Gulf of Mexico Gas Hydrate Joint Industry Project Leg II: Walker Ridge 313 Site Summary

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Abstract

In April and May of 2009 the Gulf of Mexico Gas Hydrate Joint Industry Project realized its second field program (Leg II) with the semi-submersible Helix *Q-4000* drillship. The three-week expedition drilled seven logging-while-drilling (LWD) holes at three sites that tested a variety of geologic/geophysical models for the occurrence of gas hydrate in sand reservoirs in the deepwater Gulf of Mexico. At the Walker Ridge 313 (WR 313) site, high saturation gas hydrate deposits in sands were found, where predicted both of the wells drilled. The full research-level LWD assembly deployed for Leg II collected data on formation lithology and porosity, and included quadrapole acoustic and high-resolution 3-D resistivity logs. No samples, only LWD data were collected in Leg II. Unexpectedly, a strata-bound fracture fill gas hydrate clay-prone unit was found at shallow depths at both wells. Gas hydrate was indicated in numerous thin sands and silts at both wells. Gas hydrate was found where predicted at the primary target sand at both wells. The two holes in WR 313 were drilled where sands are phase reversed across the base of gas hydrate stability (BGHS) with the phase reversal caused by high velocity gas hydrate pore fill. Pore filling gas hydrate with saturations up to 80% in a 40 ft net sheet sand was found at the primary target at WR 313-G. Likewise, 33 net feet of highly gas hydrate-saturated sand was found in a deeper sequence that was the primary target sand at WR 313-H. The JIP's discovery of thick gas hydrate-bearing sands at the WR 313 site validates the integrated geological and geophysical approach used in the pre-drill site selection and provides increased confidence in assessment of gas hydrate volumes in the Gulf of Mexico.

Introduction

In April 2009 the Gulf of Mexico Gas Hydrates Joint Industry Program (JIP) conducted Leg II logging-while-drilling (LWD) operations at sites in Alaminos Canyon block 21 (AC 21), Walker Ridge block 313 (WR 313), and Green Canyon block 955 (GC 955) in the northern Gulf of Mexico (Figure F1). The primary objectives of the JIP Leg II drilling program were to determine the occurrence of gas hydrate within sand reservoirs in the Gulf of Mexico, to assess current approaches for interpreting gas hydrate occurrence from geologic and geophysical data, and to determine the most suitable sites for additional drilling and coring in future phases of the JIP program. Initial summaries of JIP Leg II operations, scientific results, and logging-while-drilling data collection methods are provided by Collett *et al*. (2009), Boswell *et al*. (2009), and Mrozewski *et al*. (2009) respectively. This report describes the scientific rationale and initial results for the LWD program conducted at the WR 313 site. Hutchinson *et al*. (2009) provides a review of the analyses conducted to select the targets to be permitted for possible drilling. A detailed review of logging-while-drilling (LWD) operations and acquired data from the WR 313 site is provided by Cook *et al*. (2009).

The JIPs selection of sites for drilling in Leg II was based on a prospecting approach that sought to combine the elements needed to support a gas hydrate petroleum

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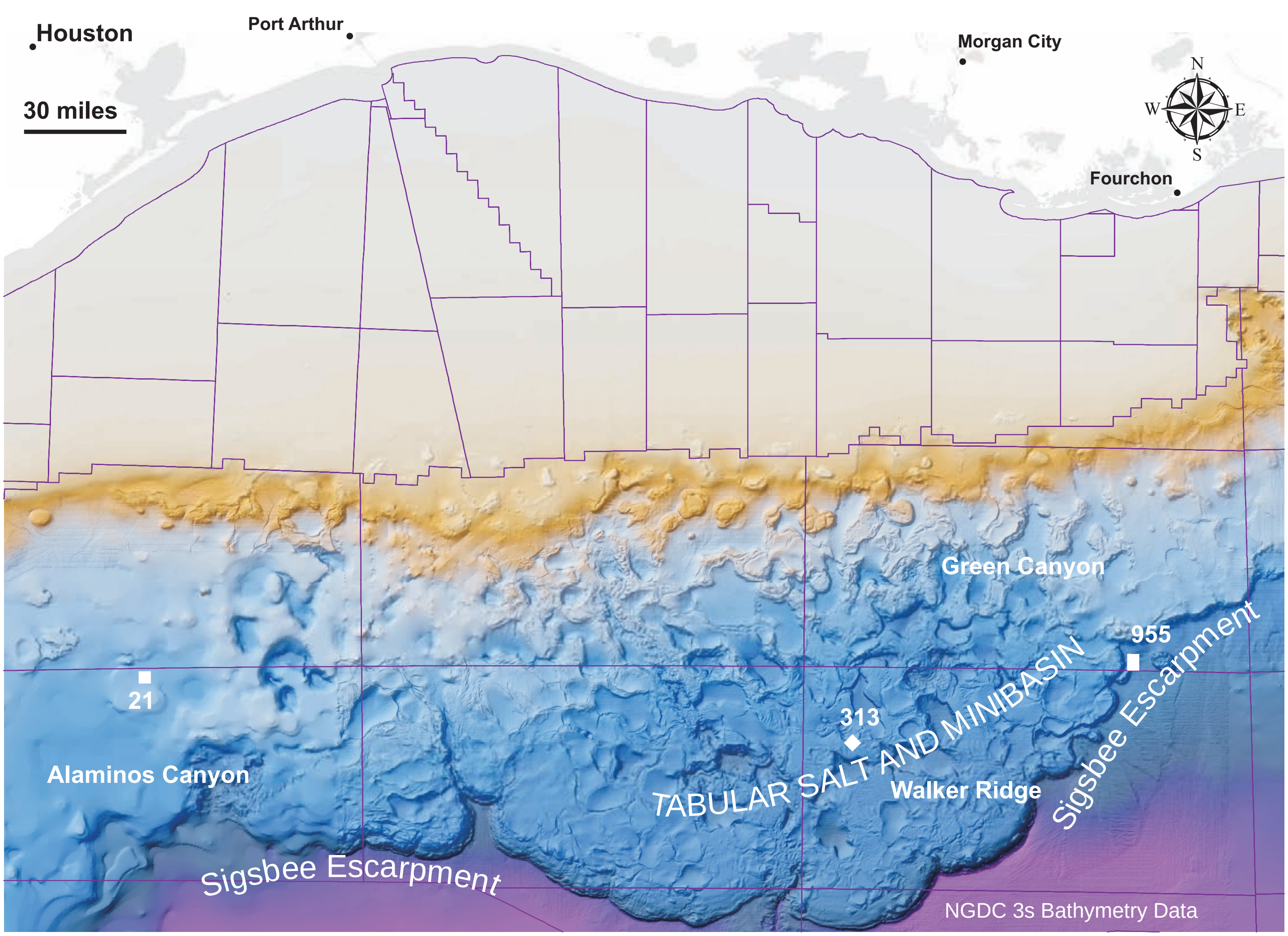

Figure F1: *Northwestern Gulf of Mexico showing tabular salt and mini-basin province, Sigsbee Escarpment and AC 21, WR 313, and GC 955 sites.*

system (appropriate temperatures and pressures, gas and water sources, and migration pathways) with the likely presence of sand reservoirs (needed to enable gas hydrate concentrations to high levels) within the gas hydrate stability zone (Hutchinson *et al*., 2008). Furthermore, the site selection process also incorporated the expectation that gas hydrate-charged sand reservoirs of sufficient thickness should be amenable to direct detection and quantification from seismic data (Dai *et al*., 2008). All of these elements were seen in the WR 313 area, providing a multitude of potential, high value sites for the JIP program (Hutchinson *et al*., 2009).

Buried gas hydrate deposits in the vicinity of the WR 313-G well location were first hypothesized using 3-D exploration seismic data in which the distribution of low-impedance seismic anomalies (bright spots) in steeply dipping strata, interpreted as gas, were at depths consistent with the base of gas hydrate stability (BGHS; McConnell and Kendall, 2002). The depths to the bright spots, when fit with a geothermal gradient of 19.5 °C/km, closely followed the gas hydrate phase stability curve modeled with gas fluid estimations and sediment velocity information from the nearby WR 313 #001 well drilled by Kerr-McGee (McConnell and Kendall, 2002). Later work showed that amplitude phase reversals are coincident with the up-dip termination of the bright spots in seismic amplitude data. Using the WR 313 #001 log data and empirical sediment density curves, the up-dip termination of the bright spots, when inverted, show as an abrupt change from low velocity-density character (interpreted as gassy sediments) to high velocity-density character (interpreted as gas hydrate pore fill) across the gas hydrate stability zone, suggesting a possible distribution of gas hydrate deposits above the seismic phase change boundary (McConnell and Zhang, 2005).

In a separate effort to characterize the potential gas hydrate resource in the Gulf of Mexico conducted within the Minerals Management Service, industry seismic and log data were reviewed for potential sand reservoir gas hydrate occurrences. That analysis revealed the broad occurrence of geophysical indicators of the BGHS seen earlier by McConnell and Kendall (2002) within the southwestern lobe of the Terrebonne mini-basin (Figure F1). The basin geometry and inferred geologic history made the shallow sedimentary section within WR 313 and bounding blocks prospective for sand, particularly where the basin is closed to the south, creating a potential blockage to encourage sand deposition. In addition, the seafloor in this area exhibited several fluid explusion features. As part of the search for specific gas hydrate drilling targets in the greater WR 313 area, it was determined that further analysis would be done within a diamond-shaped area (9 square miles in area) that included much of WR 313 and portions of lease blocks WR 269 (northwest), WR 270 (northeast) and WR 314 (southeast). Impedance and gas hydrate saturation models were produced by JIP member WesternGeco (Shelander *et al.*, *in review*) from 3-D volumes using techniques such as described in Dai *et al.* (2008). Other seismically-derived 3-D volumes produced in the gas hydrate modeling process include interval velocity, Poisson's ratio, V_p/V_s, compressional impedance, shear impedance, and gas hydrate saturations derived from both compressional impedance and the shear impedance volumes. The seismic analysis, integrated with geologic insights resulted in the selection of six specific drilling locations that were subsequently permitted for potential drilling during Leg II (Hutchinson *et al.*, 2009).

WR 313 Gas Hydrate Petroleum System

The WR 313 site is in Terrebonne Basin in the tabular salt and mini-basin province of the Gulf of Mexico approximately 215 miles south of Morgan City, Louisiana and 55 miles north of the Sigsbee Escarpment (Figure F1). A north-south trending salt-cored ridge divides the Terrebone basin into northern, western and eastern sub-basins, with the primary JIP targets being located in the western basin at water depths of 5000 to 6000 ft (Figure F2). Large allochthonous salt bodies bound this sub-basin to the south, east and west, locally cropping out at the seafloor. The basin likely formed in a manner similar to the Titan basin 50 miles to the northwest, with similar sources and mechanisms for potential hydrocarbon charge into the thick basin fill from Upper-Jurassic oil-prone source rock (Weissenberger and Borbas, 2004).

Gas and fluids sources and migration pathways

The complex evolution of a thick mini-basin clastic section between mobile salt stocks provides the potential for both the concentration of biogenic gas and possible thermogenic hydrocarbon charge. Several potential sources and migration pathways, both biogenic and thermogenic, are postulated for the sediments in WR 313. As salt vacates, the loading and filling of sediments into the newly-created accommodation space creates progressive asymmetrical steepening of older beds. This geometry may facilitate the migration and concentration of biogenic gases from across the basin to the updip basin flanks. As for thermogenic gas migration, thick secondary mini-basins such as is in WR 313 may also plumb into contact with thermogenic gasses from hydrocarbon-prospective primary basins along the margins of salt stocks and welds where salt has vacated. Several such deep welds to primary basin sediments (Pilcher, Hess Corporation, personal communication, Oct. 15, 2009) surround WR 313. In particular, there appears to be strong potential for fluid flow across a prominent weld into the mini-basin from the north. Large areas of reduced seismic amplitude in the area may also relate to areas of enhanced vertical fluid flux (Figures F3 and F4; Shedd *et al.*, 2009). There may also be potential fluid migration into carrier beds along the southwestern margin of the lower Terrebonne mini-basin where sediments onlap upon a high-angle allochthonous salt interface.

The linkage between dynamic salt movement and hydrocarbon charge into the shallow sediments is manifest in the large fluid expulsion mounds flanking the northern margin of the lower basin (Figure F3). These prominent fluid expulsion features in eastern WR 269 are an amalgamation of a number of large circular mounds with considerable sea-floor relief. Geochemical surveys of fluids gathered from piston cores found the gases in the sediments on the large mounds to be 100% methane (McConnell and Kendall, 2002). Subsequently, a survey for deepwater chemosynthetic communities found direct evidence for hydrocarbon expulsion on the mounds (MMS, 2009). Mud gas analysis of the WR 313 #001 industry well, however, suggested that the fluids in the deeper basin contained thermogenic gas (McConnell and Kendall, 2002).

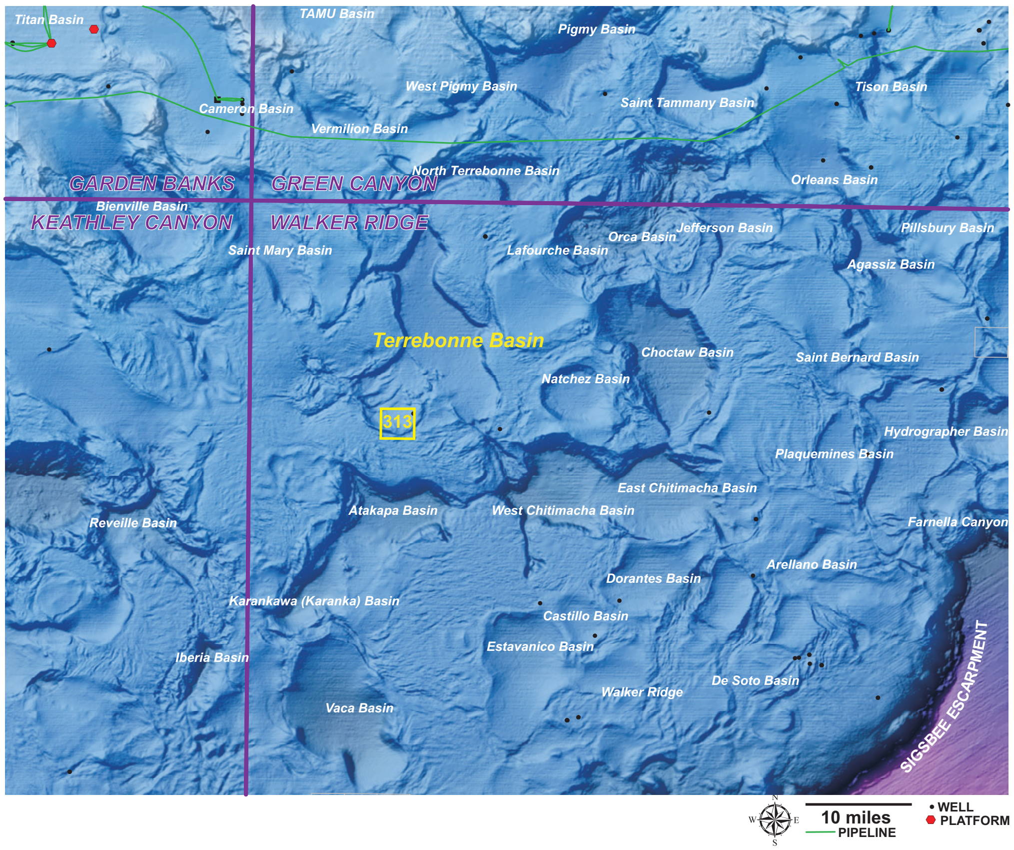

Figure F2: *NOAA regional multibeam bathymetry showing Terrebonne Basin and location of Lease Block 313 in Walker Ridge.*

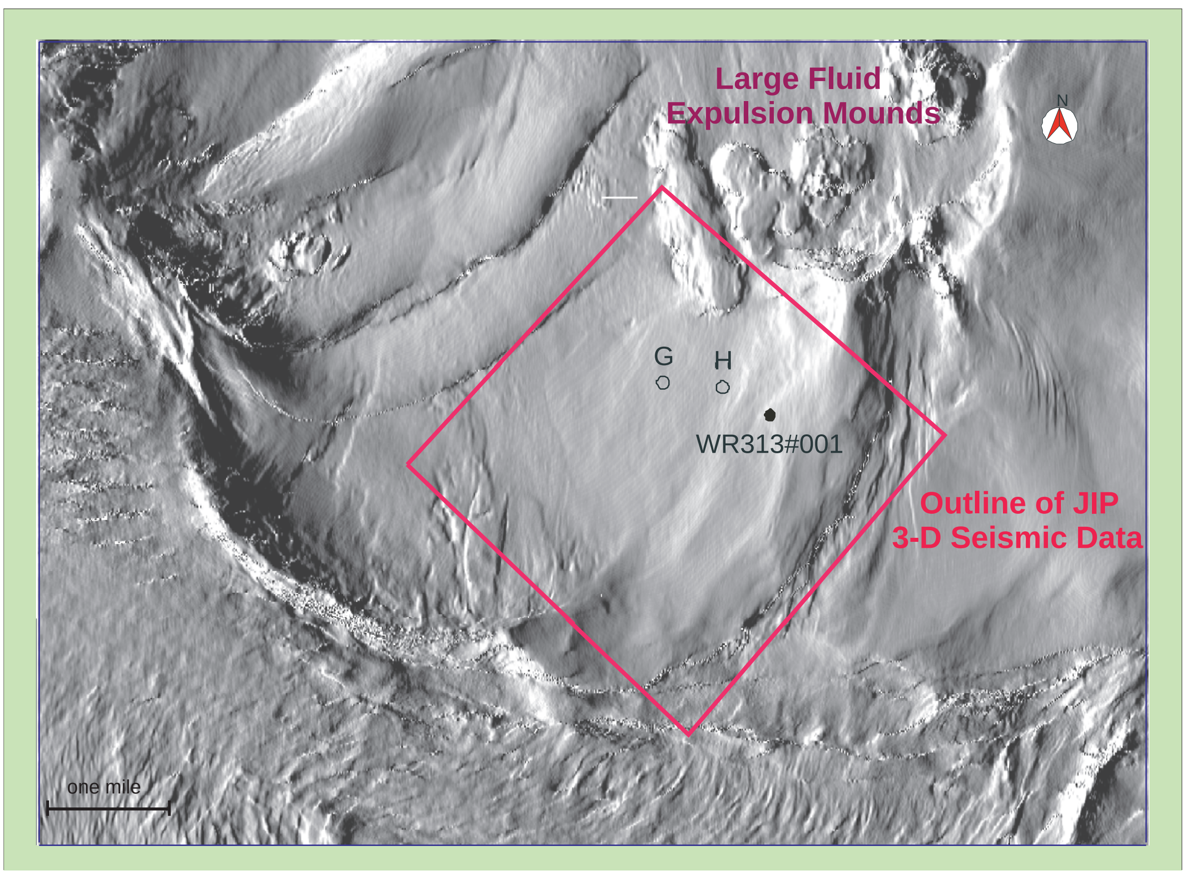

Figure F3: *Seafloor image showing large fluid expulsion mounds, locations of WR 313-G, WR 313-H, and WR 313 #001 wells, and outline of 3-D seismic data provided by Western Geco to JIP (Modified from McConnell and Kendall 2002).*

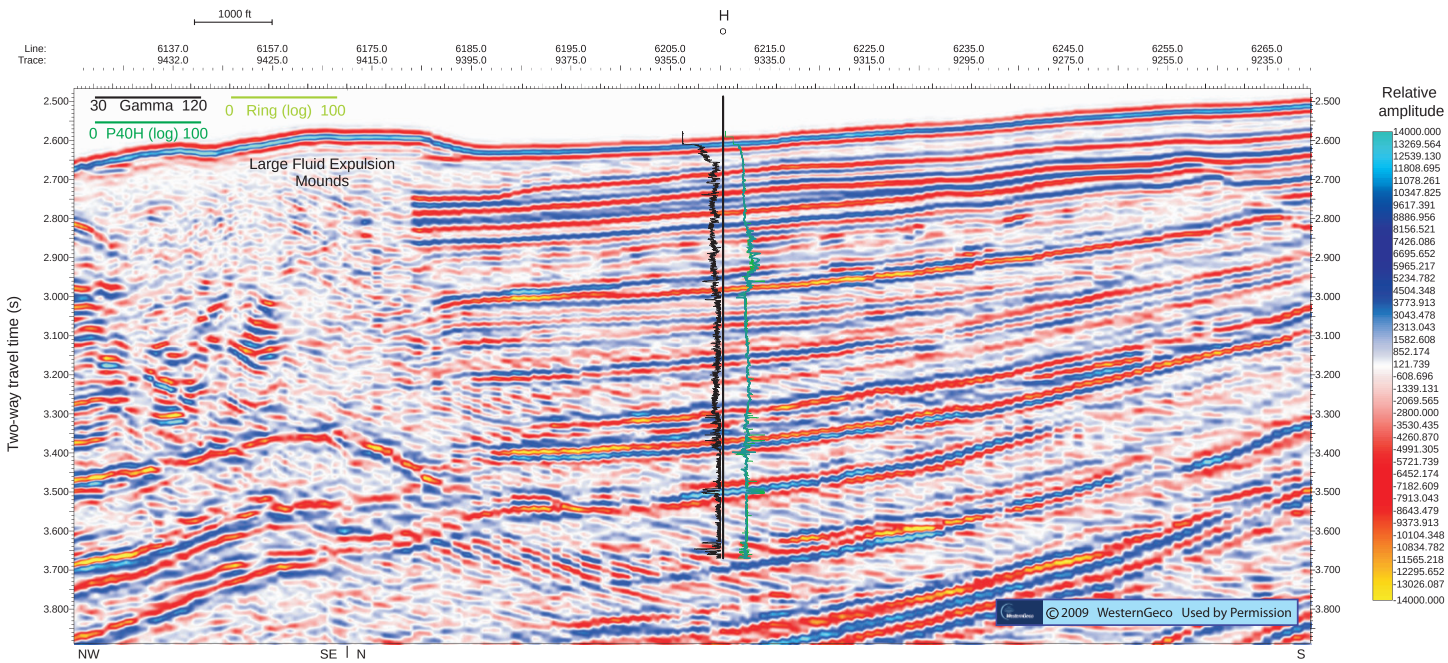

Figure F4: *Traverse through amplitude volume showing large fluid expulsion mounds and well WR 313-H. Seismic data courtesy of WesternGeco.*

Reservoirs

Stratigraphy in the upper part of the basin comprises cyclic deepwater clastic deposits of Plio-Pleistocene clays, silts, and sands. The calcareous nannoplanktic regional marker, *Gephyrocapsa caribbeanica* (< 1.7 Ma) was found at 9465 ft below the drill floor at the industry well WR 313 #001 putting the primary gas hydrate drilling targets in WR 313 in the Lower Pleistocene (MMS, 2007). Terrebonne basin sediment-fill architecture fits the type-facies that is typical of salt withdrawal basins in the Gulf of Mexico, and is characterized by fine-grained clays and interbedded silts and fine sands in sheets and channel-levee deposits with simple onlap onto the basin margin (Figure F5; Prather *et al*., 1998). Well logs from WR 313 #001 (located far up on the mini-basin flank), indicated that much of the basin is clay-prone but suggested sand potential in the ponded-fill sediments that thicken towards the basin center (Figure F5; Hutchinson *et al*., 2009). Associated channel-levee deposits have also been interpreted to occur within the basin along its central axis of the basin (McConnell and Kendall, 2002; McConnell and Zhang, 2005; and Hutchinson *et al*., 2009).

Geophysical Indications of Gas Hydrate

The model for the gas hydrate occurrence in WR 313 includes the lateral movement of free-gas bearing fluids within porous and permeable sand facies. As these fluids ascend on the basin flanks across the BGHS, gas hydrate is formed. Supporting this interpretation is the general nature of the BGHS in the area, which is manifested as a series of isolated bright spots separated by large areas in which no indications of free gas accumulations are seen ("segmented BSR" of Shedd *et al*., 2009). Other potential mechanisms for gas hydrate emplacement, *in situ* gas hydrate production, upward diffusive flux, gas coming out of solution, and concentration by recycling of low concentration gas hydrate in response to sedimentation were not considered in the pre-drill determination of primary targets.

The upper contacts of Pleistocene sands in the deepwater Gulf of Mexico, as a broad general rule, are expected to produce negative reflection co-efficients were they underlie clay-dominated lithologies. Previous work (i.e., Nur and Dvorkin, 2008) and other studies have indicated that pore-filling gas hydrate saturations in excess of roughly 35 to 40% will increase sediment strength and acoustic velocity sufficiently to reverse this impedance contrast from negative to positive, resulting in detectable "leading-peak" amplitude anomalies. The analysis of the seismic data in WR 313 suggested that this effect may be imaged, as several reflection packages show such phase reversals

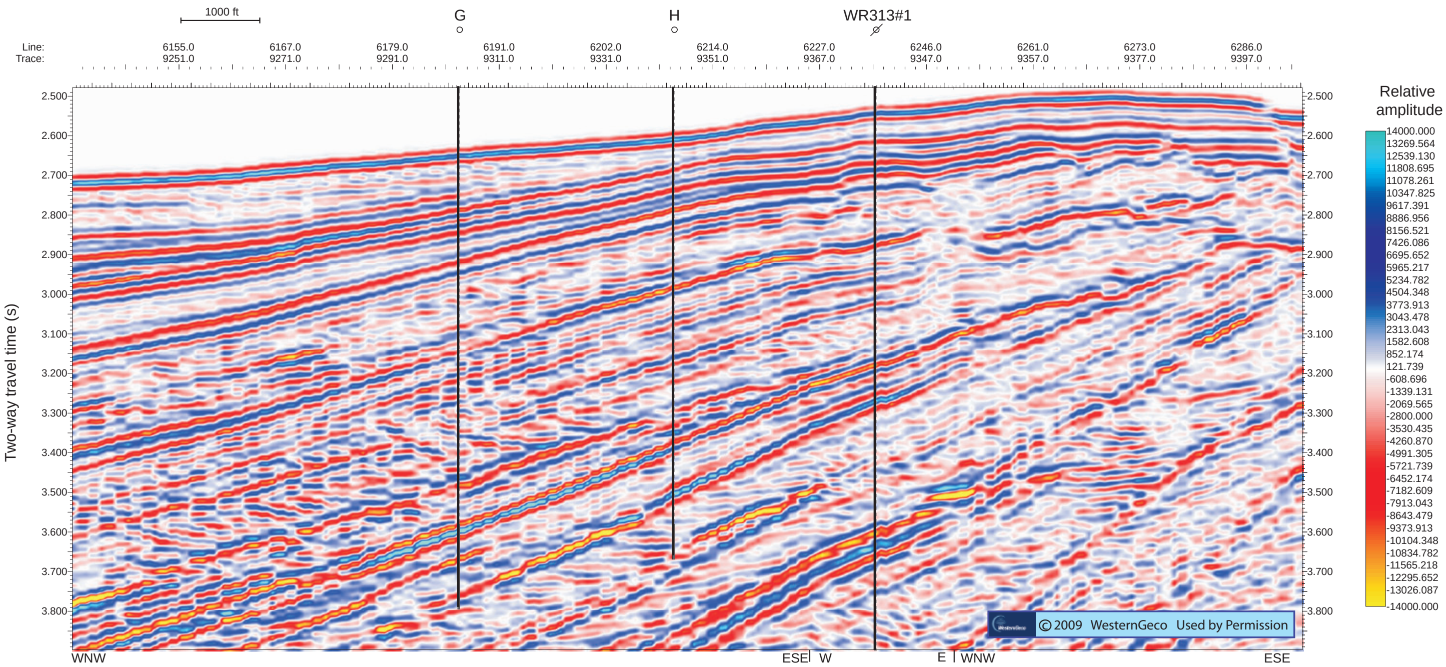

Figure F5: *Traverse through amplitude volume showing JIP and industry wells. Seismic data courtesy of WesternGeco.*

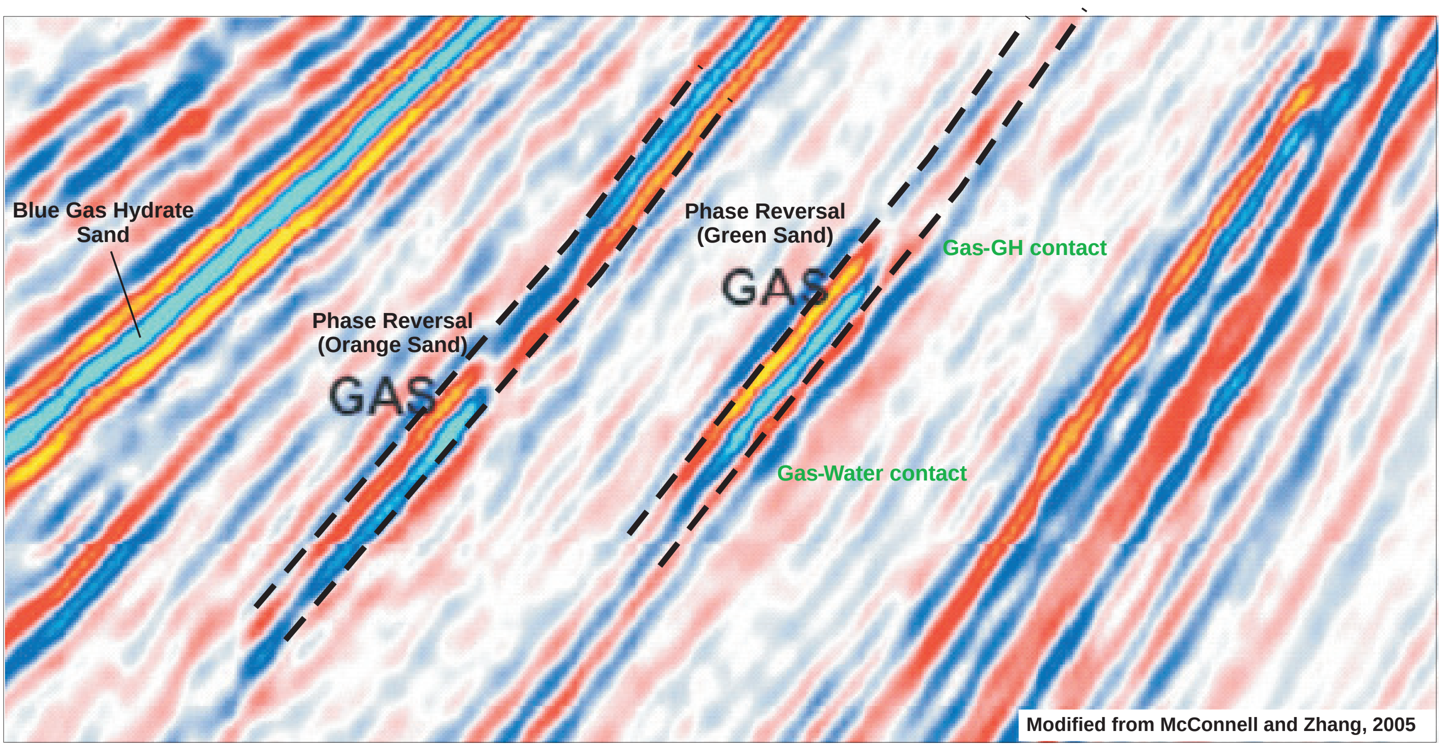

Figure F6: *Phase reversals in orange and green sands at the gas-gas hydrate contact.*

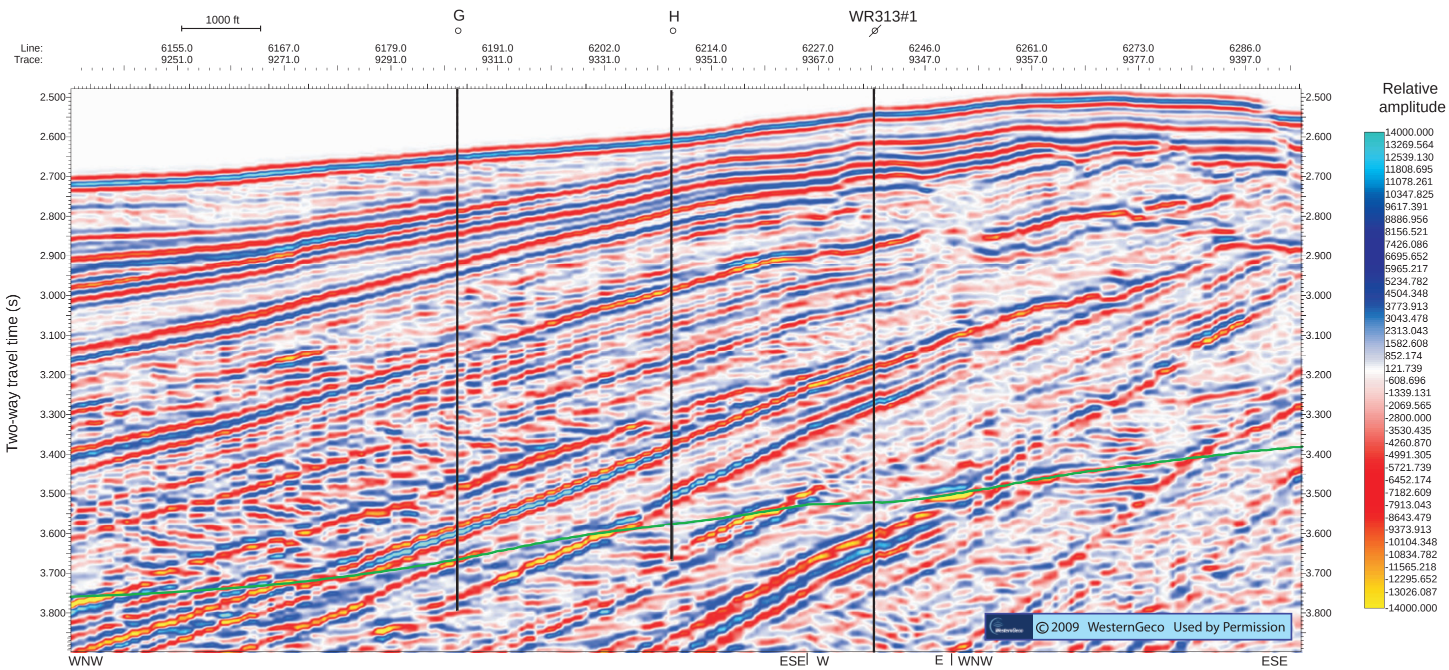

Figure F7: *Traverse through amplitude volume showing JIP and industry well and interpreted base of gas hydrate stability. Seismic data courtesy of Western Geco.*

as they cross the inferred BGHS (Figure F6). The common occurrence of this effect at several stratigraphic levels rendered all explanations other than gas hydrate fill very unlikely. The primary gas hydrate prospects identified in the region are all associated with such features and therefore trend along the BGHS (Figure F7). Each prospective horizon is observed to generally dim in amplitude as traced up-dip and higher within the gas hydrate stability zone, although none were observed to reverse phase back to negative polarities. During the pre-drill evaluation, it was not clear if this dimming was due to progressive reduction in gas hydrate saturation within generally consistent reservoir quality sediments (increasing water saturation) or to progressive reduction in reservoir quality (leading to reduced S_h without increasing S_w). The latter seemed more likely given the lack of any clear second polarity reversal, the expected loss of reservoir quality as units are traced away from the inferred depocenter in the deeper part of the basin, and the fact that well data from the WR 313 #001 well indicated that any sands in the basin had clearly thinned to below seismically-resolveable thickness at the location of that well. Therefore, key concepts that the drilling at WR 313 was designed to test include 1) confirmation of the model that phase reversals and associated segmented BSRs represent free-gas to gas hydrate transitions within discrete sand units within a variable sand-shale section; and 2) provide information on the controls on the potential up-dip extent of gas hydrate within those units.

Shallow Hazards Analysis

The risks associated withshallow drilling from a riserless deepwater platform are negligible. However, geohazards, such as gas and water flows, can require significant time to properly control. For a project such at the JIP, which is constrained to a set budget and time period, significant lost time translates directly into undrilled holes and uncollected data. In addition, JIP Leg II deployed one of the most advanced and expensive LWD tools strings ever assembled (Mrozewski *et al*., 2009). Issues such a loss of borehole stability that can result in damaged, even lost tools, must be very carefully evaluated and managed. Because all of the potential holes considered by the JIP were to be drilled open hole (without casing, risers, or blow-out preventers), the options available for management of well problems were limited to the use of weighted drilling fluid and cement. Therefore, to minimize the chances for costly downtime, the JIP ordered a thorough geohazards and wellbore stability analysis for all potential sites, even though regulations did not require that level of analysis in every case.

In order to provide optimal data throughout the section of interest, each planned well depth extended to 500 ft below the BGHS. Therefore, one of the hazards was the potential for gas flows from free gas zones in the bottom of the holes. Another key issue was the potential for slight overpressures that can cause water flows and/or wellbore

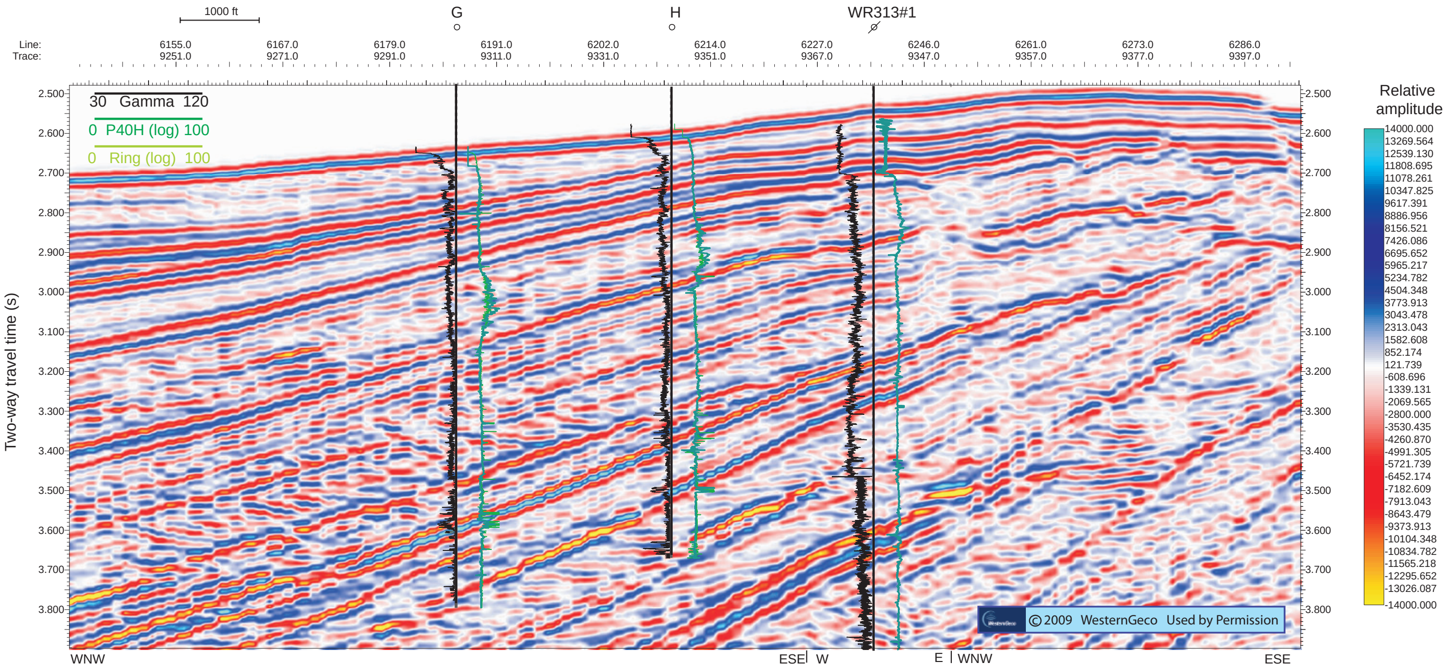

Figure F8: *Traverse through amplitude volume showing JIP and industry well with gamma and resistivity logs. Seismic data courtesy of WesternGeco.*

collapse in the unconsolidated marine sediment. The pre-drill hazards analysis evaluated all potential holes in WR 313 for these risks and moved or eliminated potential locations as required. Apart from the high negative impedance amplitudes interpreted as gas in the dipping basal sands, the BGHS appears in the seismic data as modestly enhanced amplitudes trending along the BGHS (Figure F7). There would be a risk of free gas beneath peak over trough relationships that lie flat at the BGHS, but the inclined geometry of the interpreted gas hydrate deposits to potential free gas zones in WR 313 allowed for most of the potential gas hydrate targets be assessed with negligible to low risks of gas flow upon drilling out from the BGHS. Negligible to low risks for water flows or gassy water flow were assessed at the targets because of possible gas hydrate dissociation. Wellbore stability was not predicted to be a significant hazard at the WR 313 sites in the pre-drill plan for drilling in WR 313 (Collett *et al.*, 2009).

WR 313 Drilling Results

Two holes, locations WR 313-G and WR 313-H, were drilled at the WR 313 Site (Table T1). The rationale for the prioritization of these from among the seven permitted sites is described in Hutchinson *et al*. (2009). An arbitrary seismic traverse showing the drilled locations and the industry well is shown as Figure F5 and as Figure F8 with gamma ray and resistivity log overlays. The predicted gas hydrate saturations along the same traverse are shown as Figure F9 and with gamma ray and resistivity log overlays as Figure F10. The results obtained from the two wells drilled during the program are described in Table T1.

Well WR 313-G

The target for WR 313-G is a dipping high-amplitude positive impedance reflector (called the "blue" horizon) interpreted as a sheet sand that is phase reversed from the polarity it shows beneath the BGHS (Figures F7 and F11; Hutchinson *et al*., 2009). The primary gas hydrate target at the G-location is 200 ft vertically above the BGHS (Figures

JIP Leg II Well	Latitude (NAD1927: Clarke)	Longitude (NAD1927: Clarke)	Water depth (ft)	Total depth (fbrf)
WR 313-G	26 39 47.4841 N	91 41 01.9404 W	6562	10,200
WR 313-H	26 39 44.8482 N	91 40 33.7467 W	6450	9770

Table T1: *Information on the two wells drilled in WR 313.*

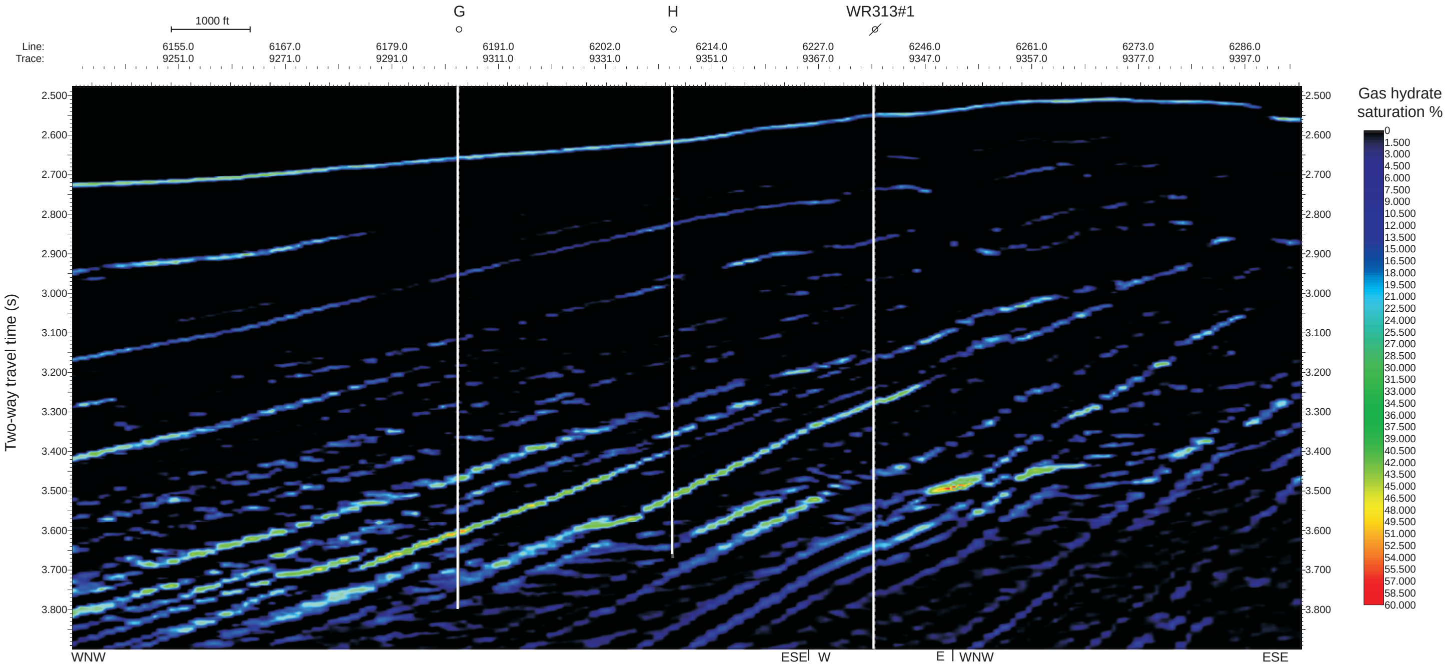

Figure F9: *Traverse through gas hydrate saturation prediction volume showing JIP and industry wells. Image provided by Schlumberger.*

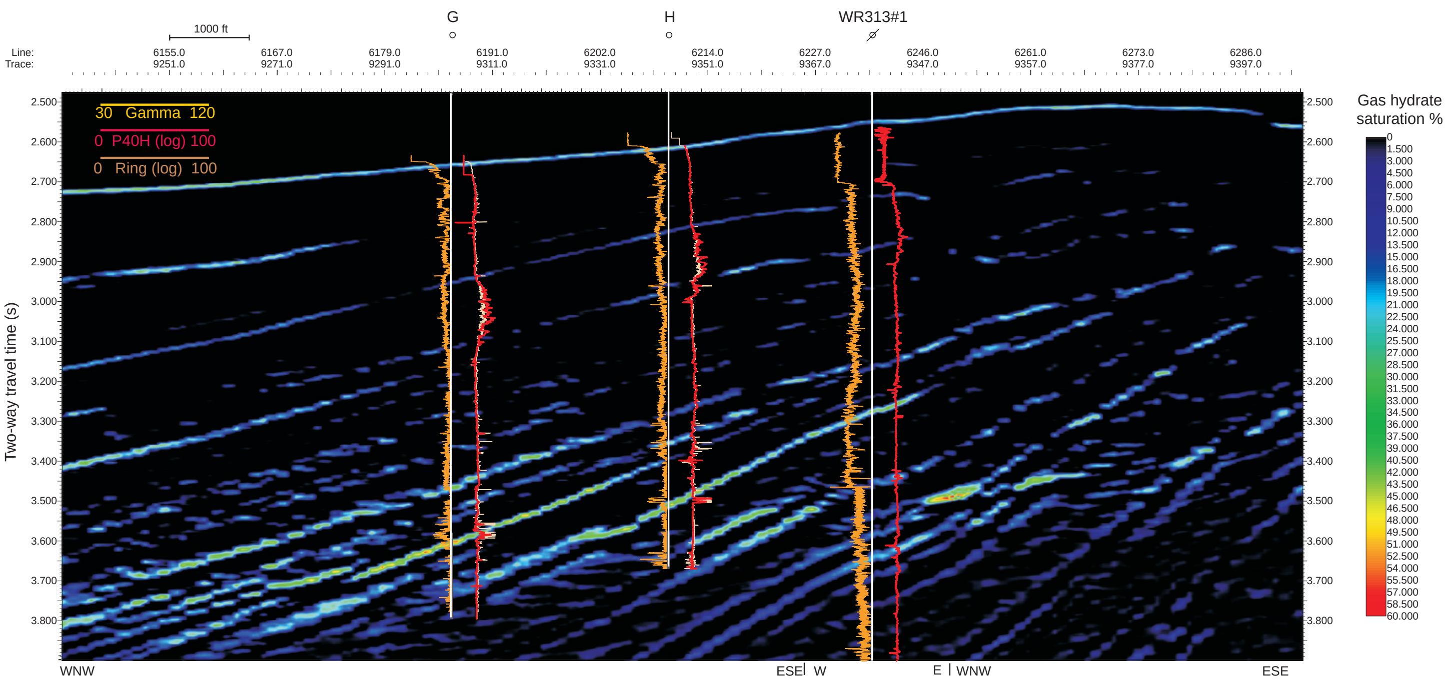

Figure F10: *Traverse through gas hydrate saturation prediction volume showing JIP and industry wells with gamma and resistivity logs. Image provided by Schlumberger.*

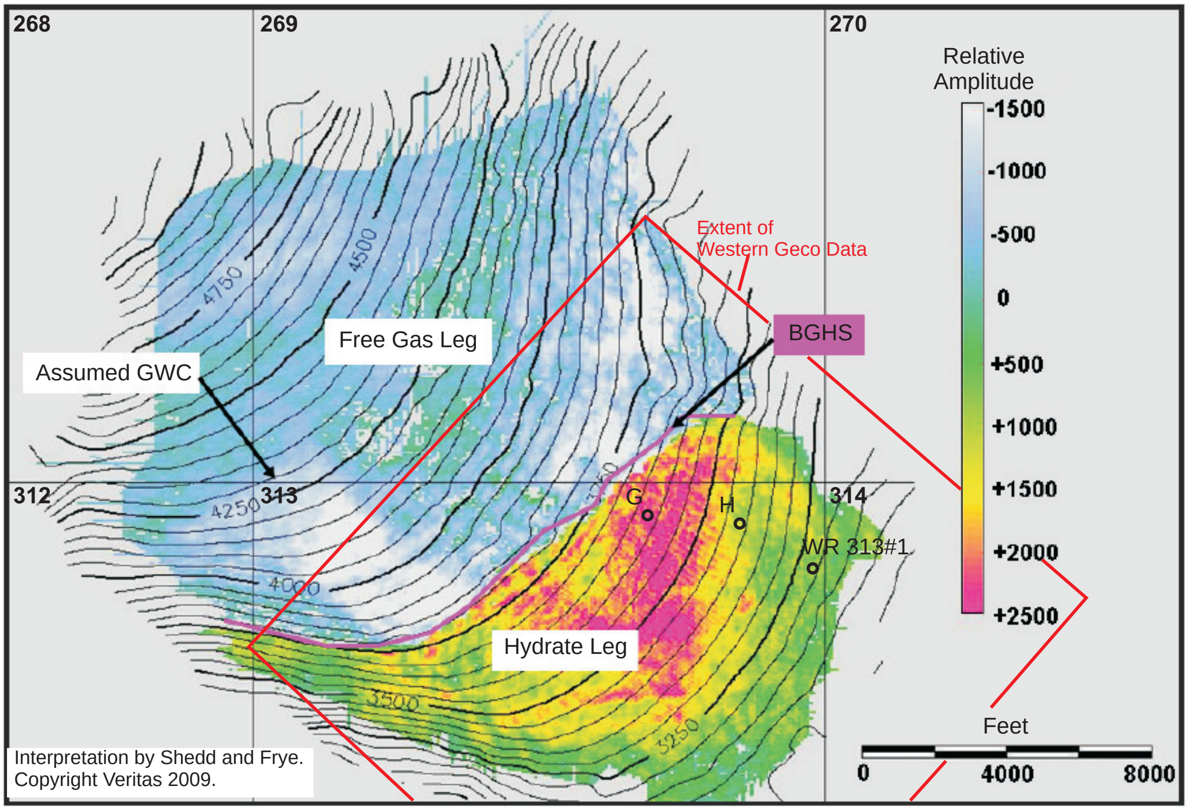

Figure F11: *Amplitude on blue horizon showing gas and gas hydrate legs spanning the base of gas hydrate stability (BGHS).*

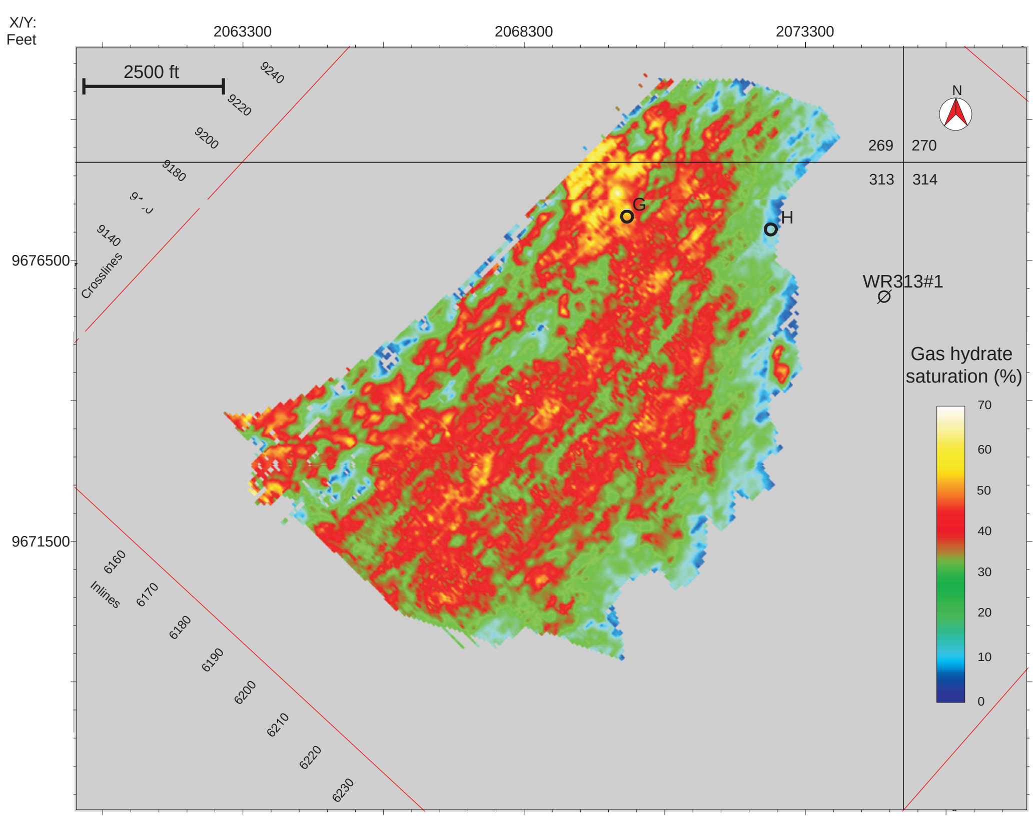

Figure F12: *Predicted gas hydrate saturation in blue sand. Image provided by Schlumberger.*

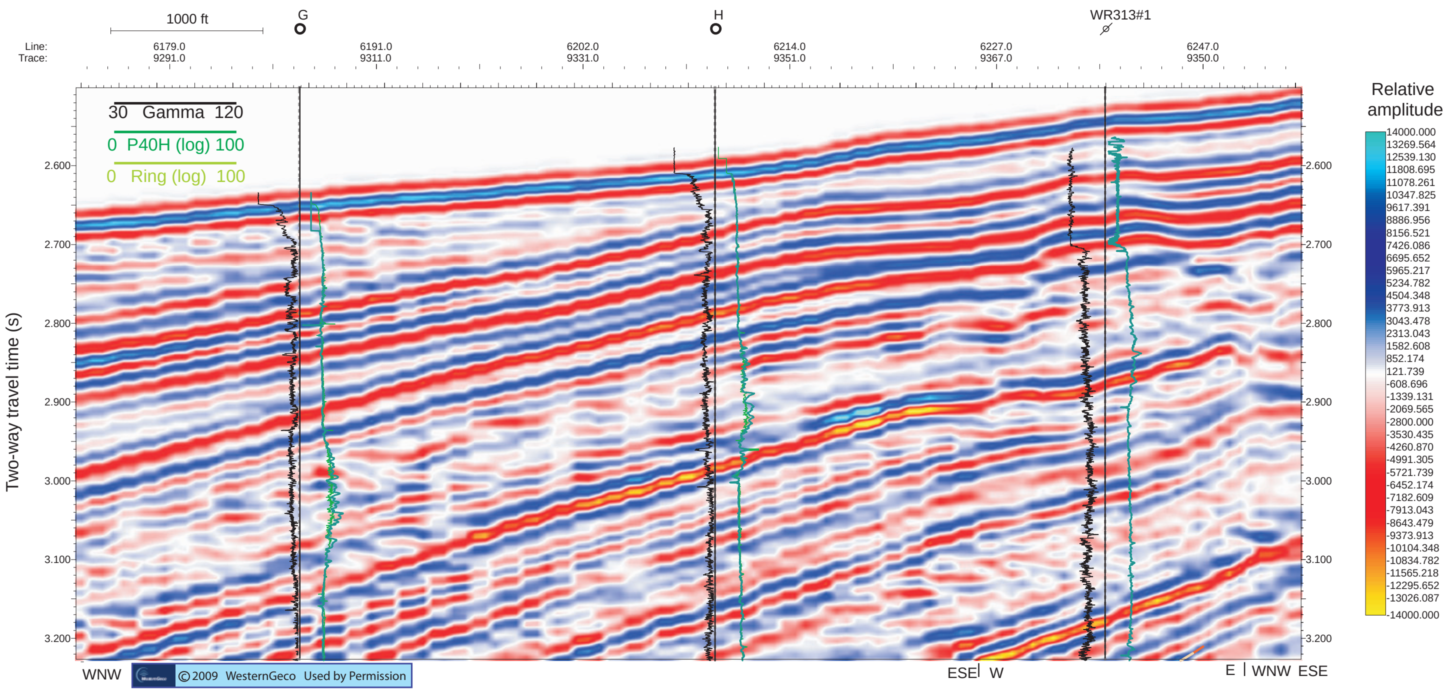

Figure F13: *Traverse showing strata-bound interpreted fracture fill gas hydrate at JIP and Industry well. Seismic data courtesy of WesternGeco.*

F5 and F7) and approximately 1000 feet up-dip from the BGHS as measured along the target horizon. The WR 313-G location is 0.9 miles west-northwest of the WR 313 #001 well. Logs from the #001 well show normal resistive clays in the stratigraphic equivalent section, indicating that the sandy facies targeted at the G-location pinch-out some distance west of the well. The pre-drill gas hydrate saturation prediction at the WR 313-G hole from the seismic inversion analyses conducted by Schlumberger ranged from 33% to 65% over an area greater than 1 sq mile, with 57% predicted gas hydrate saturation at the G-location (Figure F12; Hutchinson *et al.*, 2009; Shelander *et al., in review*).

In general, the quality of the downhole log data acquired from the WR 313-G well was good, although difficult drilling conditions, stalls and packoffs, affected the azimuthal resistivity data and the MP3 sonic tool failed below 2465 fbsf (Cook *et al*., 2009). Below 582 fbsf, the hole remained in gauge except for washouts at 614, 896, 1645, 2441 and 2894 fbsf (Cook *et al.*, 2009).

The sediments penetrated at WR 313-G are basin fill clays with interbedded sands. The upper 370 ft of section is clay-prone with a thick silt-sand infill at the base. The next three sequences (between 370 fbsf and 2467 fbsf) are also predominantly clay-prone. Within this section, 600 feet of unexpected, fracture-filling gas hydrate was detected (757 fbsf and 1390 fbsf: Figure F13). Fracture fill gas hydrate is interpreted because of the difference in values between the near and far resistivity sensors, and the clay lithology, and azimuthal resistivity images suggesting sub-vertical resistive planes (Figure F14; Cook *et al*., 2009). Below this unit, a series of thin (4 to 10-ft) and widely-separated sands interpreted as sandy turbidites occur within the clay-prone sediments. Gas hydrate appears to fully saturate virtually all of these thin sands as indicated by resistivities ranging from 4 Ω-m to 20 Ω-m, coupled with elevated acoustic velocities. Little to no gas hydrate is apparent in the thicker intervening clay units (Figure F15). The fourth sequence was penetrated at ~2400 fbsf where the well penetrated a major unconformity. The log response at 2400 fbsf shows the top of a fining upward sequence that coarsens to a 56 ft-thick (70 to 55 API) silty, shale, and sheet sand sequence within a 70 ft-thick sand-rich interval (Figures F8 and F10). The primary target "blue horizon" sand was penetrated at 2,730 fbsf. Pore-filling gas hydrate at saturations estimated up to 80% (Figures F12 and F16) are inferred based on analysis of resistivity data (Cook *et al*., 2009). Resistivities ranging from 50 Ω-m to over 200 Ω-m corresponding with velocities ranging as high as 3000 m/s were measured (Figure F17). Individual sands within this section are generally 2-3 ft-thick, with total cumulative gas hydrate -bearing sand totaling ~10 feet from four sands between

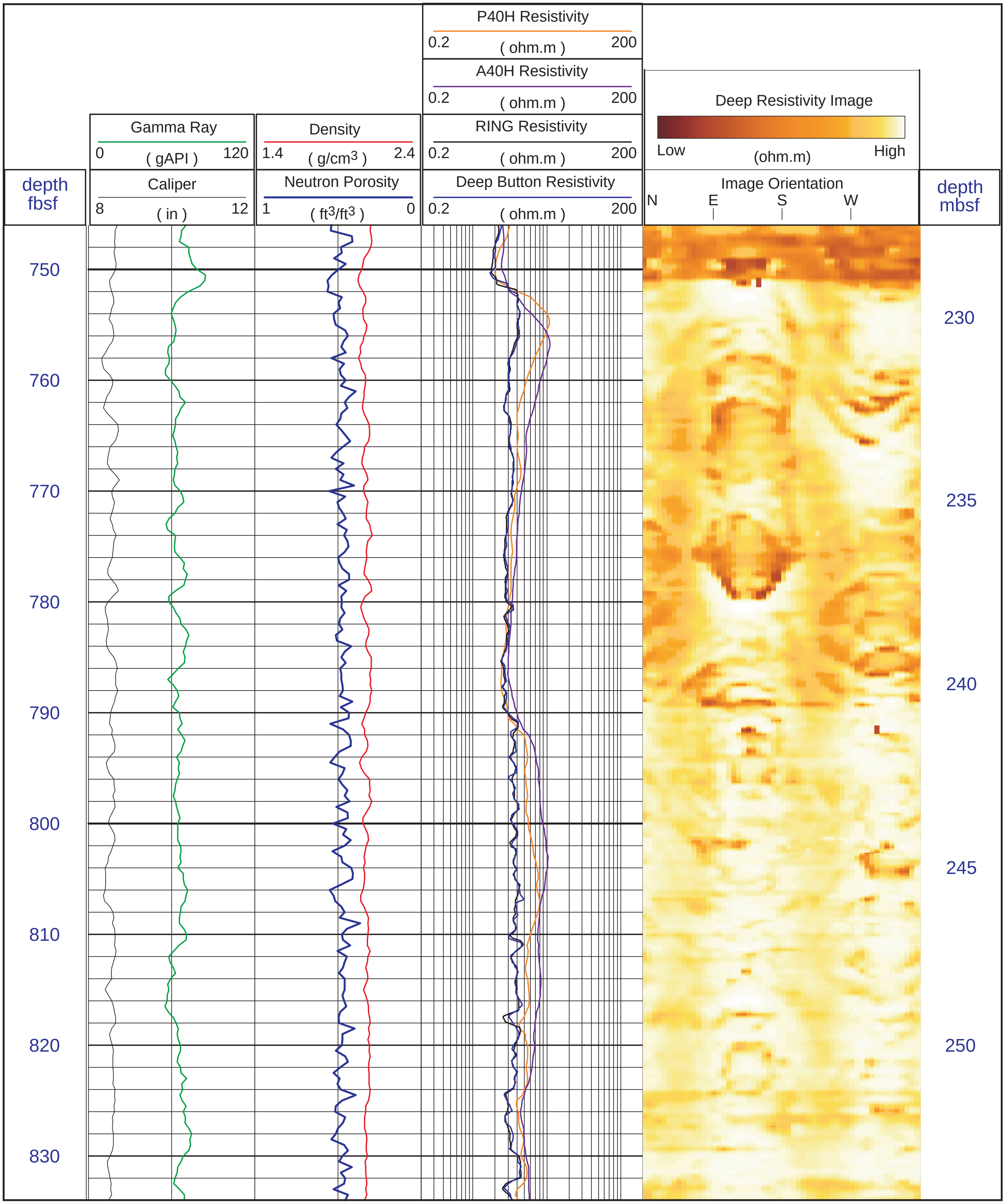

Figure F14: *Azimuthal resistivity images indicating fracture fill gas hydrate in clay at Well WR 313-H (Cook et al., 2009).*

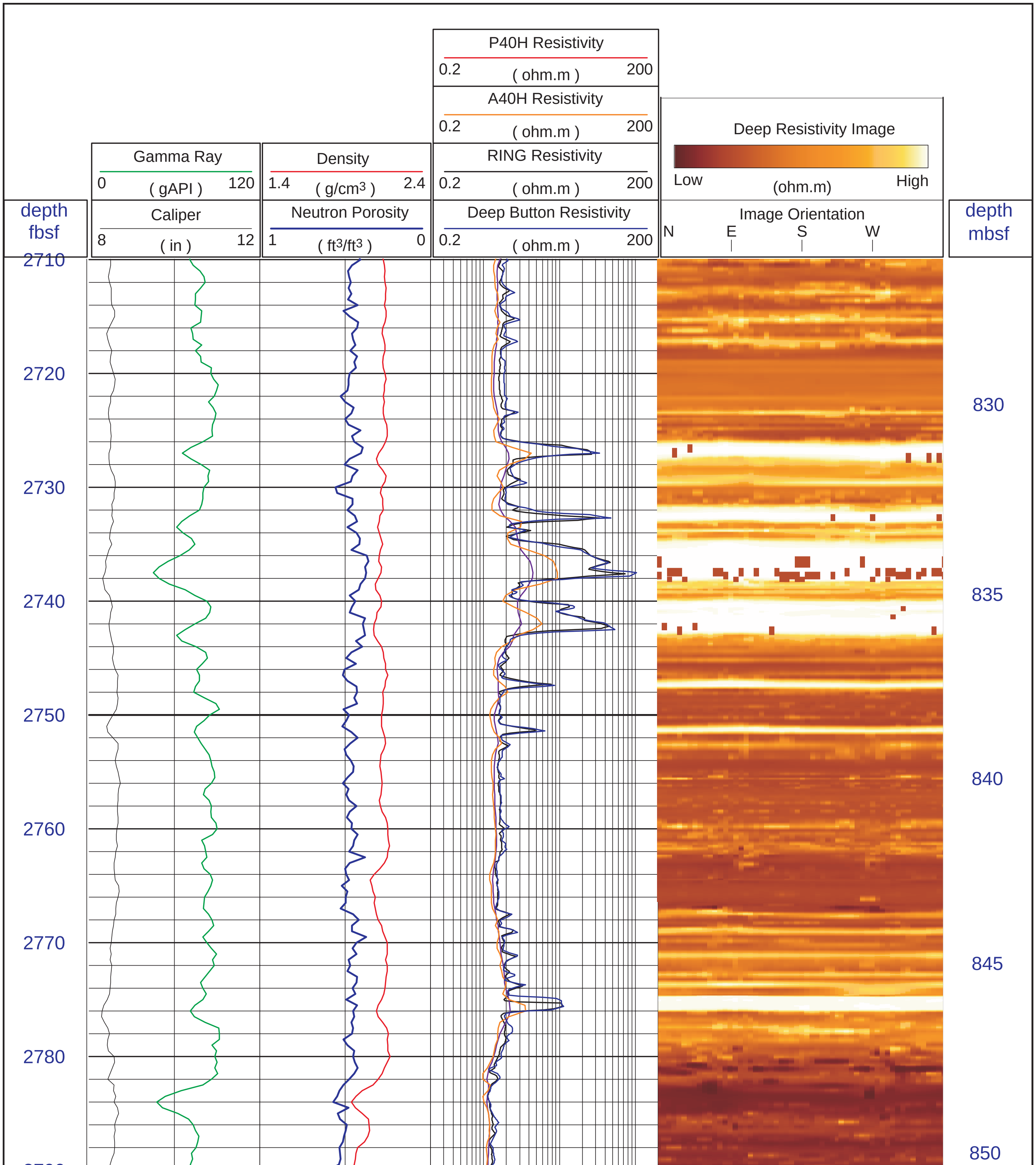

Figure F15: *Pore-filling gas hydrate in thin sands at Well WR 313-G (Cook et al., 2009).*

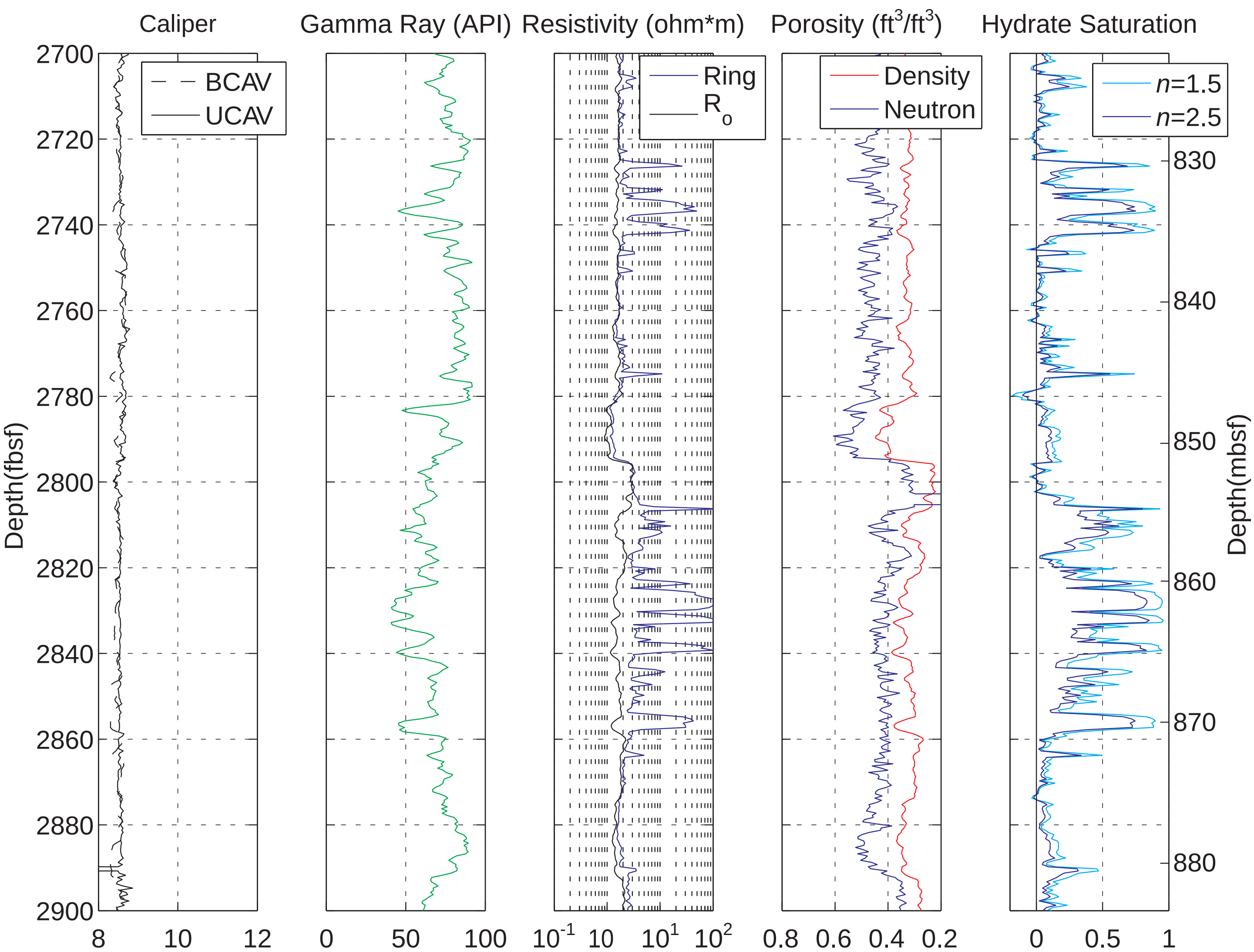

Figure F16: *Caliper, gamma, resistivity, density, and hydrate saturation logs at Well WR 313-G (Cook et al., 2009).*

2722 and 2743 fbsf, and ~40 ft from 16 sands between 2805 and 2865 fbsf. Notably, this top of this lower zone also includes a tight streak within sands from 2794 to 2805 fbsf.

The section immediately below the primary gas hydrate target is clay-prone. The log data provided no indication of gas hydrate above or increased free gas below the level of the seismically predicted BGHS at ~3114 fbsf. The primary target for the second WR 313 well (the H-well) was penetrated at 3393 fbsf at the G-location. The unit was observed to be a relatively thin, and water-saturated, sand interval as predicted.

Well WR 313-H

After the gas hydrate discovery at WR 313-G, the science team elected to drill in GC 955, allowing that there might be an opportunity to drill another target in WR 313 on a short-leg transit in route to AC 21 and vicinity (Collett *et al.*, 2009). WR 313-H afforded an opportunity to test the "blue" target at a position well updip of the G-well, as well as being able to test sands associated with the channel-levee facies associated with a second primary target near the BGHS at this location (the "orange" horizon). This horizon, similar to the "blue" target, is a dipping high-amplitude, positive impedance reflector that is phase reversed as it crosses the BGHS (Figure F7). The orange horizon showed a more heterogeneous potential hydrate occurrence than the "blue horizon", suggesting that the interval may represent a more channelized facies. The WR 313 #001 well located up-dip to the east of the H-location showed elevated resistivity (3.5 Ω-m) associated with thin sands at the approximate level of the orange horizon. The pre-drill gas hydrate saturation prediction at the WR 313-H location from the seismic inversion analyses conducted by WesternGeco ranged from

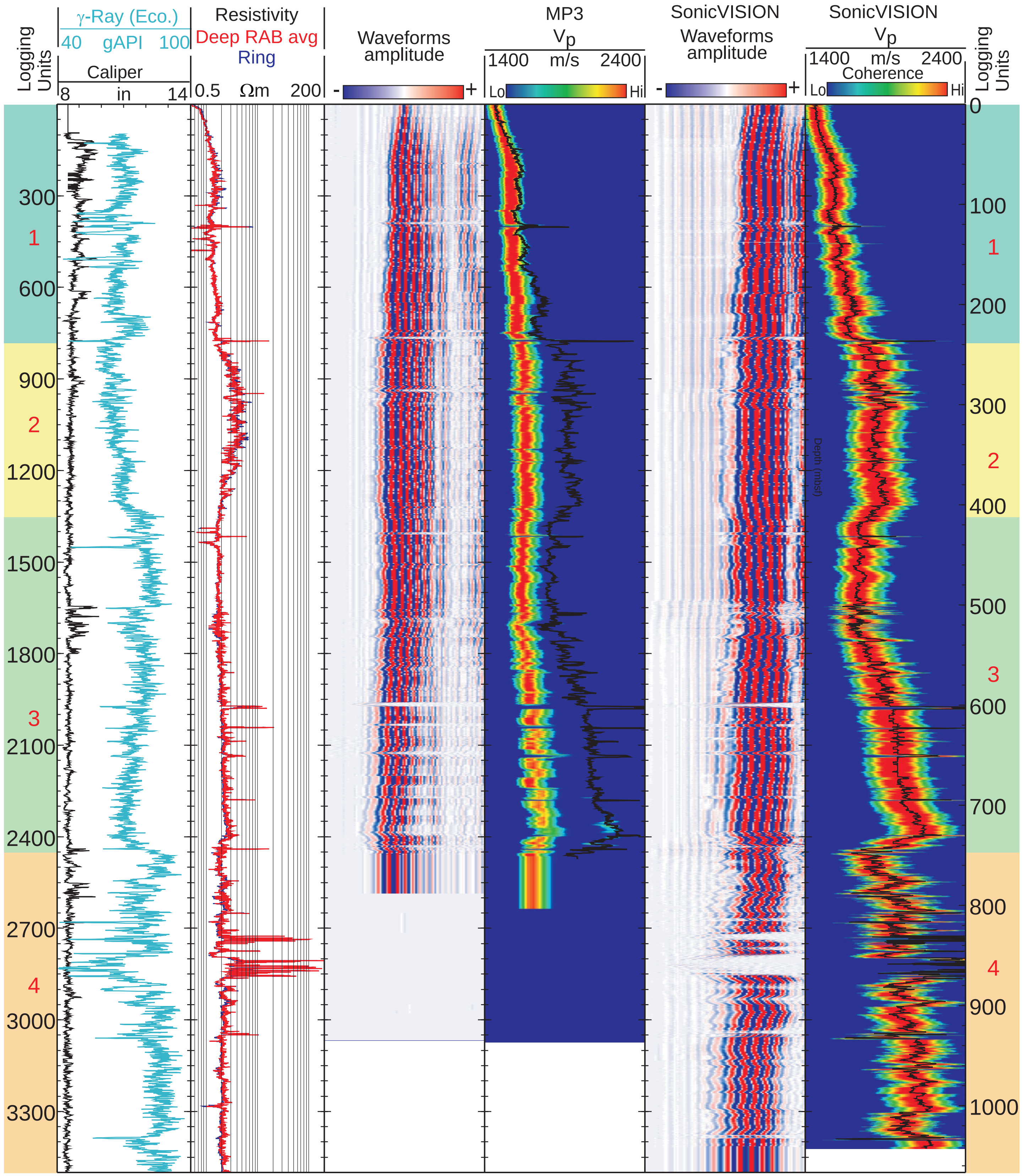

Figure F17: *Gamma, resistivity, and sonic logs at Well WR 313-G (Cook et al., 2009).*

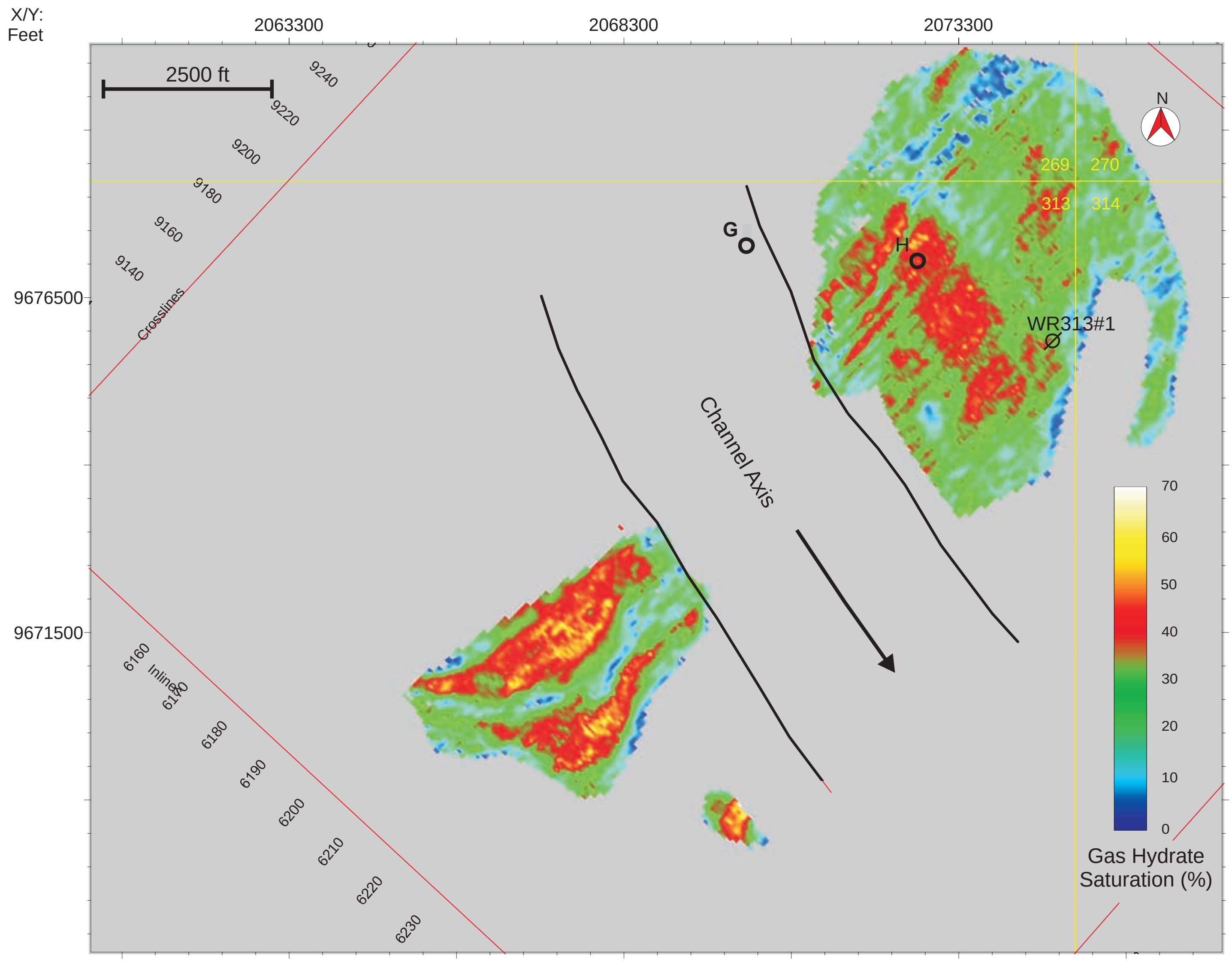

Figure F18: *Predicted gas hydrate saturation in orange sand. Image provided by Schlumberger.*

30% to 60% over an area of roughly 0.25 sq mile, with 53% predicted gas hydrate saturation at the H-location (Figure F10 and F18; Hutchinson *et al.*, 2009; Shelander *et al., in review*).

In general, the quality of the downhole log data acquired from the WR 313-H well was good (Cook *et al*., 2009). The drilling protocol was modified to include more frequent gel sweeps and earlier initiation of heavy drilling fluid use to avoid pack-offs and tight conditions experienced at the WR 313-G well (Collett *et al*., 2009). The sediments penetrated at WR 313-H are ponded basin fill that is clay prone with interbedded sands. Seven distinct sequences were penetrated. The four uppermost sequences are clay prone interbedded with widely spaced thin (4 to 10 ft) sands. Five hundred feet of stratal-bound fracture-filling gas hydrate were detected between 545 and 1045 fbsf and were interpreted to occur within the same stratigraphic interval as shallow gas hydrate seen in the earlier G-well (Figures F8 and F19; Cook *et al*., 2009). Beneath the strata-bound resistive unit (at 1033 fbsf), thin 4 to 6 Ω-m resistive sands were penetrated within the mostly clay prone section. Although fewer in number, many of the thin sands observed in the H-well correlate to those penetrated at the G-location (Figures F17 and F19). The top of the stratigraphic sequence that contained the blue and orange target sands was penetrated at 1990 fbsf. Discrete sands ranging from 2 to 9 ft, and sand-prone sections up to 40 ft-thick characterize this interpreted sheet sand and distal ponded channel-levee fill section. Nearly all the sands and sand-prone sediments are moderately to highly saturated with gas hydrate as interpreted from resistivity data

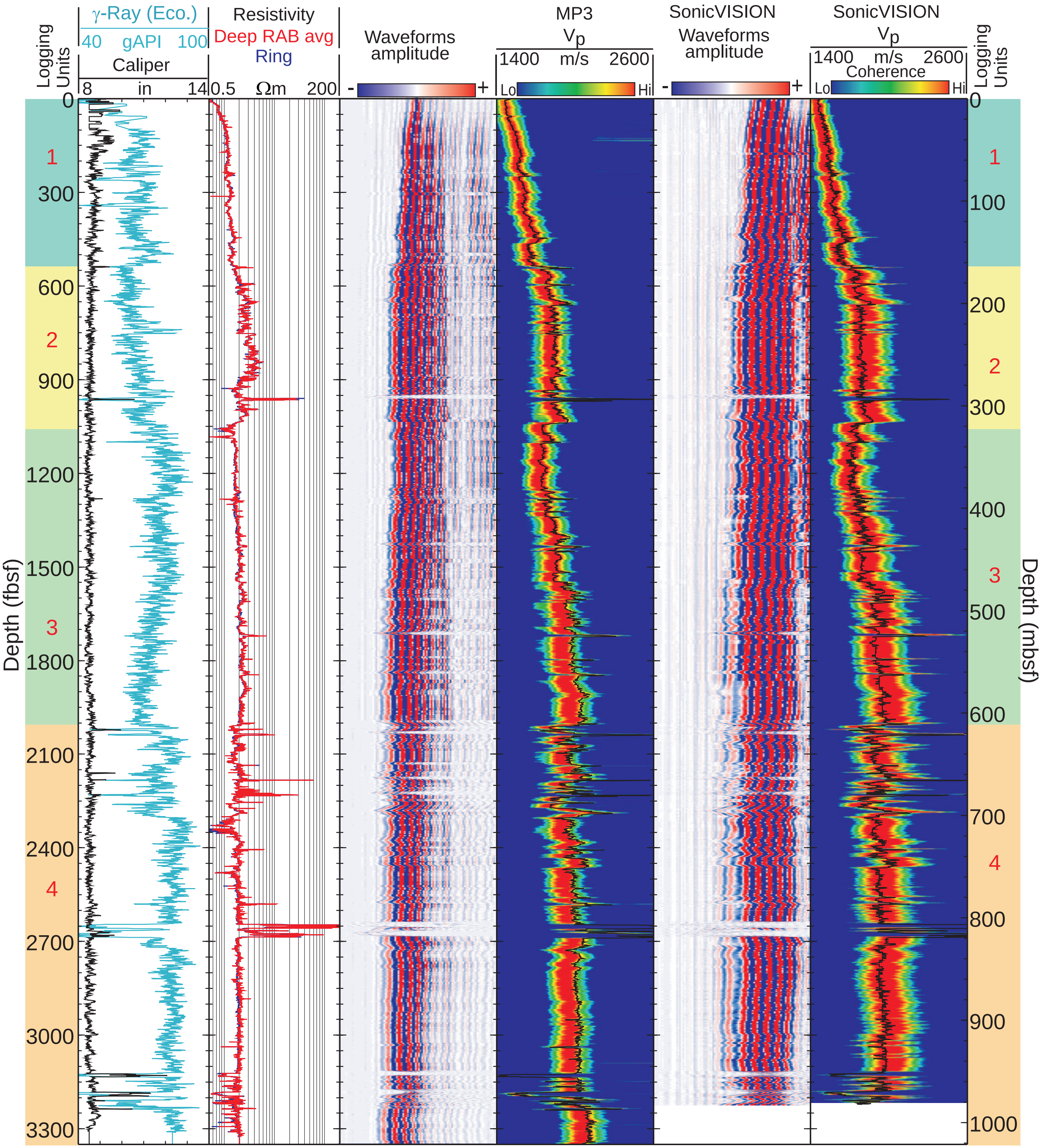

Figure F19: *Gamma, resistivity, and sonic logs at Well WR 313-H (Cook et al., 2009).*

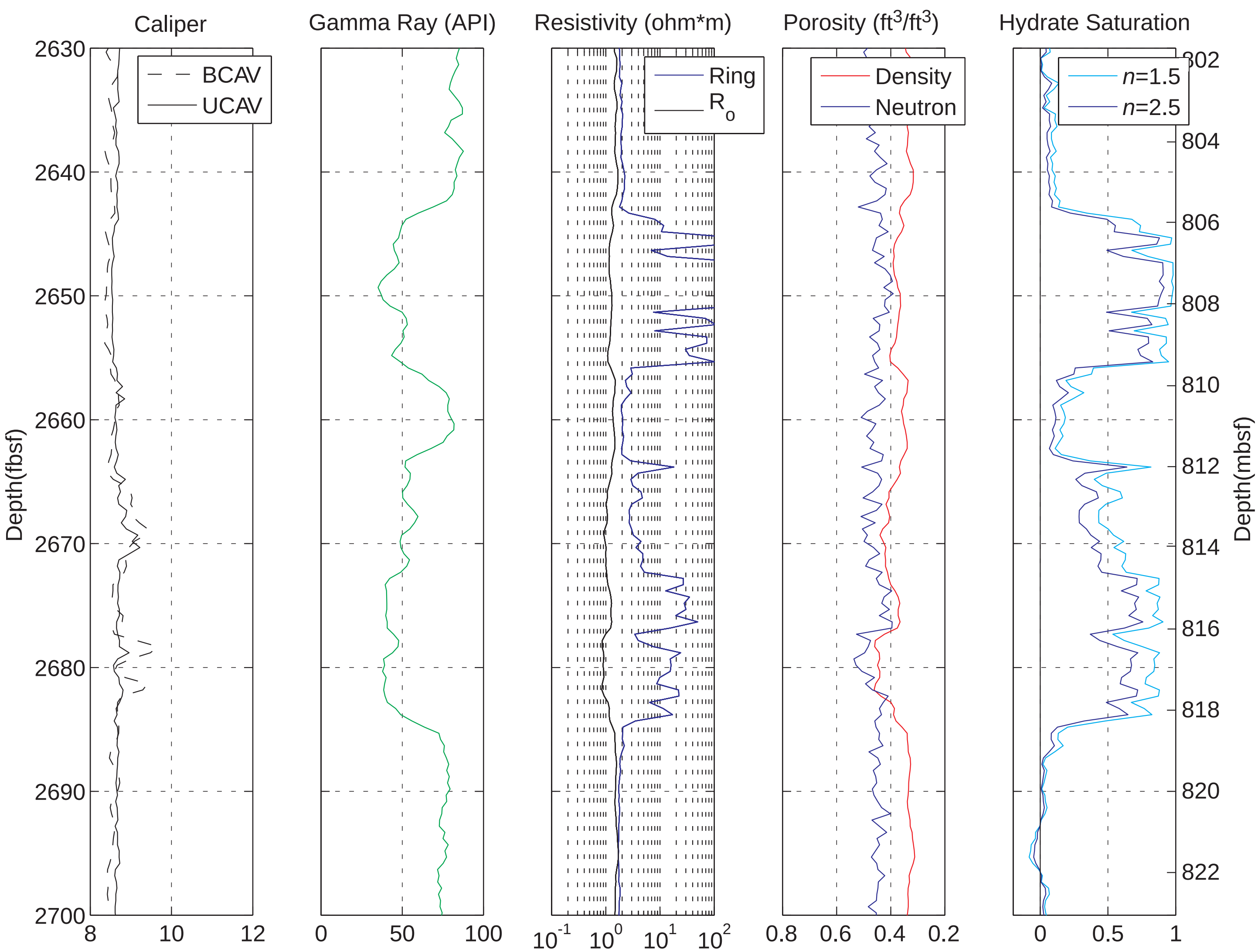

Figure F20: *Caliper, gamma, resistivity, density, and hydrate saturation logs at primary target Well WR 313-H (Cook et al., 2009).*

(resistivities of 4 Ω-m to 10 Ω-m; Figure F19). The "blue horizon" that was the primary target at the G-well was found to be saturated with gas hydrate, but significantly thinned and more shale-rich. At the level of the "orange" horizon, a total of ~33 ft of gas hydrate-bearing sand was penetrated between 2645 and 2685 fbsf. This sand occurred as two massive, clean sands (10 and 23-ft in thickness), each with sharp upper and basal contacts. The lower lobe is noted as having a zone of reduced porosity (and gas hydrate saturation) at the top. Resistivities in these sands were measured at up to 200 Ω-m and acoustic velocities again approaching 3000 m/s (Figure F19). Saturation of gas hydrate in the target sands is estimated to range from 40% to over 75% (Figure F20). The sediments from beneath these sands to the BGHS are clay prone. The LWD logs do not show any resistive or conductive anomalies marking the BGHS. Drilling continued below the BGHS in order to test a third interpreted sand unit ("the green sand") that correlates to another interpreted gas hydrate-bearing interval within channel deposits in the central part of the basin (Figures F5 and F6). A 116-ft water wet sandy interval at 3127 fbsf associated with the green horizon was confirmed.

Summary

The drilling at wells WR 313-G and WR 313-H confirmed the presence of a thick, strata-bound section of fracture-fill gas hydrate in clays at shallow depths. Below this unit, both wells encountered numerous thin, 2 to 10 ft-thick, gas hydrate saturated sands and silts. The primary target at WR 313-G, the "blue horizon" was found to have estimated gas hydrate saturations up to 80 % within 40 ft of net sand within a 140 ft gross sand and shale interval. At the WR 313-H location, the "blue" unit was observed to be significantly thinned and shale-dominated, but several thin sands present were again highly saturated with gas hydrate. The primary target at the H-well, the "orange" horizon, consisted of two clean sand lobes, totaling 33 net feet of highly gas hydrate-saturated sands. As expected, no gas was detected at either well when drilling though the inferred BGHS. The H-well was drilled deeper to confirm the occurrence of reservoir-quality sands at the "green horizon", a unit associated with other gas hydrate targets identified in the regional seismic analyses conducted in the WR 313 block.

Prior analyses indicated that WR 313 was prospective for gas hydrates. The series of en-echelon gas bright spots at depths consistent with gas hydrate stability theory, as well as the clear phase reversal in these units strongly suggested gas hydrate occurrence. Both wells at WR 313 tested a different stratigraphic horizon, and drilling confirmed both as sand reservoir packages with high levels of gas hydrate saturation. The drilling program at WR 313 confirms the integrated geological-geophysical approach used within the JIP program to assess gas hydrate occurrence from remote sensing data. The presence of fluid flow, a petroleum system, and potential reservoir, were primary elements in the exploration model adopted by the JIP for prospecting for gas hydrate accumulations in sands along the gas hydrate stability boundary. In addition, both wells found an unexpected, strata-bound fracture fill gas hydrate occurrence in the shallow section. The WR 313 site should provide a wealth of opportunities to advance our understanding of gas hydrate systems, both though the continuing evaluation of the LWD data collected in Leg II, and in future data collection programs. The high resolution acoustic and electric logs, although here used to assess the gas hydrate targets, will also provide an extraordinary resource for Pleistocene stratigraphic and acoustic studies in the Gulf of Mexico.

References

Boswell, R., Collett, T.S., Frye, M., McConnell, D., Shedd, W., 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. http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2009Reports/TechSum.pdf

Collett, T.S., Boswell, R., Mrozewski, S., Guerin, G., Cook, A., Frye, M., Shedd, W., and McConnell, D., 2009. Gulf of Mexico Gas Hydrate Joint Industry Project Leg II — Operational Summary: Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II. http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2009Reports/OpSum.pdf

Cook, A., Guerin, G., Mrozewski, S., Collett, T.S., Boswell, R., 2009. Gulf of Mexico Gas Hydrate Joint Industry Project Leg II — Walker Ridge 313 LWD Operations and Results: Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II. http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2009Reports/WR313LWDOps.pdf

Dai, J., Snyder, F., Gillespie, D., Koesoemadinata, A., Dutta, N., 2008. Exploration for gas hydrates in the deepwater, northern Gulf of Mexico: Part I. A seismic approach based on geologic model, inversion, and rock physics principles. Journal Marine and Petroleum Geology, (25), pp. 830-844.

Frye, M., compiler, 2008. Preliminary Evaluation of in-place Gas Hydrate Resources: Gulf of Mexico Outer Continental Shelf: MMS OCS Report 2008-004. http://www.mms.gov/revaldiv/GasHydrateFiles/MMS2008-004.pdf

Hutchinson, D.R., Shelander, D., Dai, J., McConnell, D., Shedd, W., Frye, M, Ruppel, C., Boswell, R., Jones, E., Collett, T., Rose, K., Dugan, B., Wood, W., and Latham, T., 2008. Site Selection for DOE/JIPGas Hydrate Drilling in the Northern Gulf of Mexico: Sixth International Conference on Gas Hydrates, Vancouver, BC., 7-10 July, 2008. https://circle.ubc.ca//handle/2429/1165.

Hutchinson, D., 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 — Walker Ridge 313 Site Selection: Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II. http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2009Reports/WR313SiteSelect.pdf

McConnell, D., and Kendall, B., 2002, Images of the Base of Gas Hydrate Stability, Northwest Walker Ridge, Gulf of Mexico: Proceedings of the Offshore Technology Conference, Houston, TX, OTC paper 14103, 10 pp.

McConnell, D., and Zhang, Z., 2005. Using acoustic inversion to image buried gas hydrate distribution: FITI newsletter, Fall, 2005, p. 3-5, http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/Newsletter/HMNewsFall05_HighRez.pdf#page=3

MMS, U.S. Department of the Interior, Gulf of Mexico Region, 2007. Paleo for Public Release, Area Block WR 313, Lease Number G18683, Well Name 001, Public Release Date 30-JUN-2007.

MMS, 2009. Investigations of Chemosynthetic Communities on the Lower Continental Slope of the Gulf of Mexico, Interim Report 2, OCS Study MMS 2009-046.

Mrozewski, S., Guerin, G., Cook, A., Collett, T.S., Boswell, R., 2009. Gulf of Mexico Gas Hydrate Joint Industry Project Leg II — LWD Methods: Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II. http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2009Reports/LWDMethods.pdf

Nur, A. and J. Dvorkin, 2008. Seismic-scale rock physics of methane hydrate – Final report, prepared by Stanford University for the National Energy Technology Laboratory.

Prather, B. E., J. R. Booth, G. S. Steffens, and Pl E. Craig, 1998, Classification and stratigraphic succession of seismic facies in intraslope basins, deep water Gulf of Mexico: AAPG Bull., 82, 701-728.

Shedd, W., Godfriaux, P., Frye, M., Boswell, R., and Hutchinson, D., 2009. Occurrence and variety in seismic expression of the base of gas hydrate stability in the Gulf of Mexico, USA: FITI newsletter, Winter, 2009, p. 11-14. http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/Newsletter/MHNewswinter09.pdf

Shelander, D., Dai, J., Bunge, G., *in review.* Predicting saturation of gas hydrates using pre-stack seismic data, Gulf of Mexico. Marine Geophysical Researches.

Weissenberger, K.S. and T. Borbas, 2004, Fluid properties, phase and compartmentalization: Magnolia field case study, deepwater Gulf of Mexico, USA, in Cubitt, J.M., W.A. England, and S. Larter (eds.), Understanding petroleum reservoirs: towards an integrated reservoir engineering and geochemical approach, Geological Society, London, Special Publications, 231-255.