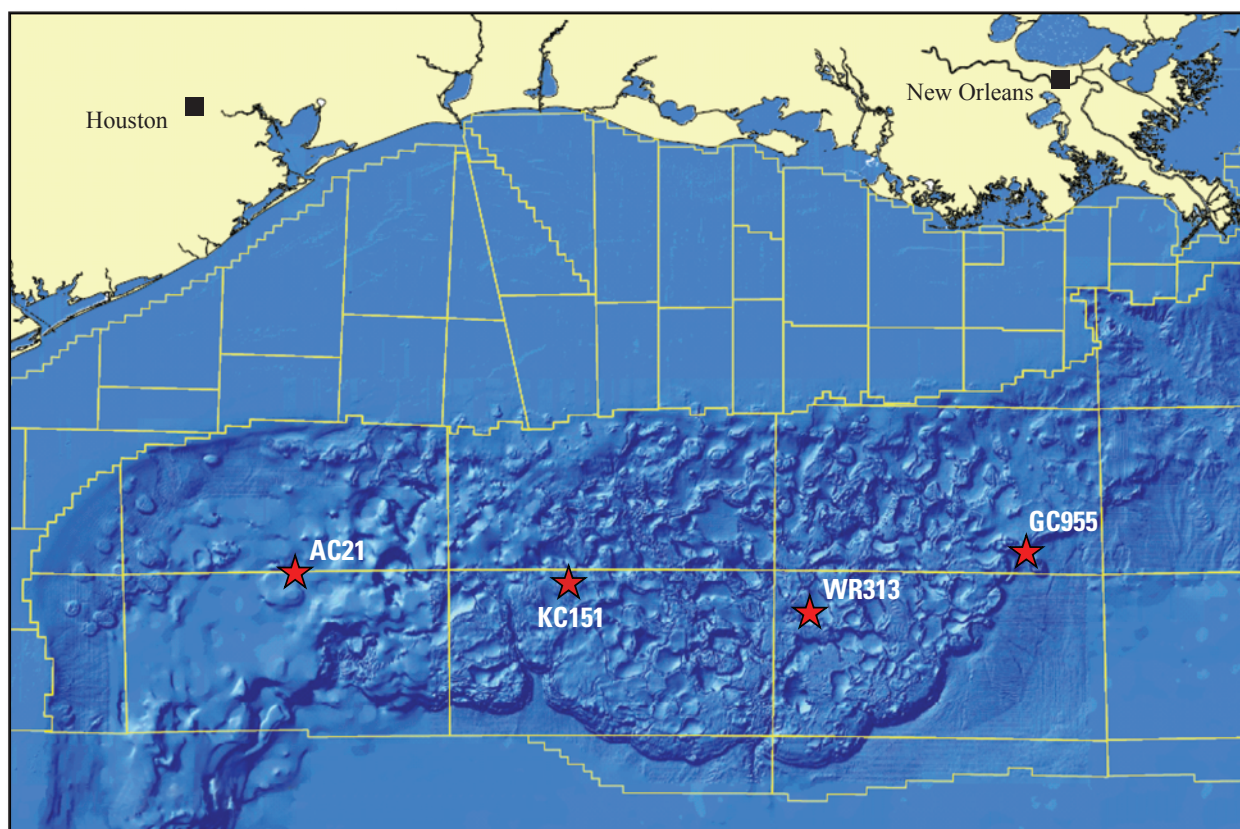# Comparison of Methods for Predicting Shear-Wave Velocities of Unconsolidated Shallow Sediments in the Gulf of Mexico

Comparison of Methods for Predicting Shear-Wave Velocities of Unconsolidated Shallow Sediments in the Gulf of Mexico

By Myung W. Lee

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit *http://www.usgs.gov* or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit *http://www.usgs.gov/pubprod*

To order this and other USGS information products, visit *http://store.usgs.gov*

Suggested citation:
Lee, M.W., 2013, Shear wave velocities of unconsolidated shallow sediments in the Gulf of Mexico: U.S. Geological Survey Scientific Investigations Report 2013–5141, 11 p., http://pubs.usgs.gov/sir/2013/5141/.

Acknowledgments

Contents

Figures

Comparison of Methods for Predicting Shear-Wave Velocities of Unconsolidated Shallow Sediments in the Gulf of Mexico

By Myung W. Lee

Abstract

Accurate shear-wave velocities for shallow sediments are important for a variety of seismic applications such as inversion and amplitude versus offset analysis. During the U.S. Department of Energy-sponsored Gas Hydrate Joint Industry Project Leg II, shear-wave velocities were measured at six wells in the Gulf of Mexico using the logging-while-drilling SonicScope acoustic tool. Because the tool measurement point was only 35 feet from the drill bit, the adverse effect of the borehole condition, which is severe for the shallow unconsolidated sediments in the Gulf of Mexico, was minimized and accurate shear-wave velocities of unconsolidated sediments were measured. Measured shear-wave velocities were compared with the shear-wave velocities predicted from the compressional-wave velocities using empirical formulas and the rock physics models based on the Biot-Gassmann theory, and the effectiveness of the two prediction methods was evaluated. Although the empirical equation derived from measured shear-wave data is accurate for predicting shear-wave velocities for depths greater than 500 feet in these wells, the three-phase Biot-Gassmann-theory -based theory appears to be optimum for predicting shear-wave velocities for shallow unconsolidated sediments in the Gulf of Mexico.

Introduction

Shear-wave (S-wave) velocities are essential in seismic modeling such as amplitude versus offset, multicomponent seismic analysis, and seismic inversion. Also, S-wave velocities are important in estimating mechanical properties of unconsolidated gas hydrate-bearing sediments (GHBS), which plays a key role in designing production test wells for the gas hydrates. Therefore, predicting, theoretically or empirically, the S-wave velocities from the compressional-wave (P-wave) velocities is needed, because S-wave velocities are rarely measured. Particularly for the study of GHBS, S-wave velocities of unconsolidated sediments at low effective pressure help to develop a more effective elastic inversion method (Lee, 2006a).

Castagna and others (1985) published an empirical relationship between S-wave velocities and the P-wave velocities for water-saturated clastic silicates, known as the mudrock line. The mudrock line can be used to derive S-wave velocities when other alternative relations are unavailable, but it underestimates S-wave velocity for unconsolidated sediment (Wang, 2000). A similar result is given by Han and others (1986). Wang (2000) introduced an empirical equation of predicting S-wave velocities, which depends on the bulk density of the saturated rock and the pore fluid modulus as well as the P-wave velocity. In contrast to the S-wave velocities predicted from Castagna and others (1985) or Han and others (1986), Wang's empirical method is valid for fluids other than water in the pore space.

Greenberg and Castagna (1992) proposed a semi-physical model based on the Biot-Gassmann theory (BGT) under the assumptions that there exists a robust relationship between P- and S-wave velocities and that nearly linear mixing laws for solid rock constituents are valid. By using laboratory measurements and well logs, they demonstrated that the precision and accuracy of S-wave velocity prediction are 9 percent and 3 percent, respectively.

Xu and White (1996) predicted S-wave velocities combining the Kuster and Toksöz theory (1974) and the differential effective medium theory (Cheng and Toksöz, 1979) and using pore-aspect ratios to characterize the compliance of the sand and clay components. They applied their method to the velocities measured at a differential pressure of 5 megaPascal (MPa) by Han and others (1986) and showed that the predicted S-wave velocities agreed well with the measured velocities (slight overestimation).

Jørstad and others (1999) compared S-wave velocities predicted from the inclusion-based effective medium theory to those estimated from empirical regressions at a North Sea reservoir. While effective medium theories are more complex than the statistical regression methods, they have the advantage of incorporating the effect of clay and pore geometry directly into the formulation. But Jørstad and others (1999) concluded that empirical methods are as effective as the inclusion-based methods and are more easily applicable.

Lee (2006b) predicted S-wave velocities using the BGT with a correction term, and Lee (2006c, 2010) used BGT with consolidation parameters to predict S-wave velocity from the

P-wave velocity and porosity. Because of the lack of S-wave velocities measured at effective pressure less than about 5 MPa, the effectiveness of each method for the shallow sediments was not rigorously investigated.

In 2009, the U.S. Department of Energy-sponsored Gas Hydrate Joint Industry Project Leg II (JIP Leg II) conducted logging-while-drilling (LWD) operations at three sites (Walker Ridge, Green Canyon, and Alaminos Canyon) in the northern Gulf of Mexico (fig. 1; Boswell and others, 2009). These locations were identified primarily from 3-D seismic data to test geological and geophysical interpretation methods to prospect for gas hydrate-bearing sand reservoirs (Hutchinson and others, 2009; Shedd and others, 2009). During this expedition, a suite of LWD well logs, including S-wave velocities at shallow depths, was acquired.

The purpose of this paper is to present the LWD logging data acquired during JIP Leg II, along with laboratory data by Zimmer (2003) and Lee and others (2008) used to investigate and compare the prediction methods for S-wave velocities applicable at low effective pressure of unconsolidated shallow sediments. This paper also presents an effective method for predicting S-wave velocities of GHBS, which can be used to estimate the dynamic moduli of GHBS.

Descriptions of Data

The S-wave velocities were acquired using SonicScope (Schlumberger's newer generation acoustic tool, Mrozewski and others, 2009) at the Walker Ridge well site (WR 313−H

well located at a water depth of 6,450 feet (ft) or 1,966 meters (m)), the Alaminos Canyon site (AC21−A well located at a water depth of 4,889 ft or 1,490 m, and AC21−B located at a water depth of 4,883 ft or 1,488 m), and the Green Canyon site (GC 955−H well located at a water depth of 6,670 ft or 2,033 m, GC 955−I located at the water depth of 6, 822 ft or 2,079 m, and GC955−Q located at a water depth of 6,516 ft or 1,986 m) (fig. 1). The measurement point on the tool was located 35.45 ft (10.8 m) from the drill bit, and it was the closest tool in the LWD logging assembly. Because of the short distance from the drill bit, the adverse effects of the borehole such as washout were minimized for the SonicScope data. The P-wave velocities were estimated from the waveform in the frequency range of 2.5–4.5 kiloherz (KHz), and S-wave velocities were processed using frequencies less than 3 KHz. Although high-quality P-wave velocities were acquired throughout the logged interval (Guerin and others, 2009), the S-wave velocities were only interpretable in limited depth ranges due to the low signal-to-noise ratio of the shear arrivals. In spite of this limitation of the S-wave velocity, the LWD S-wave data provided a critical dataset to be used to model S-wave velocities of shallow sediments in the Gulf of Mexico (GOM).

The shallowest sediment measured by SonicScope was at the AC21–A well at a depth of 468 feet below sea floor (fbsf), which corresponds to an effective pressure of about 1.5 MPa. To constrain S-wave velocities for effective pressure less than about 1.5 MPa, S-wave velocities measured for reconstituted sediments at Keathley Canyon lease block 151 (KC151) at 4,369 ft (1,323 m) water depth, in the northern Gulf of Mexico
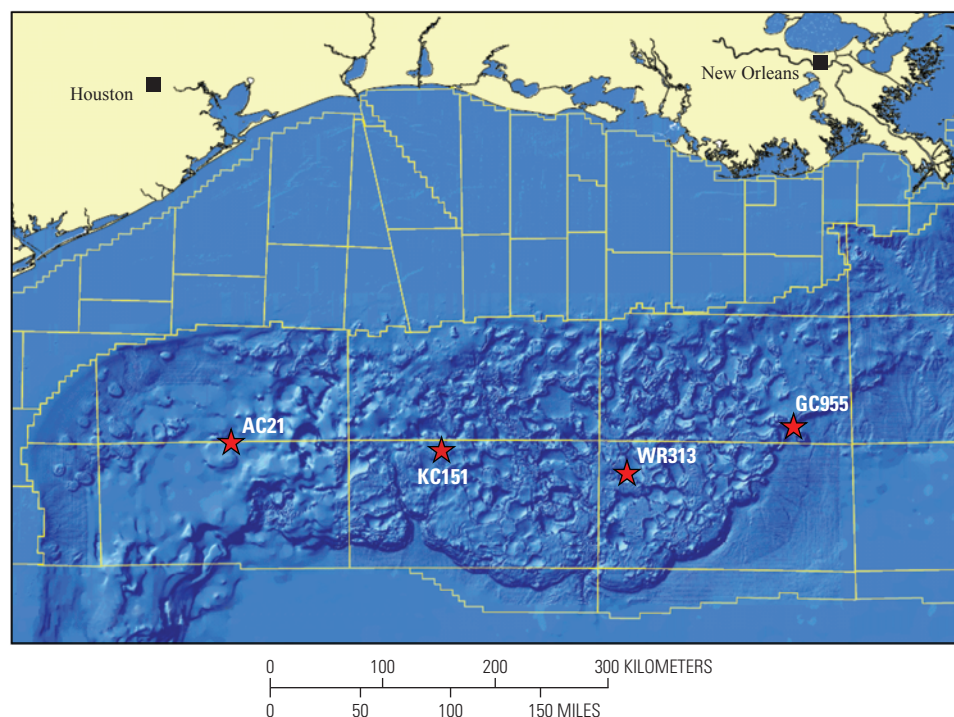
Figure 1.   Locations of sites drilled during the Joint Industry Project Leg II Expedition and the KC151 site, Gulf of Mexico (modified from Boswell and others, 2009). WR, Walker Ridge; AC, Alaminos Canyon; GC, Green Canyon; KC, Keathley Canyon.

between WC and AC sites (fig. 1), were used. Sediments in this site are classified as inorganic clays with high plasticity (Yun and others, 2006). Detailed descriptions of core samples collected at KC151 are shown in Lee and others (2008) and Yun and others (2006). Only S-wave velocities at various effective pressures less than 2.3 MPa were measured with the frequency of 5−70 KHz for the reconstituted sediments (Lee and Ruppel, 2008) and S-wave velocities measured during the loading cycle were used in this paper.

Biot-Gassmann Theory with Consolidation Parameter

The P-wave (Vp) velocity and the shear-wave velocities (Vs) of water-saturated sediment can be written as:

$$V_p = \sqrt{\frac{k + 4\mu/3}{\rho_b}} \quad \text{and} \quad V_s = \sqrt{\frac{\mu}{\rho_b}}$$

(1)

where

k and μ are bulk and shear moduli of the sediment,
ρ_b is the bulk density of sediment given by $\rho_b = \rho_s(1-\phi) + \rho_w\phi$, and
subscripts s and w refer to sediment grains and water, respectively, and
ϕ is sediment porosity.

According to the rock physics model based on BGT, the bulk modulus of the sediment is given by:

$$k = K_s(1 - \beta_p) + \beta_p^2 K_{av}$$

(2)

with

$$\frac{1}{K_{av}} = \frac{(\beta_p - \phi)}{K_s} + \frac{\phi}{K_w},$$

and the shear modulus is given by (Lee, 2005)

$$\mu = \mu_s(1 - \beta_s)$$

(3)

where

β_p and β_s are appropriate Biot coefficients for bulk and shear moduli,
K_s and μ_s are bulk and shear moduli of grains, and
K_w is the bulk modulus of pore water.

The Biot coefficients shown in equations 2 and 3 can be written as (Lee, 2005):

$$\beta_p = \frac{\phi\,(1+\alpha)}{(1 + \alpha\phi)} \quad \text{and} \quad \beta_s = \frac{\phi(1 + \gamma\alpha)}{(1 + \gamma\alpha\phi)},$$

$$\text{with } \gamma = \frac{1 + 2\alpha}{1 + \alpha}$$

(4)

where

α is the consolidation parameter (Pride, 2005; Lee, 2005). Pride (2005) used a constant value for γ, whereas Lee (2005) used γ as a function of the consolidation parameter. Lee (2005) shows that using γ as a function of α yields more accurate velocities, particularly for unconsolidated sediments. The consolidation parameter α can be estimated from the P-wave velocity and porosity with the grain properties as shown in Lee (2006c).

Measured S-wave Velocity

Figure 2 shows a relation between P- and S-wave velocities measured by the SonicScope at 6 wells in the GOM. Most of the data points fall within uncertainties of the data scattering. A least squares fit (LSF) to the data shown in figure 2 is given by:

$$V_s = 0.59V_p - 0.6$$

(5)

with a correlation coefficient of 0.88.
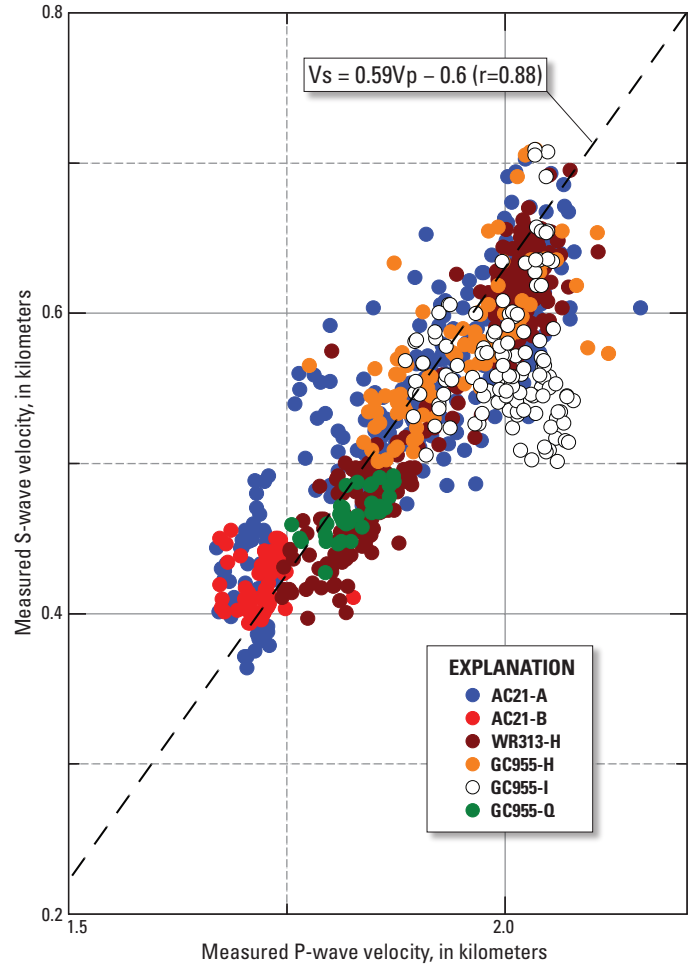
Figure 2. Relation between P- and S-wave velocities measured using SonicScope acoustic logging tool at six wells acquired during the Joint Industry Project Leg II Expedition in the Gulf of Mexico. V_p, P-wave velocity; V_s, S-wave velocity; r, correlation coefficient; WR, Walker Ridge; AC, Alaminos Canyon; GC, Green Canyon; KC, Keathley Canyon.

Predicting S-wave Velocity

A general description of predicting S-wave velocity of the water-saturated sediment (WSS) at low effective pressure is described in Lee (2010). This section of the paper presents methods of predicting S-wave velocities for WSS and GHBS from the P-wave velocities measured at low frequencies less than or equal to the logging frequencies. If the P-wave velocities were measured at higher frequencies (greater than about 200 KHz), the velocity dispersion effect should be accounted for and S-wave velocities at low effective pressure should be accurately predicted (Lee, 2010).

For Water-Saturated Sediments (WSS)

Figure 3 shows the predicted S-wave velocities at the AC21−A well using the empirical relation given in equation 5 and using the BGT as outlined in Lee (2006c). The average measured S-wave velocities at the AC21−A well is 0.541 ± 0.08 kilometers per second (km/s), whereas the predicted average S-wave velocities from the empirical and BGT are 0.529 ± 0.09 km/s and 0.546 ± 0.11 km/s, respectively. The empirical equation slightly underestimates the S-wave velocities, whereas the BGT slightly overestimates S-wave velocities. However, the difference is not significant and both methods are appropriate for predicting the S-wave velocity at the AC21−A well.

Figure 4*A* shows the predicted S-wave velocities with depth at the WR313−H well using the empirical equation along with measured SonicScope S-wave data and S-wave velocities of reconstituted sediments by Lee and others (2008). The predicted S-wave velocities using the empirical equation agree well with measured SonicScope S-wave velocities. However, the empirical equation slightly overestimates the S-wave velocities when the water depth is less than about 200 ft, or an effective pressure of about 0.6 MPa.
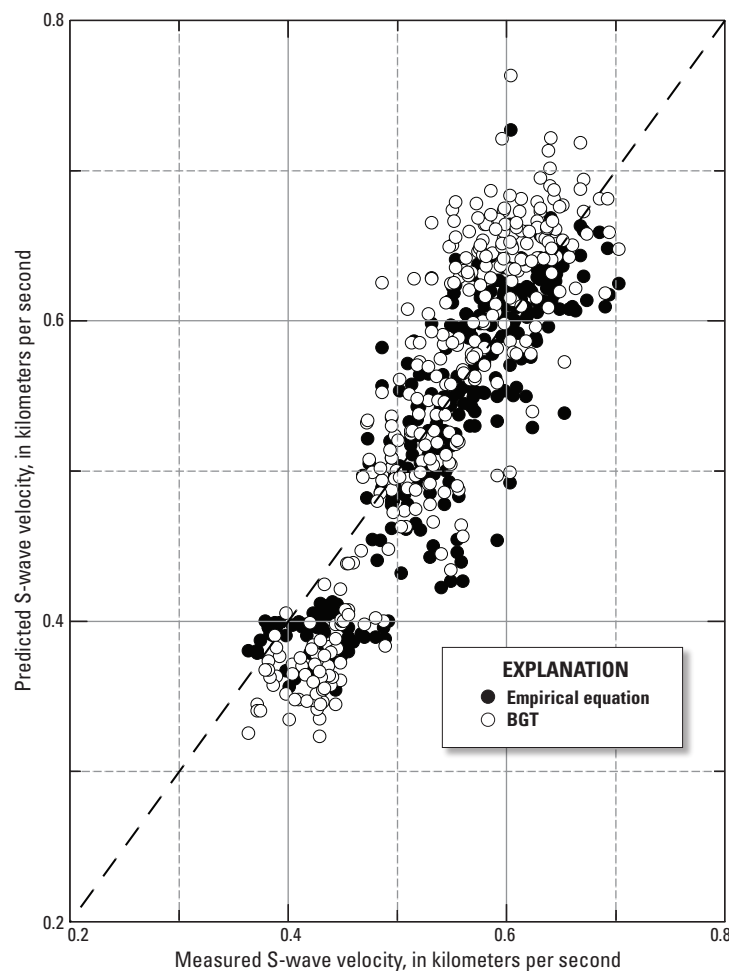
Figure 3.   Predicted S-wave velocities at the AC21–A well using the empirical equation and the Biot-Gassman theory (BGT) with a consolidation parameter (equations 1 through 4), as outlined in Lee (2006c).

S-wave velocities predicted using BGT along with measured SonicScope S-wave data at the WR313–H and S-wave velocities of reconstituted sediments are shown in figure 4B. As opposed to those shown in figure 4A, the BGT method predicts accurate S-wave velocities of reconstituted sediments by Lee and others (2008) as well as those measured by SonicScope. Therefore, it is concluded that the S-wave velocities of unconsolidated shallow sediments can be optimally predicted using the BGT (equations 1–4) method as outlined in Lee (2006c).
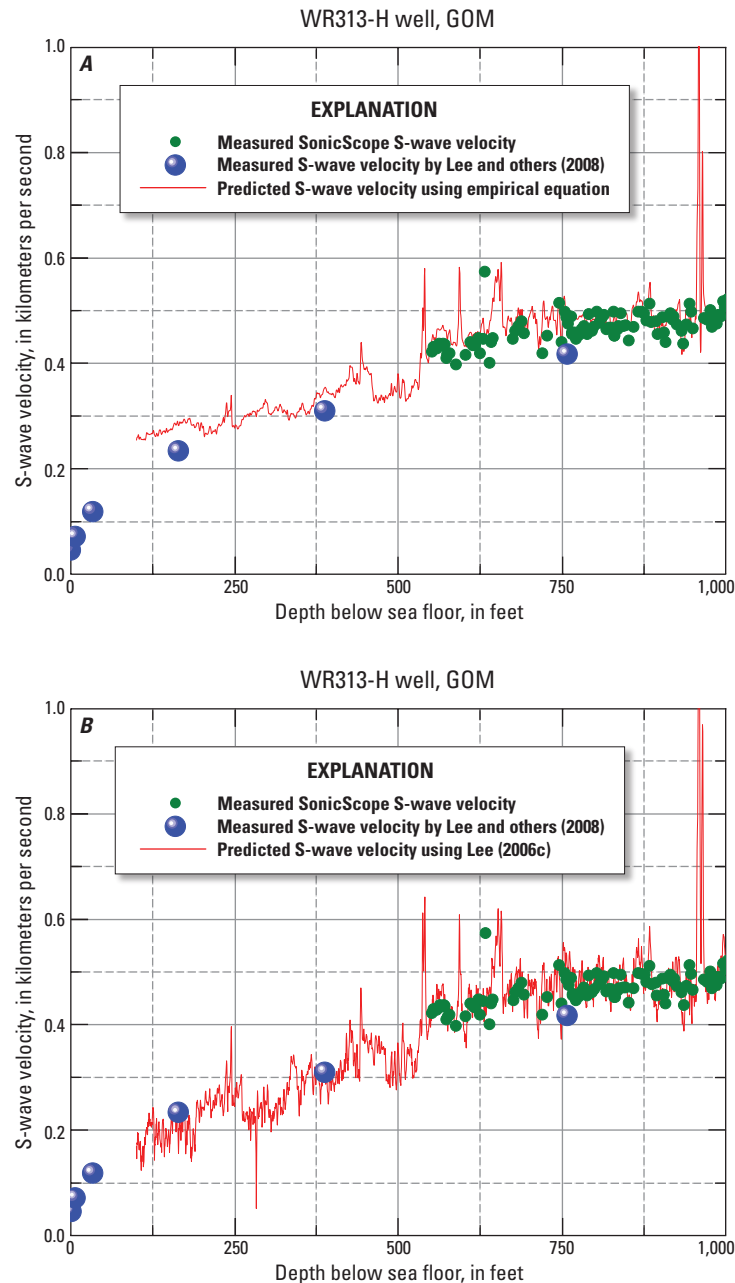
Figure 4. Predicted and measured SonicScope S-wave velocities at the WR313–H well, with S-wave velocities measured by Lee and others (2008) for the reconstituted sediment acquired at the Keathley Canyon 151–2 well (KC151–2). *A*, using the empirical equation derived from the six wells. *B*, using the Biot-Gassmann theory (BGT) with the consolidation parameter (equations 1–4) assuming that the pore space is saturated with water.

For Gas Hydrate-Bearing Sediments (GHBS)

Numerous equations can be used to calculate P- and S-wave velocities of GHBS (for example; Helgerud and others, 1999; Jakobsen and others, 2000; Lee and Waite, 2008). In this paper, the simplified three-phase Biot-type equation (STBE) (Lee, 2008; Lee and Waite, 2008) is used to calculate the S-wave velocities of the GHBS. The difference between the WSS and GHBS in the framework of STBE is as follows: the first is the *Kav* shown in equation 2, and this term is changed into

$$\frac{1}{K_{av}} = \frac{(\beta_p - \phi)}{K_s} + \frac{\phi_w}{K_w} + \frac{\phi_h}{K_h},$$ (6)

and the Biot coefficients, β_p and β_s in equation 4, are expressed using the apparent porosity ϕ_{as} instead of porosity ϕ, which is defined as
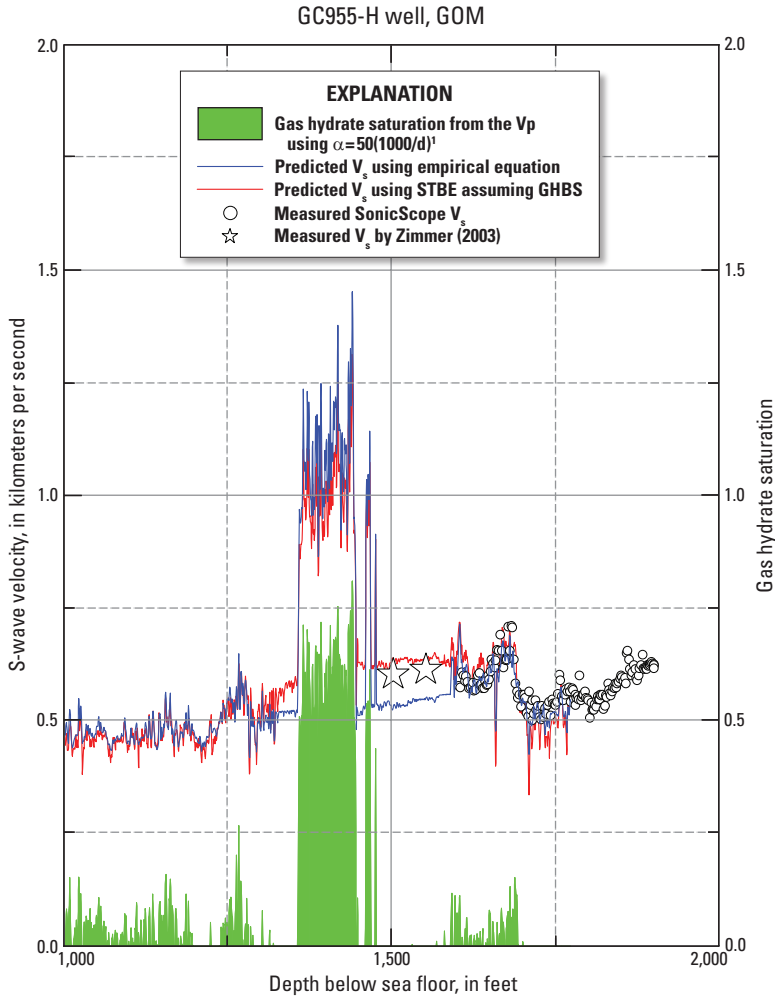
$$\phi_{as} = \phi_w + \varepsilon\phi_h,$$ (7)

where

K_h is the bulk modulus of the pure gas hydrate,
S_h is the gas hydrate saturation,
$\phi_w = (1 - S_h)\phi$, and
$\phi_h = S_h\phi$.

Lee and Waite (2008) recommended using $\varepsilon = 0.12$ to model GHBS. Also the effect of gas hydrate on the bulk density should be accounted for and is given by:

$$\rho_b = \rho_s(1 - \phi) + \rho_w\phi(1 - S_h) + \rho_h\phi S_h$$ (8)

where ρ_h is the density of gas hydrate.

To predict S-wave velocities of GHBS, the gas hydrate saturations estimated from the P-wave velocities are explicitly inserted into the velocity equation, along with an appropriate consolidation parameter. When predicting S-wave velocities from the P-wave velocity and porosity for WSS, the consolidation parameter α is estimated at each data point (Lee, 2006c). From these estimated values of α with depth, a depth-dependent consolidation parameter can be derived. Figure 5 shows the gas hydrate saturation estimated from the P-wave velocity at the GC955−H well, using $\alpha = 50(1000 / d)^1$, where d is the depth in feet below sea floor.

GC955-H well, GOM

EXPLANATION
- Gas hydrate saturation from the Vp using $\alpha = 50(1000/d)^1$
- Predicted V_s using empirical equation
- Predicted V_s using STBE assuming GHBS
- ○ Measured SonicScope V_s
- ☆ Measured V_s by Zimmer (2003)

Figure 5. Predicted and measured SonicScope S-wave velocities at the GC955–H well with gas hydrate saturations estimated from the P-wave velocity. S-wave velocity predicted using the simplified three-phase Biot-type equation (STBE), assuming that the pore space is saturated with gas hydrate (GHBS), is shown in red, and that predicted from the empirical equation ($V_S = 0.59V_p - 0.6$) is shown in blue; V_p, P-wave velocity; V_s, S-wave velocity.

Figure 5 also shows the S-wave velocities predicted
assuming that the measured P-wave velocities are those for
GHBS (for depths between 1,355 and 1,443 fbsf) using STBE
at GC955−H well. The S-wave velocities of GHBS are calcu-
lated with $\alpha = 50(1000 / d)^1$, which is the same parameter
used to estimate gas hydrate saturation. For comparison,
S-wave velocities predicted using the empirical relation
(equation 5) are also shown in figure 5. The average S-wave
velocity predicted using the empirical equation for depths
between 1,355 and 1,443 fbsf is 1.081 ± 0.124 km/s, whereas
it is 0.999 ± 0.100 km/s when using STBE. Thus, the S-wave
velocities of GHBS predicted from the empirical formula are
slightly higher than those predicted from the BGT.

Results and Discussion

S-wave Velocity for Sands

The empirical relation shown in equation 5 was derived
from S-wave data for clay-bearing sediments. Because severe
washouts occurred for sands without gas hydrate in the pore
space (Boswell and others, 2009), density porosity and the
P-wave velocity were severely affected and S-wave veloci-
ties were not measured at all. Figure 6 shows the measured
and modified porosity (fig. 6*A*) and P-wave velocity (fig. 6*B*).
The erroneous porosities inside large washout zones were
substituted by calculated porosity using a sand-shale porosity
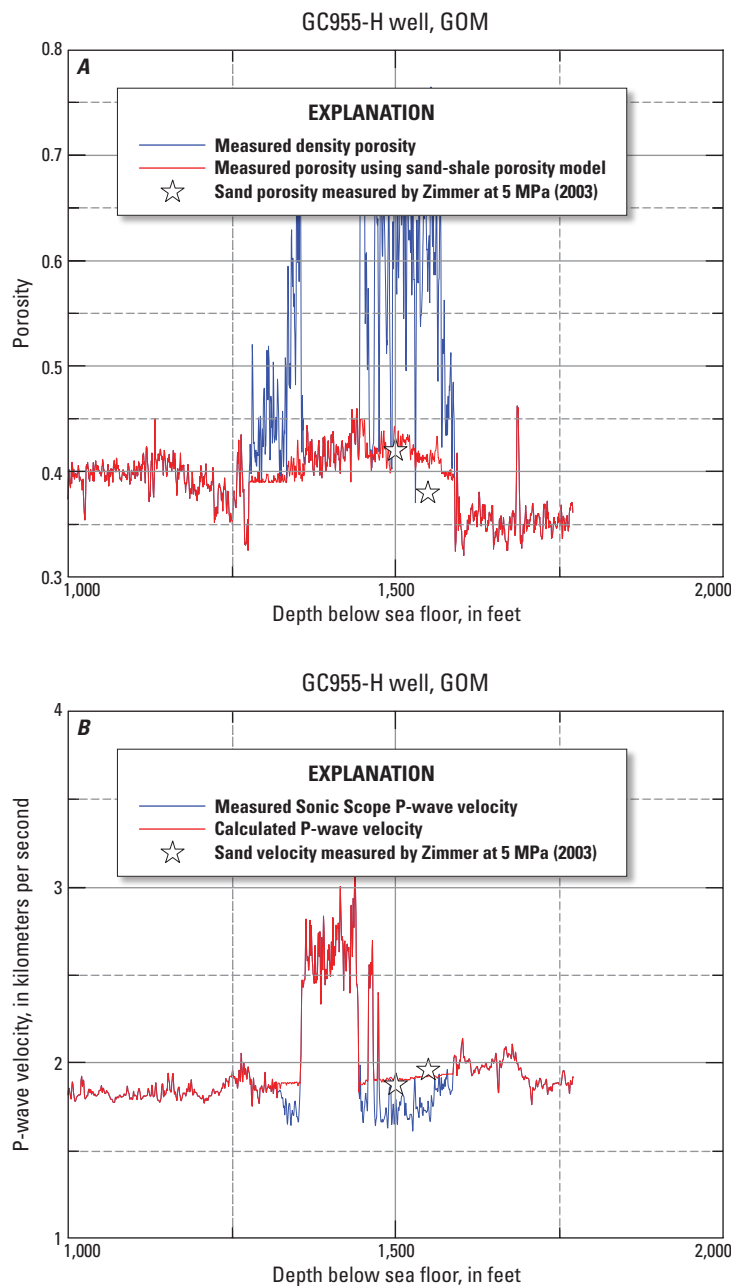
Figure 6. Measured and modified porosity and P-wave
velocity at the GC955–H well. *A*, density porosity. *B*, P-wave
velocity. MPa; megaPascal.

model by Kolterman and Gorelick (1995). The P-wave veloci-
ties inside the washout intervals were replaced by calculated
P-wave velocity using the modified porosity shown in figure
6A with the consolidation parameter $\alpha = 50(1000 / d)^1$. This
parameter is the same one used for the prediction of S-wave
velocity mentioned previously and assumes that the pore space
is saturated with water except for depths between 1,355 and
1,443 fbsf, where gas hydrates are present.

There are no independent measurements to test the accu-
racy of the modified porosity and the calculated P-wave veloc-
ity of sands at this well. Zimmer (2003) measured porosity and
velocities for reconstituted sands from the GOM and Galves-
ton, GOM, at various effective pressures. At the effective
pressure of 5 MPa, the average porosity, the P-wave velocity,
and the S-wave velocity are 0.42, 1.874 km/s, and 0.602 km/s,
respectively for Galveston sands and 0.38, 1.957 km/s, and
0.62 km/s, respectively for GOM sands. Assuming that the
depth of 1,500 ft corresponds to an effective pressure of about
5 MPa, these values were plotted in figure 6 as stars (for visual
effect, data for Galveston sand were plotted at 1,500 ft and
1,550 ft for GOM sand). When the S-wave velocities mea-
sured by Zimmer (2003) are compared, figure 6 indicates that
the modified porosity and calculated P-wave velocity using the
modified porosity appear to be more accurate than measured
values for sands at the GC955−H well.

Figure 5 shows predicted S-wave velocities using the
empirical equation and the STBE by explicitly inserting the
gas hydrate saturations into the equation. When there is no
gas hydrate in the pore space, the predicted velocity from the
STBE is the same as that from the BGT. The predicted S-wave
velocities of sands at depths near 1,500 fbsf from the empiri-
cal relation are less than those predicted from the STBE,
although velocities of the clay-bearing sediments near 1,700
fbsf are almost the same as the STBE. The predicted S-wave
velocities from the STBE are similar to those measured by
Zimmer (2003). This indicates that the empirical relation is not
accurate for sands at the GC955−H well and requires another
relation applicable to sands. However, the prediction based
on the STBE works well for both clay-bearing sediments and
sands by incorporating the effect of porosity and grains into
the prediction.

Moduli of Sediments

Geomechanics was one of the primary areas of interest
for the JIP Leg II project, and Vp-VS data were intended to be
used to model geomechanical properties of GHBS, including
borehole-stability models (J. Howard, Conocophillips, written
commun., 2010). Unfortunately, none of the S-wave velocities
were measured for GHBS and water-saturated sands. There-
fore, it was decided to use the predicted S-wave velocities to
derive mechanical properties of the sediments.

The dynamic bulk and shear moduli can be calculated
from the P- and S-wave velocities using equation 1 as:

$$\mu = \rho V_s^2$$

$$k = \rho V_p^2 - 4\rho V_s^2 / 3 \tag{9}$$

Figure 7 shows the calculated bulk and shear moduli
at GC955−H well using the P-wave velocity and predicted
S-wave velocity using STBE (fig. 5). For comparison, moduli
calculated from the measured SonicScope P- and S-wave data
for clay-bearing sediments at depths greater than 1,600 fbsf
are also shown. The bulk and shear moduli estimated from
the predicted S-wave velocities agree well with those esti-
mated from the measured SonicScope S-wave velocities for
clay-bearing sediments. Judging from the accuracy of the
predicted S-wave velocities shown in figure 5, it appears that
the moduli of GHBS shown in figure 7 are reasonable. The
shear modulus of water-saturated sand at about 1,500 fbsf is
about 0.8 gigapascals (GPa), whereas it is more than 2 GPa for
GHBS with a 64-percent gas hydrate saturation.

Comparison with Other Methods

The mudrock equation by Castagna and others (1985)
was based on a variety of in-situ and laboratory measurements
for clastic silicate rocks and is given by:

$$V_s = (V_p - 1.36) / 1.16 \tag{10}$$

The predicted S-wave velocities using equation 10 are
shown in figure 8A and compared with those using the
empirical equation 5. The average S-wave velocity pre-
dicted using equations 5 and 10 are 0.539 ± 0.089 km/s
and 0.475 ± 0.100 km/s, respectively, whereas that of the
measured S-wave velocity is 0.535 ± 0.079 km/s. As noted
by Wang (2000), the mudrock equation underestimates the
S-wave velocity, and the underestimation is about 10 percent
for the SonicScope data in GOM.

Wang's equation is based on the Biot-Gassmann equation
with empirically derived parameters and is given by the fol-
lowing equation for WSS:

$$V_s^2 = (0.4211 + 0.0061 K_w)V_p^2 - 1.1255 K_w / \rho_b. \tag{11}$$

As long as the second term is less than the first term in equa-
tion 11, the S-wave velocity can be predicted. Figure 8A also
shows the predicted S-wave velocities using equation 11.
When the P-wave velocity is less than about 1.73 km/s with
porosity greater than about 0.4, the second term becomes
greater than the first term. Thus, the S-wave velocity cannot be
predicted. The predicted S-wave velocity varies from about 0
to 0.75 km/s, and the Wang equation is not appropriate to use
for the SonicScope data measured for shallow sediments in
these areas.

Lee (2006b) proposed a method based on BGT with a
correction term ΔV_s, which is given by:

$$\Delta V_s = 0.1075 + 0.0473 e^{-p/8.623} \text{ km/s} \tag{12}$$

where *p* is the effective pressure in MPa. Figure 8*B* shows the predicted S-wave velocities using Lee (2006b), which are compared to velocities predicted using the method shown in Lee (2006c, 2010). As can be seen from figure 8*B*, Lee (2006b) underestimated the S-wave velocity, and the underestimation increases as the S-wave velocity decreases. The average S-wave velocity using Lee (2006b) is 0.516±0.122 km/s, which is about a 4-percent underestimation. However, at shallow depths of about 200 fbsf, the S-wave velocities predicted using BGT with a correction term (Lee, 2006b) differ more than 100 percent of the predicted S-wave velocity using BGT with a consolidation parameter (Lee, 2006c, 2010). Because equation 12 is based on the velocities of consolidated sands and tested for velocities of unconsolidated sediments at the effective pressure greater than about 10 MPa, the correction term may not be accurate for the shallow unconsolidated sediments in the GOM.
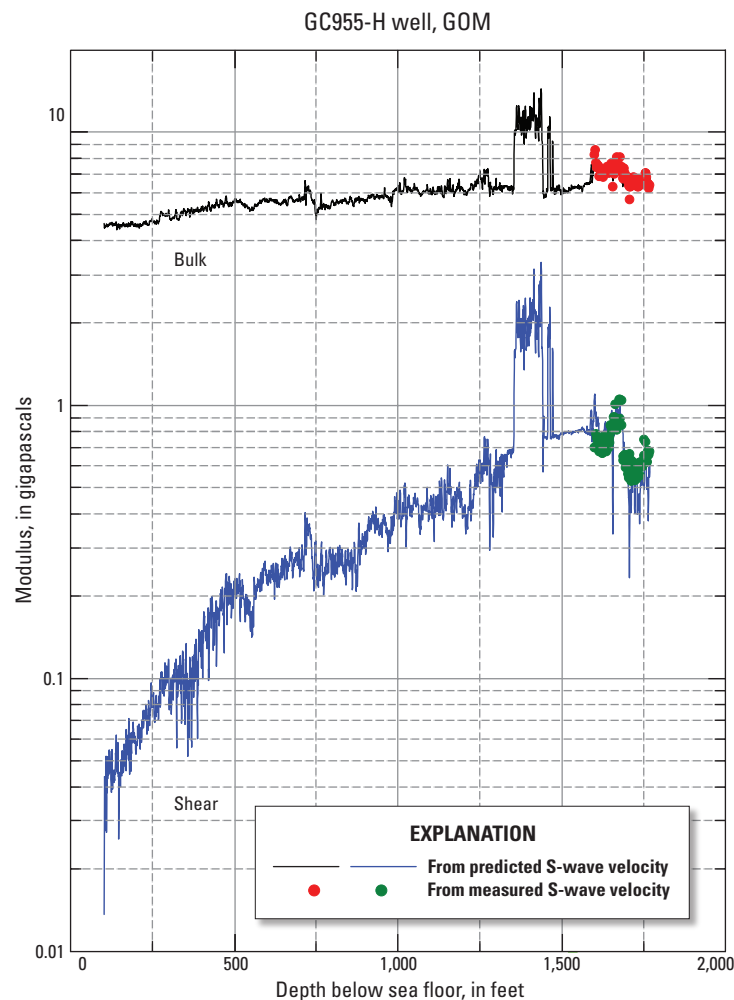
Figure 7. Estimated bulk and shear moduli of sediments at the GC995–H well.
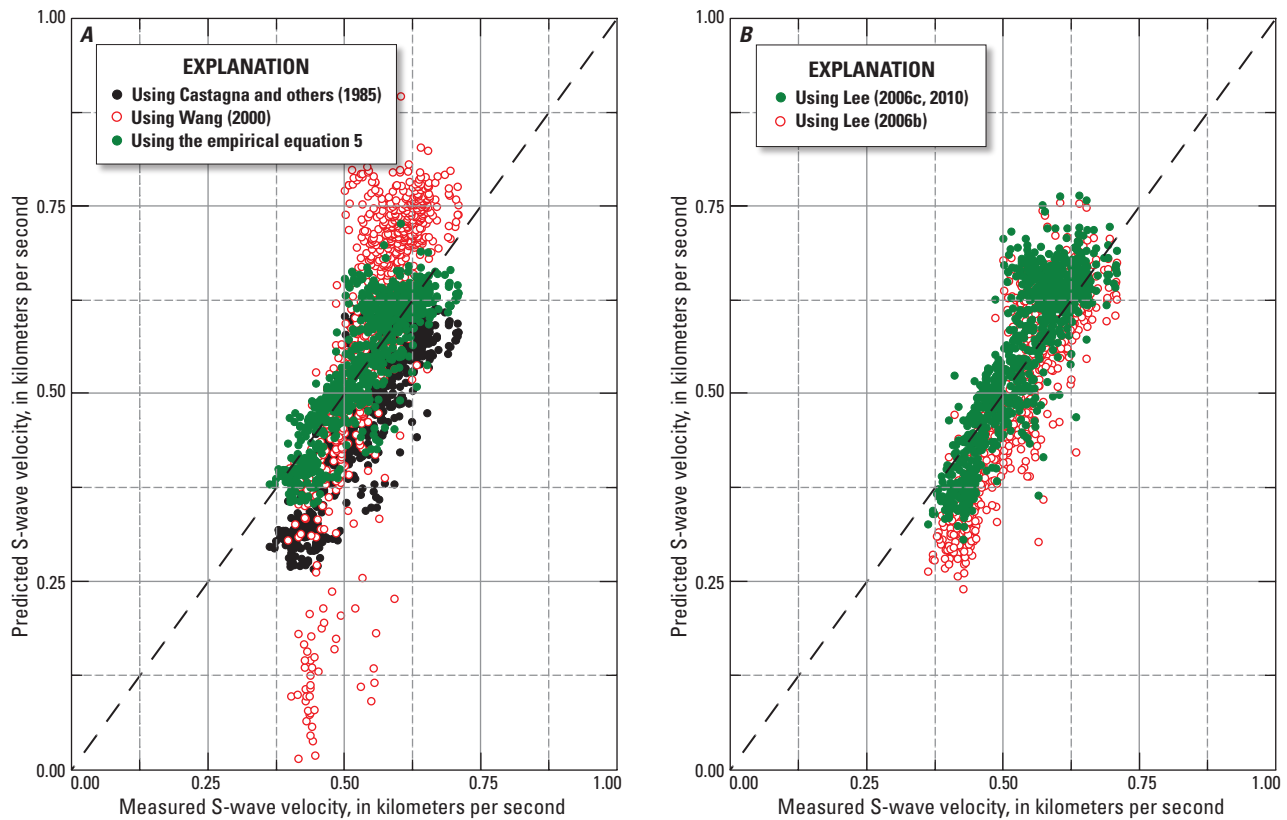
Figure 8.   Comparisons of predicted and measured SonicScope S-wave velocities in the Gulf of Mexico. *A*, using empirical equations. *B*, using the Biot-Gassman theory with a correction factor for shear wave velocity.

Summary and Conclusions

The S-wave velocities of water-saturated sediments predicted using the Biot-Gassmann theory (BGT) with a consolidation parameter are as good as those predicted using the empirical equation derived from the six wells in the Gulf of Mexico (GOM). Furthermore, the prediction based on the BGT is preferable to the empirical equation to predict S-wave velocities at very shallow depths. The empirical equation works well for clay-bearing sediments at these sites, but it appears to underestimate S-wave velocity for sands. However, the prediction of S-wave velocity based on the BGT works well for both sand and clay-bearing sediments. Although empirical equations are easy to apply, there is no guarantee that the empirical equations are accurate for a particular area because parameters of the empirical equation generally depend on the local sediment properties. Because the prediction method based on the BGT uses the measured P-wave velocity with porosity, however, it can be used in other areas as demonstrated in the GOM.

Another advantage of the BGT-based method is its ability to predict the S-wave velocities for gas hydrate-bearing sediment. By explicitly inserting gas hydrate saturations estimated from the P-wave velocity into a rock physics model based on the BGT, accurate S-wave velocities

can be predicted. It is demonstrated that the predicted S-wave velocity from the simplified three-phase equation can be used to calculate reasonable bulk and shear moduli of the sediment in the absence of measured S-wave velocity.

References

Boswell, Ray, Collett, T.S., Frye, M., McConnell, D., Shedd, W., Dufrene, R., Godfriaus, P., Mrozewski, S., Guerin, G., and Cook, A., 2009, Gulf of Mexico Gas Hydrate Joint Industry Project Leg II: Technical summary—Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II, 28 p.

Castagna, J.P., Batzle, M.L., and Eastwood, R.L, 1985, Relationship between compressional wave and shear wave velocities in clastic silicate rocks: Geophysics, v. 50, p. 571−581.

Cheng, C.H., and Toksöz, M.N., 1979, Inversion of seismic velocities for pore aspect ratio spectrum of a rock: Journal of Geophysical Research, v. 84, p. 7,533−7,543.

Greenberg, M.L., and Castagna, J.P., 1992, Shear-wave velocity estimation in porous rocks: Theoretical formulation, preliminary verification and applications: Geophysical Prospecting, v. 40, p. 195−209.

Guerin, Gilles, Cook, A., Mrozewski, S., Collett, T., and Boswell, R., 2009, Gulf of Mexico Gas Hydrate Joint Industry Project Leg II—Green Canyon 955 LWD operations and results: Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II, 29 p.

Han, D.H., Nur, A., and Morgan, D., 1986, Effects of porosity and clay content on wave velocities in sandstone: Geophysics, v. 51, p. 2,093−2,107.

Helgerud, M.B., Dvorkin, J., Nur, A., Sakai, A., and Collett, T., 1999, Elastic-wave velocity in marine sediments with gas hydrates—Effective medium modeling: Geophysical Research Letters, v. 26, p. 2,021−2,024.

Hutchinson, D.R., Boswell, R., Collett, T.S., Dai, J., Dugan, B., Frye, M., Jones, E., McConnell, D., Rose, K., Ruppel, C., Shedd, W., Shelander, D., Wood, W., 2009, Gulf of Mexico Gas Hydrate Joint Industry Project Leg II—Walk Ridge 313 site selection: Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II, 35 p.

Jakobsen, M., Hudson, J.A., Minshull, T.A., and Singh, S.C., 2000, Elastic properties of hydrate-bearing sediments using effective medium theory: Journal of Geophysical Research, v. 105, p. 561−577.

Jørstad, A., Mukerji, T., and Mavko, G., 1999, Model-based shear-wave velocity estimation versus empirical regressions: Geophysical Prospecting, v. 47, p. 785−797.

Kolterman, C.E., and Gorelick, S., 1995, Fractional packing model for hydraulic conductivity derived from sediment mixtures: Water Resources Research, v. 31, p. 3283−3297.

Kuster, G.T., and Toksöz, M.N., 1974, Velocity and attenuation of seismic waves in two-media: Part I. Theoretical considerations: Geophysics, v. 39, p. 587−606.

Lee, J.Y., Santamarina, J.C., and Ruppel, C., 2008, Mechanical and electromagnetic properties of northern Gulf of Mexico sediments with and without hydrates: Marine and Petroleum Geology, v. 25, p. 884−895.

Lee, M.W., 2005, Proposed moduli of dry rock and their application to predicting elastic velocities of sandstones: U.S. Geological Survey Scientific Investigations Report 2005−5119, 14 p.

Lee, M.W., 2006a, Inversion of elastic impedance for unconsolidated sediments: U.S. Geological Survey Scientific Investigations Report 2006−5081, 14 p.

Lee, M.W., 2006b, Explicit use of the Biot coefficient in predicting shear-wave velocity: Geophysical Prospecting, v. 54, p. 177−185.

Lee, M.W., 2006c, A simple method of predicting S-wave velocity: Geophysics, v. 71, no. 6, p. F161−F164.

Lee, M.W., 2008, Models for gas hydrate-bearing sediments inferred from hydraulic permeability and elastic velocities: U.S. Geological Survey Scientific Investigations Report 2008−5219, 15 p.

Lee, M.W., 2010, Predicting S-wave velocities for unconsolidated sediments at low effective pressure: U.S. Geological Survey Scientific Investigations Report 2010−5138, 13 p.

Lee, M.W., and Waite, W.F., 2008, Estimating pore-space gas hydrate saturations from well-log acoustic data: Geochemistry, Geophysics, Geosystems, v. 9, Q07008, doi:10,1029/2008GC002081, 8 p.

Mrozewski, Stefan, Guerin, G., Cook, A., Collett, T., Boswell, R., 2009, Gulf of Mexico Gas Hydrate Joint Industry Project Leg II—LWD Method: National Energy Technology Laboratory, Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II, 9 p.

Pride, S.R., 2005, Relationship between seismic and hydrological properties, in Rubin, Y., and Hubbard, S., eds., Hydrogeophysics: New York, Kluwer Academy, p. 217−255.

Shedd, W., Hutchinson, D., Boswell, R., Collett, T., Dai, J., Dugan, B., Frye, M., Jones, E., McConnell, D., Rose, K., Ruppel, C., Shelander, D., and Wood, W., 2009, Gulf of Mexico Gas Hydrate Joint Industry Project Leg II—East Breaks 991 and Alaminos Canyon 21 site selection: Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II, 18 p.

Wang, Z., 2000, Velocity relationships in granular rocks, in Wang, Z. and Nur, A., eds., Seismic and acoustic velocities in reservoir rocks, Recent development: Society of Exploration Geophysics, v. 3, p. 377−383.

Xu, Shiyu, and White, R.E., 1996, A physical model for shear-wave velocity prediction: Geophysical Prospecting, v. 44, p. 687−717.

Yun, T.S., Narsilio, G.A., Santamarina, J.C., 2006, Physical characterization of core samples recovered from Gulf of Mexico: Marine and Petroleum Geology, v. 23, p. 893−900.

Zimmer, M.A., 2003, Seismic velocities in unconsolidated sands—Measurements of pressure, sorting, and compaction effects: Doctoral Thesis, Stanford, Palo Alto, California, 204 p.