Gas hydrates in coarse-grained reservoirs interpreted from velocity pull up: Mississippi Fan, Gulf of Mexico

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ABSTRACT
Gas hydrates are recognized as an emerging energy resource and a submarine geohazard; they are also thought to be a modulating mechanism on the global organic carbon budget and on past climate change. Although identified primarily from reflectivity changes at the base of the stability zone, gas hydrates located above this boundary are regularly difficult to interpret, suggesting that the deposits may be present in areas previously unconsidered. Here, I introduce a nonreflectivity, traveltime-based method to detect gas hydrates in coarse-grained reservoirs. The technique uses seismic traveltime deficits located below high-velocity deposits to identify gas hydrate accumulations and magnitudes of velocity pull up to quantify in situ saturation. The approach has been applied to a portion of the central Gulf of Mexico and has uncovered continuous high-velocity accumulations contained within coarse-grained turbidites of the Quaternary Mississippi Fan. Deposits extend more than 175 km and are interpreted to be previously unidentified gas hydrate accumulations locally reaching saturations of >60%. Further application of the velocity pull-up method can help to identify and quantify remaining gas hydrate reservoirs, and to aid in the worldwide assessment of the deposits as a future energy resource.

INTRODUCTION
Gas hydrates are solid compounds composed of host molecules of water surrounding guest molecules of gas. The accumulations occur naturally in low-temperature and high-pressure environments in both onshore and offshore settings, usually within ~2000 m of Earth’s surface (Kvenvolden, 1995). In marine environments, gas hydrates accumulate in subsurface locations in water depths greater than ~300 m (984 ft) and have been found to contain hydrocarbons, primarily methane (Kvenvolden, 1995). During the past four decades, gas hydrates have received considerable industrial and academic attention, owing to the deposits being recognized as an emerging energy resource, an offshore drilling hazard, and a major component of the global organic carbon budget (Kvenvolden, 1993). Gas hydrates are also invoked as a mechanism for past climatic change, most notably during the Paleocene–Eocene Thermal Maximum (DICKENS, 2011).

Preliminary estimates suggest that ~3.0 × 10³ trillion cubic meters (tcm; 1.0 × 10³ trillion cubic feet [tcf]) of recoverable gas exists in marine gas hydrates in sandy reservoirs (Boswell and Collett, 2011). These volumes, which are comparable to the 3.7 × 10³ tcm (1.3 × 10³ tcf) of recoverable gas in global conventional and unconventional reservoirs combined (KERR, 2004), make gas hydrates an attractive target for future resource exploitation. However, locating the deposits via conventional exploration methods has remained a challenge because of nonunique seismic responses. As such, two challenges exist that will likely determine the viability of the accumulations as an exploitable energy resource: (1) the detection of gas hydrates in sandy reservoirs, and (2) the economics of long-term gas-production rates from gas hydrates (Boswell, 2009). The work presented here aims to directly address challenge 1 by introducing a seismic-based technique designed to identify and quantify gas hydrates in coarse-grained reservoirs.

GAS HYDRATE EXPLORATION
Seismic-based methods of gas hydrate exploration commonly rely on marked changes in reflectivity to delineate the base of the gas hydrate stability zone (GHSZ; see Figs. DR1A–DR1C in the GSA Data Repository1). At this location, “bottom simulating reflectors” (BSRs) have been observed to be continuous or discontinuous reverse-polarity events that are interpreted to approximate the boundary between overlying high-impedance gas hydrates and underlying low-impedance free gas (and/or water-bearing sediments). However, identifying gas hydrates above the BSR is regularly complicated by the nonunique nature of increased impedance (see Boswell et al., 2016).

To constrain interpretation above the BSR, velocity analyses are used to recognize gas hydrate accumulations. In these studies, increased interval P-wave velocities serve as the basis for delineating the deposits, and for calculating in situ saturation (see Crutchley et al., 2016; Figs. DR2 and DR3). However, in the absence of velocity data, seismic artifacts in two-way traveltime (TWTT) can be used to explore for high-velocity gas hydrate–bearing sediments (see Scholl and Cooper, 1978). To build on this concept, I introduce a geophysical technique that leverages velocity pull up (VPU) to identify and quantify gas hydrates in coarse-grained reservoirs (Figs. DR4A–DR4D, DR5, and DR6). I use the following equation to relate VPU to velocity:

\[
VPU(t) = \left( \frac{v_{gh}}{v_b} - 1 \right)T_h(t),
\]

where \(VPU(t)\) is the magnitude of velocity pull up (TWTT), \(v_{gh}\) is the P-wave velocity of gas hydrate–bearing sediments, \(v_b\) is the P-wave velocity of background sediments, and \(T_h(t)\) is the net thickness (TWTT) of gas hydrate–bearing sediments. After solving for \(v_{gh}\), velocity values are related to gas hydrate saturation (\(S_{gh}\)) via the following empirical relationship (see Fig. DR3):

\[
v_{gh} = 2582.95S_{gh} + 1356.29.
\]

MISSISSIPPI FAN, GULF OF MEXICO
Application of the VPU method to a portion of the central Gulf of Mexico (Fig. 1A) has led to the identification of high-velocity accumulations contained within the middle Mississippi Fan (Figs. 1B–1D). Based on position within the GHSZ, high impedance, underlying VPU, and reflection geometry, deposits are interpreted to be previously unidentified coarse-grained gas hydrate–bearing reservoirs.

Reflection Character
Three sets of large-scale ribbon-shaped reflections (P1–P3) are recognized within the GHSZ in the study area (Figs. 2A–2C; Fig. DR7A). Reflections are eastward-shallowing, high-impedance (peak-over-trough), high-frequency (30–40 Hz), and laterally discontinuous features in cross

1 GSA Data Repository item 2018186, methods involving creation of a gas hydrate stability curve, petrophysical calculations, conceptual diagrams, wave-length filtering, derivation of VPU equations, seismic interpretation, and geometric models, is available online at http://www.geosociety.org/daterepository/2018/ or on request from editing@geosociety.org.
Section. The youngest and largest accumulation (P3) is 2–18 km (1.2–11 mi) wide and longitudinally wedge shaped, thickening from <150 ms to >450 ms (TWTT). In medial settings, the P3 system exhibits upper and lower high-impedance units surrounding a seismically transparent zone (Fig. 2A, left).

The P1–P3 systems are inferred to be large-scale slope valley systems that transition downdip into channel levee complexes. In the absence of well-log and core data, high-impedance fill is interpreted to consist of individual channelized coarse-grained turbidites, 200–300 m (656–984 ft) wide and 4–10 ms (TWTT) thick. Weimer (1990) proposed a similar interpretation, suggesting that the P1–P2 and P3 systems are “coarse-grained channel sediments” belonged to the youngest two sequences of the Quaternary Mississippi Fan.

### Velocity Pull Up

Directly underlying the P1–P3 systems, large-magnitude VPU features track with the overlying deposits (Fig. 2D; Figs. DR8A and DR8B). In the north, VPU displays high spatial correlation with the P1–P3 systems; in the south, it tracks with the younger P3 accumulation, suggesting that high-velocity deposits exist in shallower and more distal positions. While VPU magnitude is generally consistent at large scale, TWTT values locally exceed >450 ms (TWTT). In medial settings, the P3 system exhibits upper and lower high-impedance units surrounding a seismically transparent zone (Fig. 2A, left).

Figure 1. Geologic interpretation of sidescan sonar and seismic section of the Mississippi Fan, Gulf of Mexico. A: Map (modified from Paskevich, 2000) showing mud-dominated modern fan. Locations of solid, liquid, and gas hydrocarbons are after Milkov and Sassen (2001); seafloor mounds are interpreted from circular areas of high intensity (see EEZ-Scan 85 Scientific Staff, 1987). B: Uninterpreted seismic section (zero-offset) showing mud-dominated modern fan. Locations of solid, liquid, and gas hydrocarbons are after Milkov and Sassen (2001); seafloor mounds are interpreted from circular areas of high intensity (see EEZ-Scan 85 Scientific Staff, 1987). B: Uninterpreted seismic section (zero-offset) showing mud-dominated modern fan. Locations of solid, liquid, and gas hydrocarbons are after Milkov and Sassen (2001); seafloor mounds are interpreted from circular areas of high intensity (see EEZ-Scan 85 Scientific Staff, 1987). C: Magnification of uninterpreted inset from B showing high-amplitude semicontinuous and flat reflections. D: Interpretation showing free gas– and gas hydrate–bearing accumulations.

### Velocity and Saturation Calculations

Based on the interpretation of gas hydrate–bearing sediments in the P1–P3 systems, \( v_p - S_h \) was calculated using VPU(t) (Fig. 2D), two end-member values of \( v_p \) and Th(t) (Figs. DR9A and DR9B), and Equation 2. Values of \( v_p \) were taken as 1700 m/s and 2100 m/s (see Fig. DR2) to account for both low- and high-velocity background sediments; Th(t) values of 53–158 ms (TWTT) and 98–293 ms (TWTT) were used to model a 0.35 and 0.65 net reservoir thickness, respectively (i.e., gross thickness of 150–450 ms TWTT).

Figure 3 shows the results of four \( v_p - S_h \) realizations calculated along 175 km (109 mi) of the P3 thalweg. In all models, values of \( v_p - S_h \) follow the morphology of the VPU(t) surface, decrease in an offshore direction (i.e., inverse relationship to reservoir thickness), display four main peaks (~15 km, ~27 km, ~58 km, and ~120 km), and exhibit local variability. Although models predict maximum values at ~15 km, increased values of \( v_p - S_h \) are locally associated with higher values of \( v_p \) and lower values of Th(t).

**DISCUSSION**

The interpretation of gas hydrates commonly relies on faults to focus fluids from deeper hydrocarbon sources into shallower coarse-grained
reservoirs within the GHSZ. Although this mechanism is generally the most obvious, data presented here show little to no evidence of seismic-scale deformation (see Fig. DR10A). However, based on data resolution and alternative gas-migration mechanisms, subseismic faults and short-range diffusion of dissolved gas cannot be ruled out (Fig. 4; see Malinverno and Goldberg, 2015).

The seismic architecture of the P3 system may inform our understanding of gas-migration mechanisms. For example, the presence of both upper and lower high-impedance units surrounding a seismically transparent zone (Fig. DR10B) may indicate that diffuse gas was unable reach the interior of the deposit. However, it may also represent a nonreservoir unit (i.e., mass transport complex) situated between upper and lower high-impedance reservoirs, which were filled by gas migration along short-offset (i.e., subseismic) faults. Regardless of mechanism, gas hydrates are interpreted to have formed in the P1–P3 systems in the past <86 k.y. (i.e., the approximate age of the P1–P3 systems; see Weimer, 1990, his figure 3).

CONCLUSION

A new method using seismic artifacts in TWTT is introduced to identify high-velocity accumulations well within the GHSZ. The technique,
which outlines a procedure for calculating velocity and saturation of gas hydrates in coarse-grained reservoirs, has been applied to a portion of the central Gulf of Mexico. The resulting analysis has uncovered previously unidentified high-velocity accumulations contained within the young-est two channelized systems of the Quaternary middle Mississippi Fan. Deposits extend more than 175 km and are interpreted to contain gas hydrates with local saturations reaching >60%. Further application of the VPU technique can be used to identify and quantify the worldwide distributions based on two background velocities (1700 m/s and 2100 m/s) and two estimates for net reservoir thickness (TWTT of 53–158 ms and 98–293 ms). Values >1.0 and <0.4 signify calculations that are either physically implausible or difficult to distinguish seismically (see Yun et al., 2005).

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