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

Andrew S. Madof
Chevron Energy Technology Company, Houston, Texas 77002-7308, USA

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 travelt ime 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 located 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 × 1012 trillion cubic meters (tcm; 1.0 × 1018 US 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 × 1012 tcm (1.3 × 1018 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:

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

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

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

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 length filtering, derivation of VPU equations, seismic interpretation, and geometric models, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

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/datarepository/2018/ or on request from editing@geosociety.org.
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 range from <30 ms to >95 ms and are contained in discrete regions ~10 km (6.2 mi) long by ~5 km (3.1 mi) wide (Fig. 2D).

Although VPU is interpreted to be caused by the presence of gas hydrates (Fig. DR7B), alternative lithologic, diagenetic, and structural mechanisms can create similar reflection geometries on seismic data in TWTT (Fig. DR8C). For example, convex reflections at depth can be expected 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-levée complexes. In the absence of well-log and core data, high-impedance fill is interpreted to consist of gas– and gas hydrate–bearing accumulations. Convex-shaped mounds are interpreted from circular areas of high intensity (see EEZ-Scan 85 Scientific Staff, 1987). B: Uninterpreted seismic section (zero-offset). The P1–P3 systems are “coarse-grained, metamorphic, or diagenetically altered deposits. While exogenous lithologies are inconsistent with the geologic evolution of the Quaternary Mississippi Fan (see Weimer, 1990), dense water-filled sands encased in uncompact ed (porous) muds are a possible cause of traveltime deficits. Yet, VPU magnitudes observed in the P1–P3 systems are larger than would be expected from this mechanism alone. While apparent VPU can also be caused by a buried basement high, a structural mechanism is inconsistent with the reflection geometries; the observed patterns would necessitate the deposition of systems onto a paleobathymetric high with the same morphology as the deposit itself. For these reasons, high-velocity nongas hydrates and/or anticlinal structures at depth are ruled out as probable causes of the convex-reflection geometries.

**Velocity and Saturation Calculations**

Based on the interpretation of gas hydrate–bearing sediments in the P1–P3 systems, $v^t - S^t$ was calculated using $VPU(t)$ (Fig. 2D), two end-member values of $v^t$ and $Th(t)$ (Figs. DR9A and DR9B), and Equation 2. Values of $v^t$ 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 $v^t - S^t$ realizations calculated along 175 km (109 mi) of the P3 thalweg. In all models, values of $v^t - S^t$ 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 $v^t - S^t$ are locally associated with higher values of $v^t$ 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,

Figure 2. Seismic response of the P1–P3 systems in middle Mississippi Fan, Gulf of Mexico. See Figure 1A for location. A: Uninterpreted zero-phase full-stack seismic sections (TWTT). Note presence of upper and lower high-impedance units (peak-over-trough) on left. B: Interpreted sections show slope valley systems (left) and channel-levee complexes (right) underlain by marked velocity pull ups (VPUs). Figure DR1A (see footnote 1) shows the calculation of the base gas hydrate stability zone (GHSZ). Left and right panels have same scales. C: Map of P1–P3 depositional systems. Accumulations become increasingly higher amplitude (root mean square, RMS) in successively shallower intervals and migrate eastward with time (black arrow). Detail on right shows frequency decomposition of upper unit of P3 system. Note that Deep Sea Drilling Project (DSDP) Leg 96 Sites 617, 621, and 622 did not penetrate the deeper P3 system. D: VPU (in ms, TWTT) directly below P1–P3 systems (dashed line); magnitudes of VPUs are greatest where systems locally overlap. Panels C and D have same lateral scale.
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 youngest 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 distribution of gas hydrates in coarse-grained reservoirs, which is fundamental to determining the viability of the deposits as a future energy resource.

ACKNOWLEDGMENTS


REFERENCES CITED


Manuscript received 4 January 2018
Revised manuscript received 10 April 2018
Manuscript accepted 10 April 2018
Printed in USA

562 www.gsapubs.org | Volume 46 | Number 6 | GEOLOGY

Figure 3. Four realizations for P-wave velocity ($v_p$) and saturation ($S_h$) of gas hydrate-bearing sediments, calculated along P3 thalweg. Calculations were 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).

Figure 4. Diagram for P3 system showing gas-migration mechanisms. In proximal locations (left), gas is focused into reservoir via faults associated with a salt diapir. In medial and distal settings (right), gas migrates via diffusive flow, subseismic faults, and/or additional mechanisms. Gas hydrate-free zone (GHFZ) may indicate a diffusion-limited reservoir interior, or a central nonreservoir unit (i.e., mass transport complex) intersected by short-offset faults.