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COMPRESSIONAL WAVE CHARACTER IN GASSY, NEAR-SURFACE SEDIMENTS
IN SOUTHERN LOUISIANA DETERMINED FROM
VARIABLE FREQUENCY CROSS-WELL, BOREHOLE LOGGING,
AND SURFACE SEISMIC MEASUREMENTS*

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ABSTRACT

Velocity and attenuation data were used to test theoretical equations describing the frequency dependence of compressional wave velocity and attenuation through gas-rich sediments in coastal Louisiana. The cross-well data (obtained from a variable-frequency, cross-well seismic experiment using source frequencies of 1, 3, 5, and 7 kHz) were augmented with velocities derived from a nearby seismic refraction station using a low-frequency (<20 Hz) source. Velocities obtained from the borehole-sonic tool (18 kHz) were not used, because it is unclear at this time what signal phase was being detected. Energy at 1 and 3 kHz was successfully transmitted over distances from 3.69 to 30 m; the 5- and 7-kHz data were obtained only at distances up to 20 m.

Velocity tomograms were constructed for one borehole pair and covered a depth interval of 10-50 m. Results from the tomographic modeling indicate that gas-induced low velocities are present to depths of greater than 40 m. Analysis of the velocity dispersion suggests that gas-bubble resonance must be greater than 7 kHz, which is above the range of frequencies used in the experiment. Washout of the boreholes at depths above 15 m resulted in a degassed zone containing velocities higher than those indicated in both nearby refraction and reflection surveys.

Velocity and attenuation information were obtained for a low-velocity zone centered at a depth of approximately 18 m. Measured attenuations of 1.57, 2.95, and 3.24 dB/m for the 3-, 5-, and 7-kHz signals, respectively, were modeled along with the velocity data using a silt-clay sediment type. Density and porosity data for the model were obtained from the geophysical logs; the bulk and shear moduli were estimated from published relationships. Modeling results indicate that gas bubbles measuring 1 mm in diameter occupy at least 25% to 35% of the pore space.

INTRODUCTION

In-situ, cross-well seismic measurements, using a variable frequency source, have been used to augment seismic studies of the acoustic properties of Holocene and upper Pleistocene sediments in the Mississippi delta complex in coastal Louisiana (Figure 1). The cross-well data are used to determine the percentage of gas that is trapped within the pore space and to calibrate the regional seismic data that describe the spatial distribution of gas. Compressional wave velocity and attenuation measurements may prove to be a powerful tool in identifying high-subsidence areas and in providing estimates of the global contribution of the deltaic sediments to the methane gas budget.

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Figure 2. Bulk velocity of topstratum sediment constructed from refraction-derived velocities.

predict future areas of land loss. As part of the proper control, cross-well, in-situ, variable-frequency velocity and attenuation measurements of compressional seismic waves were used to produce a quantitative measure of gas concentration in these sediments.

GEOLOGY

The Mississippi deltaic plain is one of the most thoroughly studied fluvial systems in the world. Studies by Fisk (1944), Kolb and van Lopik (1958), and Frazier (1967) have laid the framework for understanding the chronology of delta lobe development. More recently, Roberts (1985), Suter et al. (1987), Boyd et al. (1989), and Kuecher (1994) have integrated studies of current sedimentary processes with observed sequences to provide greater insight into the dynamics that govern delta development and destruction.

Since mid-Cretaceous time, thick sequences of sediments have been funneled into the Gulf of Mexico by the Mississippi River (Mazzulo, 1986). These sequences reflected a series of marine transgressions and regressions (Frazier, 1967; Kolb and Van Lopik, 1958) that developed as a response to changes in sea level. The Mississippi River excavated broad, deep valleys in response to each of the major glacial episodes; these were followed by interglacial periods of valley fill and delta progradation (Kolb and Van Lopik, 1958).

The Late Wisconsin glacial stage began approximately 25,000 years ago and produced a sea level lowstand some 130 m below its present position around 17,000 years ago (Berryhill, 1986). An erosional surface was formed by both the downcutting of tributary streams and subaerial weathering of exposed Pleistocene sediments; the surface is now marked by a widespread oxidation surface (Fisk and McFarlan, 1955) and ravinement horizon (Kolb and Van Lopik, 1958). For the next 10,000 years, the sea level rose rapidly in response to the warmer climate, and the previously entrenched Mississippi River valley was backfilled with fluvial and deltaic deposits. The transgressive event ended approximately 7,000 years ago, and delta building by the Mississippi began to push out into the Gulf of Mexico (Frazier, 1967). A series of at least six, perhaps more, delta-building episodes occurred in the last 7,000 years of the Holocene Epoch (Frazier, 1967). Of these, the Lafourche delta and its associated sedimentary package are most relevant to this study because this formation subcrops throughout most of the research area.

The sequence of Holocene sediments (including the Lafourche delta), and the underlying Pleistocene erosional surface and sediments, is divided by Fisk (1944) into Topstratum (Holocene and Late Pleistocene) and Substratum (Pleistocene). Historically, the units have been classified on the basis of mean grain size (Kuecher et al., 1993) and mapped from drill hole data as the location of the first "hard pan" surface, or the first thick (>10 m) sequence of coarse sand (Kuecher, 1994). Roberts (1985) and Penland et al. (1988) suggest that, in areas where the Lafourche delta is thick, subsidence appears to be high; in areas where the Lafourche is thin, subsidence rates appear to be low. If these observations are correct, compaction

associated with the thickest parts of the Lafourche delta may account for a significant part of the overall subsidence of this area. Studies by Kuecher et al. (1993) and Kuecher (1994) examined the various facies within the Lafourche delta and determined that the peat, bay muds, and prodelta muds show the greatest potential for subsidence.

COMPRESSIONAL WAVE DISPERSION AND ATTENUATION

Dispersion of compressional seismic waves has been examined by many researchers; results show an increase in the waves' velocity with increasing frequency. The presence of gas complicates this relationship by introducing energy losses associated with resonance of interstitial gas bubbles (Anderson and Hampton, 1980a and 1980b). The acoustic effects of gas bubbles in liquids was first addressed by Minnaert (1933), who developed a fundamental relationship describing bubble pulsation on the basis of energy considerations. Anderson and Hampton (1980a and 1980b) extended this theory by modifying the equations to fit a gassy, unconsolidated sediment case.

The following "gas effects" on P-wave velocity (V_p) are predicted by theory: (1) V_p may be nearly an order of magnitude less than that for a gas-free equivalent sediment when the seismic energy propagates at frequencies below the gas bubble resonant frequency; (2) above gas bubble resonance frequency, the V_p is approximately equal to that of the gas-free sediment, and (3) at frequencies near the bubble resonance frequency, the V_p first approaches, then rises above, the velocity of an equivalent gas-free sediment.

Energy attenuation also varies with seismic wave frequency and is highest when the compressional wave propagates at frequencies near the gas bubble resonant frequency. Below gas bubble resonance, energy attenuation increases with increasing frequency. Scientists hope to be able to take advantage of this relationship.

Anderson and Hampton (1980a and 1980b) have developed a theory for predicting the V_p through gassy sediments. In their studies, they consider the case in which the gas forms a three-phase medium with the interstitial water and surrounding sediment, and where the gas is in the form of bubbles within the pore water. When such conditions are present, the velocity through the gassy medium is determined by the following equation:

$$\left(\frac{V_p}{V_{\text{gas}}}\right)^2 = \frac{1}{2} \left(\frac{K \times X_1}{\gamma P_o + 4/3 G} \right) \times \left\{ 1 \pm \left[1 + \left(\frac{K \times Y_1 / (\gamma P_o + 4/3 G)}{1 + K \times X_1 / (\gamma P_o + 4/3 G)} \right)^2 \right]^{1/2} \right\} \quad (1)$$

where

V_p = sound speed in water-saturated sediment	K = sediment bulk modulus (dyne/cm ²)
G = dynamic shear modulus (dyne/cm ²)	γ = ratio of specific heats of gas (1.403)
P_o = ambient pressure (in atmospheres)	P_o = P^* atm
P = 1.013e6 dyne/cm ² /atmosphere	atm = the pressure multiplier in atmospheres

The terms Y_1 and X_1 are determined by the following:

$$Y_1 = \frac{n_g \cdot d_*^2}{(1 - f_*^2) + 1 - d_*^2} \text{ and } X_1 = \frac{n_g (1 - f_*^2)}{(1 - f_*^2) + d_*^2} \quad (2)$$

Here

n_g = gas fraction	f_* = f/f_o
f = sound wave frequency	f_o = gas-bubble resonant frequency
d_* = $d \times f_*^2$	d = bubble-resonance damping term

The attenuation coefficient, α (in nepers/cm), is given by the following equation:

$$\alpha = \pi f \left(\frac{V_{\text{gas}}}{V_p^2} \right) \left[\frac{K \times Y_1}{\gamma P_o + 4/3 G} \right] \quad (3)$$

The terms in the equation are as defined above. For a spherically spreading wave, the amplitude (A) at some distance (r) is related to the attenuation coefficient (α) by the following (Waters, 1980):

$$A = \frac{A_o e^{-\alpha \cdot r}}{r} \quad (4)$$

where A_o is the initial amplitude of the seismic wave. Taking the LOG_{10} of both sides and rearranging yields the following relationship:

$$\text{LOG}_{10} [Ar] = -\alpha r + \text{LOG}_{10} [A_o] \quad (5)$$

The above equation describes α line whose slope is $-\alpha$ and intercept is A_o . If N amplitude measurements are obtained at distances $r_1, r_2, \dots, r_N$, then a least-squares, or best-fit line will give an estimate of α .

Equations (1) through (5) outline the many unknowns that exist and the calculation steps needed to model gas-rich, unconsolidated sediments. Equation (1) is used to model the compressional wave dispersion over the entire frequency bandwidth considered. Plots of frequency versus velocity for different material parameters and gas concentrations are constructed to estimate gas concentration. Equations (3) through (5) are implemented when attenuation data are available for the different frequencies used. Here, observed attenuation coefficients calculated using (5) are compared with the model results computed by using equation (3). In practice, both the velocity and attenuation dependence on frequency are simultaneously modeled to best constrain the results.

CROSS-WELL SEISMIC MEASUREMENTS

Data Acquisition

First-arrival and amplitude information were obtained using source frequencies of 1, 3, 5, and 7 kHz from the borehole and raypath geometries shown in Figure 3. Only boreholes B2, B3, and B4 were used in the cross-well experiment because B1 collapsed near the surface. Gamma-ray, sonic, neutron, and induction logs, however, were run in well B1 prior to its collapse. Borehole B2 had a total depth of 64 m (209 ft) and was spaced 10.32 m (33.86 ft) from borehole B3, which was drilled to a depth of 50 m (163 ft). The collapse of B1 required that an additional borehole, B4, be drilled; this borehole was advanced to a depth of 25 m (80 ft) and located 3.69 m (12.1 ft) from B2 (approximately 14 m from B3; see Figure 3). Cross-well seismic data obtained between the borehole pair (B2 and B3) form the basis for the V_p dispersion measurements. Cross-well seismic data collected between borehole pairs B2-B4, B2-B3, and B3-B4 are the framework for the attenuation-with-frequency component of the study.

Boreholes B1 and B2 were logged for deviation from vertical. Funds were not available to perform this test for boreholes B3 and B4, but the deviation log for borehole B2 indicates a total well deviation of 0.61 m to the north at a 64-m depth, and only 0.21 m north at a depth of 25 m. For a sound wave traveling at 1,200 m/s across a 10-m gap, the borehole deviations result in errors in velocity of 35 m/s at a 25-m depth, and 73 m/s at a 64-m depth. The bulk of the velocity and attenuation analyses were in the depth range of 10 to 45 m, so maximum velocity errors of approximately ± 50 m/s due to borehole deviation can be expected.

A piezoelectric, cylindrical, bender transducer, developed by Southwest Research Institute in San Antonio, Texas (Owen and Karisch, 1989), was used as the energy source for the seismic measurements. Transducer elements (the same type used for the source tool) were implemented as a pair of matched receivers. The bender tool is rated to operate in the frequency range of 500 to 5,000 Hz when driven at excitation levels of 10 to 12 kVa (Owen and Karisch, 1989). A frequency sweep test indicated that a 7-kHz signal could be detected between the boreholes.

Figure 3. Borehole and Raypath geometries.

An EG&G StrataView seismograph was used to record the seismic energy. Recording parameters consisted of a 400-Hz (8-dB/octave) low-cut filter (highest low-cut setting available), 0.0625-millisecond (ms) sampling interval, and a record length of 256 ms. No antialiasing filter (high-cut) was implemented because the sample interval used had a folding (Nyquist) frequency of 8 kHz, and the StrataView did not support high-cut filter settings above 2,500 Hz. To improve the signal-to-noise ratio, each record was stacked 16 times.

Four traces were recorded: two containing recorded interwell signals and two for the voltage and current used in the signal generator. Figure 4 shows example field records for a 1,000-Hz and 5,000-Hz source, respectively. A sine wave 2 ms in duration was chosen as the signal for the 1-, 3-, 5-, and 7-kHz frequencies used to allow the signal generator to develop the appropriate energy. In many cases, this short-duration sine wave was easy to identify on the shot records (see Figure 4). However, this signal may have masked important secondary arrivals in the seismic coda following the initial pulse.

The velocity measurements were derived from the shot receiver geometries labeled as "Tomo" in Figure 3, which was constructed by integrating the horizontal pass logging (HPL) and narrow aperture fan (NAF) recording parameters. For the HPL, shot points were spaced every 5 ft, with one receiver at an equivalent depth and the other 10 ft below. The NAF geometry constrained the raypaths to within 45° of horizontal. Attenuation measurements were obtained from NAF geometries between borehole pairs B2-B4 and B3-B4, and from HPL and NAF geometries between boreholes B2-B3. Only those geometries that resulted in nearly horizontal rays were used for amplitude analysis. This latter restriction was necessary because of energy losses that occurred at interface boundaries.

frame inelasticity on fine-grained, water-saturated sediment and compared his theoretical modeling with published attenuation data for fine- and coarse-grain, water-saturated sediment. A series of sediment models ranging from muds to sands resulted. The attenuations measured by this study are one to two orders of magnitude larger than those predicted for a fine-grained, water-saturated case (which includes ocean bottom silt-clay). The implication is that energy losses associated with interaction of the gas bubbles with the surrounding water and sediment cause the higher-than-expected attenuations.

DISCUSSION

The low-velocity, low-relative-amplitude zone centered at a depth of 18 m (see Figures 5A and 5B) was used in a simultaneous velocity/attenuation modeling algorithm. Both the gas concentration and gas bubble size were varied until theoretical velocity and attenuation values approached those measured in the cross-well experiment. For the gas bubble size, the decade range of 0.5 to 5.0 mm (Anderson and Hampton, 1980a) was used, and gas concentrations from 0.1% to 75% of the sediment pore space were considered.

The material parameters for the sediment model were developed on the basis of an average porosity of 60% and a bulk-density of 1.6 g/cm^3 , as determined from the geophysical logs for the modeled depth interval. Empirical relationships between the dynamic frame bulk modulus and sediment porosity (Hamilton, 1971) and the dynamic rigidity modulus and grain size (Anderson and Hampton, 1980b) were used to determine values for these moduli ($K=0.15 \text{ dyn/cm}^2$ and $G=0.25 \text{ dyn/cm}^2$). A lithostatic pressure field of 3 atmospheres was used.

Figures 6A and 6B show the results of modeling the silt-clay sediment for gas bubbles with a mean size of 1 mm in diameter. The measured velocity values in Figure 6A are plotted as error bars; a black dot represents the mean velocity. The velocity data at 20 Hz were obtained from a refraction profile located approximately 30 m from the borehole site. Measured attenuation values are plotted as black dots in Figure 6B. Two to three measurements were obtained for each frequency and, because of the plot dimensions, overlap one another for the 3-, 5-, and 7-kHz data. Also shown on Figures 6A and 6B are the velocity and attenuation values for gas concentrations of 10%, 20%, 40%, and 60%.

Figure 6. Velocity (A) and attenuation (B) results for a silt-clay sediment model. A gas-fraction of 25%-35% and bubble size of 1 mm is indicated. The parameters listed below were used for the model:

Frame Bulk Modulus	= $0.15 \times 10^{10} \text{ dyne/cm}^2$	Shear Modulus	= $0.25 \times 10^{10} \text{ dyne/cm}^2$
Grain Bulk Modulus	= $50 \times 10^{10} \text{ dyne/cm}^2$	Bubble Diameter	= 1 mm
Density	= 1.6 gm/cc	Porosity	= 60%
Gas Fraction	= 10% to 60%

Figure 4. Field records for the 1 and 5 kHz frequencies.

Velocity Tomography

First arrival times measured between boreholes B2 and B3 were input into the U.S. Bureau of Mines curved ray tomographic reconstruction program (BOMCRATR) (Tweeton et al., 1992) to generate velocity-with-depth tomograms for the 1-, 3-, 5-, and 7-kHz data sets. A total of 92 shot/receiver pairs comprised the 1-kHz data, 74 pairs the 3-kHz data, 82 pairs the 5-kHz data, and 67 data pairs the 7-kHz experiment. The total possible number of shot/receiver pairs was 92 (see Figure 3). Only a straight raypath solution was used because the curved ray solutions had shadow zone problems caused by large velocity contrasts near the surface.

The model parameters consisted of eleven horizontal nodes spanning 0 to 10.36 m (for a horizontal cell dimension of 1.036 m [3.4 ft]) and forty-one vertical nodes in a depth range from 3.05 m (10 ft) to 51.8 m (170 ft) (for a vertical cell dimension of 1.22 m [4 ft]). The cell dimensions compared favorably with the 1.52 m (5 ft) shot and receiver spacing used.

Tomographic inversion of the data was limited to a 400-2,500 m/s range, which was based on results from both the sonic log and nearby surface seismic experiments. Two starting models were used: the first consisted of a uniform field of cell nodes set to 1,250 m/s and the second used velocities from the sonic log. Both starting models converged to similar results.

Figure 5A shows the final velocity with depth obtained from the 1-, 3-, 5-, and 7-kHz data sets. Also shown is a "water velocity" of 1,500 m/s and the velocities derived from the sonic logs. The tomography velocities were computed by compressing each tomogram along the horizontal axis (averaging at each depth

Figure 5. Velocity with depth (A) and attenuation with depth (B) determined from the cross-well data for the 1-, 3-, 5-, and 7-kHz signal between boreholes B2 and B3. The zone at approximately 18 m in depth was used in the resultant models.

interval). The tomography-derived velocities detail several low-velocity zones, some of which are only hinted at by the sonic-log tool. The uppermost zone, centered at a depth of approximately 18 m, was used for a combined velocity and attenuation model.

A minor component of dispersion is observed in the data as a general increase in velocity with increasing frequency. The bulk of the dispersion occurs between the 1-kHz and 3-kHz data sets; the 3-, 5-, and 7-kHz data sets all tend to have similar velocities. The observed dispersion does not fit the theoretical models of Anderson and Hampton (1980b); this discrepancy is believed to be caused by experimental error.

Attenuation Measurements

Amplitude information obtained from cross-well data sets between borehole pairs B2-B3, B2-B4, and B3-B4 were used to determine attenuation coefficients at the different frequencies considered. Preliminary analysis indicated a strong dependency on ray path orientation for the B2-B4 and B3-B4 data sets; this dependency was attributed to energy losses across sediment layer boundaries. To reduce this raypath length dependency, amplitude information was obtained only from horizontal and subhorizontal traveling rays.

Figure 5B shows amplitude with depth variations for the 1-, 3-, 5-, and 7-kHz signals in borehole pair B2-B3. In each case, the amplitude value was corrected for spherical spreading and the LOG_{10} of this number was used. As expected, amplitudes tend to decrease with increasing frequency, yet variations in amplitude with depth detail different sedimentary zones (Figure 5B). A low-amplitude zone is depicted at a depth of 18 m, and has an equivalent low-velocity zone (see Figure 5A). Amplitudes again decrease below 30-35 m in depth, where low-velocity zones are present. There appears to be a direct correlation between low velocity and lower relative amplitude, perhaps indicating a gas effect. Only the zone at the 18-m depth was modeled because the intervals below 30 m were not covered with the B2-B4 and B3-B4 data sets (hole B4 was only 25 m in depth; see Figure 3).

For each frequency, the relative amplitudes obtained from each borehole pair were plotted against borehole separation. A best-fit line was drawn through the data points and the slope of the line was determined (from Equation 5). Attenuations of 1.57, 2.95, and 3.24 dB/m were obtained for the 3-, 5-, and 7-kHz data, respectively. The 1-kHz data had attenuations of 1.45 and 0.18 dB/m. The former value cannot be modeled by theory and is assumed to be in error; the latter value was obtained from the edges of the modeled zone.

Prior to assuming a gassy sediment model case, the range of attenuations observed was first compared to the case when gas is not present. Keller (1989) used a constant-Q Biot model to analyze the effect of

Gas concentrations of 25% to 35% are needed to match this sediment model with observed velocity and attenuation data. For the range of frequencies considered, the velocity data proved useful in estimating the percent of gas in the pore space; the theoretical curves below bubble resonance are relatively flat. Attenuation information, on the other hand, allows fine-tuning of the model by estimating the dominant gas bubble size.

CONCLUSIONS

The principal conclusions derived from this study are listed below:

1. Combined attenuation and velocity modeling using theories presented by Anderson and Hampton (1980a and 1980b) indicate that, for a silt-clay sediment model, gas concentrations of 25% to 35% of the pore space are required. The attenuation data also indicate that the dominant gas bubble size must be about 1 mm in diameter.
2. Attenuation modeling over the range of frequencies considered by this study show promise, but indicate that higher frequencies (or a greater range of frequencies) must be considered to adequately model the results. Attenuations of 1.57, 2.95, and 3.24 dB/m for the 3-, 5-, and 7-kHz seismic energy can be explained by the presence of gas at concentrations ranging from 25% to 35% of the available pore space (for a silt-clay sediment model with densities and porosities that closely resemble those of the modeled zone). The measured attenuations are one to two orders of magnitude greater than those published for unconsolidated, water-saturated fine-grain sediment (Keller, 1989)
3. Compressional-wave dispersion (velocity) modeling could not predict the gas-bubble resonant frequency because of the limited range of frequencies used. However, the theory used does suggest that, for a silt-clay sediment model, a gas concentration of 25% to 30% of the pore space is needed to match the observed velocities.
4. Low-velocity zones indicated in the interwell seismic transit time measurements, and hinted at in the sonic log data, correlate with zones of lower density and higher porosity (on the geophysical logs) and with zones of higher attenuation. These zones are interpreted to be organic horizons of silt-clay lithologies.
5. Energy values of 1 and 3 kHz were successfully transmitted over distances from 3.69 to 30 m between the boreholes. An upward limit of approximately 20 m is indicated for the 5- and 7-kHz-generated signals for the source used. It may be possible to improve these distances by signal stacking at a count greater than the 16 stacks used in this study.

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