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Scientific Objectives of the Gulf of Mexico Gas Hydrate JIP Leg II Drilling

E. Jones and T. Latham, Chevron; D. McConnell, AOA Geophysics; M. Frye, J. Hunt Jr. and W. Shedd, Minerals Management Service; D. Shelander, Schlumberger; R. Boswell and K. Rose, U.S. DoE, C. Ruppel, D. Hutchinson and T. Collett, USGS; B. Dugan, Rice University; and W. Wood, Naval Research Laboratory.

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Abstract

The Gulf of Mexico Methane Hydrate Joint Industry Project (JIP) has been performing research on marine gas hydrates since 2001 and is sponsored by both the JIP members and the U.S. Department of Energy. In 2005, the JIP drilled the Atwater Valley and Keathley Canyon exploration blocks in the Gulf of Mexico to acquire downhole logs and recover cores in silt- and clay-dominated sediments interpreted to contain gas hydrate based on analysis of existing 3-D seismic data prior to drilling. The new 2007-2009 phase of logging and coring, which is described in this paper, will concentrate on gas hydrate-bearing sands in the Alaminos Canyon, Green Canyon, and Walker Ridge protraction areas. Locations were selected to target higher permeability, coarser-grained lithologies (e.g., sands) that have the potential for hosting high saturations of gas hydrate and to assist the U.S. Minerals Management Service with its assessment of gas hydrate resources in the Gulf of Mexico.

This paper discusses the scientific objectives for drilling during the upcoming campaign and presents the results from analyzing existing seismic and well log data as part of the site selection process. Alaminos Canyon 818 has the most complete data set of the selected blocks, with both seismic data and comprehensive downhole log data consistent with the occurrence of gas hydrate-bearing sands. Preliminary analyses suggest that the Frio sandstone just above the base of the gas hydrate stability zone may have up to 80% of the available sediment pore space occupied by gas hydrate.

The proposed sites in the Green Canyon and Walker Ridge areas are also interpreted to have gas hydrate-bearing sands near the base of the gas hydrate stability zone, but the choice of specific drill sites is not yet complete. The Green Canyon site coincides with a 4-way closure within a Pleistocene sand unit in an area of strong gas flux just south of the Sigsbee Escarpment. The Walker Ridge site is characterized by a sand-prone sedimentary section that rises stratigraphically across the base of the gas hydrate stability zone and that has seismic indicators of gas hydrate.

Introduction

The Gulf of Mexico Methane Hydrate JIP is a consortium of energy and service companies, as well as government organizations, that began collecting data and performing research on marine gas hydrates in the Gulf of Mexico (GOM) in 2001. The project is sponsored by both the JIP members and the US Department of Energy (DOE). The last few decades have seen considerable interest in gas hydrates from both a resource perspective and the standpoint of potential seafloor stability concerns for conventional deepwater operations. Addressing either of these issues requires obtaining fundamental data on the properties of gas hydrate-bearing sediments, the formulation of predictive models for gas hydrate distribution and concentration, an understanding of wellbore and formation stability in gas hydrate-bearing sediments, and the development of methods to analyze existing and new data to infer gas hydrate concentrations.

The GOM JIP project is divided into three phases. The first phase concentrated on collecting laboratory data and developing seismic and wellbore models for analysis of marine gas hydrate-bearing sediments. The second phase of the project, carried out in 2005, concentrated on groundtruthing predictions about gas hydrate-bearing units by logging and coring fine-grained (clay- and silt-rich) marine sediments in Atwater Valley blocks 13 and 14 and Keathley Canyon block 151. These locations were chosen for field investigation based on (a) precruise seismic analyses that indicated the potential for gas hydrate occurrence and (b) the contrasting nature of the apparent fluid and gas flux regimes at the sites. In Atwater

13/14, seafloor gas hydrate mounds and other features imply a high-flux setting where gas hydrate might be present close to the seafloor. In Keathley Canyon 151, seismic data reveal a bottom simulating reflector (BSR), a negative impedance contrast reflector that crosscuts stratigraphy and that occurs at the base of gas hydrate stability. Keathley Canyon 151 is also characterized by fewer seafloor features that might reflect rapid fluid flow, suggesting lower fluid and gas flux than at Atwater 13/14 and potential gas hydrate concentrations over a thicker part of the sedimentary section.

The third phase of the project began in October 2007 and will log and core sites in the Alaminos Canyon, Green Canyon and Walker Ridge protraction areas (Figure 1). These locations were selected by a team consisting of JIP partners, particularly Chevron, Schlumberger, AOA Geophysics, and MMS, as well as scientists from the USGS, the US DOE/National Energy Technology Lab, the Naval Research Labratory, and Rice University. Locations were selected to target sands within the gas hydrate stability zone (GHSZ) and also to assist the U.S. Minerals Management Service (MMS) with its GOM gas hydrate resource assessment (Ray et al., 2006). The sites will first be studied with reconnaissance logging while drilling (LWD) in 2008. The LWD expedition will measure sediment porosity, electrical resistivity, and acoustic velocity data that can be used to constrain the in-situ concentrations of gas hydrates. After assessment of the LWD data and potential further narrowing of sites, a second expedition will conduct coring of hydrate-bearing sand reservoirs identified by the LWD phase. Coring will be accomplished using both conventional methods and pressure coring equipment that can retain hydrate-bearing cores at in-situ hydrostatic pressure. The pressure cores will then be transferred under pressure into a vessel in which the physical properties (e.g., compressional- and shear-wave velocities, electrical properties) can be measured at restored in- situ effective stress. This vessel is a refinement of the one deployed during JIP drilling in 2005, which measured physical properties of pressure cores maintained at hydrostatic stress (Yun et al., 2006). Such advanced handling of the pressure cores provides better constraints on in-situ physical properties relevant to characterization of hydrate-bearing sediments than do other laboratory-based analyses of conventional or pressure cores.

Site Selection Process

Site selection for drilling of gas hydrate-bearing sands commenced in early 2006 with a joint MMS and USGS review of log data from more than 2000 wells in the deepwater GOM. The log data revealed the surprisingly common occurrence of sands in the shallow section, but only seven instances of elevated resistivity in sands within the upper ~600 m of the section. These locations, shown in Figure 1, were: Alaminos Canyon (AC) 24, AC 818, AC 857; Atwater Valley (AT) 92; East Breaks (EB) 597; and Garden Banks (GB) 460. The lack of resistive (hydrate-bearing) sands in the log data at many GOM sites was not surprising considering 1) the relatively poor quality of much of the data, which was acquired in oversized holes; and 2) the tendency for industry to maximize drilling safety by intentionally avoiding locations for which seismic data revealed anomalous zones in the shallow section.

Mississippi Canyon (MC) block 118, which is the focus of the Gulf of Mexico Gas Hydrate Consortium's Seafloor Observatory project, was also considered. The resistivity anomalies for the AT, EB, and GB locations were determined to be below the base of the GHSZ. Consideration was also given to Mississippi Canyon (MC) block 118, which is the focus of the Gulf of Mexico Gas Hydrate Consortium's Seafloor Observatory project, but there is no evidence of subsurface gas hydrate at this location. The JIP therefore decided to move forward with a detailed analysis of existing 3-D seismic data in the remaining blocks: AC 818 and AC 857. These analyses (reprocessing, velocity modeling, rock properties analysis, inversion, gas hydrate saturation, and others; Xu et al., 2004), coupled with geologic interpretations of the areas, suggested a number of possible drilling targets in AC818, but yielded no highly-rated potential sites in AC 857.

In July of 2007, the site selection group began assessing potential drilling targets within block AC 818 and re-opened the site selection to other areas in the GOM for which seismic and other data indicated the potential of gas hydrate-bearing sand reservoirs. In addition, areas were assessed to determine their use in aiding in the refinement of the GOM gas hydrates resource assessment underway by the MMS (Ray et al., 2006).

The site selection group reported to the JIP and DOE in October 2007 with scientific justifications for more than a dozen potential drilling targets in AC 818. In addition, the group determined that significant potential for high-saturation gas hydrates in sands existed in GC block 955 and Walker Ridge (WR) block 313. Based on this recommendation, the JIP determined to conduct additional seismic analyses of existing 3-D data in both GC 955 and WR 313 (Figure 1). A complete description of the site selection process and details of each target in AC818 can be found in Jones (2008).

Scientific Objectives for Alaminos Canyon 818

Geologic Setting of AC818

The AC 818 block (Figure 1) is just north of the U.S.-Mexico border in the northwestern GOM in water depths of ~2,700 m. The area lies ~13 km seaward of the Sigsbee Escarpment within the Perdido fold belt, a buried set of subparallel folds that were formed during Oligocene time (Fiduk et al., 1999). The large concentric box folds comprising the fold belt form some of the largest structural closures in the GOM (Fiduk et al., 1999). Because of their subparallel aspect, the folds have been numbered 1 (east) to 5 (west). The sites around AC818 are near the crest of fold 3. A published regional seismic profile (Fiduk et al., 1999) shows the deeper stratigraphy and structure across fold 3, with younger units onlapping the fold structure.

Although the Perdido fold belt deforms units of Mesozoic to Oligocene age, it is only the uppermost Oligocene Frio strata that have been uplifted into the GHSZ and preserved from erosion in this area. At the crest of fold 3, this volcaniclastic sand, which was logged during drilling of well AC 818 #1, was found to have resistivity anomalies of 30-40 Ω-m (Figure 2).

Sampling gas hydrate was not an objective of the previous drilling, but the show of gas during drilling and the combination of elevated acoustic velocities and high formation resistivities are interpreted to indicate high saturations of gas hydrate (Smith et al., 2006).

A strong BSR (Figure 3) coincides with the base of the inferred gas hydrate occurrence in the AC818#1 well and places the base of gas hydrate stability (BGHS) within the Frio sandstone unit at the crest of the structure. The gas hydrate-bearing Frio sand encountered by the AC818#1 well is immediately below an unconformity that truncates the Frio sandstone on top of the #3 fold. The most shallow preserved occurrence of Frio sand in the immediate area occurs north of the AC818#1 well on the upthrown side of a minor fault, possibly providing a thicker gas hydrate section there than encountered at the well.

From a petroleum systems perspective, the Frio sandstone forms the gas hydrate reservoir (Figure 4A), which is capped by ~450 m of fine-grained Plio-Pleistocene shale-prone deposits of the Alaminos Fan (Morton and Weimer, 2000). The AC 818#1 well encountered a high gas-oil ratio oil in the deeper Eocene section, demonstrating the presence of a methane-rich petroleum system. Excellent indicators of gas in parts of the system are seen in the seismic data, including strong reflectors (bright spots) consistent with gas-charging of units below the base of the GHSZ in some locations and the loss of high frequency content beneath and west of the fold axis at about 4.2 s two way traveltime. Such loss of high-frequency information is generally associated with attenuation caused by small amounts of free gas. Spatially, this gassy zone does not appear to extend any appreciable distance east of the edge of the fold. Faults are evident in the seismic data, suggesting the existence of transport pathways to move gas-rich fluids into the GHSZ. The reprocessed seismic data reveal minor faulting through the Frio, indicating possible compartmentalization of the gas-hydrate reservoir (Figures 4B and 4C).

Although the primary drilling targets are within the high-saturation portions of the Frio sand, several additional targets are being considered that could provide important rock properties and physical parameters for sediments not tested in the existing well and that could enable the sampling of seismic amplitude anomalies suggestive of low to moderate gas hydrate saturations in the younger Plio-Pleistocene section.

Assuming pure methane as the hydrate former and hydrostatic pressure, the regional depth to the base of the GHSZ at 3197 m below sea level (pressure of ~33 MPa) corresponds to a temperature of 23.8^{o}C. For bottom water temperature of 3°C, the estimated thermal gradient is ~44 mK/m, a value consistent with known gradients in this part of the GOM (Forrest et al., 2005). During previous drilling, gas began to flow from the formation at depths corrected to sea level of 3184 m, which is less than 4 m below the top of the seismically-inferred gas hydrate-saturated zone (Smith et al., 2006).

Drilling Targets

Initial guidance from the JIP was that 6 to 9 logging-while-drilling (LWD) holes might be drilled around the AC818 well. Based on this, the site selection group decided to identify up to twice as many potential targets in case some were disallowed for safety or other reasons. Eventually, 18 potential targets were selected for LWD near the AC818#1 well (Figure 4C). These targets are located in blocks AC818, AC819, AC774, and AC775. Broadly, the targets fall into three categories:

(1) Targets with interpreted high saturations of gas hydrate within Frio sand: *Targets 1, 2, 3, 4, 9, 10, 14, 15, and 16*.

(2) Targets with moderate to low estimated gas-hydrate saturations and with generally lower confidence in the estimates of gas hydrate occurrence and concentrations. These targets are characterized by structural and/or stratigraphic complexities that interfere with charge to the Frio, or they are associated with lower quality reservoir units near the BGHS (e.g., fine-grained Plio-Pleistocene turbidites presumably charged by the same gas source), areas where the Frio reservoir unit thins below the resolution of seismic methods, or charging of units other than the Frio: *Targets 11, 12, 13, and 17*.

(3) Reference sites to provide constraints on the characteristics of the Frio sand when it contains only water or low concentrations of gas and to study stratigraphic units that are not penetrated elsewhere (e.g., by AC818#1 or JIP LWD sites) or that are missing due to erosion across the primary structures: *Targets 5, 6, 7, 8, and 18.*

In attempting to identify sites with low to moderate gas hydrate saturations (category 2 above), it became clear that most such targets were anomalies within the Plio-Pleistocene shales or at the very thin edges of the Frio Formation. This can be clearly seen on the inferred gas-hydrate saturation map, where the highest predicted gas hydrate saturations coincide with the thickest occurrences of the Frio sandstone (Figure 4B). Hence, the Frio formation may contain high saturations of gas hydrate wherever it occurs within the GHSZ. The drilling targets identified in categories (1) and (2) should test this hypothesis.

Scientific Objectives for Green Canyon 955 and Walker Ridge 313 Areas

Geologic Setting of Green Canyon 955

Potential drilling targets in GC 955 lie at ~2000 m water depth approximately 10 km southeast of the Green Canyon reentrant, the natural spill point for sediments coming off the Sigsbee Escarpment (Heggland, 2004). Numerous Pleistocene sand "fairways," channels filled with relatively clean sands and extending laterally for many kilometers, are recognized in this area and could provide good reservoirs for gas hydrates where the sands lie within the GHSZ and have the potential for gas charge. The area was analyzed for shallow water flow hazards by McConnell (2000), and much of the background geology is either given there or explored in greater detail in Hutchinson et al. (2008).

Two wells have previously been drilled in the area: GC955 #1 and GC955 #2. Seismic data reveal channel systems at numerous stratigraphic levels, and these appear to have persistently traversed the block with NNW to SSE orientation (Figure 5, inset). Seismic and log data from the GC955 #1 well in particular indicate that a large erosional-aggradational channel complex with well-developed levees delivered thick sands across a wide area of the block, and that these sands occur above, at, and below the base of the GHSZ. Subsalt hydrocarbon extraction in a sidetracked well drilled in an adjacent block and a subsalt hydrocarbon discovery at GC955#2 imply the potential for gas charge in this area. Numerous seismic indicators of gas charge are also evident in the supra-salt section (Heggland, 2004; McConnell, 2000).

Vertical gas migration is likely aided by numerous faults that are imaged in the block. Deformation of the sediment appears to be particularly intense within a four-way structural closure that occurs in the SW quadrant of the block (Figure 5 and Figure 6). A short distance to the east of this structure, the GC 955 #1 well encountered ~150 m of fining-upward sand that straddles a poorly-organized BSR. This BSR crosscuts, but remains within, the stratigraphic interval equivalent to the sand as traced eastward across the structural high. Geophysical responses suggestive of anomalously fast intervals appear sporadically within the area of the closure, but are highly discontinuous. Based on the depth of the BSR, an assumed bottom water temperature, and Structure I methane hydrate, the expected geothermal gradient in the area is 27 to 32 mK/m.

The GC 955 #1 well drilled through the zone of thick sands considered the best reservoir for gas hydrate to test the deeper conventional exploration target. Driller's reports are a good source for documenting shallow drilling problems, but such reports were not available to the authors. However, the publicly-released attenuation derived resistivity log in GC955#1 reveals a 4.2 Ω-m anomaly within an interval where gas hydrate is predicted to occur. We caution that this is a preliminary interpretation and that the true significance of this log is not yet clear.

Final choice of LWD targets for GC955 is currently in process and will use the same types of advanced seismic analysis as was conducted for existing 3-D data from AC818.

Geologic Setting of WR313

Walker Ridge block 313 lies north of the Sigsbee Escarpment within the northern Gulf of Mexico minibasin province. The planned drill sites (Figure 7) are within the Terrebonne Basin at water depths of ~1940 m to 2000 m. The present day basin is flanked by salt ridges and has a single sediment entry point to the north. The southern margin of the basin is bifurcated by a N-S trending salt-cored ridge located near the eastern edge of WR block 313. The basin west of this ridge is bounded by salt on the west, south, and east flanks, likely resulting in the ponding and accumulation of any sands delivered into it. Several large expulsion features (McConnell and Kendall, 2002) located on the seafloor above the crest of the N-S trending ridge provide evidence for active gas venting at the seafloor.

Intriguing seismic features (Figure 8), including a laterally discontinuous BSR that covers nearly 80 km^2, were noted by the site selection team on both the western and northeastern flanks of the intervening N-S trending salt ridge. However, the only available well in this area (WR 313 #1) lies on the ridge's southwestern flank; consequently, the search for drilling locations has so far been focused on this region, which includes primarily the eastern half of WR block 313.

The potential drilling targets are located off-structure and to the west of the WR 313 #1 well. The well encountered wet sands in an up-dip position, indicating that the trap for the inferred gas hydrate prospects may be formed by the reduction in porosity related to the gas hydrate itself. The sand-rich intervals encountered in the well can be traced downdip, where they appear to thicken and produce multiple instances of a BSR-like reflection as the sandy layers cross the inferred base of the GHSZ (McConnell and Kendall, 2002). In several cases this transition is marked by a seismic phase reversal that is attributed to the acoustic velocity variation between gas hydrate and free gas (Figure 8). Seismic amplitudes gradually decrease as the units are traced updip from the phase reversals, which may be an indication of progressive reduction in gas hydrate saturation (McConnell and Zhang, 2005). This area of Walker Ridge is characterized by numerous oil and gas seeps at the seafloor, demonstrating active migration of hydrocarbons through the hydrate stability zone. Active seeps and lush chemosynthetic communities were found in WR 269 and 270, just north of WR 313, when these sites were visited by DSV Alvin in 2006 and the ROV Jason in 2008 as part of a Gulf-wide study of chemosynthetic communities sponsored by MMS and NOAA. In addition, data licensed to the MMS by the NPA Group indicate persistent sea surface oil slicks over WR 313, 269, and 270, as well as at GC 955. This implies the likelihood of active thermogenic charge at both WR 313 and GC 955.

In contrast to both AC818 and GC955, WR313 is not a structural play. Instead, the gas hydrate appears to accumulate preferentially within the lower part of the GHSZ. The targeted hydrate-bearing sands in this area are also significantly deeper than at either AC818 or GC955, occurring between 700 and 900 m below the seafloor. This corresponds to an estimated thermal gradient of ~20 mK/m, which is reasonable for this part of the GOM.

Conclusions

A primary goal of the current phase of the JIP is testing a range of exploration models for locating gas hydrate-bearing sands in the deepwater GOM. Numerous drilling, coring, and logging expeditions will be required before the full scale and complexity of gas hydrate occurrences in GOM sand reservoirs is understood. In the coming years, the DOE-sponsored Gulf of Mexico Gas Hydrates Joint Industry Project will contribute significantly to knowledge of hydrate-bearing sand reservoirs in a major petroleum basin through the first-ever targeted field investigation of such sands in the GOM during planned logging and drilling expeditions. This current phase of JIP research complements the previous phase (2001 to 2007), which culminated in 2005 drilling of two areas characterized by occurrences of gas hydrate in fine-grained sediments primarily to study geohazards related to such deepwater drilling.

The JIP is nearing the end of the site selection process for a planned multi-site LWD expedition planned for Spring 2008, to be followed by drilling and coring in 2009. The 2008 LWD expedition will collect data needed to optimize site selection for the 2009 drilling expedition, which will acquire both conventional and pressure cores to constrain particularly the physical properties of hydrate-bearing sands. The data acquired from both the LWD and direct sampling activities will improve our understanding of the resource potential and the drilling hazards represented by sands with high gas hydrate saturation. The upcoming expeditions should also provide data relevant to continued refinement of the gas hydrate assessment methodology currently being developed by the MMS.

The proposed locations for the upcoming phase of JIP drilling have been recommended by a team from the JIP partners, particularly Chevron, Schlumberger, AOA Geophysics, and MMS, as well as scientists from the USGS, the US DOE/National Energy Technology Lab, the Naval Research Labratory, and Rice University. The selection process has resulted in recommendation of three locations for investigation during field activities: AC 818, GC 955, and WR 313. These locations have been approved by the JIP Executive Board, and the selection of specific drilling sites and the advanced analysis of existing 3-D seismic data for the areas are ongoing.

The sites identified for further investigation represent three distinct gas hydrate plays. AC 818 has a relatively limited, but potentially high saturation, gas hydrate occurrence within Oligocene Frio sand in a small, four-way structural closure. The presence of gas hydrate has been confirmed by an existing well, and both the top and the base of the accumulation appear to be well imaged in existing 3-D seismic data. The primary purpose of the drilling at AC 818 is to confirm the geophysical inferences of gas hydrate saturation away from the single existing control point (well) and to select optimal sites for the collection of gas hydrate-bearing sand samples during the subsequent coring expedition.

The GC955 location has only limited indications of gas hydrate based on the currently available analyses. However, within the context of a petroleum systems framework, the data suggest that gas hydrate should be present: A sand section ~150 m thick lies within the GHSZ, and there is evidence for structural closure, gas charging, and the existence of gas migration pathways.

The WR location has compelling seismic evidence for the direct detection of gas hydrate in the form of a series of negative impedance reflectors consistent with the transition from free gas below to gas hydrate above within a sand-prone section. These discontinuous reflectors are aligned with the interpreted base of gas hydrate stability. An up-dip well encountered water-wet sand, suggesting that the trap for the inferred gas hydrate prospects may be formed by the reduction in porosity related to the gas hydrate itself.

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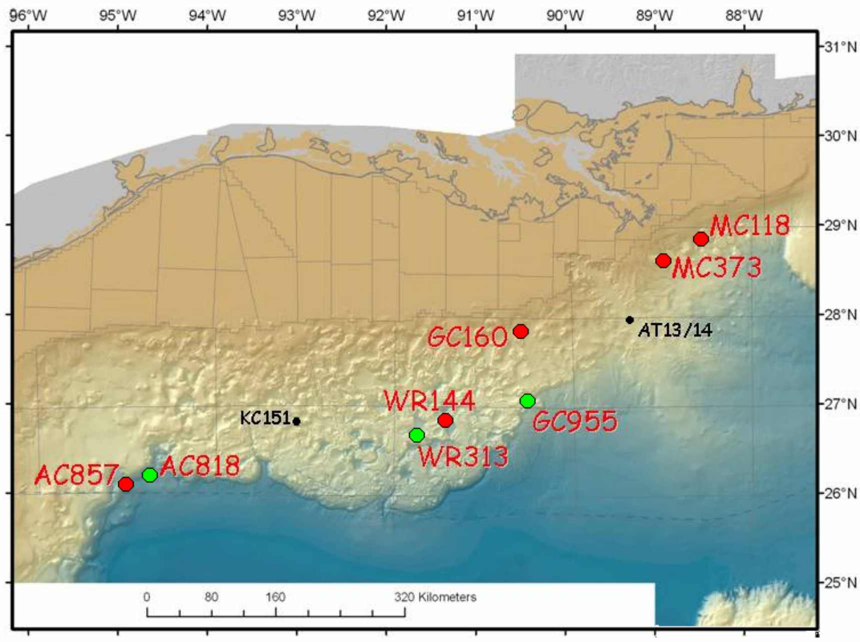

Figure 1: Location of all sites evaluated (red) and those ultimately selected (green) for the current phase of the JIP gas hydrates project. During this phase of the JIP, logging and potential future coring at Alaminos Canyon 818, Green Canyon 955, and Walker Ridge 313 will assess gas hydrate occurrences in sands and provide data for the further refinement of the MMS gas hydrate resource assessment. Sites drilled during the first phase of the JIP, which focused on geohazard issues and occurrences of gas hydrate in fine-grained sediments, are shown in black.

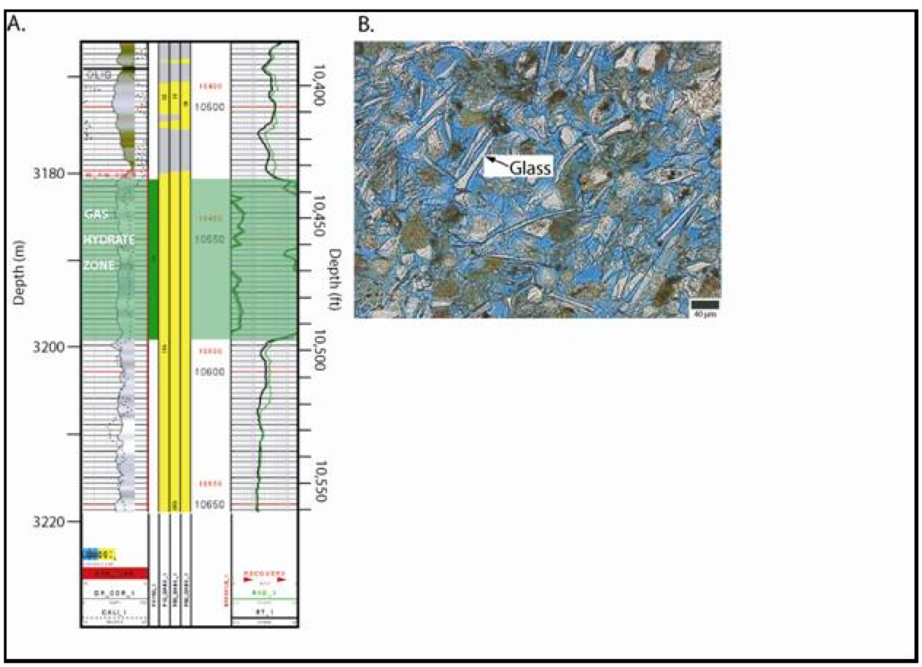

Figure 2: Data from the AC818#1 well: (A) Well log data from AC818#1 showing gamma ray response (left) and resistivity (right) with the interval of inferred gas hydrate saturation shaded green (3181 – 3197 m below sea level), from Smith et al. (2006). (B) Photomicrograph a sidewall core of the Frio sandstone in AC818#1 showing an immature lithic sandstone with high concentrations of volcanic glass, from Boswell et al. (2007). Elevated radioactivity caused by volcanic glass and potassium-feldspar bearing rock fragments explains the muted gamma ray response for these sands.

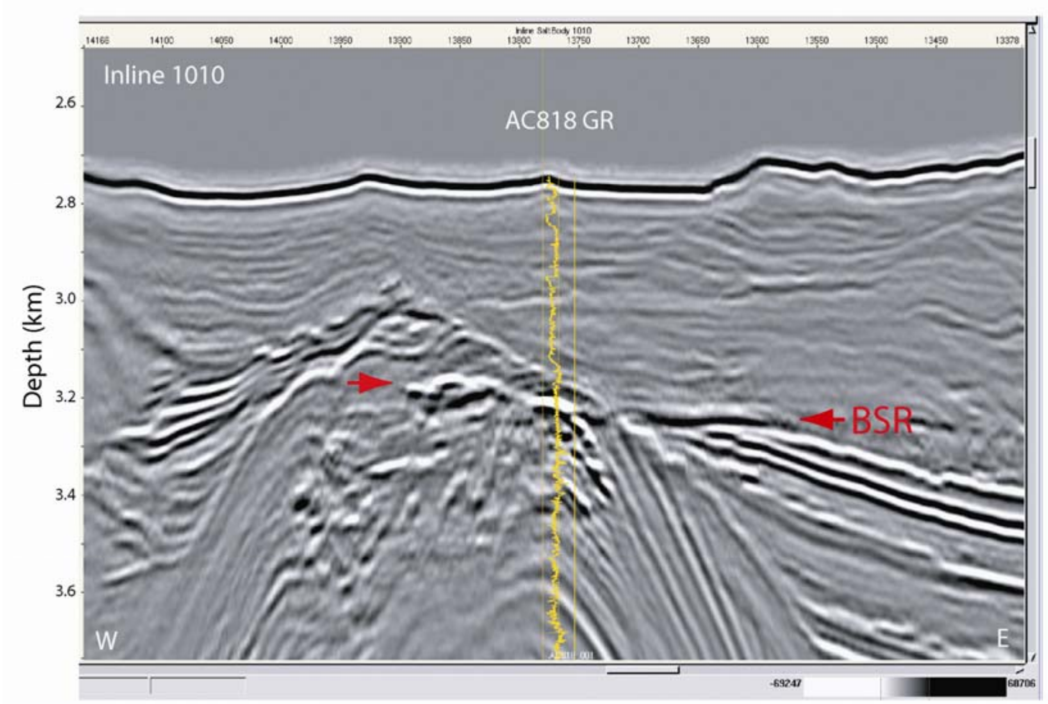

Figure 3: Depth-converted seismic profile showing inferred BSR at the location of AC818#1. The gamma ray (GR) log has been projected onto the seismic profile. From Jones (2008).

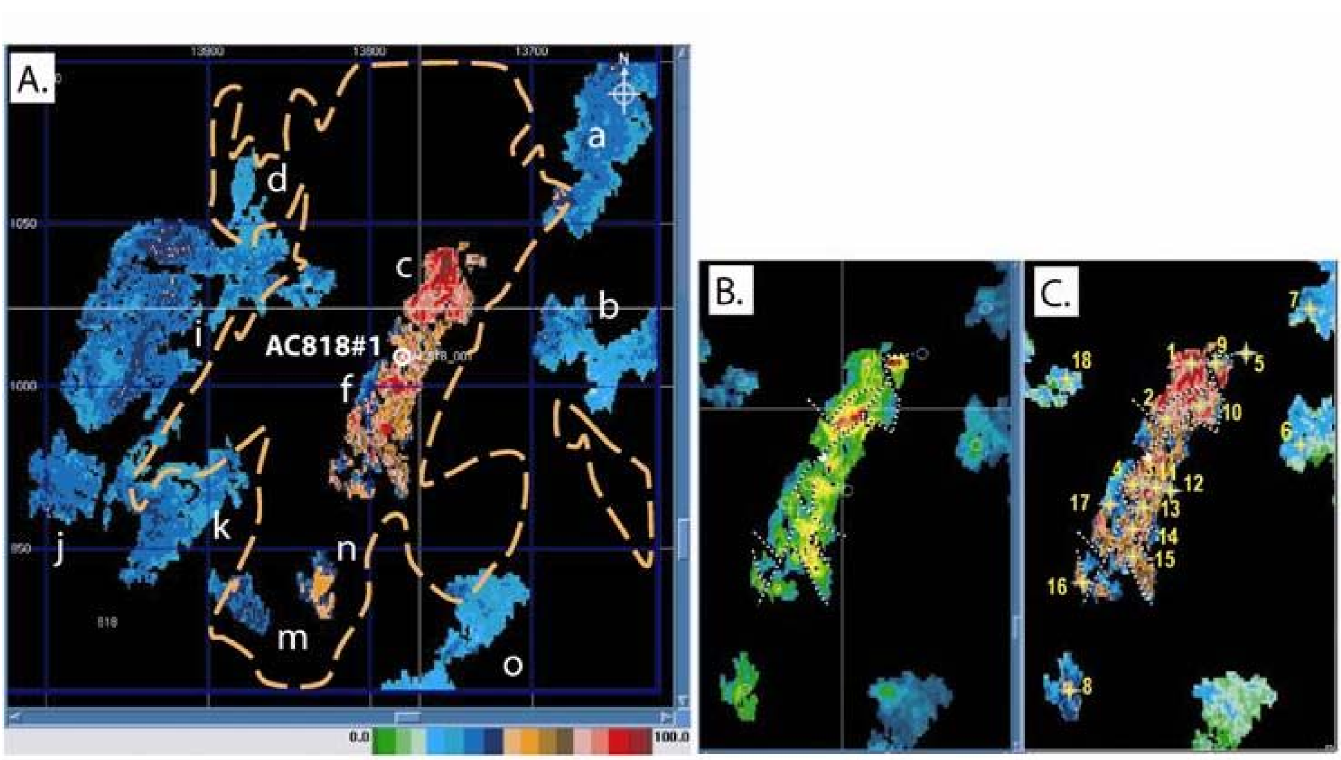

Figure 4: Seismic interpretations for AC818, modified from Jones (2008). (A) Maximum amplitude saturation of gas hydrates (blue is low, red is high). The location of the AC818#1 well is shown together with the outline (yellow dashed line) of the highest likelihood of gas beneath the base of gas hydrate stability zone. Letters refer to potential individual gas hydrate accumulations. (B) Integrated map showing where maximum (red) and minimum (blue) thicknesses of Frio sandstone and gas-hydrate saturations occur. Faults are shown as white dashed lines. (C) Map showing locations of drilling targets 1-18 superimposed on the maximum saturation map shown in (A).

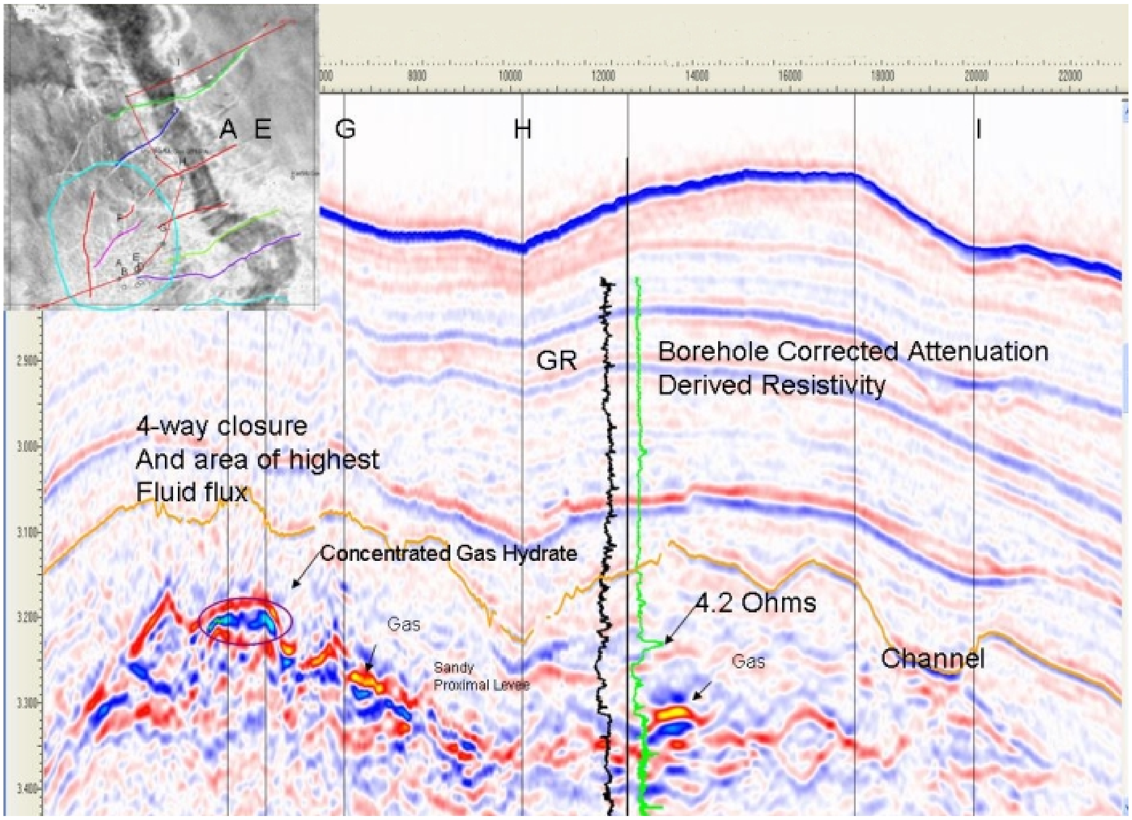

Figure 5: Arbitrary seismic line across GC block 955 along the SW to NE angular red line on the inset diagram. Inset represents amplitude from the gold-colored horizon showing the well-developed leveed erosional-aggradational channel complex with some fault plane penetrations marked in color. Dark linear feature on inset shows the channel axis, which maps to the channel on main figure. Blue circle on inset equates to area of 4-way closure as main figure. Superposed on the seismic section are GR and attenuation derived resistivity logs for GC955 #1 well. These indicate thick, fining upward sands. Bright seismic reflectors having polarities consistent with both free gas and gas hydrate are evident in this section.

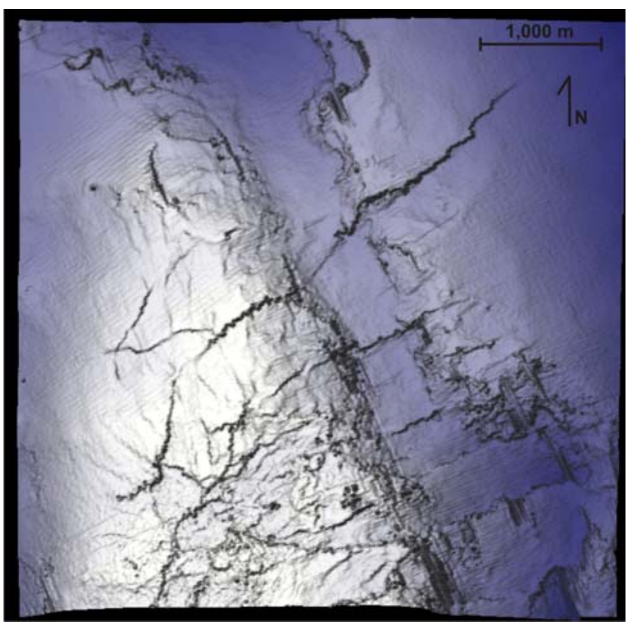

Figure 6: Time structure map in GC955 with shaded relief of the top of the well-developed and leveed erosional-aggradational channel complex that marks the top of potential sand-prone gas hydate reservoir approximately 100 m above the GHSZ. Note the intense faulting in the southwest quadrant, which defines the 4-way closure indicated in Figure 5.

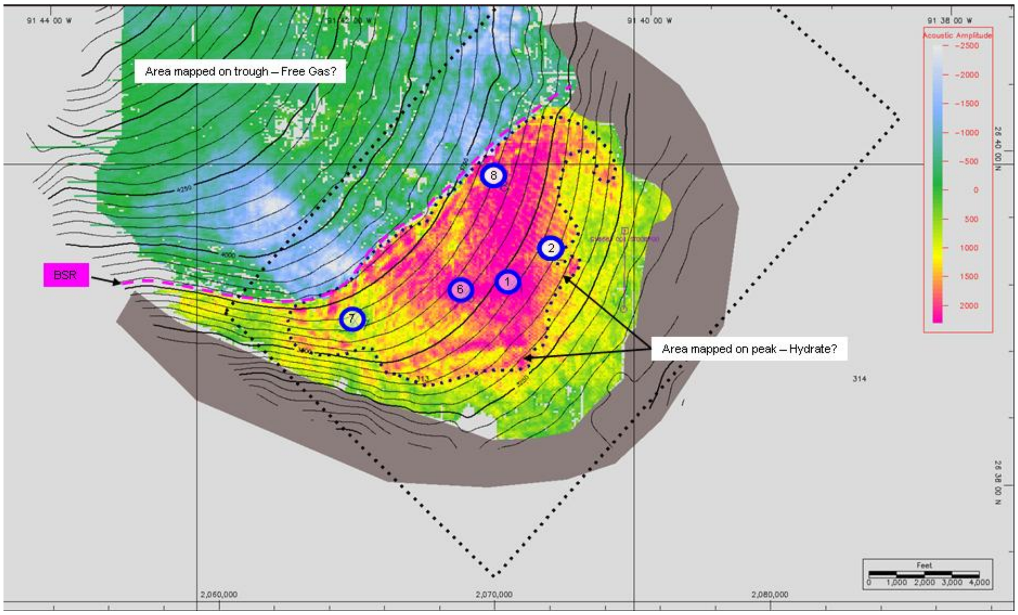

Figure 7: Time structure on selected prospective gas hydrate horizon in WR313. The image shows phase reversals at the interpreted based of GHSZ, with negative polarity (green and blue color) gas and water sands changing updip to positive polarity (yellow and red colors) gas hydrate-bearing sands towards the southeast. Image used by permission of CGG/Veritas.

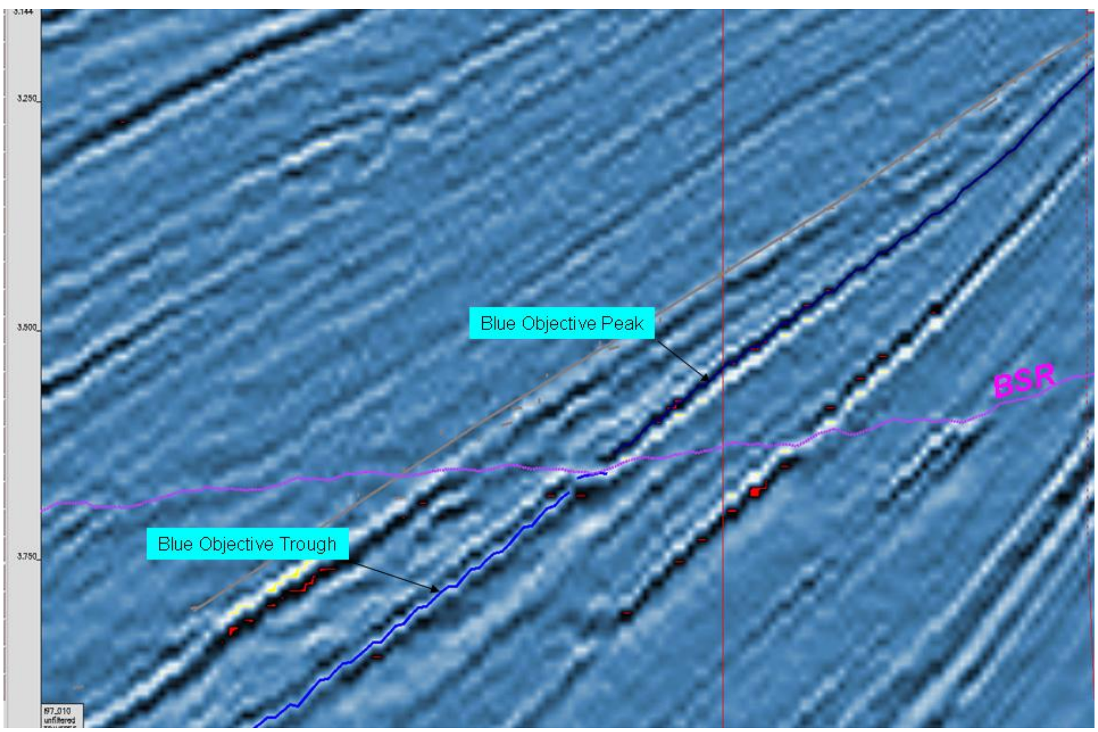

Figure 8: NW to SE seismic traverse through WR313. Note the phase reversal from a strong trough (white) to a strong peak (black) response as reflectors traverse the interpreted BSR. Depth is in two way traveltime. Image used by permission from CGG/Veritas.