978
5,594	1,705	8,172	8,397	8,174	1,318,000	.0953
5,763	1,757	7,277	7,467	7,278	1,468,000	.0856
5,833	1,778	8,054	8,269	8,055	1,560,000	.0806
5,950	1,814	7,875	8,083	7,876	1,658,000	.0758
5,985	1,824	8,057	8,271	8,058	1,693,000	.0742
6,095	1,858	8,802	9,038	8,803	1,817,000	.0692
6,135	1,870	9,274	9,524	9,275	1,891,000	.0665
6,155	1,876	8,731	8,963	8,732	1,891,000	.0665
6,195	1,888	8,805	9,038	8,806	1,963,000	.0640
6,242	1,903	9,196	9,434	9,197	1,894,000	.0663
6,272	1,912	9,038	9,267	9,039	1,943,000	.0647
6,324	1,928	9,121	9,343	9,122	1,932,000	.0650
6,365	1,940	8,893	9,102	8,894	1,867,000	.0673
6,408	1,953	8,676	8,873	8,677	1,901,000	.0661
6,445	1,964	8,751	8,943	8,752	1,842,000	.0682
6,470	1,972	8,717	8,904	8,718	1,862,000	.0675
6,518	1,987	9,137	9,327	9,138	1,781,000	.0706
6,610	2,015	8,989	9,159	8,990	1,846,000	.0681
6,665	2,013	13,051	13,322	13,052	1,743,000	.0721
6,722	2,049	9,234	9,390	9,235	1,711,000	.0734
6,757	2,060	9,089	9,235	9,090	1,541,000	.0815
6,840	2,085	13,402	13,653	13,403	1,701,000	.0739
6,885	2,099	9,172	9,314	9,173	1,842,000	.0682

Table 4

(continued)

Depth		V_o	V_∞	V	ω_c	ω/ω_c
Feet	Meters	ft/sec	ft/sec	ft/sec	Hz	
6,936	2,114	9,095	9,235	9,096	1,842,000	.0682
6,995	2,132	9,417	9,566	9,418	1,931,000	.0651
7,020	2,140	9,335	9,481	9,336	1,537,000	.0818
7,056	2,151	12,585	12,815	12,587	1,498,000	.0839
7,085	2,160	12,740	12,974	12,742	1,498,000	.0839
7,170	2,185	9,587	9,740	9,588	1,647,000	.0763
7,494	2,284	9,575	9,730	9,576	2,005,000	.0627
10,236	3,120	11,896	12,122	11,896	18,000,000	.0070
10,275	3,132	12,037	12,266	12,037	15,640,000	.0080
10,475	3,193	11,518	11,737	11,518	9,849,000	.0128
10,525	3,203	11,520	11,750	11,520	9,270,000	.0136
10,754	3,278	13,430	13,716	13,430	5,933,000	.0212
10,840	3,304	12,328	12,597	12,328	5,018,000	.0250
11,367	3,465	12,467	12,748	12,469	1,571,000	.0800
11,450	3,490	12,929	13,224	12,932	1,294,000	.0971
11,480	3,499	12,772	13,066	12,775	1,182,000	.1063
11,764	3,586	12,055	12,333	12,066	629,900	.1995
11,812	3,600	12,479	12,769	12,490	663,000	.1895
11,850	3,612	12,628	12,923	12,638	693,800	.1811
12,030	3,667	12,784	13,085	12,791	853,000	.1473
12,372	3,771	12,799	13,098	12,802	1,319,000	.0953
12,685	3,866	13,634	13,953	13,635	1,960,000	.0641
12,730	3,880	13,815	14,158	13,816	2,060,000	.0610
12,764	3,890	12,812	13,110	12,813	2,066,000	.0608
12,865	3,921	14,001	14,328	14,002	2,247,000	.0559
12,889	3,929	13,131	13,436	13,132	2,354,000	.0534
12,925	3,940	12,973	13,274	12,974	2,472,000	.0508
13,012	3,966	13,469	13,782	13,470	2,625,000	.0479
13,035	3,973	12,987	13,287	12,988	2,701,000	.0465
13,320	4,060	12,842	13,138	12,842	3,546,000	.0354
13,392	4,082	13,005	13,304	13,005	3,868,000	.0325
13,498	4,114	12,560	12,847	12,560	4,185,000	.0300
13,583	4,140	12,867	13,160	12,867	4,596,000	.0273
13,710	4,179	13,523	13,833	13,523	5,153,000	.0244
14,060	4,285	12,732	13,025	12,732	7,997,000	.0157
14,104	4,299	12,060	12,327	12,060	4,593,000	.0274
14,410	4,392	12,614	12,892	12,614	11,760,000	.0107
14,498	4,419	12,764	13,043	12,764	12,830,000	.0098
14,670	4,471	12,482	12,751	12,482	15,680,000	.0080
14,718	4,486	12,762	13,037	12,762	16,920,000	.0074
14,684	4,476	13,226	13,512	13,460	-	-
14,858	4,529	13,895	14,197	13,895	18,600,000	.0068
14,878	4,535	13,227	13,509	13,227	19,260,000	.0065

Table 4
(continued)

<u>Feet</u>	<u>Meters</u>	V_o <u>ft/sec</u>	V_∞ <u>ft/sec</u>	V <u>ft/sec</u>	ω_c <u>Hz</u>	ω/ω_c
14,960	4,560	13,392	13,677	13,392	19,810,000	.0063
15,000	4,572	13,232	13,511	13,232	20,450,000	.0061
15,027	4,580	14,269	14,576	14,269	21,500,000	.0058
15,125	4,610	13,731	14,022	13,731	23,130,000	.0054
15,200	4,633	15,501	15,839	15,501	25,020,000	.0050
15,382	4,688	15,276	15,608	15,276	31,240,000	.0040
15,404	4,695	14,263	14,560	14,263	31,640,000	.0040
15,432	4,704	14,651	14,959	14,651	33,010,000	.0038
15,565	4,744	14,960	15,274	14,960	39,390,000	.0032
15,620	4,761	15,503	15,832	15,503	38,850,000	.0032
15,642	4,768	13,558	13,883	13,690	-	-
15,674	4,778	14,859	15,168	14,859	40,840,000	.0031
15,723	4,792	14,464	14,760	14,464	40,380,000	.0031
15,770	4,807	13,093	13,353	13,093	43,070,000	.0029
15,950	4,862	13,577	13,846	13,577	52,640,000	.0024
16,000	4,877	15,295	15,609	15,295	56,990,000	.0022
16,050	4,892	15,521	15,839	15,521	58,070,000	.0022
16,130	4,916	14,882	15,182	14,882	64,020,000	.0020
16,190	4,935	14,117	14,395	14,117	63,530,000	.0020
16,215	4,942	14,121	14,399	14,121	76,570,000	.0016
16,295	4,967	14,691	14,982	14,691	86,150,000	.0015
16,355	4,985	14,506	14,792	14,506	80,410,000	.0016
16,410	5,002	15,109	15,410	15,109	93,070,000	.0014
16,430	5,008	15,114	15,413	15,114	92,330,000	.0014

Table 5

P-Wave Velocity V_p , S-Wave Velocity V_s , Bulk Density, Poisson's ratio ν , and Bulk Compressibility β from Bore Hole Compensated Long-Spaced Sonic Log (10-12 ft Spacing) and Formation Density Log, No. 2 Pleasant Bayou (from Gregory and Backus, 1980)

Depth		V_p	V_s	V_p	V_s	V_p/V_s	ν	Density	β	β
Meters	Feet	ft/sec	ft/sec	m/sec	m/sec			gm/cm ³	cm ² /dyne x 10 ⁻¹²	psi ⁻¹ x 10 ⁻⁷
4469.9	14665.0	13158	8065	4011	2458	1.64	.199	2.37	5.26	3.63
4470.0	14665.5	13333	7874	4064	2400	1.70	.232	2.37	4.78	3.30
4470.2	14666.0	13333	8065	4064	2458	1.67	.212	2.37	4.99	3.44
4470.3	14666.5	13699	8065	4175	2458	1.70	.235	2.39	4.46	3.08
4470.5	14667.0	13333	7937	4064	2419	1.69	.226	2.40	4.78	3.30
4470.7	14667.5	13699	8264	4175	2519	1.66	.214	2.39	4.66	3.21
4470.8	14668.0	13158	-	4011	-	-	-	2.37	-	-
4471.0	14668.5	13333	-	4064	-	-	-	2.37	-	-
4471.1	14669.0	13158	8130	4011	2478	1.60	.191	2.36	5.37	3.70
4471.3	14669.5	13158	8065	4011	2458	1.61	.199	2.36	5.28	3.64
4471.4	14670.0	13158	7874	4011	2400	1.67	.221	2.36	5.04	3.47
4471.6	14670.5	13158	7874	4011	2400	1.67	.221	2.37	5.02	3.46
4471.7	14671.0	13699	7937	4175	2419	1.72	.247	2.38	4.36	3.01
4471.9	14671.5	13333	7874	4064	2400	1.70	.232	2.39	4.74	3.27
4472.0	14672.0	13158	7937	4011	2419	1.65	.214	2.40	5.03	3.47
4472.2	14672.5	12658	7813	3858	2381	1.63	.192	2.38	5.74	3.96
4472.3	14673.0	12987	7874	3958	2400	1.64	.209	2.36	5.30	3.65
4472.5	14673.5	12658	7634	3858	2327	1.67	.214	2.35	5.55	3.83
4472.6	14674.0	12658	7634	3858	2327	1.67	.214	2.35	5.55	3.83
4472.8	14674.5	12346	7463	3763	2275	1.64	.212	2.34	5.89	4.06
4472.9	14675.0	12048	7407	3672	2258	1.63	.197	2.34	6.38	4.40
4473.1	14675.5	12346	7692	3763	2345	1.59	.183	2.35	6.23	4.30
4473.3	14676.0	12500	7692	3810	2345	1.65	.195	2.36	5.90	4.07
4473.4	14676.5	12987	7576	3958	2309	1.71	.242	2.38	4.91	3.39
4473.6	14677.0	12658	7634	3858	2327	1.67	.214	2.40	5.44	3.75

Table 5

(continued)

Depth		V _p	V _s	V _p	V _s	V _p /V _s		Density	β	β
Meters	Feet	ft/sec	ft/sec	m/sec	m/sec		ν	gm/cm ³	cm ² /dyne x 10 ⁻¹²	psi ⁻¹ x 10 ⁻⁷
4473.7	14677.5	13699	7634	4176	2327	1.79	.275	2.42	4.05	2.79
4473.9	14678.0	13158	7634	4010	2327	1.73	.246	2.43	4.64	3.20
4474.0	14678.5	12987	7692	3958	2345	1.68	.230	2.42	4.95	3.41
4474.2	14679.0	12987	7692	3958	2345	1.68	.230	2.37	5.06	3.49
4474.3	14679.5	12658	7634	3858	2327	1.67	.214	2.36	5.53	3.81
4474.5	14680.0	12500	7813	3810	2381	1.60	.179	2.35	6.12	4.22
4474.6	14680.5	12658	7692	3858	2345	1.65	.223	2.35	5.59	3.85
4474.8	14681.0	12500	7463	3810	2275	1.66	.233	2.36	5.56	3.83
4474.9	14681.5	12500	7463	3810	2275	1.66	.233	2.35	5.59	3.85
4475.1	14682.0	12500	7407	3810	2258	1.67	.230	2.34	5.53	3.81
4475.2	14682.5	12346	7407	3763	2258	1.66	.219	2.35	5.78	3.99
4475.4	14683.0	12048	7407	3672	2258	1.63	.196	2.35	6.36	4.39
4475.5	14683.5	12346	7576	3763	2309	1.63	.198	2.36	6.01	4.14
4475.7	14684.0	12500	7463	3810	2275	1.67	.233	2.35	5.59	3.85
4475.8	14684.5	12500	7634	3810	2327	1.64	.203	2.35	5.83	4.02
4476.0	14685.0	12500	7299	3810	2225	1.71	.241	2.36	5.35	3.69
4476.1	14685.5	12658	7576	3858	2309	1.68	.221	2.36	5.45	3.76
4476.3	14686.0	12987	7407	3958	2258	1.75	.259	2.37	4.76	3.28
4476.4	14686.5	12987	7463	3958	2275	1.73	.254	2.37	4.81	3.32
4476.6	14687.0	12658	7576	3858	2309	1.68	.221	2.36	5.45	3.76
4476.8	14687.5	12658	7813	3858	2381	1.63	.192	2.36	5.79	3.99
4476.9	14688.0	12987	7634	3958	2327	1.66	.236	2.35	5.04	3.47
4477.1	14688.5	12500	7813	3810	2381	1.60	.179	2.35	6.12	4.22
4477.2	14689.0	12500	7407	3810	2258	1.69	.229	2.35	5.51	3.80
4477.4	14689.5	12658	7692	3858	2345	1.68	.207	2.36	5.61	3.87
4477.5	14690.0	12270	7634	3740	2327	1.64	.184	2.36	6.26	4.32
4478.4	14693.0	12903	7273	3933	2217	1.67	.267	2.33	4.81	3.32
4479.6	14697.0	10526	6061	3208	1847	1.74	.252	2.17	8.02	5.53

Table 6

P-Wave Velocity V_p and S-Wave Velocity V_s from BHC Long-Spaced Sonic Log (10-12 ft Spacing)
and Bulk Density ρ_b from Formation Density Log, No. 2 Pleasant Bayou

Feet	Depth	V_p		V_s		V_p/V_s	ρ_b gm/cm ³	Lithology*
	Meters	ft/sec	m/sec	ft/sec	m/sec			
16,118	4,912.8	15,674.0	4,777.4	9,523.8	2,902.8	1.6458	2.18	Sandstone
16,119	4,913.1	15,674.0	4,777.4	9,191.2	2,801.4	1.7053	2.17	
16,120	4,913.4	15,384.6	4,689.2	9,302.3	2,835.3	1.6538	2.17	
16,121	4,913.7	15,083.0	4,597.2	9,191.2	2,801.4	1.6410	2.18	
16,122	4,914.0	14,814.6	4,515.5	8,888.9	2,709.3	1.6667	2.20	
16,123	4,914.3	14,285.7	4,354.3	8,333.3	2,540.0	1.7143	2.22	
16,124	4,914.6	14,285.7	4,354.3	8,510.6	2,594.0	1.6786	2.21	
16,125	4,914.9	14,285.7	4,354.3	8,992.8	2,741.0	1.5886	2.19	
16,126	4,915.2	14,025.2	4,274.9	8,510.6	2,594.0	1.6480	2.16	
16,127	4,915.5	13,793.1	4,204.1	8,888.9	2,709.3	1.5517	2.15	
16,128	4,915.8	14,285.7	4,354.3	8,605.9	2,623.0	1.6600	2.15	
16,129	4,916.1	14,025.2	4,274.9	8,510.6	2,594.0	1.6480	2.14	
16,130	4,916.4	13,793.1	4,204.1	8,333.3	2,540.0	1.6552	2.14	
16,131	4,916.7	14,025.2	4,274.9	8,163.3	2,488.1	1.7181	2.16	
16,132	4,917.0	13,333.3	4,064.0	7,843.1	2,390.6	1.7000	2.17	
16,133	4,917.3	14,534.9	4,430.2	8,333.3	2,540.0	1.6552	2.22	Shale
16,134	4,917.6	14,814.8	4,515.5	8,787.3	2,678.4	1.6859	2.19	
16,135	4,917.9	14,285.7	4,354.3	8,605.9	2,623.0	1.6600	2.17	
16,136	4,918.3	14,814.8	4,515.5	8,695.7	2,650.4	1.7037	2.15	
16,137	4,918.6	14,534.9	4,430.2	8,695.7	2,650.4	1.6715	2.16	
16,138	4,918.9	14,025.2	4,274.9	8,244.0	2,512.8	1.7013	2.19	
16,139	4,919.2	13,106.2	3,994.7	7,843.1	2,390.6	1.6710	2.21	
16,140	4,919.5	12,300.1	3,749.0	7,770.0	2,368.3	1.5830	2.21	
16,141	4,919.8	12,500.0	3,810.0	7,017.5	2,138.9	1.7813	2.17	
16,142	4,920.1	13,793.1	4,204.1	7,692.3	2,344.6	1.7931	2.18	Shaly Sandstone
16,143	4,920.4	13,550.0	4,130.0	7,692.3	2,344.6	1.7615	2.21	
16,144	4,920.7	12,903.2	3,932.9	7,770.0	2,368.3	1.6606	2.19	
16,145	4,921.0	13,106.2	3,994.7	7,692.3	2,344.6	1.7038	2.17	
16,146	4,921.3	13,793.1	4,204.1	7,770.0	2,368.3	1.7752	2.16	

Table 6
(continued)

	Depth		V_p		V_s		V_p/V_s	ρ_b gm/cm ³	Lithology*
	Feet	Meters	ft/sec	m/sec	ft/sec	m/sec			
	16,147	4,921.6	14,534.9	4,430.2	8,163.3	2,488.1	1.7805	2.17	
	16,148	4,921.9	15,847.9	4,830.4	8,992.8	2,741.0	1.7623	2.20	
	16,149	4,922.2	14,814.8	4,515.5	8,787.3	2,678.4	1.6859	2.22	
	16,150	4,922.5	11,933.2	3,637.2	8,000.0	2,438.4	1.4916	2.20	
	16,151	4,922.8	11,428.6	3,483.4	6,105.0	1,860.8	1.8720	2.20	
	16,152	4,923.1	12,903.2	3,932.9	6,835.3	2,083.4	1.8877	2.21	
	16,153	4,923.4	12,903.2	3,932.9	7,616.1	2,321.4	1.6942	2.22	
	16,154	4,923.7	12,903.2	3,932.9	7,843.1	2,390.6	1.6452	2.22	
	16,155	4,924.0	13,333.3	4,064.0	7,342.1	2,237.9	1.8160	2.21	
	16,156	4,924.3	13,333.3	4,064.0	7,547.2	2,300.4	1.7667	2.22	
	16,157	4,924.7	12,903.2	3,932.9	7,342.1	2,237.9	1.7574	2.24	
	16,158	4,925.0	12,690.4	3,868.0	6,724.9	2,049.7	1.8871	2.23	
43	16,159	4,925.3	12,300.1	3,749.0	6,557.4	1,998.7	1.8758	2.22	
	16,160	4,925.6	12,500.0	3,810.0	7,017.5	2,138.9	1.7813	2.21	
	16,161	4,925.9	12,690.4	3,868.0	7,204.6	2,195.9	1.7614	2.22	
	16,162	4,926.2	12,903.2	3,932.9	7,204.6	2,195.9	1.7910	2.21	
	16,163	4,926.5	13,106.2	3,994.7	7,473.8	2,278.0	1.7497	2.23	
	16,164	4,926.8	13,106.2	3,994.7	7,407.4	2,257.8	1.7693	2.22	
	16,165	4,927.1	13,333.3	4,064.0	7,342.1	2,237.9	1.8160	2.23	
	16,166	4,927.4	13,106.2	3,994.7	7,342.1	2,237.9	1.7851	2.22	
	16,167	4,927.7	13,333.3	4,064.0	7,473.8	2,278.0	1.7840	2.24	
	16,168	4,928.0	13,333.3	4,064.0	7,547.2	2,300.4	1.7667	2.24	
	16,169	4,928.3	13,550.1	4,130.0	7,407.4	2,257.8	1.8293	2.25	
	16,170	4,928.6	13,333.3	4,064.0	7,473.8	2,278.0	1.7840	2.23	
	16,171	4,928.9	14,025.2	4,274.9	8,244.0	2,512.8	1.7013	2.22	
	16,172	4,929.2	13,793.1	4,204.1	8,333.3	2,540.0	1.6552	2.20	
	16,173	4,929.5	12,903.2	3,932.9	7,272.7	2,216.7	1.7742	2.19	
	16,174	4,929.8	12,500.0	3,810.0	6,835.3	2,083.4	1.8287	2.21	
	16,175	4,930.1	13,793.1	4,204.1	7,917.7	2,413.3	1.7421	2.23	
	16,176	4,930.4	15,384.6	4,689.2	9,090.9	2,770.9	1.6923	2.24	

*Picked from SP log, Run no. 3.

Table 7

Poisson's Ratio, Elastic Moduli, and Bulk Compressibility
versus Depth in Deep Frio Sandstone/Shale Sequence
No. 2 Pleasant Bayou, Brazoria County, Texas

Depth		Poisson's Ratio	Bulk Moduli Psi ($\times 10^6$)	Young's Moduli Psi ($\times 10^6$)	Shear Moduli Psi ($\times 10^6$)	Bulk Compres- sibility Psi ⁻¹ ($\times 10^{-7}$)
Feet	Meters					
16,118	4,912.8	.2074	3.664	6.795	2.664	2.729
16,119	4,913.1	.2380	3.890	6.532	2.470	2.571
16,120	4,913.4	.2118	3.547	6.490	2.530	2.819
16,121	4,913.7	.2047	3.374	6.307	2.482	2.964
16,122	4,914.0	.2188	3.383	6.058	2.342	2.956
16,123	4,914.3	.2421	3.335	5.524	2.077	2.999
16,124	4,914.6	.2249	3.201	5.620	2.157	3.124
16,125	4,914.9	.1718	2.840	5.796	2.386	3.521
16,126	4,915.2	.2086	2.914	5.385	2.108	3.431
16,127	4,915.5	.1448	2.460	5.329	2.289	4.066
16,128	4,915.8	.2152	1.526	5.526	2.146	3.277
16,129	4,916.1	.2086	2.887	5.335	2.088	3.464
16,130	4,916.4	.2126	2.816	5.141	2.002	3.551
16,131	4,916.7	.2438	3.139	5.162	1.940	3.186
16,132	4,917.0	.2354	2.800	4.743	1.799	3.572
16,133	4,917.3	.2126	2.921	5.333	2.077	3.423
16,134	4,917.6	.2286	3.438	5.963	2.279	2.908
16,135	4,917.9	.2152	3.080	5.578	2.166	3.247
16,136	4,918.3	.2372	3.438	5.788	2.190	2.909
16,137	4,918.6	.2213	3.214	5.710	2.201	3.111
16,138	4,918.9	.2360	3.130	5.293	2.006	3.194
16,139	4,919.2	.2210	2.673	4.752	1.832	3.742
16,140	4,919.5	.1680	2.108	4.341	1.798	4.744
16,141	4,919.8	.2699	2.649	3.932	1.440	3.776
16,142	4,920.1	.2743	3.271	4.766	1.738	3.057
16,143	4,920.4	.2622	3.118	4.778	1.762	3.207
16,144	4,920.7	.2155	2.538	4.590	1.782	3.941
16,145	4,921.0	.2372	2.716	4.572	1.730	3.682
16,146	4,921.3	.2676	3.194	4.788	1.757	3.131
16,147	4,921.6	.2696	3.579	5.320	1.948	2.794
16,148	4,921.9	.2625	4.249	6.502	2.397	2.354
16,149	4,922.2	.2286	3.486	6.045	2.310	2.869
16,150	4,922.5	.0918	1.692	4.010	1.897	5.912
16,151	4,922.8	.3004	2.399	3.096	1.106	4.169
16,152	4,923.1	.3050	3.108	3.912	1.391	3.223
16,153	4,923.4	.2327	2.667	4.562	1.735	3.750
16,154	4,923.7	.2070	2.527	4.691	1.840	3.958
16,155	4,924.0	.2824	3.154	4.433	1.605	3.171

Table 7
(continued)

Depth		Poisson's Ratio	Bulk Moduli Psi (x 10 ⁶)	Young's Moduli Psi (x 10 ⁶)	Shear Moduli Psi (x 10 ⁶)	Bulk Compres- sibility Psi ⁻¹ (x 10 ⁻⁷)
Feet	Meters					
16,156	4,924.3	.2643	3.046	4.629	1.704	3.283
16,157	4,924.7	.2606	2.856	4.404	1.627	3.502
16,158	4,925.0	.3048	3.027	3.820	1.359	3.304
16,159	4,925.3	.3015	2.811	3.607	1.286	3.558
16,160	4,925.6	.2699	2.698	4.005	1.466	3.707
16,161	4,925.9	.2622	2.747	4.210	1.552	3.640
16,162	4,926.2	.2735	2.897	4.235	1.546	3.452
16,163	4,926.5	.2574	2.914	4.550	1.686	3.432
16,164	4,926.8	.2653	2.950	4.463	1.641	3.390
16,165	4,927.1	.2824	3.182	4.473	1.620	3.142
16,166	4,927.4	.2713	2.988	4.410	1.612	3.347
16,167	4,927.7	.2709	3.118	4.609	1.686	3.207
16,168	4,928.0	.2643	3.074	4.607	1.719	3.254
16,169	4,928.3	.2869	3.348	4.611	1.664	2.987
16,170	4,928.6	.2709	3.104	4.588	1.678	3.222
16,171	4,928.9	.2360	3.174	5.365	2.033	3.151
16,172	4,929.2	.2126	2.895	5.285	2.058	3.454
16,173	4,929.5	.2672	2.832	4.252	1.561	3.531
16,174	4,929.8	.2867	2.798	3.856	1.391	3.574
16,175	4,930.1	.2543	3.205	5.068	1.884	3.120
16,176	4,930.4	.2317	3.818	6.551	2.494	2.619

Figure 1. Core porosity versus depth, No. 1 and No. 2 Pleasant Bayou, Brazoria County, Texas (modified from Gregory and Backus, 1980).

Figure 2. Porosity versus permeability from core measurements, No. 1 Pleasant Bayou, Brazoria County, Texas (after Gregory and Backus, 1980).

Figure 3. Porosity versus permeability from core measurements, No. 2 Pleasant Bayou, Brazoria County, Texas (after Gregory and Backus, 1980).

Figure 4. Permeability versus depth from core measurements and production flow tests, No. 1 and No. 2 Pleasant Bayou, Brazoria County, Texas.

Figure 5. Comparison of porosity from acoustic transit times with core porosity.

Figure 6. Bulk densities calculated for brine-saturated sandstone cores from Pleasant Bayou wells, Brazoria County, Texas.

Figure 7. Comparison of bulk densities calculated from core data for brine-saturated sandstones and bulk densities from well logs, Pleasant Bayou wells, Brazoria County, Texas.

Figure 8. Shale bulk density versus depth, Pleasant Bayou wells, Brazoria County, Texas.

Figure 9. Density-velocity relationship for Pleasant Bayou wells (shale data is from FDC log, shallow SS data from neutron log of Pleasant Bayou No. 1 well, deep SS data from FDC log of Pleasant Bayou No. 2 well).

Figure 10. Bulk density-velocity data from Pleasant Bayou wells superimposed on velocity-density relationships in rocks of different lithology reported by Gardner, Gardner, and Gregory (1974).

Figure 11. Long-spaced sonic log (LSSL) sonde and transit time channels (after Gregory and Backus, 1980).

Figure 12. Effect of position of sonde in borehole on acoustic response (LSSL) (after Gregory and Backus, 1980).

Figure 13. Four-channel P-wave aligned plot, No. 2 Pleasant Bayou (after Gregory and Backus, 1980).

Figure 14. Channel 1 (10 ft spacing) P-wave aligned plot, No. 2 Pleasant Bayou (after Gregory and Backus, 1980).

Figure 15. Well logs for relatively shallow Tertiary clastic sediments, No. 2 Pleasant Bayou, and comparison of transit times of No. 1 and No. 2 Pleasant Bayou (after Gregory and Backus, 1980).

Figure 16. Four-channel sonic waveform displays in deep Frio geopressured sandstone showing P-wave and S-wave arrivals, No. 2 Pleasant Bayou (after Gregory and Backus, 1980).

Figure 17. Core velocity versus effective pressure, No. 1 Pleasant Bayou, Brazoria County, Texas.

Figure 18. Reflection coefficient versus depth for Miocene sediments of the Gulf Coast (after Gregory, 1977).

Figure 19. Reflection coefficients versus depth for Tertiary sediments, Pleasant Bayou wells, Brazoria County, Texas.

Figure 20. Plot showing region where wave velocity is frequency-dependent for water-saturated sandstones (after Geertsma, 1961). Mass coupling factor, $\kappa = 3$.

Figure 21. Well log velocity of brine-saturated sandstones and calculated velocity of gas-saturated (dry) sandstones versus depth, Pleasant Bayou wells, Brazoria County, Texas.

Figure 22. Comparison of velocities computed at zero and infinite frequencies for Pleasant Bayou wells, Brazoria County, Texas.

Figure 23. Difference between wave velocities at zero and infinitely large frequencies versus depth, Pleasant Bayou wells, Brazoria County, Texas.

Figure 24. Dispersion at well log frequencies predicted for sandstone zones when values of frequency number ω/ω_c are between 0.1 and 5.0.

Figure 25. Comparison of elastic moduli showing effect of porosity and pore fluids on samples of consolidated sedimentary rocks under moderate confining pressure (after Gregory, 1976).

Figure 26. Variation of V_p/V_s with porosity for water-saturated and gas-saturated rocks at confining pressures from 0 to 10,000 psi (0 to 68.9×10^3 kPa) (after Gregory, 1976).

[Cross-hatched areas are for laboratory core measurements; points plotted are in-situ values, geopressured sandstones, No. 2 Pleasant Bayou, Brazoria County, Texas.]

Figure 27. P-wave velocity (V_p), S-wave velocity (V_s), velocity ratio (V_p/V_s), Poisson's ratio, and bulk compressibility versus depth in the primary production zone of deep Frio geopressed sandstone, No. 2 Pleasant Bayou, Brazoria County, Texas (after Gregory and Backus, 1980).

Figure 28. P-wave velocity (V_p), S-wave velocity (V_s), velocity ratio (V_p/V_s), and bulk density (ρ_b) versus depth in deep Frio sandstone/shale sequence, No. 2 Pleasant Bayou, Brazoria County, Texas.

Figure 29. Poisson's ratio, elastic moduli, and bulk compressibility versus depth in deep Frio sandstone/shale sequence, No. 2 Pleasant Bayou, Brazoria County, Texas.

Figure 30. General rock consolidation stages with increasing depth of burial. Porosity curve at top of figure is for matrix-free sandstone (after Loucks, Dodge, and Galloway, 1979).

Figure 31. Potential for high quality reservoirs suitable for the production of geopressured-geothermal energy in the lower Tertiary stratigraphic section along the Texas Gulf Coast (after Loucks, Dodge, and Galloway, 1979).

Figure 32. Secondary porosity as a percent of total porosity versus depth for lower Tertiary sandstones (after Loucks, Dodge, and Galloway, 1979).

Figure 33. Acoustilog sandstone velocity versus depth showing low velocities through enhanced dissolution porosity zone, Pleasant Bayou wells, Brazoria County, Texas.

Figure 34. Comparison of acoustilog velocities in Pleasant Bayou wells (Miocene-Oligocene sandstones) with Miocene sandstone velocities and velocities of experimental sand packs at pressures corresponding to these depths, reported by Gardner, Gardner, and Gregory (1974).

Figure 35. Acoustic impedance of sandstones versus depth shows possible effect of leached (dissolution) porosity, Pleasant Bayou wells, Brazoria County, Texas.

Appendix A

Calculation of P-Wave Velocity, Bulk Modulus, and Bulk Compressibility of Dry (Gas Saturated) Sandstones in Pleasant Bayou Wells When Well Log Acoustic Velocity and Bulk Density are Known

In order to solve equations (5) and (6) for theoretical wave velocities V_0 and V_∞ , the dry rock parameters $\bar{C}_b$ and $\bar{G}_b$ must be determined for sandstones as a function of depth. Evaluation of the dry rock compressibility $\bar{C}_b$ involves the most work. Since dry rock S-wave velocity values are not available, it is necessary to assume a value for Poisson's ratio $\bar{\nu}$ when there is no fluid in the pores. For many dry sandstones and unconsolidated sands, $\bar{\nu}$ is about 0.1 and is independent of pressure. It was found that the calculated P-wave velocity is not very sensitive to the value of $\bar{\nu}$; therefore, any reasonable value can be used. We assume that $\bar{\nu} = 0.10$ for sands and sandstones at all depths.

Use is made of the theory of wave propagation (Biot, 1956) in the form and notation given by White (1965). The method has been discussed previously by Gardner and Gregory (1968); Gardner, Gardner, and Gregory (1974); and Gregory (1977).

The plane wave modulus $\bar{M}$ of the dry (gas saturated) skeleton of the rock is related to the bulk modulus $\bar{K}$ and Poisson's ratio $\bar{\nu}$ by

$$\bar{M} = S\bar{K} \quad (A1)$$

where
$$S = \frac{3(1 - \bar{\nu})}{1 + \bar{\nu}}$$

White's equation (3-53), page 132, is

$$\bar{M} = S\bar{K} + \frac{(1 - \bar{K}/k_s)^2}{\phi/k_f + (1 - \phi)/k_s - \bar{K}/k_s^2} \quad (A2)$$

Equation (A2) is used to solve for $\bar{k}$. If we let

$$y = 1 - \bar{k}/k_s, \quad (A3)$$

we obtain

$$y^2(S-1) + y\{\phi S(k_s/k_f - 1) - S + M/k_s\} - \phi(S - M/k_s)(k_s/k_f - 1) = 0. \quad (A4)$$

Having solved equation (A4) for y , we obtain $\bar{k}$ from equation (A3) and $\bar{M}$ from equation (A1). The P-wave velocity $\bar{V}_p$ of the dry (gas saturated) skeleton of the rock is given by

$$\bar{V}_p = (\bar{M}/\bar{\rho}_b)^{1/2} \quad (A5)$$

The dry rock bulk density $\bar{\rho}_b$ is obtained from

$$\bar{\rho}_b = (1 - \phi)\rho_s + \phi\rho_f \quad (A6)$$

where ρ_s = grain density of rock, and

ρ_f = density of fluid saturant.

In the case of dry (gas saturated) rocks, the second term in equation (A6) has little influence and can be neglected. Equation (A5) in the general form can be used to obtain M for any fluid saturant.

Input data and results from calculations using the above equations are given below for the sandstone located at an average depth of 6,518 ft (1,987 m) in No. 1 Pleasant Bayou.

Formation temperature	= 72°C (161°F)
Formation fluid salinity	= 83,000 ppm NaCl
Porosity	= 18 percent
Formation well log velocity (V_p)	= 2.7459×10^5 cm/sec (9,009 ft/sec)
Formation fluid velocity (V_f)	= 1.618×10^5 cm/sec (5,310 ft/sec)
Formation well log bulk density (ρ_b)	= 2.29 gm/cm ³
Grain density (ρ_s)	= 2.65 gm/cm ³

$$\text{Dry skeleton bulk density } (\bar{\rho}_b) = 2.17 \text{ gm/cm}^3$$

$$\text{Formation fluid density } (\rho_f) = 1.06 \text{ gm/cm}^3$$

$$\text{Bulk modulus of quartz grains } (k_s) = 38 \times 10^{10} \text{ dynes/cm}^2 \text{ (from White, 1965)}$$

$$\text{Dry skeleton Poisson's ratio } (\bar{\nu}) = 0.10$$

$$M = \rho_b \bar{V}_p^2 = 17.2665 \times 10^{10} \text{ dynes/cm}^2$$

$$y = 0.923 \quad (\text{from equation A4})$$

$$\bar{k}/k_s = 1 - y = 0.077$$

$$\bar{k} = 2.92 \times 10^{10} \text{ dynes/cm}^2$$

$$\bar{M} = 7.17 \times 10^{10} \text{ dynes/cm}^2 \quad (\text{from equation A1})$$

$$\bar{V}_p = 181,661 \text{ cm/sec (5,960 ft/sec) (from equation A5)}$$

$$\bar{C}_b = 1/\bar{k} = 3.42 \times 10^{-11} \text{ cm}^2/\text{dyne}$$

Additional detailed input data and calculated results are given for sandstones versus depth in the Pleasant Bayou wells (table A1) and for formation brines (table A2).

Table A1

Properties (no superscripts) of brine-saturated sandstones, Pleasant Bayou wells, Brazoria County, Texas, and calculated skeleton properties (bar superscripts) of these sandstones when brine pore fluid is replaced by gas.

V_p = Formation well log P-wave velocity T_e = Formation equilibrium temperature $\bar{k}$ = Bulk modulus of skeleton
 ϕ = Average fractional porosity from figure 1 $\bar{V}_p$ = P-wave velocity of skeleton $\bar{c}_b$ = Bulk compressibility of skeleton
 ρ_b = Average bulk density from figure 7 $\bar{M}$ = Plane wave modulus of skeleton $\bar{G}_b$ = Bulk shear modulus of skeleton, assuming that Poisson's ratio = 0.10.

PB Well No.	Depth		V_p (Log) ft/sec	ϕ	ρ_b gm/cm ³	$\bar{\rho}_b$ gm/cm ³	T_e		$\bar{k}$ dynes/cm ²	$\bar{M}$ dynes/cm ²	$\bar{V}_p$ ft/sec	$\bar{c}_b$ cm ² /dyne	$\bar{G}_b$ dynes/cm ²
	Feet	Meters					°F	°C					
1	1,715	523	6,494	.352	2.18	1.72	95	35	1.08×10^{10}	2.66×10^{10}	4,090	9.22×10^{-11}	1.18×10^{10}
	1,770	539	6,944	.350	2.19	1.72	96	36	1.65×10^{10}	4.05×10^{10}	5,030	6.06×10^{-11}	1.80×10^9
	1,895	578	6,369	.347	2.19	1.73	97	36	8.93×10^9	2.19×10^{10}	3,690	1.12×10^{-10}	9.73×10^9
	1,944	593	6,452	.345	2.19	1.74	98	37	9.72×10^9	2.39×10^{10}	3,850	1.03×10^{-10}	1.06×10^{10}
	2,055	626	6,993	.342	2.19	1.74	100	38	1.62×10^{10}	3.98×10^{10}	4,960	6.16×10^{-11}	1.77×10^{10}
	2,100	640	6,494	.340	2.19	1.75	100	38	9.67×10^9	2.37×10^{10}	3,820	1.03×10^{-10}	1.05×10^{10}
	2,160	658	6,897	.339	2.19	1.75	101	38	1.46×10^{10}	3.59×10^{10}	4,700	6.84×10^{-11}	1.60×10^{10}
	2,226	678	6,579	.336	2.19	1.76	102	39	1.02×10^{10}	2.51×10^{10}	3,920	9.76×10^{-11}	1.12×10^{10}
	2,246	685	6,993	.336	2.20	1.76	103	39	1.58×10^{10}	3.87×10^{10}	4,860	6.35×10^{-11}	1.72×10^{10}
	2,278	694	6,667	.334	2.20	1.76	103	39	1.13×10^{10}	2.78×10^{10}	4,120	8.83×10^{-11}	1.24×10^{10}
	2,367	721	6,803	.332	2.20	1.77	104	40	1.28×10^{10}	3.14×10^{10}	4,370	7.81×10^{-11}	1.40×10^{10}
	2,402	732	6,897	.330	2.20	1.78	105	41	1.38×10^{10}	3.39×10^{10}	4,540	7.23×10^{-11}	1.51×10^{10}
	2,435	742	6,667	.329	2.20	1.78	105	41	1.07×10^{10}	2.63×10^{10}	3,990	9.32×10^{-11}	1.17×10^{10}
	2,656	810	7,463	.323	2.20	1.79	109	43	2.08×10^{10}	5.10×10^{10}	5,530	4.81×10^{-11}	2.27×10^{10}
	2,690	820	7,194	.322	2.20	1.80	109	43	1.69×10^{10}	4.14×10^{10}	4,980	5.93×10^{-11}	1.84×10^{10}
	2,810	856	6,993	.319	2.21	1.80	111	44	1.40×10^{10}	3.43×10^{10}	4,520	7.16×10^{-11}	1.52×10^{10}
	2,834	864	6,667	.318	2.21	1.81	111	44	9.55×10^9	2.35×10^{10}	3,740	1.05×10^{-10}	1.04×10^{10}
	2,900	884	7,143	.316	2.21	1.81	112	44	1.56×10^{10}	3.82×10^{10}	4,760	6.42×10^{-11}	1.70×10^{10}
	3,065	934	7,576	.312	2.21	1.82	114	46	2.14×10^{10}	5.25×10^{10}	5,570	4.67×10^{-11}	2.33×10^{10}
	3,172	967	7,407	.308	2.22	1.83	116	47	1.88×10^{10}	4.61×10^{10}	5,200	5.33×10^{-11}	2.05×10^{10}
	3,225	983	7,042	.307	2.22	1.84	117	47	1.35×10^{10}	3.32×10^{10}	4,410	7.40×10^{-11}	1.48×10^{10}
	3,310	1,009	6,993	.304	2.22	1.84	118	48	1.22×10^{10}	3.00×10^{10}	4,180	8.18×10^{-11}	1.33×10^{10}
	3,462	1,055	7,194	.301	2.22	1.85	120	49	1.46×10^{10}	3.59×10^{10}	4,570	6.84×10^{-11}	1.60×10^{10}
	3,490	1,064	6,944	.299	2.22	1.86	121	49	1.09×10^{10}	2.69×10^9	3,940	9.14×10^{-11}	1.20×10^9
	3,596	1,096	6,135	.296	2.22	1.87	122	50	1.28×10^8	3.15×10^9	4,260	7.80×10^{-9}	1.40×10^9
	3,654	1,114	7,407	.294	2.23	1.87	123	51	1.71×10^{10}	4.19×10^{10}	4,910	5.85×10^{-11}	1.86×10^{10}

Table A1

(continued)

PB Well No.	Depth		V_p (Log) ft/sec	ϕ	ρ_b gm/cm ³	$\bar{\rho}_b$ gm/cm ³	T_e		$\bar{k}$ dynes/cm ²	$\bar{M}$ dynes/cm ²	$\bar{V}_p$ ft/sec	$\bar{C}_b$ cm ² /dyne	$\bar{G}_b$ dynes/cm ²
	Feet	Meters					°F	°C					
1	3,688	1,124	7,576	.293	2.23	1.87	123	51	1.95×10^{10}	4.78×10^{10}	5,240	5.14×10^{-11}	2.12×10^{10}
	3,770	1,149	8,197	.291	2.23	1.88	125	52	2.89×10^{10}	7.08×10^{10}	6,370	3.46×10^{-11}	3.15×10^{10}
	3,812	1,162	9,009	.290	2.23	1.88	125	52	4.22×10^{10}	1.04×10^{11}	7,700	2.37×10^{-11}	4.62×10^{10}
	3,935	1,199	8,403	.288	2.23	1.89	127	53	3.15×10^{10}	7.74×10^{10}	6,650	3.17×10^{-11}	3.44×10^{10}
	3,955	1,205	9,615	.287	2.23	1.89	127	53	5.27×10^{10}	1.29×10^{11}	8,580	1.90×10^{-11}	5.73×10^{10}
	3,980	1,213	8,264	.286	2.23	1.89	128	53	2.87×10^{10}	7.05×10^{10}	6,340	3.48×10^{-11}	3.13×10^{10}
	4,054	1,236	7,813	.285	2.23	1.89	129	54	2.14×10^{10}	5.25×10^{10}	5,460	4.68×10^{-11}	2.33×10^{10}
	4,078	1,243	8,333	.284	2.24	1.90	129	54	2.99×10^{10}	7.34×10^{10}	6,450	3.34×10^{-11}	3.26×10^{10}
	4,118	1,255	7,246	.283	2.24	1.90	130	54	1.28×10^{10}	3.15×10^{10}	4,220	7.79×10^{-11}	1.40×10^{10}
	4,230	1,289	7,143	.281	2.24	1.91	131	55	1.10×10^{10}	2.70×10^{10}	3,910	9.09×10^{-11}	1.20×10^{10}
	4,275	1,303	7,463	.280	2.24	1.91	132	56	1.52×10^{10}	3.74×10^{10}	4,590	6.57×10^{-11}	1.66×10^{10}
	4,331	1,320	7,874	.278	2.24	1.91	133	56	2.13×10^{10}	5.22×10^{10}	5,420	4.70×10^{-11}	2.32×10^{10}
	4,385	1,337	7,407	.277	2.24	1.92	133	56	1.39×10^{10}	3.42×10^{10}	4,380	7.18×10^{-11}	1.52×10^{10}
	4,425	1,349	8,065	.276	2.24	1.92	134	57	2.40×10^{10}	5.89×10^{10}	5,750	4.16×10^{-11}	2.62×10^{10}
	4,445	1,355	7,519	.276	2.24	1.92	134	57	1.54×10^{10}	3.79×10^{10}	4,610	6.48×10^{-11}	1.68×10^{10}
	4,525	1,379	8,547	.274	2.24	1.92	135	57	3.14×10^{10}	7.71×10^{10}	6,570	3.18×10^{-11}	3.43×10^{10}
	4,575	1,394	8,065	.273	2.25	1.93	136	58	2.35×10^{10}	5.77×10^{10}	5,680	4.25×10^{-11}	2.56×10^{10}
	4,630	1,411	8,000	.271	2.25	1.93	137	58	2.22×10^{10}	5.45×10^{10}	5,510	4.50×10^{-11}	2.42×10^{10}
	4,685	1,428	6,993	.270	2.25	1.93	138	59	6.69×10^9	1.64×10^{10}	3,020	1.49×10^{-11}	7.29×10^9
	4,725	1,440	8,475	.269	2.25	1.94	138	59	2.99×10^{10}	7.33×10^{10}	6,380	3.35×10^{-11}	3.26×10^{10}
	4,754	1,449	7,813	.268	2.25	1.94	139	59	1.88×10^{10}	4.61×10^{10}	5,060	5.32×10^{-11}	2.05×10^{10}
	4,782	1,458	8,403	.268	2.25	1.94	139	59	2.85×10^{10}	7.00×10^{10}	6,230	3.51×10^{-11}	3.11×10^{10}
	5,148	1,569	7,752	.259	2.26	1.96	144	62	1.68×10^{10}	4.12×10^{10}	4,750	5.95×10^{-11}	1.83×10^{10}
	5,277	1,608	8,000	.256	2.26	1.97	146	63	2.04×10^{10}	5.00×10^{10}	5,220	4.91×10^{-11}	2.22×10^{10}
	5,375	1,638	8,333	.254	2.26	1.98	147	64	2.57×10^{10}	6.30×10^{10}	5,860	3.90×10^{-11}	2.80×10^{10}
	5,410	1,649	8,065	.253	2.26	1.98	148	64	2.10×10^{10}	5.15×10^{10}	5,290	4.77×10^{-11}	2.29×10^{10}
	5,555	1,693	8,475	.250	2.27	1.99	150	66	2.78×10^{10}	6.83×10^{10}	6,080	3.59×10^{-11}	3.04×10^{10}
	5,594	1,705	8,065	.249	2.27	1.99	150	66	2.07×10^9	5.07×10^{10}	5,240	4.84×10^{-11}	2.25×10^{10}
	5,763	1,757	7,143	.245	2.27	2.00	153	67	5.43×10^{10}	1.33×10^{11}	2,680	1.84×10^{-11}	5.91×10^9
	5,833	1,778	7,937	.243	2.27	2.01	154	68	1.76×10^{10}	4.33×10^{10}	4,820	5.67×10^{-11}	1.92×10^{10}
	5,950	1,814	7,751	.240	2.28	2.01	155	68	1.44×10^{10}	3.54×10^{10}	4,350	6.94×10^{-11}	1.57×10^{10}
	5,985	1,824	7,937	.240	2.28	2.01	155	68	1.75×10^{10}	4.29×10^{10}	4,790	5.73×10^{-11}	1.91×10^{10}
	6,095	1,858	8,696	.237	2.28	2.02	156	69	3.02×10^{10}	7.42×10^{10}	6,290	3.31×10^{-11}	3.30×10^{10}
	6,135	1,870	9,174	.236	2.28	2.02	157	69	3.90×10^{10}	9.58×10^{10}	7,140	2.56×10^{-11}	4.26×10^{10}
	6,155	1,876	8,621	.236	2.28	2.02	157	69	2.87×10^{10}	7.05×10^{10}	6,120	3.48×10^{-11}	3.13×10^{10}

Table A1
(continued)

PB Well No.	Depth		V_p (Log) ft/sec	ϕ	ρ_b gm/cm ³	$\bar{\rho}_b$ gm/cm ³	T_e		$\bar{k}$ dynes/cm ²	$\bar{M}$ dynes/cm ²	V_p ft/sec	$\bar{c}_b$ cm ² /dyne	$\bar{c}_b$ dynes/cm ²
	Feet	Meters					°F	°C					
1	6,195	1,888	8,696	.234	2.28	2.03	157	69	2.98×10^{10}	7.31×10^{10}	6,230	3.36×10^{-11}	3.25×10^{10}
	6,242	1,903	9,091	.226	2.28	2.05	158	70	3.60×10^{10}	8.85×10^{10}	6,810	2.78×10^{-11}	3.93×10^{10}
	6,272	1,912	8,929	.221	2.28	2.06	158	70	3.22×10^{10}	7.91×10^{10}	6,420	3.10×10^{-11}	3.52×10^{10}
	6,324	1,928	9,009	.213	2.28	2.09	159	71	3.25×10^{10}	7.97×10^{10}	6,410	3.08×10^{-11}	3.54×10^{10}
	6,365	1,940	8,772	.206	2.28	2.10	159	71	2.68×10^{10}	6.58×10^{10}	5,800	3.73×10^{-11}	2.92×10^{10}
	6,408	1,953	8,547	.199	2.29	2.12	160	71	2.17×10^{10}	5.32×10^{10}	5,200	4.61×10^{-11}	2.36×10^{10}
	6,445	1,964	8,621	.193	2.29	2.14	160	71	2.19×10^{10}	5.38×10^{10}	5,200	4.57×10^{-11}	2.39×10^{10}
	6,470	1,972	8,584	.188	2.29	2.15	161	72	2.02×10^{10}	4.96×10^{10}	4,980	4.95×10^{-11}	2.20×10^{10}
	6,518	1,987	9,009	.180	2.29	2.17	161	72	2.67×10^{10}	6.55×10^{10}	5,700	3.75×10^{-11}	2.91×10^{10}
	6,610	2,015	8,850	.165	2.29	2.21	162	72	2.00×10^{10}	4.92×10^{10}	4,890	4.99×10^{-11}	2.19×10^{10}
	6,665	2,013	12,987	.156	2.29	2.24	163	73	1.17×10^{11}	2.87×10^{11}	11,800	8.55×10^{-12}	1.28×10^{10}
	6,722	2,049	9,091	.146	2.29	2.26	164	73	1.96×10^{10}	4.82×10^{10}	4,790	5.10×10^{-11}	2.14×10^{10}
	6,757	2,060	8,929	.141	2.29	2.28	164	73	1.47×10^{10}	3.61×10^{10}	4,130	6.80×10^{-11}	1.60×10^{10}
	6,840	2,085	13,333	.135	2.29	2.29	165	74	1.23×10^{10}	3.02×10^{10}	11,900	8.14×10^{-11}	1.34×10^{10}
	6,885	2,099	9,009	.135	2.30	2.29	166	74	1.47×10^{10}	3.61×10^{10}	4,110	6.81×10^{-11}	1.60×10^{10}
	6,936	2,114	8,929	.135	2.30	2.29	166	74	1.30×10^{10}	3.19×10^{10}	3,870	7.69×10^{-11}	1.42×10^{10}
	6,995	2,132	9,259	.135	2.30	2.29	167	75	1.99×10^{10}	4.89×10^{10}	4,790	5.02×10^{-11}	2.17×10^{10}
	7,020	2,140	9,174	.135	2.30	2.29	167	75	1.81×10^{10}	4.45×10^{10}	4,570	5.52×10^{-11}	1.98×10^{10}
	7,056	2,151	12,500	.135	2.30	2.29	168	76	9.99×10^{10}	2.45×10^{11}	10,700	1.00×10^{-11}	1.09×10^{10}
	7,085	2,160	12,658	.135	2.30	2.29	168	76	1.04×10^{10}	2.56×10^{10}	11,000	9.58×10^{-12}	1.14×10^{10}
	7,170	2,185	9,434	.135	2.30	2.29	169	76	2.37×10^{10}	5.82×10^{10}	5,230	4.22×10^{-11}	2.59×10^{10}
	7,494	2,284	9,259	.135	2.31	2.29	173	78	2.04×10^{10}	5.00×10^{10}	4,840	4.91×10^{-11}	2.22×10^{10}
	10,236	3,120	11,765	.138	2.37	2.28	217	103	8.83×10^{10}	2.17×10^{11}	10,100	1.13×10^{-11}	9.64×10^{10}
	10,275	3,132	11,905	.138	2.37	2.28	218	103	9.20×10^{10}	2.26×10^{11}	10,300	1.09×10^{-11}	1.00×10^{10}
	10,475	3,193	11,364	.139	2.37	2.28	222	106	7.80×10^{10}	1.91×10^{11}	9,500	1.28×10^{-11}	8.49×10^{10}
	10,525	3,203	11,364	.147	2.37	2.26	222	106	7.98×10^{10}	1.96×10^{11}	9,660	1.25×10^{-11}	8.71×10^{10}
	10,754	3,278	13,334	.156	2.38	2.24	227	108	1.36×10^{11}	3.34×10^{11}	12,700	7.35×10^{-12}	1.48×10^{11}
	10,840	3,304	12,196	.164	2.38	2.22	228	109	1.06×10^{11}	2.59×10^{11}	11,200	9.47×10^{-12}	1.15×10^{11}
	11,367	3,465	12,346	.170	2.39	2.20	238	109	1.11×10^{11}	2.73×10^{11}	11,600	8.99×10^{-12}	1.21×10^{11}
	11,450	3,490	12,820	.172	2.39	2.19	239	115	1.25×10^{11}	3.06×10^{11}	12,200	8.03×10^{-12}	1.36×10^{11}
	11,480	3,499	12,658	.174	2.40	2.19	240	116	1.21×10^{11}	2.97×10^{11}	12,100	8.26×10^{-12}	1.32×10^{11}
	11,764	3,586	11,909	.175	2.40	2.19	245	118	1.01×10^{11}	2.47×10^{11}	11,000	9.92×10^{-12}	1.10×10^{11}
	11,812	3,600	12,346	.176	2.40	2.18	246	119	1.13×10^{11}	2.76×10^{11}	11,700	8.88×10^{-12}	1.23×10^{11}
	11,850	3,612	12,500	.177	2.40	2.18	246	119	1.17×10^{11}	2.87×10^{11}	11,900	8.56×10^{-12}	1.28×10^{11}
	12,030	3,667	12,658	.178	2.41	2.18	249	121	1.22×10^{11}	2.99×10^{11}	12,100	8.22×10^{-12}	1.33×10^{11}

Table A1

(continued)

PB Well No.	Depth		V_p (Log) ft/sec	ϕ	ρ_b gm/cm ³	$\bar{\rho}_b$ gm/cm ³	T_e		$\bar{k}$ dynes/cm ²	$\bar{M}$ dynes/cm ²	$\bar{V}_p$ ft/sec	$\bar{C}_b$ cm ² /dyne	$\bar{G}_b$ dynes/cm ²
	Feet	Meters					°F	°C					
1	12,372	3,771	12,658	.176	2.41	2.18	255	124	1.21×10^{11}	2.98×10^{11}	12,100	8.24×10^{-12}	1.32×10^{11}
	12,685	3,866	13,513	.173	2.42	2.19	259	126	1.46×10^{11}	3.59×10^{11}	13,300	6.85×10^{-12}	1.60×10^{11}
	12,730	3,880	13,699	.173	2.42	2.19	260	127	1.52×10^{11}	3.72×10^{11}	13,500	6.60×10^{-12}	1.65×10^{11}
	12,764	3,890	12,658	.173	2.42	2.19	260	127	1.21×10^{11}	2.98×10^{11}	12,100	8.23×10^{-12}	1.32×10^{11}
	12,865	3,921	13,889	.172	2.43	2.19	262	128	1.58×10^{11}	3.88×10^{11}	13,800	6.33×10^{-12}	1.72×10^{11}
	12,889	3,929	12,987	.172	2.43	2.19	262	128	1.31×10^{11}	3.22×10^{11}	12,600	7.61×10^{-12}	1.43×10^{11}
	12,925	3,940	12,820	.172	2.43	2.19	263	128	1.27×10^{11}	3.11×10^{11}	12,300	7.90×10^{-12}	1.38×10^{11}
	13,012	3,966	13,334	.171	2.43	2.20	264	129	1.41×10^{11}	3.47×10^{11}	13,000	7.08×10^{-12}	1.54×10^{11}
	13,035	3,973	12,820	.171	2.43	2.20	265	129	1.26×10^{11}	3.10×10^{11}	12,300	7.93×10^{-12}	1.38×10^{11}
	13,320	4,060	12,658	.169	2.44	2.20	270	132	1.22×10^{11}	2.99×10^{11}	12,100	8.21×10^{-12}	1.33×10^{11}
	13,392	4,082	12,820	.169	2.44	2.20	272	133	1.26×10^{11}	3.10×10^{11}	12,300	7.91×10^{-12}	1.38×10^{11}
	13,498	4,114	12,346	.168	2.44	2.20	274	134	1.13×10^{11}	2.77×10^{11}	11,600	8.87×10^{-12}	1.23×10^{11}
	13,583	4,140	12,658	.167	2.44	2.21	276	136	1.21×10^{11}	2.97×10^{11}	12,000	8.26×10^{-12}	1.32×10^{11}
	13,710	4,179	13,334	.166	2.44	2.21	278	137	1.41×10^{11}	3.45×10^{11}	13,000	7.11×10^{-12}	1.53×10^{11}
	14,060	4,284	12,500	.164	2.45	2.22	285	141	1.17×10^{10}	2.86×10^{11}	11,800	8.57×10^{-12}	1.27×10^{11}
	14,104	4,299	11,765	.163	2.45	2.22	286	141	9.57×10^{10}	2.35×10^{11}	10,700	1.04×10^{-11}	1.04×10^{11}
	14,410	4,392	12,346	.159	2.46	2.23	293	145	1.12×10^{11}	2.74×10^{11}	11,500	8.95×10^{-12}	1.22×10^{11}
	14,498	4,419	12,500	.157	2.46	2.23	295	146	1.16×10^{11}	2.84×10^{11}	11,700	8.65×10^{-12}	1.26×10^{11}
	14,670	4,471	12,196	.155	2.46	2.24	298	148	1.07×10^{11}	2.62×10^{11}	11,200	9.38×10^{-12}	1.16×10^{11}
	14,718	4,486	12,500	.154	2.47	2.24	299	148	1.16×10^{11}	2.84×10^{11}	11,700	8.63×10^{-12}	1.26×10^{11}
2	14,684	4,476	12,987	.154	2.46	2.24	299	148	1.29×10^{11}	3.17×10^{11}	12,300	7.74×10^{-12}	1.41×10^{11}
	14,858	4,529	13,699	.152	2.47	2.25	302	150	1.52×10^{11}	3.72×10^{11}	13,400	6.60×10^{-12}	1.65×10^{11}
	14,878	4,535	12,987	.151	2.47	2.25	303	151	1.30×10^{11}	3.18×10^{11}	12,300	7.72×10^{-12}	1.41×10^{11}
	14,960	4,560	13,158	.150	2.47	2.25	304	151	1.35×10^{11}	3.31×10^{11}	12,600	7.43×10^{-12}	1.47×10^{11}
	15,000	4,572	12,987	.149	2.47	2.26	305	152	1.29×10^{11}	3.17×10^{11}	12,300	7.75×10^{-12}	1.41×10^{11}
	15,027	4,580	14,085	.149	2.47	2.26	306	152	1.63×10^{11}	4.01×10^{11}	13,800	6.12×10^{-12}	1.78×10^{11}
	15,125	4,610	13,518	.148	2.47	2.26	308	153	1.45×10^{11}	3.57×10^{11}	13,000	6.88×10^{-12}	1.59×10^{11}
	15,200	4,633	15,385	.146	2.48	2.26	309	154	2.07×10^{11}	5.09×10^{11}	15,600	4.83×10^{-12}	2.26×10^{11}
	15,382	4,688	15,152	.147	2.48	2.26	313	156	2.00×10^{11}	4.90×10^{11}	15,300	5.01×10^{-12}	2.18×10^{11}
	15,404	4,695	14,085	.143	2.48	2.27	314	157	1.64×10^{11}	4.02×10^{11}	13,800	6.11×10^{-12}	1.79×10^{11}
	15,432	4,704	14,493	.143	2.48	2.27	314	157	1.77×10^{11}	4.35×10^{11}	14,400	5.65×10^{-12}	1.93×10^{11}
	15,565	4,744	14,815	.141	2.48	2.28	317	158	1.88×10^{11}	4.60×10^{11}	14,800	5.33×10^{-12}	2.04×10^{11}
	15,620	4,761	15,385	.140	2.49	2.28	318	159	2.08×10^{11}	5.10×10^{11}	15,500	4.81×10^{-12}	2.27×10^{11}
	15,642	4,768	13,333	.140	2.49	2.28	319	159	1.40×10^{11}	3.44×10^{11}	12,800	7.13×10^{-12}	1.53×10^{11}

Table A1

(continued)

PB Well No.	Depth		V_p (Lbg) ft/sec	ϕ	ρ_b gm/cm ³	$\bar{\rho}_b$ gm/cm ³	T_e		$\bar{k}$ dynes/cm ²	$\bar{M}$ dynes/cm ²	$\bar{V}_p$ ft/sec	$\bar{C}_b$ cm ² /dyne	$\bar{G}_b$ dynes/cm ²
	Feet	Meters					°F	°C					
2	15,675	4,778	14,706	.139	2.49	2.28	320	160	1.85×10^{11}	4.53×10^{11}	14,600	5.42×10^{-12}	2.01×10^{11}
	15,723	4,792	14,286	.138	2.49	2.28	321	161	1.71×10^{11}	4.19×10^{11}	14,000	5.86×10^{-12}	1.86×10^{11}
	15,770	4,807	12,821	.138	2.49	2.28	322	161	1.24×10^{11}	3.05×10^{11}	12,000	8.06×10^{-12}	1.36×10^{11}
	15,950	4,862	13,333	.135	2.49	2.29	325	163	1.39×10^{11}	3.42×10^{11}	12,700	7.18×10^{-12}	1.52×10^{11}
	16,000	4,877	15,152	.134	2.49	2.29	326	163	1.99×10^{11}	4.89×10^{11}	15,100	5.02×10^{-12}	2.17×10^{11}
	16,050	4,892	15,385	.133	2.49	2.30	327	164	2.07×10^{11}	5.08×10^{11}	15,400	4.83×10^{-12}	2.26×10^{11}
	16,130	4,916	14,706	.132	2.50	2.30	329	165	1.85×10^{11}	4.53×10^{11}	14,600	5.42×10^{-12}	2.01×10^{11}
	16,190	4,935	13,889	.131	2.50	2.30	330	166	1.57×10^{11}	3.86×10^{11}	13,400	6.36×10^{-12}	1.72×10^{11}
	16,215	4,942	13,889	.131	2.50	2.30	331	166	1.57×10^{11}	3.86×10^{11}	13,400	6.36×10^{-12}	1.72×10^{11}
	16,295	4,967	14,493	.129	2.50	2.31	333	167	1.77×10^{11}	4.34×10^{11}	14,200	5.65×10^{-12}	1.93×10^{11}
	16,355	4,985	14,286	.129	2.50	2.31	334	168	1.70×10^{11}	4.17×10^{11}	13,900	5.88×10^{-12}	1.85×10^{11}
	16,410	5,002	14,925	.128	2.50	2.31	335	168	1.91×10^{11}	4.70×10^{11}	14,800	5.22×10^{-12}	2.09×10^{11}
	16,430	5,008	14,085	.127	2.50	2.31	336	169	1.63×10^{11}	4.00×10^{11}	13,600	6.14×10^{-12}	1.78×10^{11}

Table A2

Formation Fluid (Brine) Properties versus Depth,
Pleasant Bayou wells, Brazoria County, Texas

	Depth		V _f * ft/sec	Viscosity** cp	ρ_f 3 gm/cm ³	Salinity ppm NaCl (x 1,000)
	Feet	Meters				
PB Well #1	1,715	523	5,100	.72	1.01	27
	1,770	539	5,108	.72	1.01	28
	1,895	578	5,126	.72	1.01	29
	1,944	593	5,134	.72	1.01	29
	2,055	626	5,150	.72	1.01	31
	2,100	640	5,156	.71	1.01	31
	2,160	658	5,165	.71	1.01	32
	2,226	678	5,175	.71	1.01	32
	2,246	685	5,178	.70	1.01	32
	2,278	694	5,182	.70	1.01	33
	2,367	721	5,192	.70	1.01	34
	2,402	732	5,200	.70	1.01	34
	2,435	742	5,204	.70	1.01	34
	2,656	810	5,231	.69	1.01	37
	2,690	820	5,235	.69	1.01	37
	2,810	856	5,250	.69	1.01	38
	2,834	864	5,252	.69	1.01	38
	2,900	884	5,257	.69	1.01	39
	3,065	934	5,270	.67	1.01	41
	3,172	967	5,278	.67	1.01	43
	3,225	983	5,282	.66	1.01	45
	3,310	1,009	5,288	.66	1.02	46
	3,462	1,055	5,300	.66	1.02	49
	3,490	1,064	5,302	.65	1.02	50
	3,596	1,096	5,311	.65	1.02	52
	3,654	1,114	5,316	.65	1.02	53
	3,688	1,124	5,319	.65	1.02	54
	3,770	1,149	5,326	.64	1.02	55
	3,812	1,162	5,330	.64	1.03	56
	3,935	1,199	5,340	.64	1.03	59
	3,955	1,205	5,342	.64	1.04	59
	3,980	1,213	5,344	.63	1.04	60
	4,054	1,236	5,350	.63	1.04	61
	4,078	1,243	5,352	.63	1.04	62
	4,118	1,255	5,357	.63	1.04	63
	4,230	1,289	5,368	.62	1.04	66
	4,275	1,303	5,373	.62	1.05	67
	4,331	1,320	5,378	.62	1.05	68
	4,385	1,337	5,384	.62	1.05	69
	4,425	1,349	5,388	.62	1.05	70
	4,445	1,355	5,390	.62	1.05	71

Table A2

(continued)

	Depth		V _f * ft/sec	Viscosity** cp	ρ _f 3 gm/cm ³	Salinity ppm NaCl (x 1,000)
	Feet	Meters				
PB Well #1	4,525	1,379	5,400	.61	1.06	73
	4,575	1,394	5,402	.61	1.06	74
	4,630	1,411	5,405	.61	1.06	75
	4,685	1,428	5,408	.61	1.06	76
	4,725	1,440	5,410	.60	1.06	77
	4,754	1,449	5,411	.60	1.06	78
	4,782	1,458	5,412	.60	1.06	78
	5,148	1,569	5,430	.59	1.06	83
	5,277	1,608	5,437	.59	1.06	83
	5,375	1,638	5,441	.58	1.06	83
	5,410	1,649	5,443	.58	1.06	83
	5,555	1,693	5,450	.57	1.06	83
	5,594	1,705	5,451	.57	1.06	83
	5,763	1,757	5,456	.56	1.06	83
	5,833	1,778	5,458	.56	1.06	83
	5,950	1,814	5,461	.56	1.06	83
	5,985	1,824	5,462	.55	1.06	83
	6,095	1,858	5,465	.55	1.06	83
	6,135	1,870	5,466	.55	1.06	83
	6,155	1,876	5,467	.55	1.06	83
	6,195	1,888	5,468	.55	1.06	83
	6,242	1,903	5,469	.54	1.06	83
	6,272	1,912	5,470	.54	1.06	83
	6,324	1,928	5,471	.54	1.06	83
	6,365	1,940	5,473	.54	1.06	83
	6,408	1,953	5,474	.54	1.06	83
	6,445	1,964	5,475	.54	1.06	83
	6,470	1,972	5,477	.54	1.06	83
	6,518	1,987	5,479	.53	1.06	83
	6,610	2,015	5,481	.53	1.06	83
	6,665	2,031	5,482	.53	1.06	83
	6,722	2,049	5,483	.53	1.06	83
	6,757	2,060	5,486	.52	1.06	83
	6,840	2,085	5,487	.52	1.06	83
	6,885	2,099	5,488	.52	1.06	83
	6,935	2,114	5,490	.52	1.06	83
	6,995	2,132	5,490	.51	1.06	83
	7,020	2,140	5,490	.51	1.06	83
	7,056	2,151	5,490	.51	1.06	83
	7,085	2,160	5,490	.51	1.06	83
	7,170	2,185	5,490	.51	1.06	83
	7,494	2,284	5,490	.49	1.06	83

Table A2

(continued)

	Depth		V _f * ft/sec	Viscosity** cp	P _f 3 gm/cm ³	Salinity ppm NaCl (x 1,000)
	Feet	Meters				
PB Well #1	10,236	3,120	5,380	.39	1.02	29
	10,275	3,132	5,379	.38	1.02	29
	10,475	3,193	5,376	.38	1.02	30
	10,525	3,208	5,375	.37	1.02	30
	10,754	3,278	5,371	.37	1.02	31
	10,840	3,304	5,369	.36	1.02	31
	11,367	3,465	5,360	.34	1.02	35
	11,450	3,490	5,365	.34	1.02	36
	11,480	3,499	5,367	.34	1.02	37
	11,764	3,586	5,384	.33	1.02	40
	11,812	3,600	5,387	.32	1.02	40
	11,850	3,612	5,389	.32	1.02	41
	12,030	3,667	5,400	.31	1.03	42
	12,372	3,771	5,417	.30	1.03	48
	12,685	3,866	5,433	.29	1.03	53
	12,730	3,880	5,435	.29	1.03	53
	12,764	3,890	5,437	.29	1.03	54
	12,865	3,921	5,442	.28	1.03	55
	12,889	3,929	5,443	.28	1.03	55
	12,925	3,940	5,445	.28	1.03	56
	13,012	3,966	5,449	.28	1.03	57
	13,035	3,973	5,450	.27	1.04	58
	13,320	4,060	5,471	.26	1.04	63
	13,392	4,082	5,476	.26	1.04	65
	13,498	4,114	5,484	.26	1.04	67
	13,583	4,140	5,491	.25	1.05	68
	13,710	4,179	5,500	.25	1.05	71
	14,060	4,285	5,513	.23	1.05	78
	14,104	4,299	5,574	.23	1.06	79
	14,410	4,392	5,525	.22	1.06	88
	14,498	4,419	5,521	.22	1.07	91
	14,670	4,471	5,514	.21	1.07	96
	14,718	4,486	5,512	.21	1.07	98
PB Well #2	14,684	4,476	5,513	.21	1.08	96
	14,858	4,529	5,506	.20	1.08	103
	14,878	4,535	5,505	.20	1.08	104
	14,960	4,560	5,502	.20	1.08	107
	15,000	4,572	5,500	.20	1.09	108
	15,027	4,580	5,497	.20	1.09	109
	15,125	4,610	5,485	.19	1.09	111
	15,200	4,633	5,475	.19	1.09	112

Table A2

(continued)

	Depth		V_f^* ft/sec	Viscosity** cp	ρ_f^3 gm/cm ³	Salinity ppm NaCl (x 1,000)
	Feet	Meters				
PB Well #2	15,382	4,688	5,453	.18	1.09	116
	15,404	4,695	5,450	.18	1.09	116
	15,432	4,704	5,450	.18	1.09	117
	15,565	4,744	5,450	.17	1.09	120
	15,620	4,761	5,450	.17	1.09	120
	15,642	4,768	5,450	.17	1.09	120
	15,675	4,778	5,450	.17	1.09	120
	15,723	4,792	5,450	.17	1.09	120
	15,770	4,807	5,450	.17	1.09	120
	15,950	4,862	5,450	.16	1.09	120
	16,000	4,877	5,450	.16	1.09	120
	16,050	4,892	5,450	.16	1.09	120
	16,130	4,916	5,467	.15	1.09	120
	16,190	4,935	5,459	.15	1.09	120
	16,215	4,942	5,461	.15	1.09	120
	16,295	4,967	5,466	.15	1.09	120
	16,355	4,985	5,470	.14	1.09	120
	16,410	5,002	5,474	.14	1.09	120
	16,430	5,008	5,475	.14	1.09	120

*Brine velocity corrected for salinity, temperature, and pressure (Wyllie, M. R. J., 1957; Formation Evaluation Data Handbook, 1978).

**Brine viscosity corrected for salinity, temperature, and pressure (see fig. G4, p. 158, Matthews and Russell, 1967).

THE UNIVERSITY OF TEXAS AT AUSTIN
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University Station, Box X
Phone 512-471-1534
471-7721

February 6, 1980

Mr. Bob Holliday
Program Manager
Division of Geothermal Energy, RA-233
U.S. Department of Energy
M.S. 3344, Federal Building
12th and Pennsylvania, N.W.
Washington, D. C. 20461

Dear Bob:

The original tasks for the elastic properties project are listed with our comments and suggestions following each task listing. Some of the tasks, or portions of tasks, require data processing techniques that have not yet been developed and will require more time to complete than is presently being considered. More specifically, these long-term tasks refer to (1) methods for extracting shear transit times in shales (at any depth) and in shallow sandstones, (2) any task which requires the use of velocity survey data, and (3) work relating to determination of attenuation coefficients.

When the original tasks (revised herein) have been completed and a final report made, we hope that you will consider reviving the extension to this project that was submitted in July, 1979.

Three additional months of work will be required to accomplish the revised original tasks at a cost of \$28,738. The final termination date for the project will be May 31, 1980. Also, as discussed with you previously, I believe we should change the principal investigator at this time. This will allow the Bureau to administer the contract for the rest of the period.

Sincerely,

A handwritten signature in cursive script that reads "Bob Morton".

Robert A. Morton
Geothermal Coordinator

RAM:lh

cc: K. Westhusing
R. Stearns
M. Dorfman

A Proposal to Extend
a study of

**EFFECTS OF GEOPRESSURED GEOTHERMAL
SUBSURFACE ENVIRONMENT ON ELASTIC
PROPERTIES OF TEXAS GULF COAST SANDSTONES
AND SHALES USING WELL LOGS, CORE DATA,
AND VELOCITY SURVEYS**

Submitted to

U.S. Department of Energy

by

Bureau of Economic Geology
The University of Texas at Austin
University Station, P. O. Box X
Austin, Texas 78712

Extension period: 3/1/80-5/31/80
Amount requested: \$28,738

Endorsements

R. A. Morton
Principal Investigator

W. L. Fisher, Director
Bureau of Economic Geology

G. J. Fonken
Vice President for Research
The University of Texas at Austin

ELASTIC PROPERTIES PROJECT

Part 1 - Listing of Tasks from Appendix to Original Proposal

C. 1. Program 1

Tasks using well log and velocity survey data only, (10 months). (Figures, equations, and sections referred to below are found in the original proposal).

- C. 1a. Use compressional wave velocities from sonic log to determine porosity as a function of depth according to the time average relationship described in Section B. 3f. Determine compaction correction factor C_p (equation 13) using core analysis porosity data for the geopressed sandstones. Relate corrected porosity to permeability of formations derived from core analysis and from pressure buildup data.

BEG: This task has been completed in draft form.

- C. 1b. Determine density versus depth from formation density log for brine-saturated sandstones and shales as shown in Figure 10 and discussed in Section B. 3g. Comparisons will also be made with lithology-velocity-density plots (Fig. 9).

BEG: Compensated formation density and neutron logs were run in the No. 1 Pleasant Bayou well in the depth interval 1,315-8,478 ft and in the No. 2 Pleasant Bayou well in the interval 14,259-16,474 ft. No neutron or density

logs were run in the middle portion (8,478-14,259 ft) of either hole to the best of our knowledge.

We will compute density ρ from the relation $\rho = 0.23V^{0.25}$ where velocity V will be obtained from the acoustilog run in the depth interval 8,481-14,758 ft in the No. 1 Pleasant Bayou. This will give fairly complete density information for the whole section, however we cannot predict how realistic the computed densities will be in the middle section. Comparisons will be made with published relationships between velocity and density.

- C. 1c. Determine shear velocity versus depth from wavetrain analysis of data from the Schlumberger long-spaced sonic log with wavetrain digitizing module. We hope to obtain variable density displays from Schlumberger showing both P-wave and S-wave arrivals. Shear wave velocities from velocity survey (section D.8) will also be obtained from comparison with well log data.

BEG: The first part of this task will be done by Anderson (student of Dr. Backus) for selected sandstones in the deepest 500 ft of No. 2 Pleasant Bayou. He will obtain both P-wave and S-wave transit times for sandstones from the long-spaced -sonic-log wavetrains. Only P-wave arrivals can be identified in shales at this time. If an extension to this contract is approved, an effort will be made to identify shear wave arrivals in shales and shallow sandstones by data processing techniques.

No variable density displays were obtained from Schlumberger but these are being made with the UT Phoenix computer.

We will not be able to obtain shear wave velocities from the velocity survey since a horizontal source was not available for use.

- C. 1d. Determine P- and S-wave reflection coefficient R as a function of depth for the geothermal test well at shale-sand-shale interfaces as discussed in section B. 3i and illustrated in Figure 13. Determine reflectivity $R_i(t, z_i)$ and acoustic impedance versus depth from three component geophone as discussed in section D. 16. Attempt three-dimensional description of geopressures, sand bodies and presence of free gas in geopressured zones.

BEG: P-wave reflection coefficients will be computed for shale-sand-shale interfaces in portions of the Pleasant Bayou wells where both velocity and density data are available. No velocity or density logs were run in the middle portion (8,478-14,259 ft) of No. 2 Pleasant Bayou.

S-wave reflection coefficients cannot be computed at sand-shale interfaces since shear velocities cannot be extracted for shales at this time.

The remainder of this task cannot be started until processed velocity survey data is received from Birdwell. Results would not be available in the short-time frame being considered here.

- C. 1e. Compute theoretical wave velocities at zero and infinite frequencies (equations 2 and 3, and Fig. 1). Look for evidence of dispersion at well log and seismic frequencies (section D. 16).

BEG: Equations 2 and 3, given in the original proposal, were developed by Geertsma and Smit in an effort to predict dispersion zones for frequencies used in well logging, seismic, and laboratory studies of sandstones of given porosity and permeability.

We will use these equations to look for evidence of dispersion at well log frequencies. Evidence will be based on criteria discussed by Geertsma and Smit.

- C. 1f. Compute V_p/V_s ratios and elastic moduli (bulk modulus, Young's modulus, shear modulus, Poisson's ratio and bulk compressibility) at depths where V_s from logs and clamped geophones can be determined. Relate above parameters to lithology, porosity, and show influence of geopressures and geotemperatures on elastic moduli. Prepare plots showing how elastic moduli change with depth (as in Figure 5) with SP log superimposed to indicate shale and sandstone zones. Look for anomalies in elastic moduli that may be related to leached porosity zones or free gas.

BEG: V_p/V_s ratios and elastic moduli (listed above) will be determined from well logs in depth intervals where shear velocity and density data are available. These parameters will be plotted versus depth with lithology, temperature, pressure, and porosity information also shown.

- C. 1g. Compute attenuation coefficients from relative amplitudes of digitized wave-trains from long-spaced sonic log and vertical seismic profiling data (sections B.2, D.9, D.10, and D.16). Attempt to relate attenuation to frequency, physical properties of reservoir rocks, and presence of gas as determined from well logs, core analysis, and production records.

BEG: This task cannot be done in the short time frame being considered here. The long-term approach to the problem was outlined in the proposed extension to this contract submitted to DOE in July, 1979.

- C. 1h. Review all data obtained from well logs and velocity survey to look for correlations between measured or computed parameters and the leached porosity zones that might be located by seismic exploration techniques. Plots similar to Figure 8 may be useful for detecting velocity anomalies.

BEG: Data from the velocity survey will not be available for this task in the short term.

- C. 1i. Interpret data, write monthly and final reports.

BEG: A final report will be written to satisfy the original tasks as revised herein.

Appendix C

**to Final Report on
Elastic Properties Project
May 1980**

**P-Wave and S-Wave Transit Times, No. 2 Pleasant Bayou,
Brazoria County, Texas (6S-39E-9)
Report No. 80-01**

by

Richard G. Anderson

Approved by Milo M. Backus

Appendix C

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Preface

by Milo M. Backus

Report 80-01 provides detailed information on the initial stage of detailed analysis of P-wave transit times observed on the conventional BHC sonic log and as deduced from analysis of full waveform digital sonic log data. This report covers only 500 ft at the bottom of the hole. This initial analysis of one segment of the hole provides insight into the measurement of P-wave transit time data and represents the initial stage of data preparation for more detailed analysis of P-wave amplitudes and waveforms and for the analysis of shear wave data.

Appendix C' shows the transit time data derived from the long-spaced sonic digital waveform data in conjunction with the other logs. Some observations may be made as follows.

(1) The sonic log derived by this method does not have the smoothing filter normally applied on the conventional BHC sonic log. The depth resolution is thus improved and is better than any of the other logs with the possible exception of the shallow-focused electrical log.

(2) On the basis of our analysis of the data, this sonic log has an instantaneous random error of about 2 microseconds/ft, and a bias which appears to be on the order of a small fraction of 1 microsecond/ft (see fig. 16 in report).

Thus, transit times integrated over 50 ft may be accurate to better than one-half percent. This accuracy should be adequate for evaluation of the dispersion issue. As indicated in Appendix E'* and in figure 16, the conventional BHC sonic is in agreement with the

*Appendix E', a computer printout, is not included in this report.

long-spaced sonic result to first order but still shows roughly a one percent bias due to very minor borehole alteration effects. This bias is in the opposite direction for the expected $1\frac{1}{2}$ to $3\frac{1}{2}$ percent dispersion effect discussed in the Gregory report. Since this portion of the hole is minimally altered (deepest part of hole), we conclude that detailed analysis of long-spaced sonic log data is necessary if we hope to test the dispersion issue by comparing sonic well log data with low frequency seismic data.

(3) A variable cable stretch between different tool runs is quite evident in this data and is illustrated in Appendix C'. Care must be used in comparing logs. This differential cable stretch must be accurately removed if digital cross plots are to be made.

(4) The near duplication of the neutron log and the sonic log in this geopressured clastic section is quite notable.

(5) The lack of duplication between FDC density and transit times clearly indicates the importance of including density in synthetic seismogram studies in this environment.

(6) The detailed relationship between the transit time data and lithology has not yet been studied.

Appendix D' represents the major output of this initial transit time study for this 500 ft interval. The digital waveforms are shown after time correction according to the times used for the computed transit times. The degree of alignment and duplication of the first arrivals provides simple, direct quality control on the picking process.

The first order P-wave amplitude variations due to coupling are readily apparent. The observation that Q-type loss effects are second

order is readily evident, so Q extraction will receive rather detailed processing.

The later arriving shear wave is apparent and is well-developed in the sands, which generally have a V_p/V_s ratio on the order of 1.7. A relative reduction in V_s and in shear wave amplitude in the shale intervals is evident. Detailed processing will be necessary to exploit the very key shale shear modulus data available in the data, and some shale sections may be untractable for shear modulus determination.

It is felt that analysis of the entire well in the manner illustrated here and the further detailed analysis of amplitude, waveform, and shear will be extremely valuable on this excellent set of digital waveform sonic data.

PLEASANT BAYOU #2
BRAZORIA COUNTY
TEXAS GULF COAST

Appendix C'

SARABAND BULK
VOLUME ANALYSIS
(by Schlumberger
using Dresser Atlas
Dual Induction)

CALIPER
(Dresser Atlas)

SPONTANEOUS
POTENTIAL
(Dresser Atlas)

DUAL INDUCTION
FOCUSED
(Dresser Atlas)

CALIPER
(Schlumberger)

GAMMA RAY
(Schlumberger)

COMPENSATED NEUTRON

(Schlumberger)

FORMATION DENSITY
(Schlumberger)

BORE HOLE COMPENSATED
TRANSIT TIME, LONG TOOL,
12 - 10 FT OFFSET

(U/T picks from Schlumberger log)

Appendix C

P-Wave and S-Wave Transit Times, No. 2 Pleasant Bayou, Brazoria County, Texas

Abstract

This report analyzes data from full waveform digital sonic logs run in GCO/DOE No. 2. Two tools were used: one with 12, 10, and 8 ft source-receiver offsets and one with 5 and 3 ft source-receiver offsets. The short tool has a greater tendency to tilt than the long tool. The BHC transit time from the long tool is unaffected by shale alteration, while the BHC transit time from the short tool is slightly increased by shale alteration. The effect of shale alteration is second order and is negligible for the purpose of qualitative well log interpretation. There is a differential cable stretch between the two tools which has a magnitude of up to 2.8 ft. A quantity can be calculated from the interval transit times that is more sensitive to borehole rugosity than the caliper log.

In this part of the well, the conventional BHC sonic provides reliable transit time data. The long-spaced digital waveform data has been brought to a stage appropriate for the subsequent detailed analysis of amplitude, waveform, and shear wave data.

Introduction

This report is a partial summary of work done during 1979-1980 by a University of Texas at Austin research team supervised by Dr. Milo M. Backus. The dataset analyzed was a suite of full waveform digital sonic logs from GCO/DOE No. 2 (Pleasant Bayou No. 2), a test geothermal well

located at the Austin Bayou Prospect in the Brazoria Fairway of the Texas Gulf Coast. The digital sonic log was recorded by Schlumberger in the 1,390 to 8,514 ft and 14,262 to 16,470 ft intervals. It was logged at 6 inch intervals with a sampling rate of 5 microseconds.

This report analyzes compressional (P) wave transit times in the 16,040 to 16,465 ft interval. This interval is below the geothermal production zone at 14,700 ft and is within the lower Frio Formation, an Oligocene sandstone-shale sequence.

P-Wave Arrival Time Picking

In order to determine the P-wave velocity, the arrival time of the first P-wave event must be determined. The fundamental problem that must be overcome is distinguishing this event from the noise. The noise has three components: a positive dc bias, a low frequency ac component, and a high frequency ac component. The first two components are artifacts of the tool and recording system hardware; the high frequency component is due to background noise. The low frequency component is probably caused by coupling between tool circuits. The electrical pulse that activates the source creates electromagnetic fields which induce an oscillation in the receiver circuits that decays with time. The amplitude of the noise is often on the same order of magnitude as the amplitude of the first peak of the P-wave; for this reason, picking methods are based on picking on or near the first trough.

The Schlumberger picking process is done in real time. It has the advantage of speed and low cost but the potential disadvantage of reduced accuracy. The log operator can vary the amplitude threshold at which picks are made during the logging operation to compensate for variations

in the signal-to-noise ratio or amplitude. However, if the changes are rapid, many bad picks could be made before the operator can take corrective action.

The U/T picking method is an interactive process between a computer operator and a SSC Phoenix computer (a CDC 6600 computer was also used in the process, but this was not necessary). The key computer program used is called Autopick (see Appendix A'*). Autopick uses an amplitude threshold equal to an operator-determined factor, multiplied by the average amplitude of the noise. Once the program has determined the approximate location of the first trough, it continues to search for the lowest point on that trough. An alternative approach would be to search for the first peak, but it is much more difficult to distinguish the peak from the noise. In intervals where the waveform is distorted by the interference of scattered waves with the first trough picking on the trough, inaccurate transit times can result; but in the interval examined in this report, this effect was not significant.

The advantage of the U/T picking process is that it is not done in real time, so the picking parameters can be adjusted for optimum results. Also, any bad picks made by Autopick can be corrected by the operator by using either hand picks or, as was done for this report, a computer program that corrects bad picks by interpolating transit times from adjacent accurate picks (see Appendix A'*). Figure 1 is a flowchart of the U/T picking process. The most significant step of the process is the display of the original waveforms after a static shift has been applied to align the first P-wave arrivals. This display permits a simple visual quality control of the process. Figure 2 shows examples of picking errors made by the Autopick program and the final corrected picks. The error due to

*Appendix A' is not included in this report.

interpolation is no larger than the error that can result from distortion of the waveform.

Results of U/T Transit Time Picking

In the depth interval covered by this report, two different sondes were used. Reel 3-1 has data from the sonde with 12, 10, and 8 ft source-receiver offsets (the long tool, fig. 3). Reel 3-9 has data from the sonde with 5 and 3 ft source-receiver offsets. The source-receiver geometry of the two tools is shown in figure 4.

The results of the U/T picking process are displayed in figures 5 and 6. Since the waveform recorded on all four channels has traversed almost the same path (ignoring differences due to different source-receiver offsets, tool tilt, etc.), the curves have roughly the same shape.

In all figures in this report, the depth decreases toward the right; this is also the direction that the tool moves during the logging operation. All figures in this report are plotted with a depth scale of 5 inches/100 ft to match the Schlumberger logs. All plots of borehole compensated (BHC) transit times use a time axis scale of 5 inches/(100 microseconds/ft) to match the Schlumberger logs. All plots of data resulting from borehole compensation calculations use an empirically determined depth corresponding to the depths on the Schlumberger conventional sonic log. Figures 5, 6, 7, and 8 use the depths recorded at the time the digital sonic was logged (the "U/T format" depth), which corresponds to the Phoenix format depths in figure 2 and Appendix D'. A more detailed explanation of depth conventions and formulae used is presented in Appendix B'.

The reproducibility of the picks can be checked by subtracting arrival times from channels with equal source-receiver offsets, after an appropriate depth shift has been applied so that the two source-receiver pairs are at the same depths. Figures 7 and 8 show the results of these calculations; hereafter, these quantities will be referred to as transit time differences (see Appendix B' for the calculations). Ideally, the differences should be zero; deviations from zero may indicate tool tilt, variations in tool position, variations in the source pulse, variations in the tool hardware from channel to channel, or errors in the picking process.

Figure 7 shows two transit time differences from the short tool, one for the two 5 ft channels and one for the two 3 ft channels. There is a low frequency oscillation in the interval 16,355 to 16,460 ft caused by a gradual change in tool tilt. The anomalous values at 16,246 and 16,105 ft are caused by sudden changes in tool tilt. There is a picking error on one of the 5 ft channels at 16,455.5 ft.

Figure 8 displays transit time differences for the short and long tool. There are no picking errors on the two 10 ft channels; the anomalous values on the 10 ft curve at 16,208.5, 16,249.0, and 16,117.0 ft are due to distorted waveforms with unusually long intervals between the peaks and troughs. The transit time differences from the two tools are practically independent.

Histograms of the transit time differences are shown in figure 9. The transit time difference from the long tool has a near-zero mean, while the transit time differences from the short tool have negative means. Because of the arithmetic involved (see Appendix B') and the tool geometry (see fig. 4), this implies that the short tool tends to tilt so that the top of the tool is closer to the center of the hole than the bottom of the tool. In this configuration, the wave recorded by the upper two channels must

travel a greater distance through the low velocity (190 microseconds/ft) borehole fluid than the wave recorded by the lower two channels. This is consistent with the geometry of a tool being dragged up an inclined hole by a cable attached to its top. The hole is 8 to 10 degrees off vertical in this interval, as determined by a gyroscope survey.

The mean of the 3 ft transit time difference is more negative than the mean of the 5 ft transit time difference, which implies that the 3 ft channels are affected by the tool tilt more than the 5 ft channels. This is also consistent with the tool geometry. Since the long tool is two to three times as long as the short tool, it has less clearance in the borehole and does not tilt as much as the short tool, so the 10 ft transit time difference has a near-zero mean.

Borehole Compensation Calculations

The borehole compensation (BHC) process consists of averaging the differences between transit times from different channels (see fig. 4 and Appendices A' and B'). The BHC process partially compensates for tool tilt, variations in tool position, and near-hole effects (borehole rugosity). Because of the sampling interval and arithmetic involved, the BHC transit time is digitized in 1.25 microsecond intervals. The long tool BHC calculation uses transit times from tool positions 10 ft apart and so does not allow the calculation of BHC transit times for the first 10 ft logged. The long tool data allows the calculation of two BHC transit times: one using the difference between the 12 and 10 ft channel transit times (the 12-10 ft BHC) and one using the difference between the 10 and 8 ft channel transit times (the 10-8 ft BHC). The BHC transit time for

the short tool will be referred to as the 5-3 ft BHC. Empirical tests show that the BHC transit time calculated from the long tool data using transit times from the deeper depth Z and the shallower depth Z-10 ft corresponds to the Schlumberger BHC transit time on the conventional log at a depth Z-12 ft. The BHC transit time calculation for the short tool using transit times from depth Z corresponds to the Schlumberger BHC transit time at a depth Z-2 ft. All BHC transit time data in this report are plotted using depths corresponding to the Schlumberger depths.

Results of Borehole Compensation Calculations

Figure 10 shows the two BHC transit times from the long tool. There is essentially no difference between the 12-10 and 10-8 ft BHC, which implies that the 8 ft offset is long enough so that the BHC transit time is not affected by near-hole alteration. Figure 11 shows one of the BHC transit times from the long tool and the BHC transit time from the short tool. The shift between the two curves in the intervals 16,465 to 16,415 and 16,125 to 16,090 is due to a differential cable stretch during the two logging operations. The differential cable stretch has a maximum of 2.8 ft. At the bottom of the hole (16,415 to 16,465 ft), the short tool was hanging up, and in the interval 16,090 to 16,125 ft, the long tool was hanging up. Since the two curves are fairly congruent (ignoring the differential cable stretch), the differences between the two tools do not have a major effect on the BHC transit time in this part of the hole.

Figure 12 shows the U/T BHC transit time from the long tool and the Schlumberger BHC transit time from the short tool. The U/T BHC transit time was smoothed by convolution with a (0.25, 0.50, 0.25) filter to give

it the smoothness of the Schlumberger BHC transit time. The differential cable stretch is evident, although an attempt was made to compensate for it when the Schlumberger log was traced off by applying a horizontal shift (the shift is constant over each 100 ft interval). Figure 13 shows the U/T 5-3 ft BHC transit time and the Schlumberger BHC transit time from the same tool. On both figure 12 and 13, the U/T BHC transit time is consistently higher than the Schlumberger BHC transit time. This is probably because the Schlumberger transit times are picked near the first zero crossing of the waveform and the U/T transit times are picked on the trough. Dispersion of seismic waves tends to spread out a wavelet as it propagates through the earth; if this effect is significant over a 2 ft interval, it could account for the difference between the two transit times. Distortion of the waveform, which usually increases the time interval between the peak and the trough, may also be a contributing factor.

The difference between the 12-10 and 10-8 ft BHC transit times is shown in figure 14. The two BHC transit times are in good agreement except for the intervals 16,415 to 16,460 and 16,085 to 16,110. Since these are the sections of the hole where the differential cable stretch is a maximum, it is possible that the cable stretch and the discrepancy between the two BHC transit times are related. The picking errors at 16,237.5 and 16,196.5 cause errors in the BHC transit time at two different depths because the BHC calculation for the long tool uses transit times from two tool positions 10 ft apart.

The difference between the BHC transit times from the long and short tool is shown in figure 15. The difference is greatest in the intervals where the differential cable stretch is a maximum.

Histograms of the differences between the three BHC transit times are shown in figure 16. Because of the differential cable stretch, the differences between the BHC transit times from the long and short tools have greater variances than the difference between the BHC transit times from the long tool. The differences between the BHC transit times from the long and short tool have negative means. Since the differential cable stretch cannot affect the mean for this many samples, this indicates that the short tool is recording slightly longer transit times than the long tool. This is because the long tool has a greater depth of penetration than the short tool and is less affected by shale alteration due to exposure to the drilling fluid, which makes the formation velocity lower near the hole. The 12-10 minus the 10-8 ft BHC transit time has zero mean, which implies that the 8 ft offset is long enough to avoid the effect of near-hole alteration. This figure suggests that a reasonable estimate of the error in the BHC transit time for the long tool is ± 2.5 microseconds/ft.

The BHC delta is defined as the difference between the two quantities (2 ft transit times) that are averaged to calculate the BHC transit time (for the calculation, see Appendix B'). The BHC deltas are plotted with the two caliper logs in figures 17 and 18. The two calipers are not in good agreement in this part of the hole, possibly because the hole does not have a circular cross section and the caliper arms made contact with different points on the side of the hole. The BHC deltas from the two tools are highly correlative, which implies that the deltas are responding to effects that are independent of the tool, i.e., borehole rugosity. Since the deltas are calculated using the arrival times of the minimum travel time event (which travels up the side of the hole nearest the tool), the deltas are only affected by the rugosity of the near wall; the rugosity

of the far wall affects the arrival times of later events. Because of the inclination of the hole, the two tools followed almost the same path up the side of the hole; if the hole was precisely vertical, the deltas from different tools would not be as highly correlative. A comparison of the BHC deltas and the calipers suggests that the deltas are more sensitive to borehole rugosity than the calipers.

Histograms of the BHC deltas are shown in figure 19. The variances are tool-independent since the deltas are measures of borehole rugosity. The delta from the short tool has a negative mean because the short tool has a greater tendency to tilt than the long tool.

Figure 20 shows the 12-10, 10-8, and 5-3 ft BHC transit times smoothed by convolution with a 50 ft long Gaussian curve. Because of end effects, the first and last 25 ft should be ignored. This smoothing approximates the resolution of the reflection seismogram and, assuming negligible density variation, simulates the impedance that the seismogram would see. This figure shows that the strongest reflector in this depth is the silty shale zone at about 16,325 ft.

Conventional well logs are presented in Appendix C'. The neutron and the sonic log are highly correlative. The (unsmoothed) sonic delineates the boundaries between beds more clearly than the other logs.

The waveform displays* of the P-wave aligned digital sonic are presented in Appendix D'. Timing lines are at 100 microsecond intervals. A detailed interpretation of these displays is beyond the scope of this report; instead, two simple examples are presented. There is a sharp transition from a silty shale zone to a silty sand zone at 16,149.5 ft; the effect of this transition zone is evident on the waveform displays at the Phoenix format depths 1,710 on the long tool and 1,620 on the short

*Waveform displays (Appendix D') are voluminous and are not included in most copies of this report.

tool. The amplitude of the wave is markedly reduced as the tools enter the transition zone because of scattering by the high impedance contrast. Another transition from a silty shale zone to a silty sand zone occurs at 16,301.0 to 16,303.5 ft. This transition zone is apparent at about 3,205 on the long tool waveform display and 3,095 on the short tool waveform display. There is a rapid increase in the shear wave velocity at this point, which is most easily distinguished on the two 10-ft channels (the two left channels on the long tool display). The shear wave usually has a higher amplitude than the P-wave. On channel 1 (the leftmost channel) of the long tool at 3,185, the first peak of the shear wave is on the ninth timing line from the left.

Conclusions

In General Crude Oil/Department of Energy Pleasant Bayou No. 2 in the interval 16,040 to 16,465 ft:

1. The error in the long tool BHC transit time is ± 2.5 micro-seconds/ft.
2. The BHC transit time from the short tool is slightly less accurate because of the (second order) effect of shale alteration. For qualitative well log interpretation, the difference between the BHC transit times from the long and short tools is negligible.
3. The short tool has a greater tendency to tilt than the long tool.
4. There was a differential cable stretch during the two logging operations involving the sonic tools of a magnitude less than or equal to 2.8 ft.

5. A quantity (the BHC delta) can be calculated from the transit times that is more sensitive to borehole rugosity than the caliper.

Acknowledgments

Many of the ideas in this report were developed during conversations with Dr. Milo M. Backus and John Castagna. Thanks are also due to Dave Mosely and Russ Andress for assistance with the data processing.

Figure 1. A flowchart of the U/T P wave picking process. The Autopick program and all plotting was executed on an SSC Phoenix computer. The data were transferred to a CDC 6600 computer at point A and were transferred back to the Phoenix at point B. The most important step is the final inspection and correction.

Figure 2. Examples of picking errors made by the Autopick program that were corrected by interpolating the transit times from adjacent accurate picks. The picking errors are marked by X's; the corrections are marked by C's. These data are all from the channel with the 12 foot source-receiver offset; picking is most difficult on this channel because of the low signal to noise ratio due to attenuation and scattering. Timing lines are at 100 microsecond intervals. The bottommost set of traces are a case where correctly picking the trough of the waveform led to misaligning the peak because the waveform is distorted.

Figure 3. The Schlumberger long sonic tool.

Figure 4.

$$\text{BHC transit time} = \frac{C + D}{4} \frac{\mu\text{sec}}{\text{ft}}$$

Figure 4. The source receiver geometry and method of bore hole compensating transit times for the long and short sonic tools. The essential differences between the two tools are:

- 1) The BHC transit time calculations for the long tool use transit times from two different tool positions. If tool tilt varies significantly over the ten foot interval the long tool BHC transit time calculation will not compensate for tool tilt as effectively as the calculation for the short tool.
- 2) The longer the source receiver offset the greater the depth of penetration of the wave. Therefore the short tool is affected more by near hole alteration than the long tool.

P WAVE TRANSIT TIME, LONG TOOL

UPPER 10 FT OFFSET=SOLID CURVE, LOWER 10 FT OFFSET=DASH, 8 FT OFFSET=DOT, 12 FT OFFSET=DOT-DASH

FIGURE 5.

The U/T picks of the arrival times of the first trough of the P wave for the long tool. The curves for the two 10 foot offsets are almost identical except for a two foot shift. The differences between them are due to tool tilt, variations in tool position, picking errors, or variations in tool hardware.

P WAVE TRANSIT TIMES, SHORT TOOL

UPPER 5 FT OFFSET=SOLID CURVE, LOWER 5 FT OFFSET=DOT-DASH,

UPPER 3 FT OFFSET=DOT, LOWER 3 FT OFFSET=DASH

FIGURE 6.

The U/T picks of the arrival time of the first trough of the P wave for the short tool. The curves for the two 3 foot offsets are almost identical except for a 5 foot shift; the curves for the two 5 foot offsets are almost identical except for a 3 foot shift. The differences between them are due to tool tilt, variations in tool position, picking errors, or variations in tool hardware.

P WAVE TRANSIT TIME DIFFERENCES, SHORT TOOL

5 FT DIFFERENCE=SOLID CURVE, 3 FT DIFFERENCE=DOT

FIGURE 7.

The transit time differences for the short tool. The upper 5 foot channel transit time at a given depth was subtracted from the lower 5 foot channel transit time at a depth 3 feet up the hole. The upper 3 foot channel transit time at a given depth was subtracted from the lower 3 foot channel transit time at a depth 5 feet up the hole.

There is a picking error on a 5 foot channel at 16455.5. The low frequency oscillation in the interval 16360 to 16430 feet is caused by tool tilt. The anomalous values at 16246 and 16105 are due to sudden changes in tool tilt.

P WAVE TRANSIT TIME DIFFERENCES, SHORT AND LONG TOOL

5 FT DIFFERENCE (SHORT TOOL)=SOLID CURVE, 10 FT DIFFERENCE (LONG TOOL)=DOT

FIGURE 8.

The transit time differences for the long tool and the short tool. The 5 foot difference is identical to the curve on figure 7; the 10 foot difference is the result of subtracting the upper 10 foot offset transit time at a given depth from the lower 10 foot transit time at a depth two feet up the hole. The anomalous values on the 10 foot curve at 16208.5, 16249.0, and 16117.0 are mispicks due to unusually long intervals between the peak and trough of the waveforms.

P WAVE TRANSIT TIME DIFFERENCES

Histograms of the transit time differences for the long and short tool. The sampling bins are 5 microseconds wide. The transit time difference for the long tool has a near zero mean while the transit time differences for the short tool have negative means. This indicates that the short tool has a tendency to tilt so that the top of the tool is closer to the center of the hole than the bottom of the tool. Because of the tool geometry the 3 foot difference is affected more by the tilt than the 5 foot difference.

FIGURE 9.

P WAVE BHC TRANSIT TIMES, LONG TOOL

10-8 FT OFFSET=SOLID CURVE, 12-10 FT OFFSET=DOT

DEPTH IN FEET (Schlumberger format)

FIGURE 10.

The bore hole compensated transit time using the U/T picks for the long tool. Since the BHC transit time is calculated by subtracting and averaging transit times it is less affected by bore hole rugosity, tool tilt, and picking errors than the original transit times. The most distinctive lithologic feature is the silty shale zone in the interval 10300 to 10340 feet.

P WAVE BHC TRANSIT TIME, LONG TOOL AND SHORT TOOL

LONG TOOL (12-10 FT OFFSET)=SOLID CURVE, SHORT TOOL (5-3 FT OFFSET)=DOT

DEPTH IN FEET (Schlumberger format)

FIGURE 11.

The bore hole compensated transit times for the long tool and the short tool. There is a differential cable stretch in the intervals 10415 to 10465 and 10090 to 10125 feet. The differential cable stretch has a maximum of 2.8 feet. The BHC transit time for the short tool is almost the same as the BHC transit time for the long tool, so to first order near hole alteration does not affect the BHC transit time.

P WAVE BHC TRANSIT TIME, U/T AND SCHLUMBERGER PICKS

SCHLUMBERGER PICK (SHORT TOOL)=SOLID CURVE, U/T PICK (LONG TOOL)=DOT

FIGURE 12.

The U/T picks of BHC transit time for the long tool and the Schlumberger picks of BHC transit time for the short tool. The U/T curve is the average of the 12-10 ft and 10-8 ft BHC transit time smoothed with a (.25, .5, .25) filter. An attempt was made to compensate for the differential cable stretch by applying a shift to the Schlumberger curve (constant for each 100 feet).

P WAVE BHC TRANSIT TIME, U/T AND SCHLUMBERGER PICKS

SCHLUMBERGER PICK (SHORT TOOL)=SOLID CURVE, U/T PICK (SHORT TOOL)=DASH

FIGURE 13.

The U/T and Schlumberger picks of BHC transit time for the short tool. The U/T curve is the 5-3 ft BHC transit time smoothed with a (.25, .5, .25) filter. Since both BHC transit times are from the same tool the differential cable stretch is not evident.

P WAVE 12-10 FT BHC TRANSIT TIME MINUS 10-8 FT BHC TRANSIT TIME

FIGURE 14.

The difference between the BHC transit time calculated using the 12 and 10 foot offsets and the BHC transit time calculated using the 10 and 8 foot offsets. The two BHC transit times are in good agreement except in the intervals where there is a differential cable stretch between the two tools (10420 to 10465 and 10085 to 10110 feet).

P WAVE BHC TRANSIT TIME FROM LONG TOOL MINUS BHC TT FROM SHORT TOOL

12-10 FT BHC TT MINUS 5-3 FT BHC = SOLID CURVE, 10-8 FT BHC MINUS 5-3 FT BHC = DOT

FIGURE 15.

The difference between the BHC transit time from the long tool and the short tool. The discrepancy between them is a maximum in the intervals where the differential cable stretch is a maximum.

P WAVE BHC TRANSIT TIME DIFFERENCES

Histograms of the difference between the BHC transit times from the long tool and the short tool. The sampling bins are 2.5 microseconds wide. Because of the cable stretch the differences between the BHC transit times from the long tool and short tool have larger variances than the difference between the BHC transit times from the long tool. The differences between the times from the long and short tool have negative means due to shale alteration, which increases the transit time.

FIGURE 16.

P WAVE BHC DELTAS, LONG TOOL

10-8 FT BHC DELTA=SOLID CURVE, 12-10 FT BHC=DOT

FIGURE 17

The difference between the two quantities (2 foot transit times) that are averaged to calculate the BHC transit time for the long tool. Deviations from zero indicate tool tilt, bore hole rugosity, variations in tool position, or picking errors.

P WAVE BHC DELTAS, LONG TOOL AND SHORT TOOL

5-3 FT BHC DELTA=SOLID CURVE, 12-10 FT BHC DELTA=DOT

FIGURE 18.

The difference between the two quantities (2 foot transit times) that are averaged to calculate the BHC transit time for the long tool and the short tool. Since the curves from two different logging operations are highly correlative, the deviations from zero are due mainly to bore hole rugosity.

P WAVE BHC DELTAS

Histograms of the P wave BHC deltas. The sampling bins are 2.5 microseconds wide. The delta from the short tool (5-3 foot offset) has a negative mean because the short tool has a tendency to tilt in a particular direction. The variances are equal because the delta is a measure of bore hole rugosity.

FIGURE 19.

P WAVE BHC TRANSIT TIME SMOOTHED WITH 50 FT GAUSSIAN CURVE

10-8 FT BHC TRANSIT TIME=SOLID, 12-10 FT BHC=DOT, 5-3 FT BHC=DASH

FIGURE 20.

The P wave BHC transit times from the long tool and short tool smoothed by convolution with a 50 foot Gaussian curve. This approximates the resolution of the reflection seismogram. The strongest reflector in this depth interval is the silty shale at 16325 feet.

Appendix B'

Depth Conventions and Formulae
Used in Calculations

Appendix B'

Depth Conventions and Formulae Used in Calculations

Depth Conventions

In all the formulae that follow, depth (Z) is positive upwards, i.e., Z+10 is 10 ft above Z. Since the tool moves up the hole during the logging operation, this convention is consistent with the way the data is formatted on tape. All depths are in feet and all transit times are in microseconds.

The raw transit times and transit time differences are plotted using "U/T format" depths, which correspond to the Phoenix format depths used on all full waveform displays. The conversion formula is:

$$\text{U/T format depth} = 16,000 + (\text{Phoenix format depth}) \times 0.1.$$

The relationship between the U/T format depth and the depths on the Schlumberger logs was determined empirically by aligning two BHC transit time plots on a light table. Since the BHC calculations for the two tools are different, there are two different conversion formulae. The long tool BHC transit time calculated from transit times at U/T depths Z and Z+10 corresponds to the BHC transit time at the Schlumberger depth Z+12. The BHC transit time from the short tool calculated from data at the U/T depth Z corresponds to the BHC transit time at the Schlumberger depth Z+12. All displays of data resulting from BHC calculations are displayed using the Schlumberger format depths.

Since the BHC calculation for the long tool uses data from two depths 10 ft apart, the BHC transit time cannot be calculated for the first 10 ft logged. For example, if data from the long tool is available over the interval 16,300 to 16,400 inclusive (U/T format depths), then the BHC

transit time can be calculated over the interval 16,298 to 16,378 inclusive (Schlumberger format depths). If data is available from the short tool over the interval 16,300 to 16,400 inclusive (U/T format depths), then the BHC transit time can be calculated over the interval 16,288 to 16,388 inclusive (Schlumberger format depths).

Whenever an interpreter is attempting to correlate between two logs, it is important to remember that there may be a cable stretch problem. In GCO/DOE Pleasant Bayou No. 2, a differential cable stretch was observed at about 16,450 ft with a magnitude of 2.8 ft.

Formulae Used in Transit Time Calculations

All depths are in feet and all times are in microseconds. Depth is positive upwards, i.e., depth Z+10 is 10 ft above depth Z. CH1(Z) refers to the transit time in microseconds recorded for channel 1 of a given tool. The source-receiver geometries for the two tools are:

Long Tool

- Channel 1 - upper 10 ft offset
- Channel 2 - 8 ft offset
- Channel 3 - 12 ft offset
- Channel 4 - lower 10 ft offset

Short Tool

- Channel 1 - upper 5 ft offset
- Channel 2 - upper 3 ft offset
- Channel 3 - lower 5 ft offset
- Channel 4 - lower 3 ft offset

Transit Time Differences

Long tool

$$1. \quad 10 \text{ ft difference } (Z) = CH4(Z) - CH1(Z-2)$$

Short tool

$$2a. \quad 5 \text{ ft difference } (Z) = CH1(Z) - CH4(Z-3)$$

$$2b. \quad 3 \text{ ft difference } (Z) = CH2(Z) - CH4(Z-5)$$

Borehole Compensated (BHC) Transit Times

Long tool

$$3a. \quad 10-8 \text{ ft BHC tt } (Z) = [(CH4(Z) - CH2(Z)) + (CH1(Z-10) - CH2(Z-10))]/4$$

$$3b. \quad 12-10 \text{ ft BHC tt } (Z) = [(CH3(Z) - CH1(Z)) + (CH3(Z-10) - CH4(Z-10))]/4$$

Short tool

$$4. \quad 5-3 \text{ ft BHC tt } (Z) = [(CH1(Z) - CH2(Z)) + (CH3(Z) - CH4(Z))]/4$$

Borehole Compensated (BHC) Deltas

Long tool

$$5a. \quad 10-8 \text{ ft BHC delta } (Z) = [(CH4(Z) - CH2(Z)) - (CH1(Z-10) - CH2(Z-10))]/2$$

$$5b. \quad 12-10 \text{ ft BHC delta } (Z) = [(CH3(Z) - CH1(Z)) - (CH3(Z-10) - CH4(Z-10))]/2$$

Short tool

$$6. \quad 5-3 \text{ ft BHC delta } (Z) = [(CH1(Z) - CH2(Z)) - (CH3(Z) - CH4(Z))]/2$$

Sampling Intervals

<u>Quantity</u>	<u>Sampling Interval (microseconds)</u>
Transit times	5
Transit time differences	5
BHC transit times	1.25
BHC deltas	2.5

Appendix C'

Well Log Data

Appendix D'

Full Waveform Digital Sonic Logs

Appendix D'

Full Waveform Digital Sonic Logs

The two foldouts* (attached to back cover) are full waveform displays of the digital sonic logs from General Crude Oil/Department of Energy Pleasant Bayou No. 2 over the interval 16,052.0 to 16,516.5 ft. Reel 3-9 (the short tool) covers a smaller interval (16,098.0 to 16,505.5 ft) than reel 3-1 (the long tool). The waveforms are truncated at the approximate arrival time of the mud wave (the wave that has traveled directly through the borehole fluid). Timing lines are at 100 microsecond intervals.

Each foldout has all four channels of data from each tool with the troughs of the first P-wave event aligned. The positions of the troughs are as follows:

Long Tool (Reel 3-1)

upper 10 ft channel	-	0.15 msec
lower 10 ft channel	-	1.65 msec
12 ft channel	-	3.15 msec
8 ft channel	-	4.95 msec

Short Tool (Reel 3-9)

upper 5 ft channel	-	0.33 msec
lower 5 ft channel	-	1.83 msec
lower 3 ft channel	-	3.33 msec
upper 3 ft channel	-	4.83 msec

*Waveform displays are bulky and have very limited distribution. Most copies of this report will not contain waveform displays.

The depths have been shifted so that all four traces on a given line have their upper component (source or receiver) at the same depth, ignoring the effect of tool tilt and cable stretch. Thus, the effect of a particular bed will be apparent on all four traces on a given line. However, since the longer offsets straddle more of the hole, they will also include effects from beds that do not appear on the shorter offsets.

Appendix F'

Integrated Transit Times

Appendix F'

Integrated Transit Times

The integrated transit times are between points where vertical seismic profile data was taken. The U/T data from the long tool is the average of the 12-10 and 10-8 ft BHC transit times; the U/T data from the short tool is the 5-3 ft BHC transit time. The Schlumberger data was obtained by counting tic marks that were placed every 2,000 microseconds on the print of the BHC transit time. It was also necessary to linearly interpolate the Schlumberger data. The attempt to hand digitize the VSP data failed because of the low quality of the data.

<u>Depth (feet)</u>	<u>U/T Pick (Long Tool) (microseconds)</u>	<u>U/T Pick (Short Tool) (microseconds)</u>	<u>Schlumberger Pick (Short Tool) (microseconds)</u>
16,400	-	-	-
16,375	3,868	3,916	3,704
16,350	4,120	3,831	3,774
16,275	11,759	11,891	11,842
16,274	166	144	142

Appendix G'

S-Wave Transit Times

This report summarizes the results of hand-picked shear wave transit times in the interval 16,198 to 16,120 ft in the General Crude Oil/Department of Energy No. 2 well (Pleasant Bayou No. 2). The depth conventions and formulae used are identical to the P-wave report.

Figures G'1 and G'2 show the transit time differences for the two tools. With the exception of a few obvious picking errors, these transit time differences are of the same order as those for the computer-picked P-wave transit times. As with the P-wave transit time differences, the greater tilt of the short tool gives the 5 and 3 ft transit times negative means, while the mean of the 10 ft curve from the long tool is near zero.

The S-wave BHC transit times are shown in figures G'3 and G'4. Two lithologies are apparent: a silty sand in the shallower interval and a silty shale in the deeper interval, separated by a sharp transition zone.

The differences between the BHC transit times are shown in figures G'5 and G'6. The differences are fairly small except at the sharp transition zone at 16,149 ft. The histograms (fig. G'7) show that the BHC transit times from the long tool are in good agreement; the BHC transit time from the short tool is slightly larger than those from the long tool due to shale hydration. The error in the BHC transit times from the long tool is ± 6 microseconds/ft.

One of the S-wave BHC transit times divided by 1.73 and a P-wave transit time are shown in figure G'8. Both transit times have similar responses to the various lithologies; the S-wave transit time changes more than the P-wave transit time.

Figures G'9 and G'10 show the P-wave to S-wave velocity ratio. In general, the ratio is higher in the shaly zone than it is in the sandy zone.

Histograms of the P-wave and S-wave BHC transit times are shown in figures G'11 and G'12. Because of the small number of samples, the histograms are fairly irregular. Since there are two primary lithologies present, each histogram should approximate two superimposed Gaussian curves, each with a different mean value. This is much easier to distinguish on the S-wave histograms than on the P-wave histograms; hence, it is easier to distinguish various lithologies by S-wave data than by P-wave data.

Histograms of the BHC deltas for P-waves and S-waves are shown in figures G'13 and G'14. Since the deltas are measures of borehole rugosity, their variances are nearly equal. The BHC deltas from the short tool have negative means because of tool tilt.

Further studies of shear wave transit times will be based on computer-picked transit times. After the shear wave has been enhanced by digital filtering, the transit time will be determined by cross correlation techniques.

S WAVE TRANSIT TIME DIFFERENCES, 5 FT=DOT, 3 FT=SOLID

S-Wave Figures

Appendix G'

Figure G'1

G'-4

S WAVE TRANSIT TIME DIFFERENCES, 10 FT=SOLID, 5 FT=DOT

Appendix G'

S-Wave Figures

Figure G'2

G'-5

LONG TOOL S WAVE BHC TRANSIT TIME, 10 FT=SOLID, 12 FT=DOT

S-Wave Figures

Appendix G'

Figure G'3

S WAVE BHC TT, SHORT TOOL(5 FT)=SOLID, LONG TOOL(10 FT)=DOT

Appendix G'

S-Wave Figures

Figure G'4

G'-7

S WAVE BHC DIFF, 12-10 MINUS 10-8=SOLID, 10-8 MINUS 5-3=DOT

Figure G'5

G'-8

S-Wave Figures

Appendix G'

S WAVE BHC DIFF, 12-10 MINUS 10-8=SOLID, 12-10 MINUS 5-3=DOT

S-Wave Figures

Appendix G'

Figure G'6

G'-9

Figure G'7

LONG TOOL 12-10 BHC, P WAVE=SOLID, S WAVE/1.73=DOT

Appendix G'
S-Wave Figures

Figure G'8

G'-11

BHC P TO S WAVE VELOCITY RATIO, 10-8 FT=DOT, 5-3 FT=SOLID

Figure G'9

G'-12

S-Wave Figures

Appendix G'

BHC P TO S WAVE VELOCITY RATIO, 12-10=SOLID, 10-8=DOT

Figure G'10

G'-13

S-Wave Figures

Appendix G'

Figure G'11

S WAVE 12-10 FT BHC

S WAVE 10-8 FT BHC

S WAVE 5-3 FT BHC

Figure G'13

S WAVE 10-8 BHC DELTA

S WAVE 12-10 BHC DELTA

S WAVE 5-3 BHC DELTA

Figure G'14

APPENDIX D

Special Core Analysis Study

for

BUREAU OF ECONOMIC GEOLOGY

**Pleasant Bayou No. 1 Well
Brazoria County, Texas**

CORE LABORATORIES, INC.

Special Core Analysis

October 23, 1979

Bureau of Economic Geology
University of Texas
Box X
Austin, Texas 78712

Attention: Mr. A. R. Gregory

Subject: Special Core Analysis Study
General Crude - D.O.E.
Pleasant Bayou No. 1 Well
Brazoria County, Texas
File Number: SCAL-78336-S

Gentlemen:

In telephone conversations with Mr. A. R. Gregory in July and August, 1978, Core Laboratories, Inc., was requested to perform the following tests: (1) Conventional Vertical Permeability to Air and Boyle's Law Porosity measurements, (2) Dry Bulk Density and Wet Bulk Density measurements, and (3) Acoustic Velocity measurements for both compression and shear waves measured under specified overburden pressures ranging from 1000 psi to 10,000 psi. In addition, photographs of oscilloscope wave patterns at the 2000 psi and 8000 psi measurements were requested. These tests were to be performed on sandstone and shale full-diameter well core segments recovered from the subject well. The cores used in this study are lithologically described as to sample number and depth on Page 1.

Twenty-one full-diameter well core segments were submitted in seven separate shipments from August through November, 1978. The segments represented depths ranging from 10,223 feet to 15,583 feet. Due to core size limitations for our acoustic velocity equipment it was necessary to reduce the core segment diameters to three inches. This was done using a lathe. After machining, the ends of the segments were trimmed normal to the vertical core axis. Each sample was extracted of any hydrocarbon traces with toluene, leached of salt with methyl alcohol and dried in a conventional oven. Vertical permeabilities to air and Boyle's law porosities were measured. Each of the samples was evacuated and saturated with a 45,000 ppm sodium chloride brine. Appropriate weight and volumetric measurements were made and both dry and wet bulk densities were calculated.

Bureau of Economic Geology
Pleasant Bayou No. 1 Well
Page Two

Eight of the samples were deemed unsuitable for the acoustic velocity test. Samples 5 (no depth was given for this sample but it was received with Samples 1 and 2), 6, 7, 8, 9, 14, and 21 were shale and sandy-shale lithologies which were badly weathered and no attempt was made to prepare these cores for the acoustic velocity test. Pieces of these samples were processed for porosity and dry and wet bulk density determinations. Samples 2, 11, and 16 failed along bedding planes after being saturated. All requested measurements which were possible were performed on these three samples. The permeability, porosity and bulk density data are presented on Page 2.

Each of the remaining eleven samples were placed in a specially designed core cell and hydrostatic overburden pressures were applied. Direct measurements of transit times were performed for both compression and shear waves under increasing overburden pressure increments of 1000 psi from 1000 psi through 10,000 psi. The results of these measurements are reported in tabular form on Pages 3 through 5, and in graphical form on Pages 6 and 7.

Polaroid photographs of oscilloscope wave-form patterns were taken for each sample for both compression and shear measurements at both 2000 psi and 8000 psi overburden pressures. An arrow on each photograph indicates the peak used in computing transit times. These photographs are presented on Pages 8 through 29 of copy one of this report.

The reported transit times are within the range of values expected for samples of sand and shaley-sand lithologies with the possible exception of Sample 12. The transit times for Sample 12 seem anomalously high. Remeasurements have confirmed the reported values and as can be seen in the photographs the peaks chosen for pulse arrival times are clearly the best selections. Upon examination of the core sample no structural or lithologic features which may explain this anomaly are readily apparent.

The shear wave transit times for Sample 10 under overburden pressures less than 4000 psi are anomalously high. All peaks were carefully tracked through all increasing overburden pressures. At overburden pressures equal to or greater than 4000 psi a very large and clear peak becomes visible as the indicator of wave arrival. Using its associated arrival time the computed transit times fall within normal values. Below 4000 psi, however, this peak completely disappears from the scan. The computed values of transit time for the lower overburden pressures are based on a peak which most clearly indicates wave arrival.

Bureau of Economic Geology
Pleasant Bayou No. 1 Well
Page Three

It was a pleasure working with the Bureau of Economic Geology on this study. Should you have any questions pertaining to these test results or if we can be of further assistance, please do not hesitate to contact us.

Very truly yours,

Core Laboratories, Inc.

A handwritten signature in dark ink, appearing to read "John M. Dacy", is written over the typed name and title.

John M. Dacy
For Duane L. Archer, Manager
Special Core Analysis

JMD:mc

7 cc. - Addressee

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS 75247

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Page 1 of 29
File SCAL-78336-S

Company Bureau of Economic Geology Formation _____
Well Pleasant Bayou No. 1 County Brazoria
Field _____ State Texas

Identification and Description of Samples

Sample Number	Depth, Feet	Lithological Description
1	10,223.5-10,224.5	Ss, dk gry, med gr, sl/calc, well indurated
2	10,266.5-10,267.5	Ss, gry, v/fn gr, calc, mod/indurated
5	Not Given	Sh, gry, mod/indurated
3	11,739	Ss, gry, fn gr, sl/calc, well indurated
4	11,771	Ss, gry, fn gr, sl/calc, well indurated
6	11,752	Sh, gry, mod/indurated
7	12,591-12,592	Sh, dk gry, mod/indurated
8	12,622	Sh, dk gry, mod/indurated
9	12,625	Sh, dk gry, mod/indurated
10	14,055.5-14,056.4	Ss, gry, fn gr, well indurated
11	14,068.1-14,068.8	Sh, gry, mod/indurated
12	14,096.5-14,097.5	Ss, lt gry, fn gr, well indurated, sl/calc
13	14,750	Ss, gry, crs gr, well indurated
14	14,755	Sh, dk gry, v/sandy, (laminations), frac
15	14,762.5-14,763	Ss, gry br, crs gr, well indurated
16	15,159.9	Sh, dk gry, sdy, fri
17	15,176.3-15,177.2	Ss, lt gry, fn gr, shly
18	15,179.7-15,180.5	Ss, gry, med gr, well indurated, shly
19	15,553.3-15,554	Ss, gry, fn gr, well indurated, shly/lam
20	15,559.8-60.5	Ss, lt gry, med gr, sl/calc, well indurated
21	15,583	Sh, dk gry, mod/indurated

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS 75247

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Page 2 of 29
File SCAL-78336-S

Permeability, Porosity and Density

<u>Sample Number</u>	<u>Depth, feet</u>	<u>Vertical Air Permeability, Millidarcies</u>	<u>Porosity, Percent</u>	<u>Dry Bulk Density</u>	<u>Wet Bulk Density</u>
1	10,223.5-10,224.5	0.13	13.2	2.13	2.32
2	10,266.5-10,267.5	0.02	4.4	2.45	2.48
5	Not given		8.1	2.46	2.54
3	11,739	42	22.9	2.02	2.23
4	11,771	89	19.5	2.12	2.32
6	11,752		8.3	2.46	2.54
7	12,591-12,592		7.3	2.45	2.53
8	12,622		6.6	2.47	2.54
9	12,625		7.6	2.44	2.51
10	14,055.5-14,056.4	17	21.3	1.97	2.28
11	14,068.1-14,068.8	<0.01	4.9	2.46	2.51
12	14,096.5-14,097.5	0.06	15.3	2.22	2.38
13	14,750	122	18.9	2.10	2.29
14	14,755		7.5	2.41	2.49
15	14,762.5-14,763	187	19.9	2.08	2.27
16	15,159.9	<0.01	4.5	2.49	2.54
17	15,176.3-15,177.2	0.10	11.2	2.26	2.38
18	15,179.7-15,180.5	0.27	13.5	2.28	2.41
19	15,553.3-15,554	0.03	10.5	2.36	2.47
20	15,559.8-15,560.5	<0.01	4.0	2.52	2.56
21	15,583		1.2	2.53	2.54

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS 75247

Page 3 of 29
File SCAL-78336-S

Acoustic Velocity Data

Sample Number:	<u>1</u>	<u>3</u>	<u>4</u>	<u>10</u>	<u>1</u>	<u>3</u>	<u>4</u>	<u>10</u>
Porosity, Percent:	13.2	22.9	19.5	21.3	13.2	22.9	19.5	21.3
Effective Overburden Pressure, PSI	Transit Time, Micro-Seconds/Ft.							
	Compression				Shear			
1000	91.54	93.55	93.49	90.03	142.91	215.73	146.21	373.58*
2000	86.54	92.56	88.15	86.13	136.91	211.75	139.81	361.08*
3000	83.55	89.08	84.95	84.56	132.91	201.81	135.54	354.82*
4000	82.05	87.09	81.75	83.78	130.91	193.86	129.13	162.56
5000	79.05	85.60	80.68	82.22	128.92	191.87	129.13	159.44
6000	77.05	84.60	78.55	81.44	126.92	185.91	127.00	156.31
7000	76.05	83.61	77.48	80.66	124.92	183.92	124.87	154.75
8000	75.05	83.11	77.48	80.66	124.92	181.93	124.87	153.18
9000	74.05	82.61	76.41	79.87	118.92	179.94	122.73	151.62
10,000	73.05	81.91	75.88	79.87	118.92	177.95	120.60	150.06

* See discussion of results

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS 75247

Page 4 of 29
File SCAL-78336-S

Acoustic Velocity Data

Sample Number:	<u>12</u>	<u>13</u>	<u>15</u>	<u>17</u>	<u>12</u>	<u>13</u>	<u>15</u>	<u>17</u>
Porosity, Percent:	15.3	18.9	19.9	11.2	15.3	18.9	19.9	11.2
Effective Overburden Pressure, PSI	<u>Transit Time, Micro-Seconds/Ft.</u>							
	<u>Compression</u>				<u>Shear</u>			
1000	97.53	85.83	84.71	80.71	271.78	135.36	209.75	130.80
2000	95.99	81.82	80.66	78.68	265.62	129.34	185.43	126.74
3000	94.97	78.31	78.63	77.67	261.52	125.33	179.35	124.72
4000	93.94	76.80	77.01	76.65	257.42	121.32	175.30	124.72
5000	92.92	75.30	76.61	75.64	253.32	119.32	175.30	122.69
6000	91.89	74.80	76.00	75.13	251.27	117.31	173.27	120.66
7000	91.38	74.80	75.79	73.61	247.16	117.31	171.25	120.66
8000	90.35	74.30	75.39	73.11	245.11	115.30	171.25	118.63
9000	88.81	74.30	75.19	72.60	241.01	115.30	169.22	118.63
10,000	88.30	73.80	75.19	72.09	236.91	115.30	169.22	116.60

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS 75247

Page 5 of 29
File SCAL-78336-S

Acoustic Velocity Data

Sample Number:	<u>18</u>	<u>19</u>	<u>20</u>	<u>18</u>	<u>19</u>	<u>20</u>
Porosity, Percent:	13.5	10.5	4.0	13.5	10.5	4.0
Effective Overburden Pressure, PSI	<u>Transit Time, Micro-Seconds/Ft.</u>					
	<u>Compression</u>			<u>Shear</u>		
1000	83.92	82.45	61.01	137.16	181.13	103.51
2000	80.87	81.70	60.74	127.00	178.64	100.78
3000	79.35	80.70	60.47	127.00	178.64	100.78
4000	77.83	79.95	60.47	124.97	176.14	100.78
5000	76.30	79.20	60.20	122.94	176.14	100.78
6000	75.29	78.20	59.92	120.90	176.14	100.78
7000	74.27	77.70	59.92	118.87	173.64	100.78
8000	73.76	76.95	59.92	118.87	173.64	99.42
9000	72.75	75.95	59.65	118.87	168.64	99.42
10,000	72.24	75.70	59.65	116.84	168.64	99.42

Company Bureau of Economic Geology Formation _____
Well Pleasant Bayou No. 1 County Brazoria
Field _____ State Texas

Acoustic Velocity
Compression 8000 psi Overburden

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS

Page 7 of 29
File SCAL-78336-S

Company Bureau of Economic Geology Formation _____
Well Pleasant Bayou No. 1 County Brazoria
Field _____ State Texas

Acoustic Velocity
Shear 8000 psi Overburden

Acoustic Velocity
Oscilloscope Photograph of Compression Wave

Sample Number: 10

Depth, feet:
14,055.5-14,056.4

Porosity, Percent:
21.3

2000 psi Overburden

8000 psi Overburden

Acoustic Velocity
Oscilloscope Photograph of Shear Wave

Sample Number: 10

Depth, feet:
14,055.5-14,056.4

Porosity, Percent:
21.3

2000 psi Overburden

8000 psi Overburden

CORE LABORATORIES, INC.

Special Core Analysis

July 24, 1980

Bureau of Economic Geology
University of Texas
Box X
Austin, Texas 78712

Attention: Mr. A. R. Gregory

Subject: Special Core Analysis Study
General Crude-D.O.E. Pleasant Bayou No. 2 Wildcat
Brazoria County, Texas
File Number: SCAL-79193-I

Gentlemen:

By telephone communication on July 31, 1979, Mr. A. R. Gregory of the Bureau of Economic Geology, requested that Core Laboratories, Inc., perform Acoustic Velocity Tests for both compressional and shear waves at specified overburden pressures on sandstone core material recovered from the subject well. In addition, Core Laboratories, Inc., was requested to obtain photographs of oscilloscope wave patterns at designated overburden pressure measuring points. Results of the requested analyses are submitted herein. One set of Polaroid photographs are presented as an appendix to copy one of this report. The samples tested are lithologically described and identified as to sample number and depth interval on Page 1. Results of gas-water relative permeability tests performed on plug-size samples from the subject well are presented in a separate report (File Number: SCAL-309-80090).

Six full-diameter core segments, representing depth intervals ranging from 14,696 feet to 15,665 feet, were submitted for use in this study. Due to core size limitations of the acoustic velocity equipment, it was necessary to reduce the core segment diameters to 3 inches, using a lathe. Following this procedure, the end of each segment was trimmed perpendicular to the vertical core axis. The samples were then extracted of hydrocarbons with injections of toluene, leached of salt with methyl alcohol, and dried. Air permeabilities and helium (Boyle's Law) porosities were determined for each of the six samples. The core segments were evacuated and saturated with a brine containing approximately 30,000 parts per million sodium chloride and 10,000 parts per million calcium chloride. Sample 7 (depth: 15,622 feet) fractured during saturation, and was therefore eliminated from further testing.

Bureau of Economic Geology
General Crude et. al, No. 2 Wildcat
Page Two

Each of the five remaining samples was placed in a specially designed core cell and hydrostatic overburden pressure was applied. Direct measurements of transit times were performed for both compressional and shear waves, under increasing overburden pressures ranging from 200 psi to 10,000 psi. Results of these measurements are reported in tabular form on Pages 2 and 3, and in graphical form on Pages 4 and 5. The reported transit times are within the range of values normally observed for samples of sand and shaley sand lithologies.

Polaroid photographs of oscilloscope wave form patterns were taken, for each sample, for both compressional and shear wave measurements at 2000 psi and 8000 psi overburden pressures. An arrow on each photograph indicates the peak used in computing transit times. These photographs are presented on Pages I through XII of the Appendix in copy one of this report.

It has been a pleasure to provide the Bureau of Economic Geology with this study. Should you have any questions or require further assistance, please do not hesitate to contact us.

Very truly yours,

Core Laboratories, Inc.

Maryam Mathis

Maryam Mathis
for Duane L. Archer, Manager
Special Core Analysis

MM:jf

7 cc. - Addressee

1 cc. - Myron H. Dorfman
University of Texas at Austin
Austin, Texas 78712

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS 75247

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Page 1 of 5
File SCAL-79193-I

Company Bureau of Economic Geology
Well General Crude D.O.E. Pleasant
Bayou No. 2 Wildcat

Formation _____
County Brazoria
State Texas

Identification and Description of Samples

<u>Sample Number</u>	<u>Depth, Feet</u>	<u>Lithological Description</u>
4	14696	Ss, gry-brn, med-fn gr, silica, mod/indurated
5	14700	Ss, gry-brn, med-fn gr, silica, mod/indurated
6	15617	Ss, gry-brn, med gr, silica, mod/indurated
7	15622	Sh, drk-gry, v/fn gr, fri/slatey
8	15648	Ss, lt gry-brn, med-fn gr, sl/calc, mod indurated
9	15665	Ss, gry-brn, med gr, sl/calc, mod/indurated

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS 75247

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Page 2 of 5
File SCAL-79193-I

Acoustic Velocity Data
Compression

Sample Number:	<u>4</u>	<u>5</u>	<u>6</u>	<u>8</u>	<u>9</u>
Porosity, Percent:	17.0	21.1	15.4	9.9	19.6
Effective Overburden Pressure, PSI	<u>Transit Time, Micro-Seconds/Ft.</u>				
200	-	-	-	-	-
1000	82.88	92.42	82.22	73.64	89.72
2000	79.87	85.63	76.73	69.69	84.78
3000	77.46	83.13	74.19	67.13	81.04
4000	75.42	81.05	72.08	65.75	80.04
5000	73.97	79.94	70.61	64.77	78.43
6000	72.89	79.11	69.76	64.17	77.44
7000	72.05	78.42	68.92	63.58	76.70
8000	71.45	77.86	68.28	62.79	75.58
9000	71.20	77.86	68.07	62.79	75.58
10,000	70.84	77.59	67.65	62.60	75.46

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS 75247

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Page 3 of 5
File SCAL-79193-I

Acoustic Velocity Data

Shear

Sample Number:

Porosity, Percent:

<u>4</u>	<u>5</u>	<u>6</u>	<u>8</u>	<u>9</u>
17.0	21.1	15.4	9.9	19.6

Effective Overburden
Pressure, PSI

Transit Time, Micro-Seconds/Ft.

200	-	-	-	-	-
1000	180.56	-	234.30	201.49	210.81
2000	173.35	180.27	217.41	187.69	205.85
3000	167.33	176.11	208.97	181.77	197.17
4000	160.10	170.56	204.75	177.83	190.97
5000	156.50	169.18	200.53	173.89	187.24
6000	152.88	167.79	196.30	171.92	184.76
7000	151.68	166.41	192.08	169.95	183.52
8000	149.27	166.41	189.97	167.98	181.04
9000	149.27	165.02	189.97	166.00	181.04
10,000	148.07	165.02	187.76	164.03	181.04

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS

Page 4 of 5
File SCAL-79193-I

Company Bureau of Economic Geology Formation _____
Well General Crude D.O.E. Pleasant County Brazoria
Bayou No. 2 Wildcat State Texas

8000 psi Overburden

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS

Page 5 of 5
File SCAL-79193-I

Company Bureau of Economic Geology Formation _____
Well General Crude D.O.E. Pleasant County Brazoria
Bayou No. 2 Wildcat State Texas

8000 psi Overburden