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Gas-Rich Sediment and Coastal Wetland Loss in Louisiana*

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ABSTRACT

High rates of wetland loss in southern Louisiana provide the impetus for examining the role that trapped, biogenic gases play in regulating subsidence of coastal areas. A significant cause for wetland loss in this region is relative sea-level rise produced by sediment-volume reduction. Dewatering, grain reorientation and packing, and oxidation of organic-rich sediments are thought to be the main processes for volume loss. It is argued that natural and anthropogenic causes for sediment degasification play a critical role in sediment-volume reduction.

Compressional wave velocities were measured at 34 sites in both the abandoned (Holocene) and modern parts of the Mississippi Delta. A low-frequency source (<200 Hz) was used to maximize sound-wave dispersion caused by interstitial gas bubbles. Compressional wave velocities measured at low frequencies relative to the gas-bubble resonant-frequency undergo maximum change from the velocity for a gas-free sediment.

Seismic refraction studies and velocity measurements using standard reverse-spread profiling indicate that the upper 40-70 m of the sedimentary section has sound velocities significantly less than the speed of sound through water (1,500 m/s), despite the fact that the water table is within 3 m of the ground surface. The low-velocity zone has average velocities ranging from 800 to 1,150 m/s in the Holocene delta and from 900 to 1,300 m/s in the modern delta. Uphole traveltimes obtained from approximately 90 km of continuous-coverage, seismic reflection profiles yield velocity estimates that range from 900 to 1,300 m/s. First and secondary arrivals determined from the reflection profiles are currently being used to model the low-velocity zone.

Theoretical velocity modeling, using material properties consistent with observed sediment types, suggests that approximately 6-20% of the available pore space must be occupied by gas to account for the observed velocities. This gas is believed to be trapped in unconnected pore spaces to exist in the form of methane gas bubbles within the interstitial pore waters.

The trapped gas acts to buoy overlying sediment against subsidence. Any quick-release triggering mechanism for the gas, such as trenching, digging canals,

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or extensive drilling, could cause localized increases in subsidence rates. From an inspection of compressional velocities observed in Holocene and recent sediments in the Louisiana wetlands, a 3- to 4-m drop in elevation would occur if all the gas in a 60-m-thick section were quickly released.

INTRODUCTION

Regional, near-surface seismic data have been acquired in southern Louisiana by Argonne National Laboratory (ANL) in a project designed to determine the volume of gas stored in the shallow sediments. The gas-volume-velocity project is part of a research program investigating the high rates of coastline and wetland loss in Louisiana. The study area is approximately 11,000 square kilometers and encompasses both abandoned and modern Mississippi deltas (Figure 1). A total of 45 refraction stations were occupied during two field seasons, but only 34 sites yielded information on the total thickness of the Holocene section. In addition, first arrivals determined from existing industry seismic reflection profiles are being used to measure the velocity of the shallow sediments.

The initial study of McGinnis *et al.* (1991) found that natural gas in shallow sediments caused abnormally low velocities. They argued that degasification subsidence may play an important role in wetland loss in Louisiana. They suggested that the final height of the "degassed" column of sediment could be determined from the sediment's P-wave velocity, density, and shear and bulk moduli. McGinnis *et al.* (1992 a&b) indicated that velocity depression due to gas is ubiquitous throughout the wetland areas of Louisiana and that this low velocity zone extends to depths of 50-60 m. A correlation of one seismic profile with lithologic and sediment parameters from a nearby borehole suggests that the base of the low velocity zone approximates the Holocene-Pleistocene contact.

THEORY

Seismic wave propagation theory developed by Anderson and Hampton (1980 a&b) shows that compressional waves are dispersive in water-saturated, unconsolidated sediments when natural gas is present in the interstitial pore space. Compressional wave velocities (V_p) may reach 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. Above gas bubble resonance frequency, V_p is approximately equal to that of the gas-free sediment. In addition, at frequencies near the gas-bubble resonant frequency, the seismic wave velocity first approaches and then exceeds the velocity for an equivalent, gas-free saturated sediment.

This dispersive nature of compressional waves (P-waves) requires careful consideration of the energy source (signal frequency) used, so that velocity measurements can be compared between sites without regard to gas-bubble size. Figure 2 shows theoretical velocities for a 100-Hz sound wave propagating through a "harbor mud" at various gas concentrations and ambient pressures. The equations used to compute the curves in Figure 2 are described in Appendix A. Calculations were also performed for a 500-Hz sound wave, and theoretical velocities were within 5% of those shown in Figure 2. The resonant frequency for the gas bubbles varies from 9,000 Hz at 10% gas to approximately 12,800 Hz at 100% gas (i.e., all of the available pore space is filled).

Figure 1. Location map showing study area (rectangle) and distribution of Holocene and Pleistocene sediments.

Figure 2. Gas-induced changes in bulk velocity for a 100-Hz P-wave propagating through a harbor mud at ambient pressures of 1, 2, 5, and 10 atm. The equations used to calculate these curves are listed in Appendix A. A pressure of 10 atm is approximately equal to 88 m of water depth.

The "harbor mud" used in the calculations represents a mean sediment type for southern Louisiana. In this region, sediment type ranges from sands to clays. The ambient pressure of 10 atmospheres corresponds to approximately 88 m of water depth.

The low frequency P-waves used by this study are ideal for studying gas concentration in the Mississippi delta because, below a critical bubble resonant frequency, P-wave velocity no longer changes with frequency, but is a function of lithology and gas volume. P-waves propagating at frequencies up to 500-Hz in gassy sediments are applicable to gas-volume studies.

SURVEY DESIGN

The velocity-gas-content program required sampling a large area in order to compare sediment velocities between different parts of the Mississippi delta plain. A refraction station normally consisted of only a single, reversed spread of 24 geophones, though multispread profiles were recorded when time and conditions permitted. The shot geometry for each spread consisted of one center shot and up to three off-end shots fired in both the forward and reverse profile directions. The shot-receiver geometries used were designed so that either the GRM (Palmer, 1980) or the SIPT (Scott, 1973 & 1977) methods could be used to generate velocity and depth from the refraction data.

Receiver spacings of 10 m were predominantly used throughout the study, although 2 and 5 m spacings were used when it was necessary to accurately define shallower refractors. Two sites used both 10- and 50-m geophone intervals. The farthest shot-to-detector distance successfully used was approximately 1.2 km.

INSTRUMENTATION

An EG&G ES-2401 24-channel seismograph was used to record the refraction data in southern Louisiana. In most cases, a 60-Hz notch and a 250-Hz highcut filter were adequate to record first arrivals. In some cases, a more narrow bandwidth bandpass digital filter (10 Hz-70 Hz) was applied during the interpretation phase to reduce noise associated with wind and cultural activities.

A BISON Elastic Wave Generator (EWG) was used as the energy source for all 34 refraction stations. The EWG provided ample energy at dominant signal frequencies ranging from 5 to 70 Hz. Figure 3 shows an example refraction record obtained using the EWG as the energy source and using detectors spaced at 10-m intervals.

VELOCITY MEASUREMENTS

Analyses of the results from two refraction stations, Cocodrie and Belle Amie, and the uphole velocities obtained from the Amoco reflection profile JJG-288, are discussed in this section. Refer to Figure 4 for the location of these stations.

Record #8: Cocodrie Refraction Profile

Figure 3. Refraction record 8 from the Cocodrie station. The BISON EWG was used as the energy source and receiver spacing is 10 m. The shot-to-far-detector distance is 240 m. The heavy gray line indicates the first arrival energy (apparent velocities are noted).

Bulk Velocity of Holocene Sediments

Figure 4. Contour diagram constructed from 34 refraction stations showing the bulk P-wave velocity for the Holocene section. Low velocities correspond to zones of higher gas concentration. Bays from the Gulf of Mexico are represented by the stippled areas.

Cocodrie Refraction Station

The Cocodrie station was located at the gate to the Louisiana Universities Marine Consortium research center (LUMCON) and consists of two overlapping refraction spreads using 5- and 10-m detector spacings. The profile at this station was shot parallel to highway 56 and was oriented north-south. The 5-m detector spread consisted of two shots, offset 5 m from each end of the spread. The 10-m spread consisted of four off-end shots, with offsets of 10 and 470 m on either end of the profile.

Figure 5 shows the time-distance curves and resulting velocity-depth profile for the Cocodrie station. The GRM method was used to calculate refractor velocity and depth for the three layers interpreted from the data. The shallowest layer averages 3-4 m in thickness and probably represents the effect of the road bed on the near-surface marsh deposits. The next two layers have velocities of 1,025 and 1,500 m/s and are interpreted as Holocene and Pleistocene sediments, respectively. The Holocene-Pleistocene contact shown in Figure 5 ranges from 45 to 54 m in depth.

The interpretation of the Holocene-Pleistocene contact shown in Figure 5 is based on an analysis of a borehole approximately 120 m distant from the refraction profile. Both sonic and density logs were run in the borehole, and core analyses indicate that the depth to the Holocene-Pleistocene contact is 47 m. This depth corresponds to a change in velocity from 800 to 1,200 m/s for Holocene sediments to 1,560 m/s for Pleistocene sediments.

Belle Amie Refraction Station

The Belle Amie station was located on an abandoned road construction site approximately 2 km east of Bayou Lafourche (see Figure 4). The profile was constructed using two end-to-end refraction spreads with receiver spacings of 50 m. For each spread, a center shot and two 50 m offset shot points were used. The maximum shot-to-detector distance was 1,200 m.

Figure 6 shows the three-layer traveltime curves and resulting velocity-depth profile. The shallowest layer averages approximately 8 m thick and is interpreted to represent a combination of road bed and shallow marsh sediments. The second unit is inferred to be Holocene sediment and shows a north-to-south increase in velocity. A north-to-south increase in depth for the base-of-Holocene may indicate the presence of a buried alluvial valley.

Uphole Velocity Profile

Figure 7 depicts the "uphole velocities" obtained from the north-south oriented Amoco reflection profile, JJG-288 (see Figure 4 for location). The uphole times were converted to velocity by dividing the shot depth by the traveltime. Velocities computed by this method are probably higher than the true Holocene bulk velocity because traveltime path includes a portion of the Pleistocene section (the shots were placed below the base of the low-velocity layer). Of interest is that the gas-induced low velocity is not constrained to isolated pockets but is continuous over all of the study area. A similar analysis was performed on the east-west oriented profile (JIG-600), which also showed that the low velocity is continuous over the entire seismic profile.

An extremely-low-velocity zone (less than 800 m/s) is centered near shot point 400 (Figure 7) and corresponds to the western-most low-velocity anomaly in Figure 4. This correspondence in velocity suggests that using uphole and first-arrival times from industry seismic reflection profiles is a useful tool for estimating the gas fraction in the shallow sediments.

Figure 5. Time-distance graph and velocity-depth profile for the Cocodrie station. Overlapping spreads with 5- and 10-m spaced detectors were used to construct the profile. The farthest shot-to-detector offset was 470 m. Apparent velocities are indicated in m/s on the time-distance curves.

Figure 6. Time-distance graph and velocity-depth profile for the Belle Amie station. Geophone spacing equals 50 m, and the farthest shot-to-detector offset equals 1200 m. Apparent velocities are indicated in m/s on the time-distance curves. This figure illustrates how bulk velocity increases with increasing Holocene sediment thickness.

Figure 7. N-S velocity profile obtained by converting uphole traveltimes and shot depth into velocities. The low-velocity zone centered near shot point 400 corresponds to a two-station velocity anomaly shown in Figure 4. The spikiness of the plot results from uphole-time picking errors.

VELOCITY DISTRIBUTION

Figure 4 shows the regional velocity distribution for Holocene sediments constructed from 34 refraction stations. Gross variations in Holocene sediment velocity and two probable gas "hot spots," marked by exceptionally low velocities, are depicted the Figure. The velocity contours suggest a north-to-south increase in velocity that most probably is due to a bulk velocity increase associated with increasing Holocene sediment thickness and corresponding overburden pressure. If the velocity analysis were constrained to the upper 10 m of sediment, the picture would look greatly different.

Two low-velocity anomalies are observed in the west and southwest part of the region shown in Figure 4. The low-velocity anomaly centered on the western edge of the diagram is also observed on the uphole-traveltime velocity profile for reflection line JJG-288. Using the data in Figure 2 as a guide, a rough estimate for the amount of gas in this region would exceed 20% of the available pore space. The other low-velocity anomaly is constrained by only a single refraction station that was located along a road within the center of a salt marsh.

CONCLUSIONS

Specific conclusions drawn from research to date are

- 1) Coastal marsh and delta plain sediments of Louisiana are gas-rich as indicated by the abnormally low compressional wave velocities. Gas percentages of 6-20% of the available pore-space are indicated by the measured P-wave velocities.
- 2) Low-velocity P-waves may prove useful for determining the percent gas in the sediments because the velocity measurements are dependent on compressional wave dispersion associated with gas-bubble resonance.
- 3) Existing industry seismic reflection profiles contain vital velocity information for the shallow sediments. The seismic profiles will also allow spot velocity measurements to be tied directly from site to site.

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APPENDIX A

This appendix lists the basic equations and parameters used to generate the theoretical velocity curves shown in Figure 2. The equations have been incorporated into a FORTRAN computer program to allow modeling P-wave velocity for various sediment types, gas concentrations, and signal frequencies.

Anderson and Hampton (1980 a&b) derive formulas for computing the P-wave velocity through gas-bearing, water-saturated sediment. The calculations involve specifying the material properties of the sediment, the ambient pressure, the signal frequency, and the percent gas in the available pore space. The frequency at which the gas bubbles resonate is also determined.

For a nongaseous sediment, the velocity V_n can be computed by

$$V_n = \sqrt{\frac{(K_b + 4/3G)}{\rho_{sat}}} \quad (1)$$

where G = dynamic shear modulus (dyn/cm²),
 K_b = the bulk modulus of the nongas sediment,
and ρ_{sat} = bulk density of the water-saturated, nongas sediment.

The velocity through a gas-bearing equivalent $v(gas)$, is then determined by

$$V(gas) = \frac{V_n}{(1/2) [1 + K_x/D] \{ 1 + \sqrt{1 + [(K_y/D)/(1+K_x/D)]^2} \}^{1/2}} \quad (2)$$

where

$K_x = K_g * X_1$,
 $K_y = K_g * Y_1$,
 $D = y * P_o + (4/3) * G$
 y = ratio of specific heats of gas (=1.403),
 P_o = the ambient pressure (in atmospheres),
 K_g = the gas-modified bulk modulus for the sediment,

and $X1$ and $Y1$ are determined from equations (4).

Bulk moduli Kg and Kb are determined by the following

$$Kg = \frac{Km (Kf + Fg)}{(Kf + Fg)}, \quad Kb = \frac{Km (Kf + Fw)}{(Km + Fw)} \quad (3)$$

where

$$\begin{aligned} Fg &= K'w (Km - Kf) / [n (Km - K'w)], \\ Fw &= Kw (Km - Kf) / [n (Km - Kw)], \\ n &= \text{sediment porosity,} \\ Km &= \text{mineral particle bulk modulus,} \\ Kf &= \text{sediment frame bulk modulus,} \\ Kw &= \text{interstitial water bulk modulus,} \\ K'w &= \text{gas modified interstitial water bulk modulus computed by,} \\ &\quad Kw * y * Po / \{ng * Kw + (1 - ng) * y * Po\}, \end{aligned}$$

and ng = gas fraction (e.g. 0.1 = 10% of pore space is gas).

The terms $X1$ and $Y1$ used in equation 1 are determined from

$$Y1 = \frac{ng d^*2}{(1 - f^*2)^2 + d^*2} \quad X1 = \frac{ng (1 - f^*2)}{(1 - f^*2)^2 + d^*2} \quad (4)$$

where $f^* = f/fo$,

$$d^* = d \cdot f^*2,$$

f = seismic wave propagation frequency,

fo = gas-bubble resonant frequency,

and d = damping constant for gas-bubble resonance:

$$d = dr + df + dt,$$

dr = radiance loss term,

df = friction loss term, and

dt = thermal loss term.

The gas-bubble resonant frequency fo is calculated with

$$fo = \frac{1}{2\pi r} \sqrt{\frac{3 y P}{A P_{sat}} + \frac{4 G}{P_{sat}}} \quad (5)$$

where y , P_{sat} , and G are as above, and

r = gas-bubble radius

P = ambient pressure (1.013×10^6 dynes/cm² per atmosphere),

and A = gas polytropic coefficient. "A" ranges from 1.0 for adiabatic bubble compression to 1.403 for isothermal bubble compression.

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