Gulf of Mexico Gas Hydrate Joint Industry Project Leg II: Technical Summary

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Abstract

The Gulf of Mexico gas hydrates Joint Industry Project ("The JIP"), a cooperative research program between the U.S. Department of Energy and an international industrial consortium under the leadership of Chevron, conducted its "Leg II" logging-while-drilling operations in April and May of 2009. JIP Leg II was intended to expand the existing JIP work from previous emphasis on fine-grained sedimentary systems to the direct evaluation of gas hydrate in sand-dominated reservoirs. The selection of the locations for the JIP Leg II drilling were the result of a geological and geophysical prospecting approach that integrated direct geophysical evidence of gas hydrate-bearing strata with evidence of gas sourcing and migration and occurrence of sand reservoirs within the gas hydrate stability zone (GHSZ).

Logging-while-drilling operations included the drilling of seven wells at three sites. The expedition experienced minimal operational problems with the advanced LWD tool string, and successfully managed a number of shallow drilling challenges, including borehole breakouts, and shallow gas and water flows. Two wells drilled in Walker Ridge block 313 (WR 313) confirmed the pre-drill predictions by discovering gas hydrates at high saturations in multiple sand horizons with reservoir thicknesses up to 50 ft. In addition, drilling in WR 313 discovered a thick, strata-bound interval of shallow fine-grained sediments with abundant gas hydrate filled fractures. Two of three wells drilled in Green Canyon block 955 (GC 955) confirmed the pre-drill prediction of extensive sand occurrence with gas hydrate fill along the crest of a structure with positive indications of gas source and migration. Well GC 955-H discovered ~100 ft of gas hydrate in sand at high saturations. Two wells drilled in Alaminos Canyon block 21 (AC 21) confirmed the pre-drill prediction of potential extensive occurrence of gas hydrates in shallow sand reservoirs at low saturations. However, further data collection and analyses at AC 21 will be needed to better understand the nature of the pore filling material.

JIP Leg II fully met its scientific objectives with the collection of abundant high-quality data from gas hydrate-bearing sands in the Gulf of Mexico that will enable further validation of the geophysical methods used to detect and characterize the occurrence of gas hydrate, and will provide valuable locations for future JIP drilling, logging and coring operations.

Introduction

The Gulf of Mexico Gas Hydrate Joint Industry Project ("The JIP") is a cooperative research program between the U.S. Department of Energy and an international industrial consortium under the management of Chevron. The project was initiated in 2001 to investigate the occurrence, nature, and implications of gas hydrate in the Gulf of Mexico. In 2005, the JIP completed Leg I drilling, logging, and coring operations designed primarily to assess gas hydrate-related hazards associated with drilling through the clay-

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dominated sediments that typify the shallow sub-seafloor in the deepwater Gulf of Mexico (Ruppel *et al.*, 2008).

In order to properly characterize the nature and implications of gas hydrates in the Gulf of Mexico, the JIP has supported a number of critical fundamental science and technology development efforts, including development of improved tools and techniques for remote sensing (Xu *et al.*, 2004; Dai *et al.*, 2008), wellbore stability modeling (Birchwood *et al.*, 2007), and field sample analysis (Yun *et al.*, 2006). The JIP has also contributed extensive experimental datasets related to impact of gas hydrate on the physical properties of sediments of various grain sizes (Santamarina and Ruppel, 2008).

Upon analysis of Leg I results, the JIP determined that it had a solid grasp on drilling safety issues related to gas hydrate at moderate to low concentrations in fine-grained sediments (Birchwood *et al.*, 2008). Therefore, the JIP and the DOE decided to expand its effort to assess a range of issues related to the occurrence of gas hydrate within coarser-grained sediments (Jones *et al.*, 2008). To enable this work, geoscientists from the U.S. Geological Survey (USGS), the Department of Energy's National Energy Technology Laboratory (NETL), the Minerals Management Service (MMS), AOA Geophysics, the Naval Research Lab, and Rice University collaborated to evaluate and prioritize various prospects with respect to the potential of encountering high concentrations of gas hydrate in sand reservoirs (Hutchinson *et al.*, 2008). The group evaluated these sites through integrated geological and geophysical analyses and ultimately developed the site descriptions and prioritizations that were implemented in JIP Leg II (Hutchinson *et al.*, 2009a, 2009b, and 2009c; Shedd *et al.*, 2009b).

JIP Leg II Scientific Objectives

The ultimate goal of the current phase of the JIP effort is to gain further insight into the nature, formation, occurrence and physical properties of gas hydrate-bearing sediments for the purpose of both resource appraisal and to extend earlier JIP studies on gas hydrate-related drilling hazards. The primary objective of the JIP Leg II program was the collection of a comprehensive suite of logging-while-drilling (LWD) data within gas hydrate-bearing sand reservoirs. In the near term, the JIP will analyze these data (and conduct additional integrated geological/geophysical studies) to support the selection of locations for future drilling, logging and coring programs such as the proposed JIP Leg III.

A critical component of both gas hydrate resource and hazard assessments is our ability to reliably estimate the occurrence, distribution, and concentration of gas hydrates prior to drilling. JIP Leg II drilled at three sites that were selected through an integrated geological/geophysical prospecting approach designed to identify gas hydrates at high concentrations in sand reservoirs (Hutchinson *et al.*, 2009a, 2009b, and 2009c; Shedd *et al.*, 2009b). At two of these sites JIP partner Schlumberger/WesternGeco produced pre-drill estimates of gas hydrate saturation through analysis of existing 3-D seismic data. Comparison of these estimates with drilling results should enable further calibration of these techniques. To further aid in the development of gas hydrate exploration technologies, the DOE awarded a contract to Scripps Institute of Oceanography to collect controlled source electromagnetic (CSEM) surveys over a series of Gulf of Mexico targets, including several JIP Leg II drill sites (Weitemeyer *et al.*, 2009). A priority for the DOE and JIP effort will be to apply the LWD data collected over these sites to the integrated calculation of gas hydrate saturation that incorporates both the seismic and CSEM datasets.

Another question that is fundamental to both gas hydrate hazard and resource issues is further assessment of the occurrence of gas hydrate in the Gulf of Mexico. This question was the subject of a recent assessment conducted by the MMS (Frye, 2008) that estimated more than 20,000 tcf gas-in-place in with more than 6700 tcf of that total in-place in sand reservoirs. This assessment utilized the most current information and models on gas hydrate controls and occurrence in nature, but did not have many actual known gas hydrate occurrences to test its predictions. A key contribution of the JIP Leg II program was to provide data from relevant test sites that would assist in the further refinement of this basin-wide assessment.

Additional objectives of the JIP are to contribute new data on the nature and occurrence of gas hydrate systems to advance the general understanding of the controls on the formation of gas hydrate accumulations. JIP Leg II has collected an unprecedented LWD data set (Mrozewski *et al.*, 2009) over significant sand- and mud-hosted gas hydrate deposits that is expected to yield substantial new information on the 3-D architecture of both the reservoirs and the pore filling constituents. The DOE and the JIP are committed to making these data publically available in the future to support a wide range of scientific studies. In addition, this data, together with the an invaluable operational experience and drilling performance database gathered (Collett *et al.*, 2009b), will be used by the JIP to further refine drilling parameters for future JIP drilling and coring efforts.

Site Selection

In 2006, the JIP and its collaborators began detailed geologic and geophysical evaluations of numerous potential drill sites in the Gulf of Mexico, seeking evidence for active petroleum systems: gas sources and migration pathways co-located with sand-prone lithofacies. An initial primary target was provided by Chevron through public release of well and seismic data around the "Tigershark" well in Alaminos Canyon (AC) 818 (Smith *et al.*, 2006; Boswell *et al.*, 2008). Subsequently, a review of gas hydrate indicators within existing industry well log data throughout the Gulf of Mexico conducted by JIP partner the Minerals Management Service yielded evidence of extensive sand occurrence within the shallow sediments, but provided no additional compelling evidence of gas hydrate-bearing sands in the available downhole log datasets. Therefore, in 2007, the JIP conducted an open workshop to identify additional drilling opportunities, in which locations in Walker Ridge (WR) block 313 and Green Canyon (GC) block 955 were brought forward (Figure F1).

By 2008, the JIP and its collaborators had compiled for the AC 818, GC 955, and WR 313 drill sites the following: 1) geologic interpretations and prioritized drilling targets from the site selection group coordinated by the USGS (Hutchinson *et al.*, 2008); 2) pre-stack, full-waveform 3-D inversions for gas hydrate saturation from WesternGeco; 3) drilling hazards assessments from AOA Geophysics; and 4) borehole stability models and operational recommendations from Schlumberger Geomechanics. Analysis of the AC 818 site revealed evidence of formation overpressures, and the site was dropped from further consideration for the Leg II drilling program. Leg II LWD

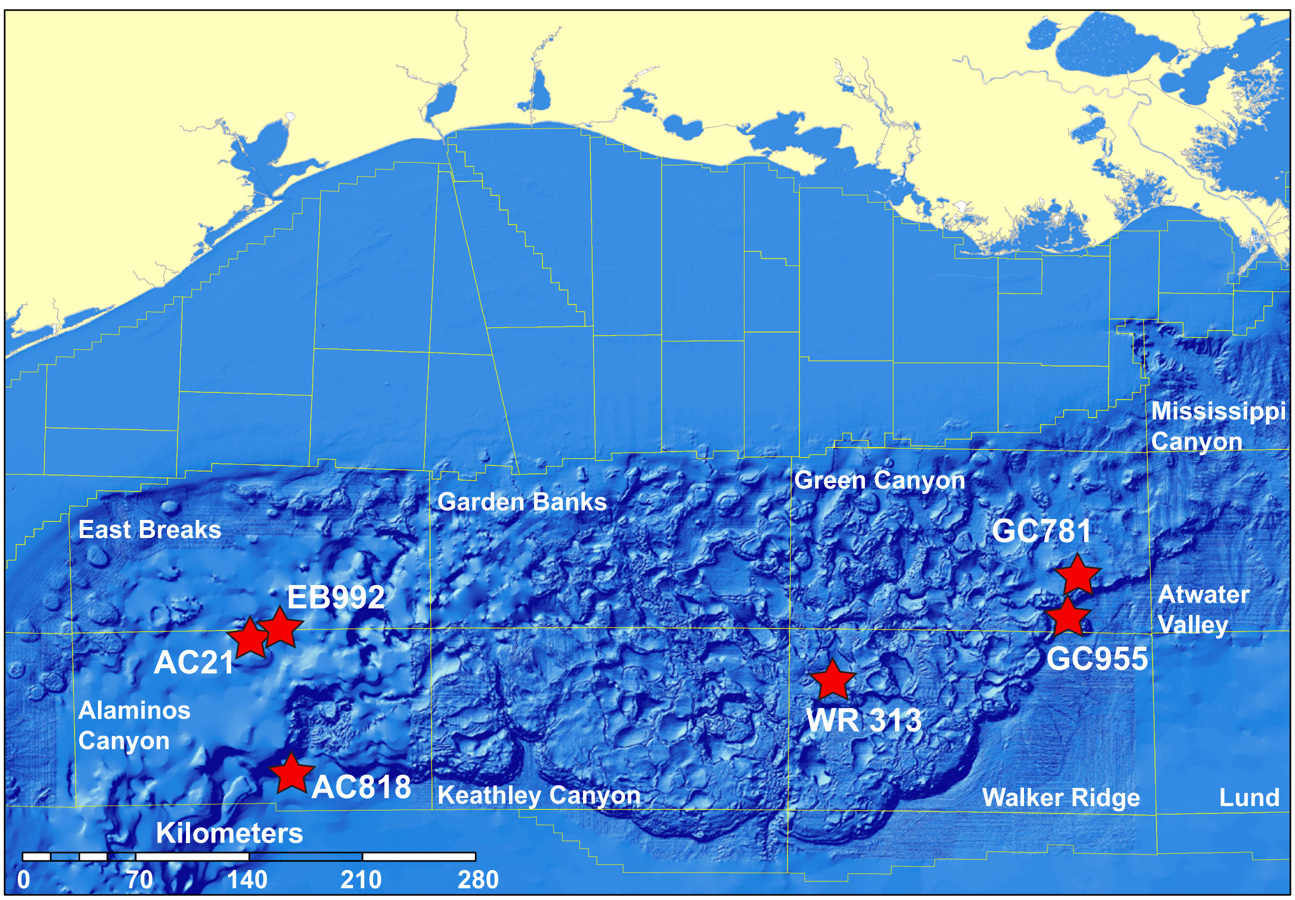

Figure F1: *Location of various proposed and drilled JIP Leg II field sites.*

operations were slated for the spring of 2008, but the JIP and the DOE elected to postpone operations when delivery of the drill rig was delayed until mid-July, well into the 2008 hurricane season. Plans were then made to conduct Leg II in the spring of 2009.

The JIP used the additional time to continue site evaluation activities through the rest of 2008 and early 2009. This effort continued to benefit greatly from continuing work within the Minerals Management Service's ongoing assessment of Gulf of Mexico resources. This work revealed additional opportunities to target gas hydrates in coarse-grained sediments at sites in East Breaks (EB) 922, GC 781/825, and AC 21/65 (Figure F1).

The schematic geologic settings for the site drilled during Leg II are shown in Figure F2. Hazards analysis and permitting activities were then begun for these sites late in 2008. However, as the date of the expedition approached, it was clear that permissions to occupy the GC 781/825 site would not be gained from companies operating in nearby facilities. As a result, the site was dropped from the drilling plans early in 2009. In total, the JIP, with the support of AOA Geophysics, conducted hazard analyses and obtained permits for more than 20 locations in the WR 313, GC 955, AC 21/65, and EB 992 sites.

JIP Leg II Operations

An extensive review of Gulf of Mexico Gas Hydrate JIP Leg II LWD program operations is provided by Collett *et al.* (2009b). In summary, the expedition was conducted from April 16 to May 7, 2009 aboard the Dynamically-Positioned (DP) Modular Drilling Unit (MODU) *Q-4000* owned and operated by Helix, Inc. On-board science operations were managed and conducted by project participants from the U.S. Geological Survey, the U.S. Department of Energy, the Minerals Management Service, AOA Geophysics, and Lamont-Doherty Earth Observatory of Columbia University. Baker-Hughes drilling fluid engineering expertise also played a critical role in project operations.

The science team, in daily consultation with Chevron drill site managers, as well as Chevron project managers and Schlumberger Geomechanics engineers onshore,

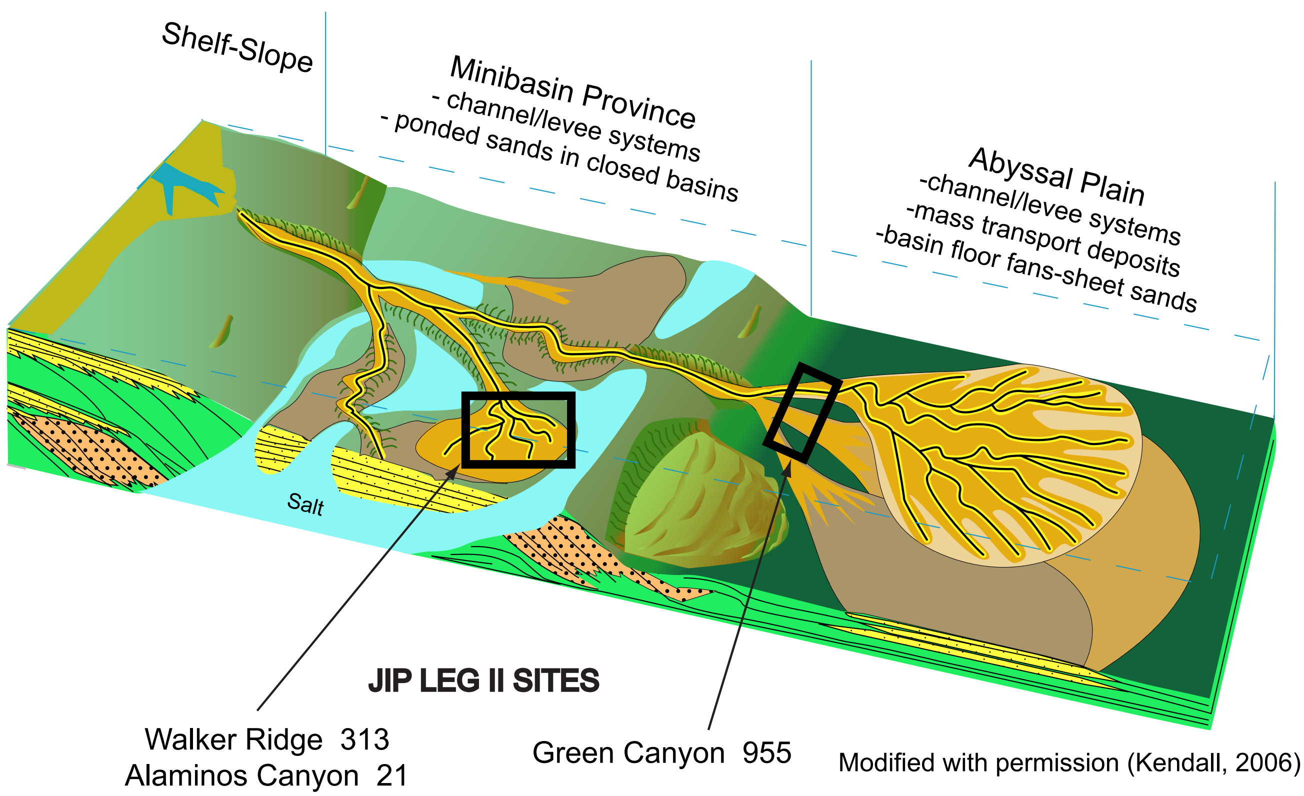

Figure F2: *Schematic illustration of Gulf of Mexico geologic environments with general setting of the three JIP Leg II drill sites indicated (modified from and used by permission of Kendall, 2006).*

recommended the course of day-to-day operations and data acquisition over the course of the 22-day expedition. Selection and sequence of drilling locations from among the 20 permitted locations was determined during the course of the expedition through discussion by the science team and Chevron management onshore, as were drilling depth and drilling/logging parameters (Collett *et al.*, 2009b). Selected drill locations were modified up to 500 ft from permitted locations per MMS regulations based on insights from previous drilling during the expedition (Figure F3).

JIP Leg II focused exclusively on the collection of a comprehensive suite of logging-while-drilling (LWD) data. The bottom-hole-assembly (Figure F4) featured a state-of-the-art tool configuration that provided the most detailed log data yet acquired in a marine gas hydrate project. Data collected include gamma-ray, neutron and density porosity, neutron spectroscopy data, as well as full azimuthal resistivity and acoustic velocity, including both compressional and shear-wave measurements. These tools provided full 3-D information on both acoustic (both compressional and shear wave) and electrical properties of the sediment enabling the improved evaluation of gas hydrate in both pore-filling and fracture-filling modes. The LWD and associated MWD tools also provided "real-time" drilling performance data that allowed us to optimize the drilling plan as we advanced through the program. LWD

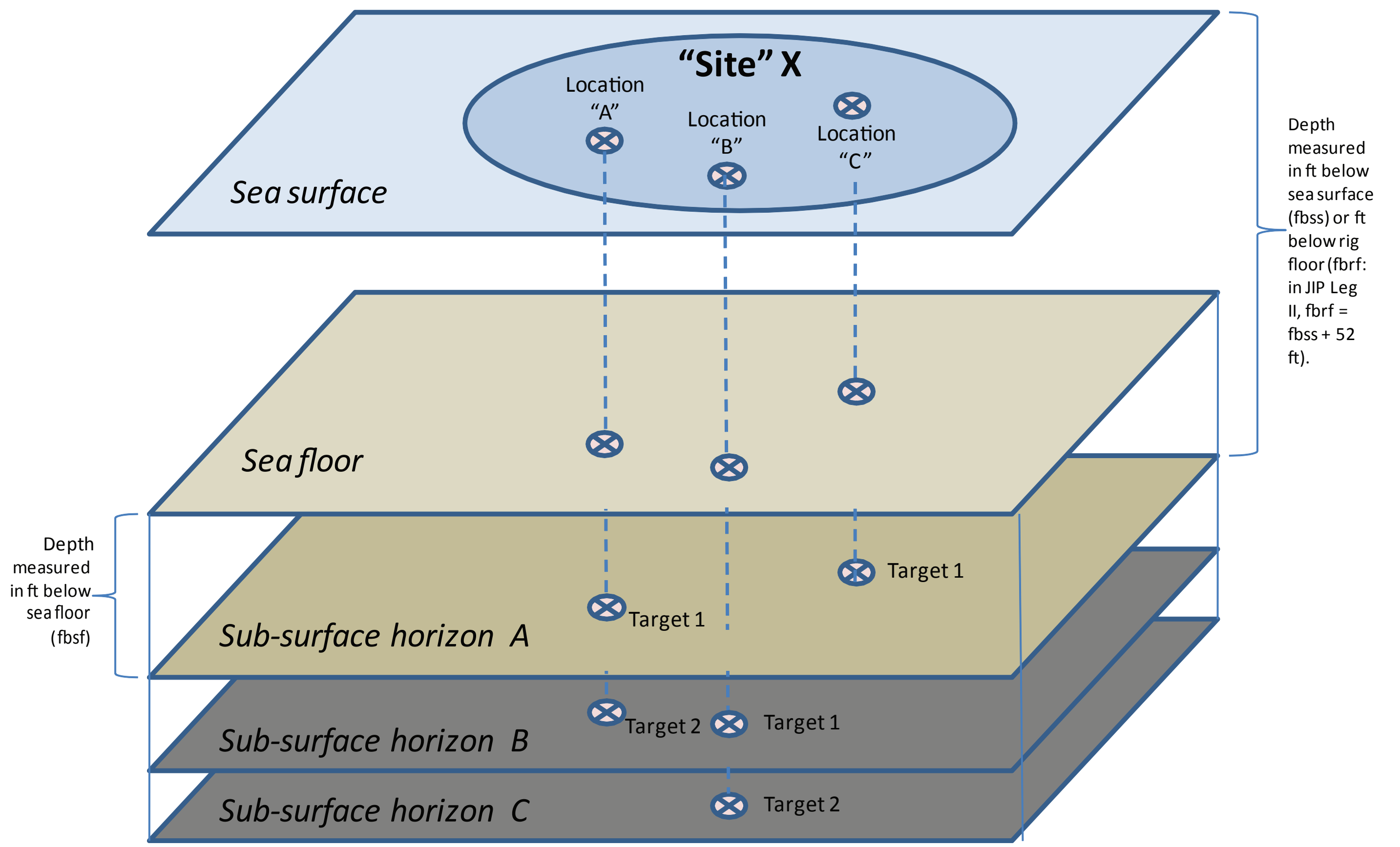

Figure F3: *Description of the terminology used to describe sites, locations, and targets in JIP Leg II. "Site" is used for a group of related drilling locations which test associated geologic features and that can be drilled from a single deployment of the drill string below the rig floor. Each location may have one or more drilling targets, which refer to stratigraphic intervals of interest at that location. The diagram also indicates the various terms used to describe drilling depths in the reports on JIP Leg II, including feet below sea-floor (fbsf), feet below sea-level (fbsl), and feet below rig floor (fbrf).*

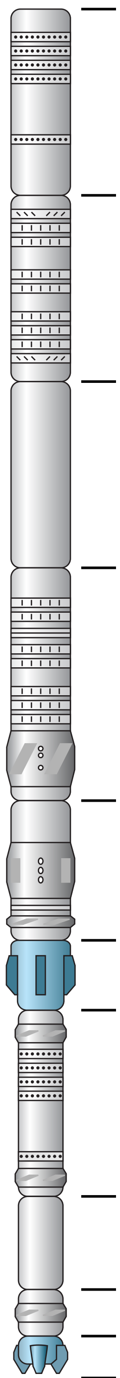

Figure F4: *Schematic diagram of the bottom-hole assembly employed in JIP Leg II LWD operations (modified from Mrozewski et al., 2009).*

logging methods, operations and results are summarized by Mrozewski *et al.* (2009), Cook *et al.* (2009), and Guerin *et al.* (2009a and 2009b).

The expedition acquired LWD data from over ~17,000 ft of sedimentary section in seven holes drilled at the WR 313, GC 955, and AC 21 sites. The performance of the *Q-4000* crew in safely and efficiently drilling the wells was outstanding. Similarly, the complex, state-of-the-art Schlumberger LWD tool string functioned extremely well, with only minimal operational issues (Mrozewski *et al.*, 2009; Cook *et al.*, 2009; Guerin *et al.*, 2009a and 2009b).

Drilling operations within JIP Leg II were marked by the constant challenge of optimizing data quality by maintaining borehole stability, which is difficult to achieve within shallow unconsolidated sediments. In addition, several of the targets were exceptionally deep: the two wells drilled in Walker Ridge 313 (at more than 3000 feet below the seafloor) exceed by more than 1000 ft the previous record for the deepest gas hydrate research wells (NGHP Expedition 01 Site 17, Andaman Islands; Collett *et al.*, 2008). The process of drilling the JIP Leg II wells provided new insights into the optimal drilling strategies for marine open-hole drilling programs (Collett *et al.*, 2009b). Most notably, original plans to drill these deep holes with minimal drilling fluid use were revised due to difficulties with borehole stability observed in the first well drilled (WR 313-G). In fact, despite the large volumes of gas hydrate that the expedition encountered, it is apparent that many of the primary drilling hazards that needed to be managed during the drilling program were not gas hydrate related, but were instead the common problems that face all drilling programs: borehole stability, drill cutting removal, gas releases into the borehole, and water flows. These issues are particularly acute in shallow scientific drilling and coring data in which the wells are drilled “open-hole” without surface conductors or drilling fluid returns. Additional experience was also gained relative to the expected response of thick gas hydrate-bearing units to drilling, providing further opportunities to improve future gas hydrate drilling protocols (Collett *et al.*, 2009b).

JIP Leg II was began at 15:30 on April 16, 2009, when the *Q-4000* completed work for another client at Green Canyon block 195. The vessel sailed to its first location in Walker Ridge block 313, and the WR 313-G well was spud at 17:30 April 18. The well reached a total depth of 10,200 ft (RKB) at 19:00 April 20. Initial plans to then move in “dynamic positioning (DP) mode” (a short intra-site move taken between locations with the drill string lifted approximately 500 above the seafloor) to a second Walker Ridge site were changed in order to assess the condition of the LWD string and to address several potential tool data quality issues (Mrozewski *et al.*, 2009; Cook *et al.*, 2009;

Hole	API Number	Latitude (N)	Longitude (W)	Water Depth (ft)	Hole Depth (fbrf)	Hole Depth (fbsf)
AC21A	608054007000	26 55 23.8503	94 54 00.0702	4889	6700	1760
AC21B	608054007100	26 56 39.1900	94 53 35.6216	4883	6050	1116
GC955H	608114053700	27 00 02.0707	90 25 35.1142	6670	8654	1933
GC955 I	608114054400	27 00 59.5305	90 25 16.8928	6770	9027	2205
GC955Q	608114054300	27 00 07.3484	90 26 11.7156	6516	8078	1511
WR313G	608124003900	26 39 47.4841	91 41 01.9404	6562	10200	3586
WR313H	608124004000	26 39 44.8482	91 40 33.7467	6450	9770	3269

Table T1: *Final surveyed locations with water depth and measured depth in feet below rig floor (fbrf) and feet below sea floor (fbsf).*

Guerin *et al.*, 2009a and 2009b). The ship sailed to Green Canyon block 955 and drilled three holes (GC 955-I, GC 955-H, and GC 955-Q) from 11:30 April 22 to 20:00 April 28. The ship then returned to Walker Ridge and drilled the WR 313-H well, completing operations at 11:00 May 1. A 175-nm transit was then made to Alaminos Canyon block 21, where the AC 21-A and AC 21-B wells were drilled. Planned operations in EB 992, where the JIP had permitted four sites, were complicated by the arrival of the drilling rig *Ocean Valiant* in northeastern AC 24 on May 2 to conduct development operations on behalf of ExxonMobil. ExxonMobil representatives were extremely supportive of the JIP project, and gave permission for two locations (EB 992-A and EB 992-C) to be drilled. However, based on drilling results from AC 21-A and AC 21-B, the science team determined that further drilling was not cost-effective, and at midnight on May 4/5 drilling operations were ended. (Table T1). The *Q-4000* was then demobilized at sea with the assistance of the M/V *Mia*, and Leg II ended at approximately noon on May 6, 2009.

Site Summary – Walker Ridge 313

A detailed review of pre-drill evaluation of the WR 313 site can be found in Hutchinson *et al.* (2009a). Review of the initial scientific results of the JIP Leg II LWD operations at the WR 313 site can be found in McConnell *et al.* (2009a) and Cook *et al.* (2009). The following is an overview of key events and findings.

Setting

The WR 313 drill sites lie in ~6500 ft of water within the "Terrebonne" mini-basin in the northern Gulf of Mexico. The basin is elongated from north to south, with a central salt-cored ridge that splits the basin into eastern and western halves (Figure F5). The western basin was intermittently bounded by structural highs on the west, south, and east, resulting in a reversal of the slope gradient for any channelized/turbidity flows entering from the north.

During periods of relative uplift of these bounding ridges, coarser sediment delivery systems experience reduced-to-reversed gradients, with resulting diminishment of channelized facies and the deposition of "ponded" sheet sands within the mini-basin. The ongoing uplift of the margins continued to deform the sedimentary section through recent time, with much of the strata exhibiting steep dips from the basin flanks into the basin center. An existing industry well (the WR 313 #001), located high on the eastern margin of the western Terrebonne mini-basin, showed signs of elevated resistivity throughout the well, but log data was often poor, and no sands of seismically-resolveable thickness were apparent.

The basin architecture also was favorable for the deposition of sands at it represented a closed low within a likely sand delivery fairway (Hutchinson *et al.*, 2009a).

The primary attribute of the WR 313 site that was prospective for gas hydrate in sands were a series of anomalous seismic responses that aligned with the inferred base of gas hydrate stability (McConnell and Kendall, 2002; Shedd *et al.*, 2009a; Hutchinson *et al.*, 2009a). Several of these seismic events, when traced downdip to the west, switch seismic "polarity" from a strong positive response to a strong negative response at a common horizon that cross-cuts stratigraphy (Figure F6). This configuration of seismic responses was interpreted to indicate of free gas accumulations (the negative anomalies) being trapped within porous and permeable sand horizons by significant accumulations of overlying gas hydrate within the sediment pore space. McConnell and Zhang (2005) had also indicated

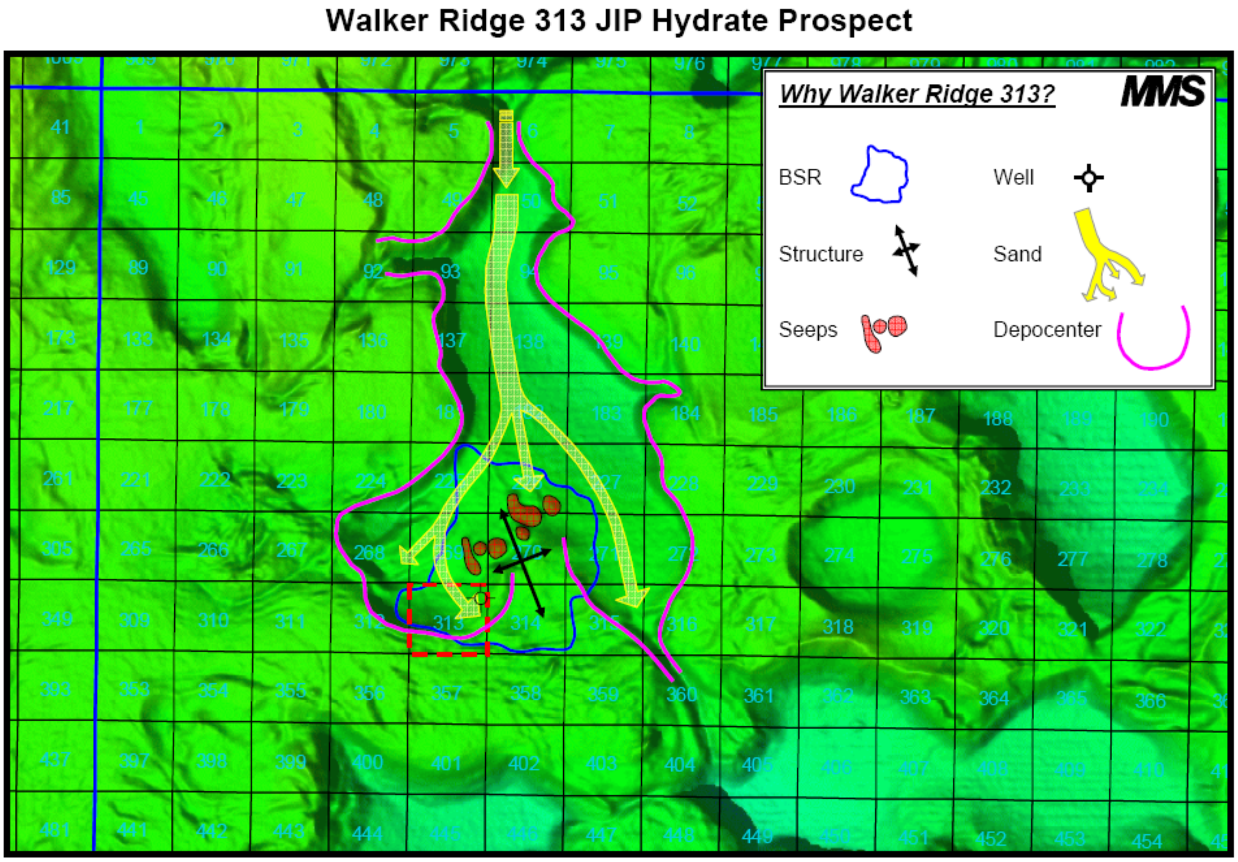

Figure F5: *Sea-floor topography of northwestern Walker Ridge protraction area. Pink line outlines the Terrebonne sub-basin, with inferred sand dispersal "fairways" indicated with yellow arrows. Block 313 (red dashed outline) occurs within a closed sub-basin. The extent of geophysical evidence of the base of the gas hydrate stability zone is shown in blue (courtesy MMS).*

the presence of geobodies with elongate geometries suggestive of sand delivery systems. MMS's detailed mapping of the area revealed several such prospective seismic horizons, providing numerous potential drilling opportunities within different units (labeled as blue, orange, green, etc.). Pre-drill estimates of gas hydrate saturation conducted by WesternGeco indicated high saturations within several of these units (Figure F7). In addition to testing the hypothesis linking these phase reversals to gas hydrate filled sands, the site offered the opportunity to drill multiple targets at a single location, as well as drill a single unit horizons are multiple locations (ascending further up into the stability zone) to test the lateral heterogeneity of gas hydrate and to determine the controls on degree of reservoir fill above the base of GHSZ. It should also be noted that these drilling target were exceptionally deep, occurring as much 3000 fbsf.

Two wells were drilled at the WR 313 Site. The first well (WR 313-G) was located further down into the basin, and targeted a bright amplitude within a unit informally known as the "blue" unit. Pre-drill seismic estimate of gas hydrate saturation at this location was 57%. The second well (WR 313-H) was drilled ~1 nm updip to the east. This location tested the blue horizon at approximately the updip termination of the mapped gas hydrate occurrence, with the primary target for the WR 313-H well being the deeper "orange" unit. The pre-drill estimate of gas hydrate saturation for the "orange" target was 53%.

Drilling Results

While drilling the primarily muddy sediments above the blue target at the WR 313-G well, a zone of elevated resistivity (from 4 to 10 Ω-m) was encountered through a thick interval from 7458 ft to 7850 fbrf. Further up dip, the

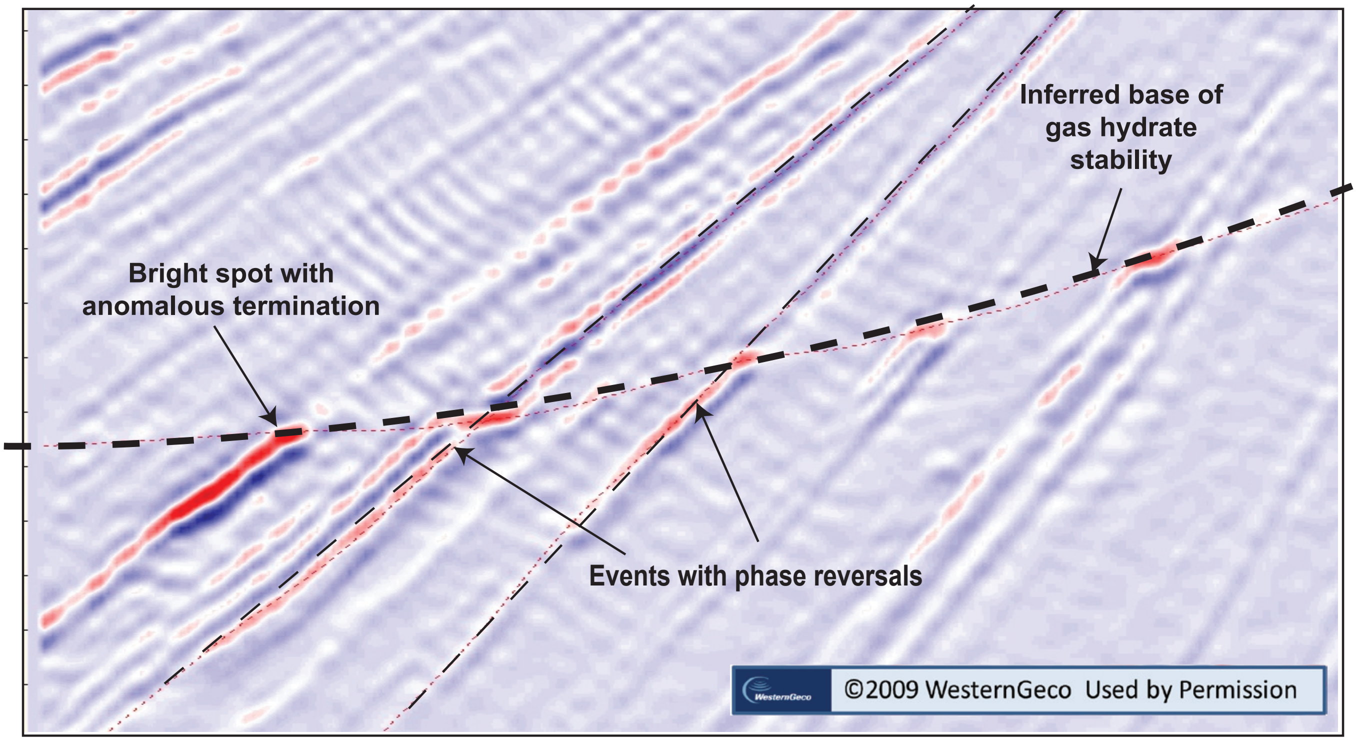

Figure F6: *East west seismic line through Walker Ridge 313 showing the geophysical features noted at the base of gas hydrate stability including anomalies aligned bright spots and phase reversals (from Shelander et al., in review). Image courtesy of WesternGeco.*

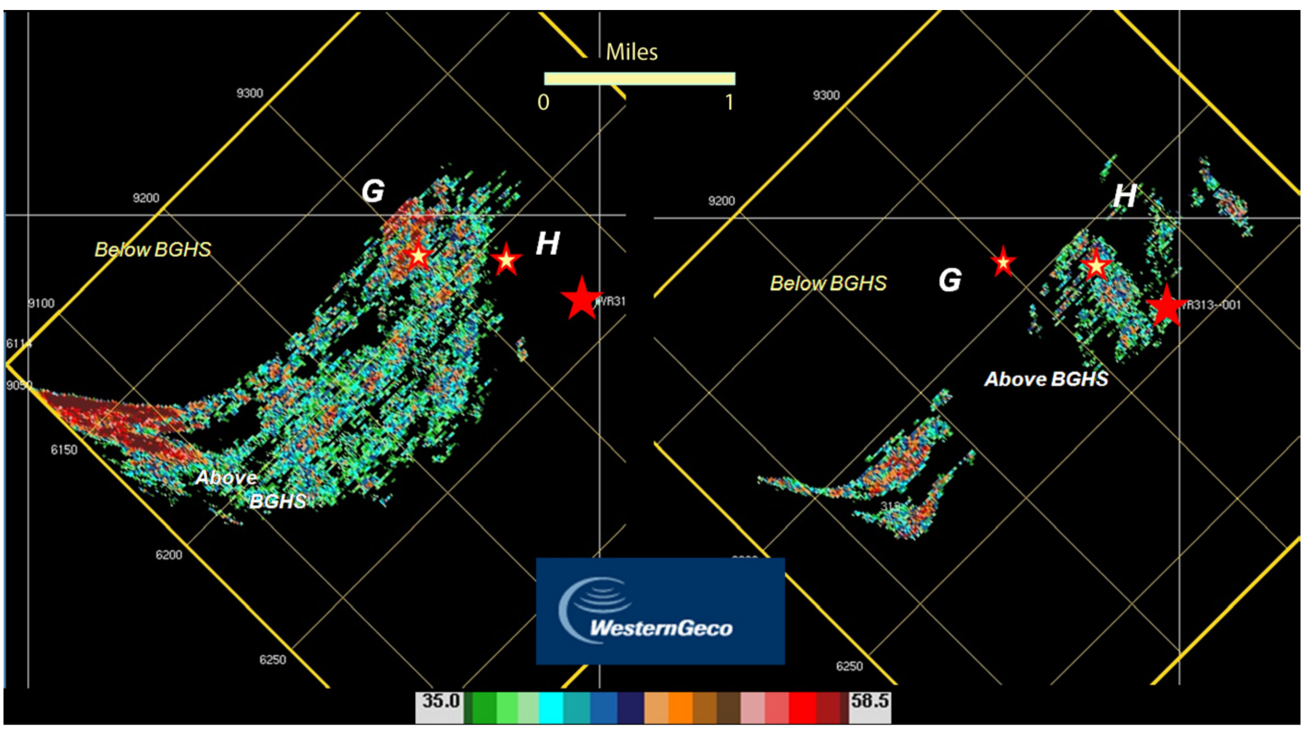

Figure F7: *Inferred gas hydrate saturations for two target horizons ("blue" left; "orange" right) in Walker Ridge 313. Locations of WR 313-G and WR 313-H wells are indicated. Solid red star is pre-existing industry well (WR 313 #001). Image courtesy of WesternGeco.*

pre-existing industry well (Walker Ridge 313 #001) shows a similar occurrence within the correlative stratigraphic interval at that location. Initial interpretation is that this zone marks a stratal-bound interval of clay-dominated sediments with fracture-filling gas hydrate.

The sedimentary section logged from 7840 to 9400 fbrf in the WR 313-G well included numerous thin sands and silts within a predominantly fine-grained section. Notable gas hydrate-filled sands were encountered at 8588 fbrf (10-ft thick – 6 Ω-m) and at 9342 fbrf (10 ft net sand at 6-10 Ω-m within a 26-ft interval). As drilling proceeded at WR 313-G, the lack of use of heavy drilling fluids and slow penetration rates (both designed intentionally to maximize the quality of the data recorded by the logging tools) made it difficult to remove cuttings or well-bore cavings from around the drill string. At a depth of about 9600 fbrf, a decision was made to continuously pump a 10.5 ppg drill fluid which improved the hole cleaning capabilities and the well could be advanced with minimum hole stability problems. The "blue" target was observed from 9412 to 9482 fbrf. A net of ~30 ft of sand containing gas hydrate at high saturations was confirmed within the 70-ft gross interval. A summary log display of the WR 313-G well is provided in Figure F8. For more detail, see McConnell *et al.* (2009a) and Cook *et al.* (2009).

The WR 313-H well was located ~1 nm to the east of the G well. The shallow, fracture-filling gas hydrate occurrence (give depth interval) was again observed in this location with a thickness of ~315 ft. As with the G-well, the underlying sediments contained interbedded muds and thin sands, including four gas hydrate-bearing sands ranging from 4 to 8-ft thick. Sediments interpreted to be correlative with the "blue" seismic reflector were reached at 2305 fbsf and had graded into a more mud-rich interval with reduced porosity and only limited occurrence of gas hydrate. The top of the main target "orange" unit was logged at 2646 fbsf. This unit consisted of two lobes of very clean sand, each with sharp basal and upper contacts. Resistivity in the upper (15 ft-thick) lobe were very high (~30 to 300 Ω-m), resulting in a preliminary estimate of gas hydrate saturation ranging upwards from 75%.

The lower lobe (21 ft-thick) was less resistive (~3 to 30 Ω-m), with gas hydrate saturation estimates ranging from 30% to 70% (Cook *et al.*, 2009). Drilling continued below the inferred BGHS, penetrating additional reservoir-quality sands attributed to the "green" event. These sands are observed in seismic data to ascend above the BGHS in the eastern portion of WR 313, where several anomalies indicative of gas hydrate occurrence occur. A summary log display of the WR 313-H well is provided in Figure F9. For more detail, see McConnell *et al.* (2009a) and Cook *et al.* (2009).

The results of WR 313 LWD operations confirms the geological/geophysical model that links phase reversals of strong amplitude and appropriate polarity of substantial accumulations of gas hydrate in deeply buried sand reservoirs. Most notable is the observation that gas hydrate is found in virtually every sand unit encountered within the GHSZ in both wells. Also notable is the apparently strata-bound nature of the shallow gas hydrate-filled fractured mud occurrence. A summary display of well and seismic data for the WR 313 site is provided as Figure F10.

Only two wells were drilled at the site, and therefore additional prospective units, as well as other potential facies within the units drilled, could not be tested. In addition, we achieved only two penetrations in the primary 'blue" unit. The data appear to suggest that the reduction in seismic amplitude observed as the unit is traced up-dip to the east relates primarily to loss in reservoir quality. Additional data will be needed to answer the question of how far up-dip gas hydrate might occur in such a unit given uniform reservoir properties.

Site Summary – Green Canyon Block 955

A detailed review of the pre-drill evaluation of the GC 955 site can be found in Hutchinson *et al.* (2009b). Review of the initial scientific results of the JIP Leg II LWD operations at the GC 955 site can be found in McConnell *et al.* (2009b) and Guerin *et al.* (2009a). The following is an overview of key events and findings.

Setting

The JIP site selection team identified numerous potential targets in Green Canyon block 955. This site is located in over 6500 ft of water just seaward of a major embayment in the Sigsbee Escarpment ("Green Canyon") which appears to have served as a persistent focal point for sediment delivery into the deep Gulf of Mexico. The area is traversed by a prominent and long-lived channel/

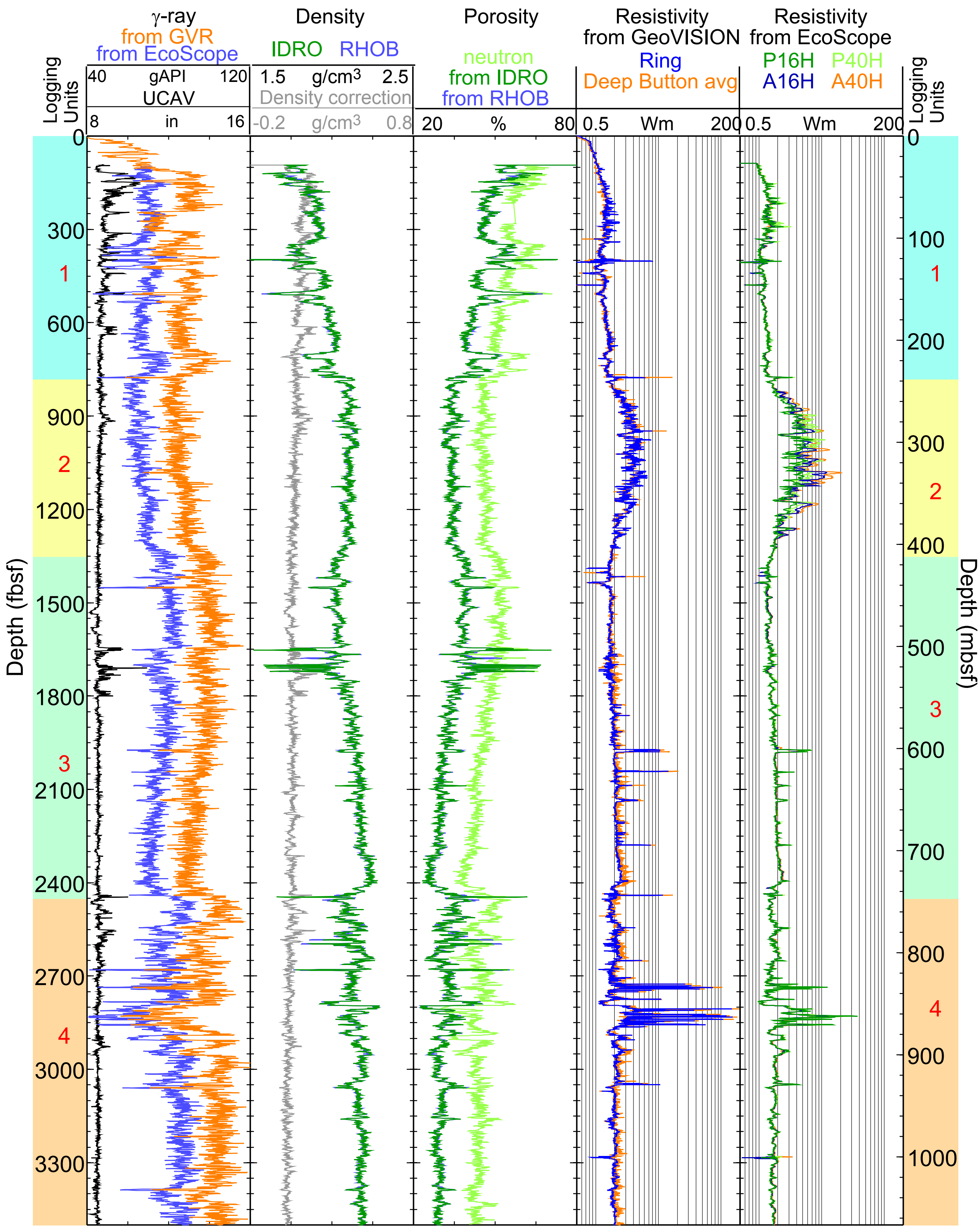

Figure F8: *Summary log data display for the WR 313-G well. Primary target "blue" horizon was encountered just below 2800 fbsf. See Cook et al. (2009) for additional information.*

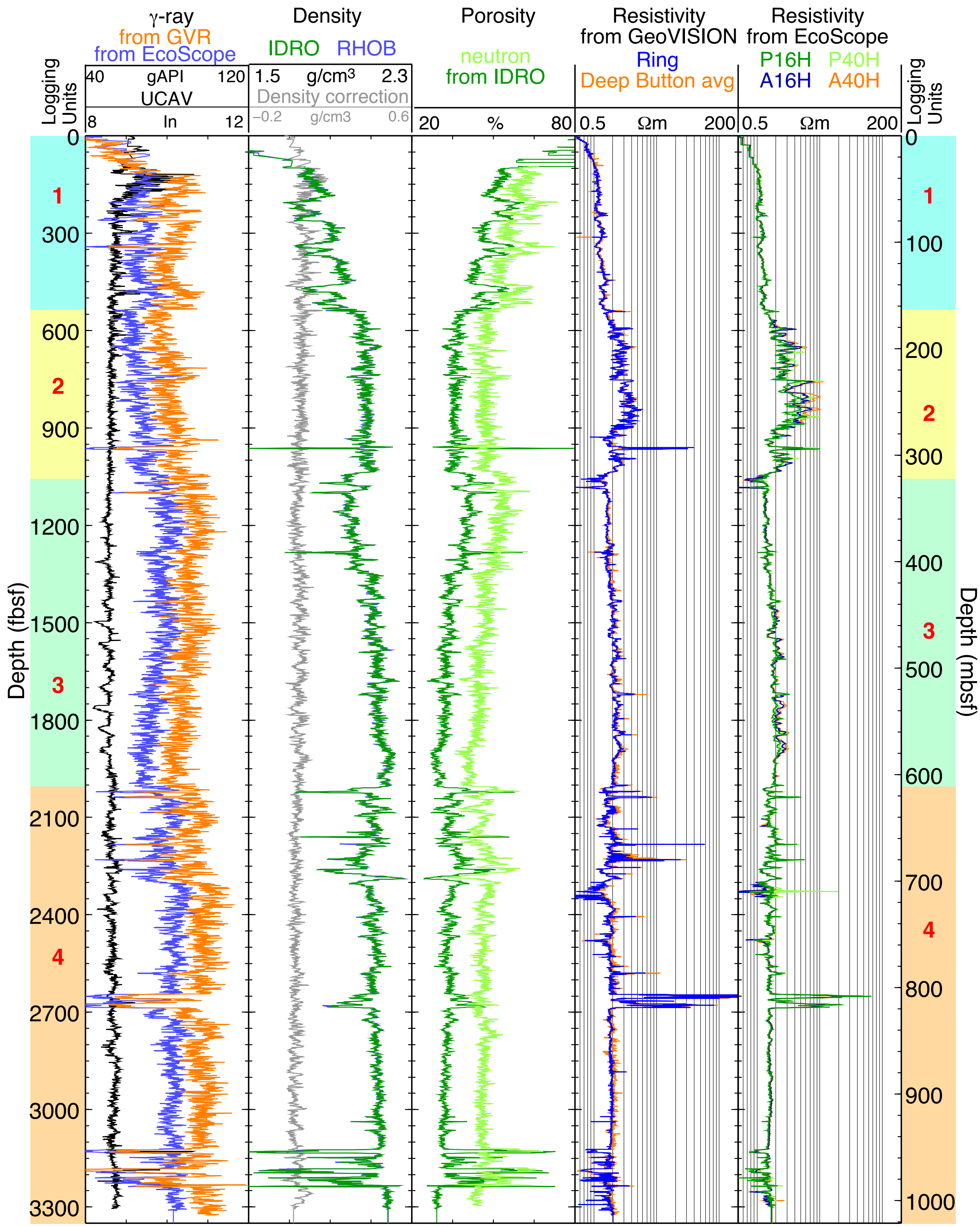

Figure F9: *Summary LWD data display from the WR 313-H well. The primary target "orange" sand was encountered at 2650 fbsf. The secondary target "blue" unit was found at 2200 fbsf. The target "green" sand was found as expected below the estimated base of gas hydrate stability at ~3100 fbsf. Base of gas hydrate stability is at approximately 2900 fbsf. See Cook et al. (2009) for additional information.*

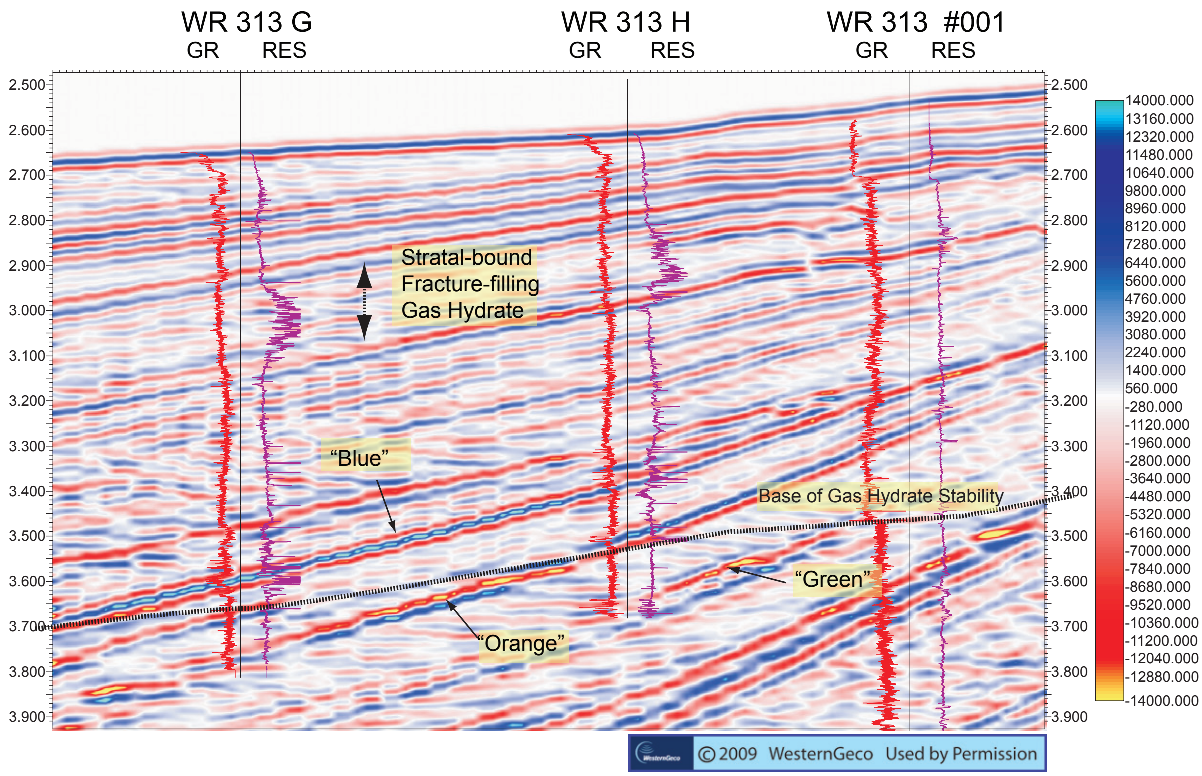

Figure F10: *Overlay of JIP Leg II LWD data with seismic. Black curves are gamma-ray; blue curves are resistivity. Scale at right shows relative amplitude. Seismic data courtesy WesternGeco.*

levee complex that has transported and deposited large volumes of sandy sediment from Green Canyon to the deep Gulf of Mexico abyssal plain. The southwest corner of Block 955 includes a recently formed structural high caused by deeper mobilization of salt. The crest of the structural high is cut by complex network of faults that can provide potential pathways for migrating fluids and gases (McConnell, 2000; Heggeland, 2004). Geophysical data reviewed during assessment of the site revealed a complex set of geophysical responses near the inferred base of gas hydrate stability (Figure F11). Some of these responses are suggestive of free gas and some indicative of gas hydrate, but all are limited to depths that are near or below the inferred base of the gas hydrate stability zone. The pre-drill predictions of gas hydrate saturations developed by WesternGeco are shown in Figure F12.

The Green Canyon site combines many of the features required for the formation of significant gas hydrate accumulations, including sources of gas and migration pathways (the faults) for gas to migrate into the gas hydrate stability zone as well as porous sands within the stability zone in which gas hydrate can accumulate. A motivation behind the JIP's selection of this site was to test the hypothesis that gas hydrate accumulations within sands at the base of gas hydrate stability restrict the vertical migration of gas into shallower units within the structure. In addition, the drilling was designed to test the hypothesis that gas hydrate could exist in the seismically-muted section just above the inferred base of gas hydrate stability (BGHS). One possibility was that gas hydrates concentrated within sands occur in close association with faults or fractures in orientations not readily recorded in the seismic data. Another hypothesis was that the gas hydrate saturation at the top of the seismically inferred sand package was broadly gradational, serving to mute the seismic response of the *in-situ* gas hydrate.

Drilling Results

Three wells were drilled in Green Canyon from April 22 to April 28. The first (GC 955-I) was drilled very close to a prominent, late-stage channel axis (to maximize the occurrence of sand reservoirs) in a location with relatively muted geophysical indications (i.e., seismic amplitudes) of gas hydrate. Pre-drill gas hydrate saturations for this

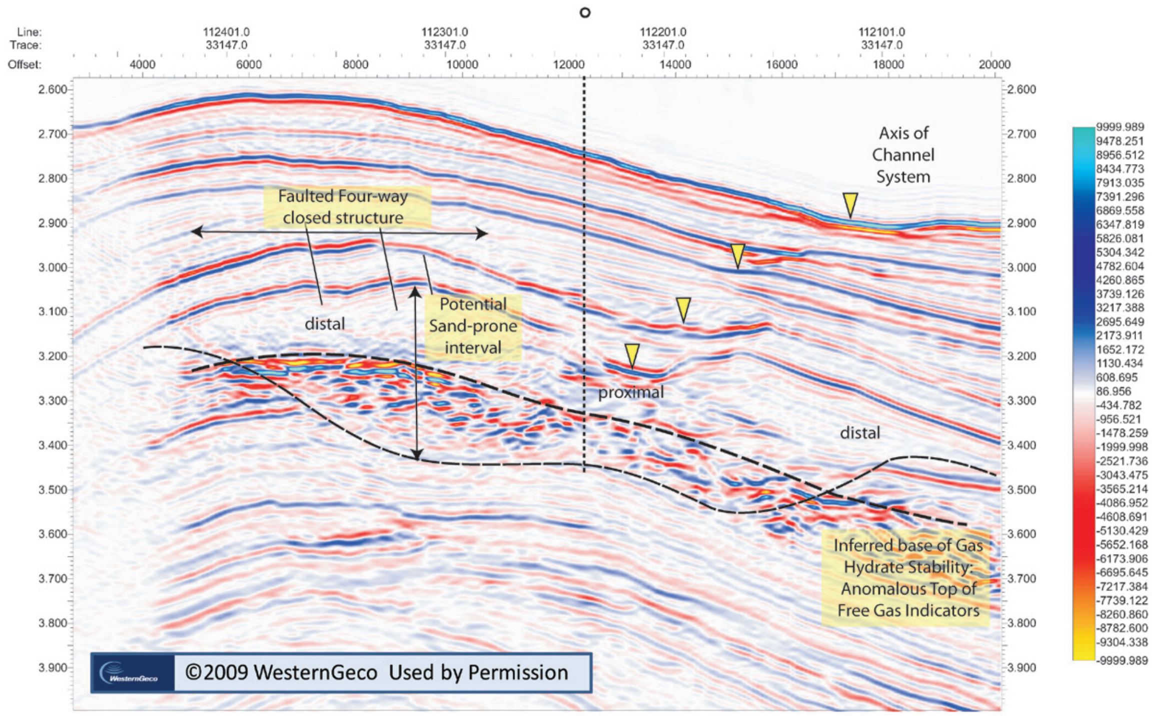

Figure F11: *Seismic data in Green Canyon block 955. The data show a persistent channel location, and high seismic amplitudes suggesting the presence of gas. Scale to right shows reflection coefficient values. Seismic data courtesy WesternGeco.*

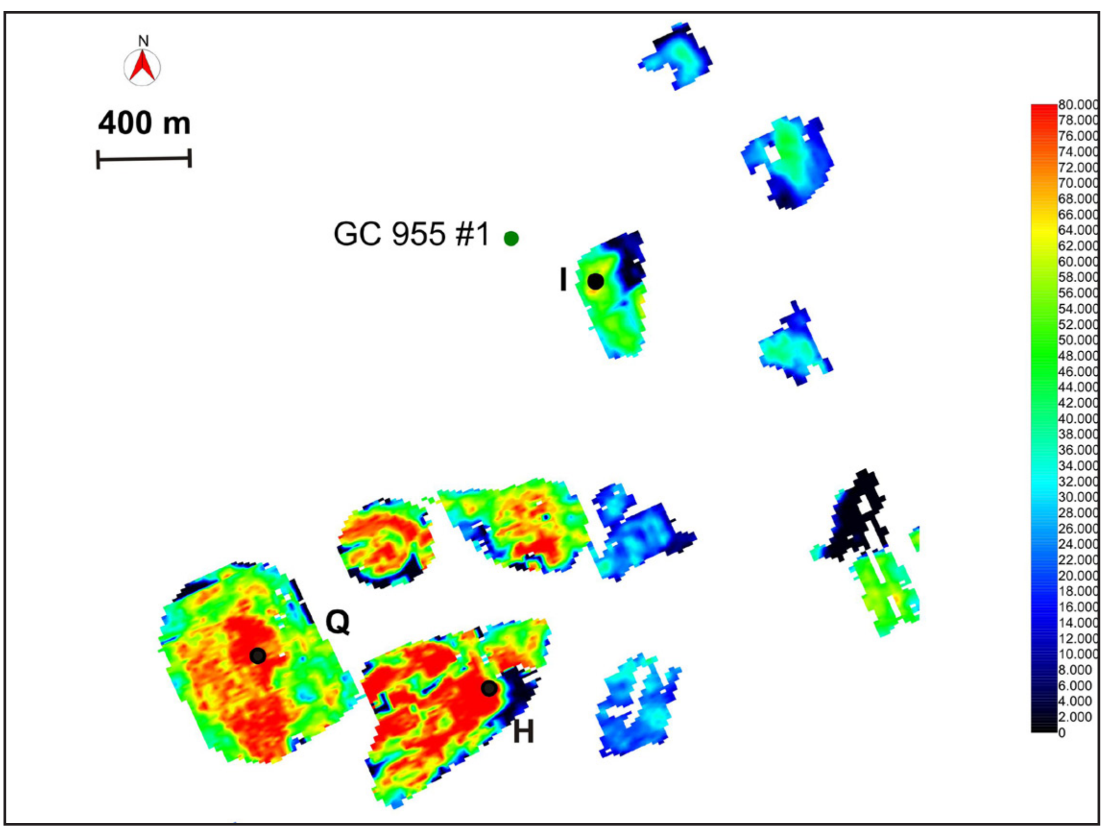

Figure F12: *Pre-drill estimates of gas hydrate saturation within southwestern GC block 955. Letters "I," "H," and "Q" indicate locations of JIP Leg II wells. Scale to right shows reflection coefficient values.*

location ranged from 66% (p-impedance method) to 44% (combined p- and s-impedance method). The "I" well encountered more than 300 ft of porous sands as predicted; however the sands contained primarily water – with only modest indications of gas hydrate. The well also flowed water (presumably from within these thick, porous sand zones), requiring roughly a day of effort to control the flow. A summary log display of the GC 955-I well is provided in Figure F13. For more detail, see McConnell *et al.* (2009b) and Guerin *et al.* (2009a).

The second well, GC 955-H, was drilled about 1 mile southwest of the I-location in a structurally higher position on the domal structure. The well targeted strong geophysical anomalies with features suggestive of gas hydrate at a projected depth of 1355 ft below the sea floor. Pre-drill estimated of gas hydrate saturation for the site were 95% (p-impedance) and 68% (from p- and s-impedance). While drilling the shallow section, a thick zone of gas hydrate-filled fractures in mud-rich sediments was observed from ~600 to ~1000 fbsf. As drilling proceed below a depth of 1230 fbsf, the gamma-ray measurement of the sediments began to gradually decrease, indicative of sands. At 1305 fbsf, the well encountered the top of a thick gas hydrate-bearing sand interval. Three gas hydrate-bearing zones of 88 ft, 13 ft, and 3 ft-thick were logged. Unexpectedly, these zones are separated by thin zones of apparently water-bearing sands. Log quality within the sand is highly-erratic, with resistive zones displaying almost perfectly in-guage holes, and water-bearing zones being significantly washed out. Additional analysis of the well log data will be required to more fully understand these units. Below the gas hydrate, the sediments that had been assessed as having a "modest risk" of free gas were found to be primarily water-bearing sands, although low saturations of gas may be present. A summary log display of the GC 955-H well is provided in Figure F14. For more detail, see McConnell *et al.* (2009b) and Guerin *et al.* (2009a).

Based on the results of the GC 955-H well, the science team and the JIP elected to drill the GC 955-Q well, which was located in a separate fault block in a structurally-higher position, potentially placing the sand reservoir higher into the GHSZ. On seismic data, this location exhibited a thick sequence of high-amplitude geophysical responses that had been assessed a "high" risk of free gas in pre-expedition hazards analysis (McConnell *et al*., 2009b). The science team determined that this risk had been sufficiently mitigated by the lack of significant free gas observed below hydrate in the H well and the drill fluid handling capabilities of the *Q-4000*. At a depth of 1405 fbsf, the GC 955-Q well encountered gas hydrate-bearing sand. The sand continued to a depth of at least 1458 fbsf (the deepest datapoint provided by the LWD tool string). Initial review of the available data indicate a complex acoustic response - further processing and evaluation of the LWD and MWD data will be required to better understand the potential distribution of gas hydrate and free gas. At a depth of 1498 fbsf, drilling was halted when a single gas release from the well was visually observed by the *Q-4000*'s remotely operated vehicle (ROV). The well was non-flowing; however, additional well-control measures were implemented by increasing drilling fluid weight.

Gas flows were later observed while the LWD assembly was removed. The well was then re-entered and cemented. A summary log display of the GC 955-Q well is provided in Figure F15. For more detail, see McConnell *et al.* (2009b) and Guerin *et al.* (2009a).

In summary, gas hydrate occurrence in sands at GC 955 were found to occur in close agreement with major seismic amplitude events of positive ("peak") polarity. No significant sand reservoirs were found in the overlying section. Interestingly, a thick zone of fracture dominated gas hydrate occurrence in muds was also observed at the H location, but was absent at the nearby Q and I locations. Additional drilling, and integration of existing drilling results with seismic data will be needed to completely understand the occurrence of gas hydrate in GC 995. However, it appears that gas hydrate occurrence at the site is highly complex, potentially controlled by significant lateral variations in gas delivery, thermal gradients, pore-water salinities, and other features. A summary display of drilling results is shown in Figure F16.

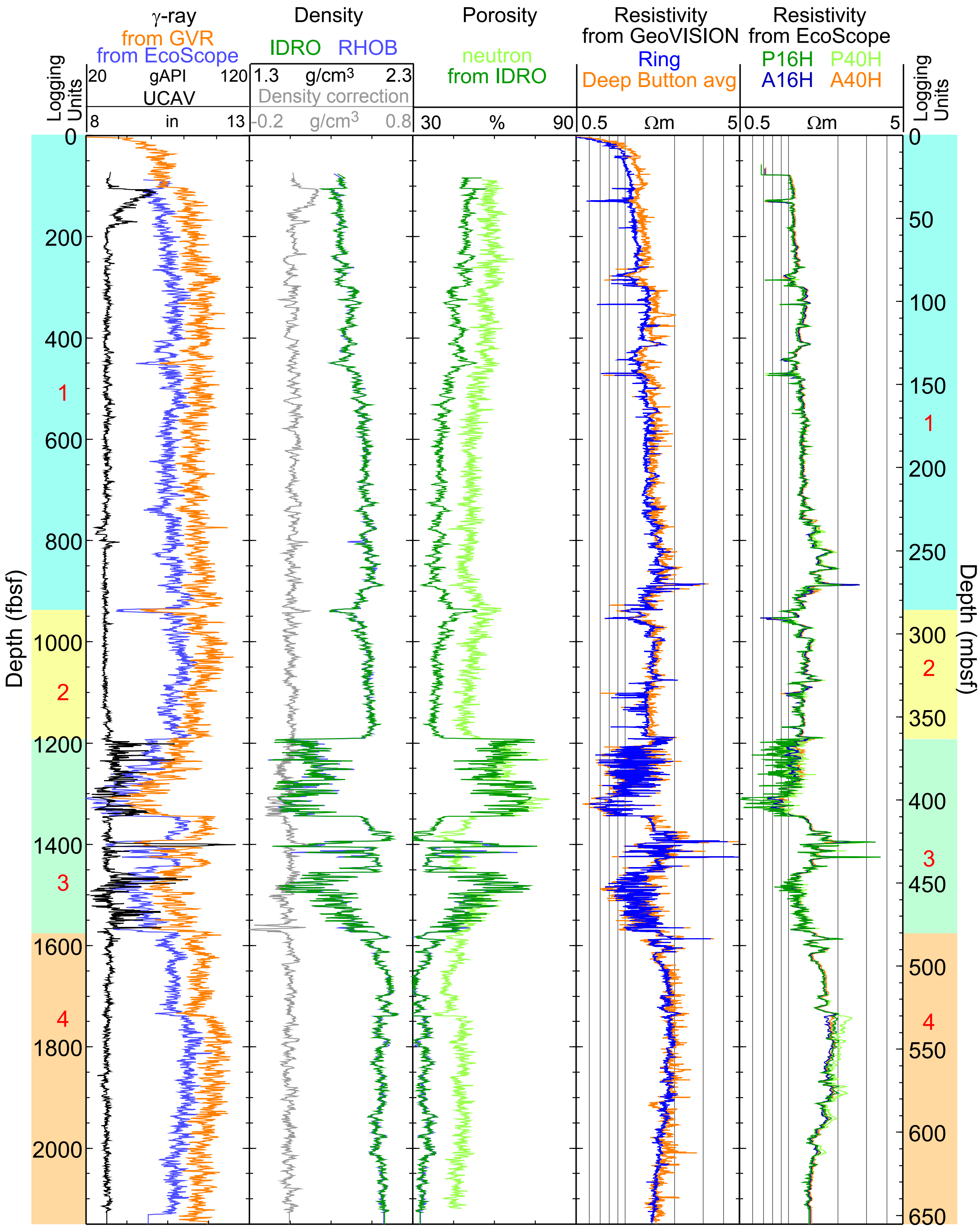

Figure F13: *Summary LWD data display for the GC 955-I well. The target sand (Logging Unit 3) was encountered between 1200 and 1550 fbsf, and was primarily water-bearing. See Guerin et al. (2009a) for further information.*

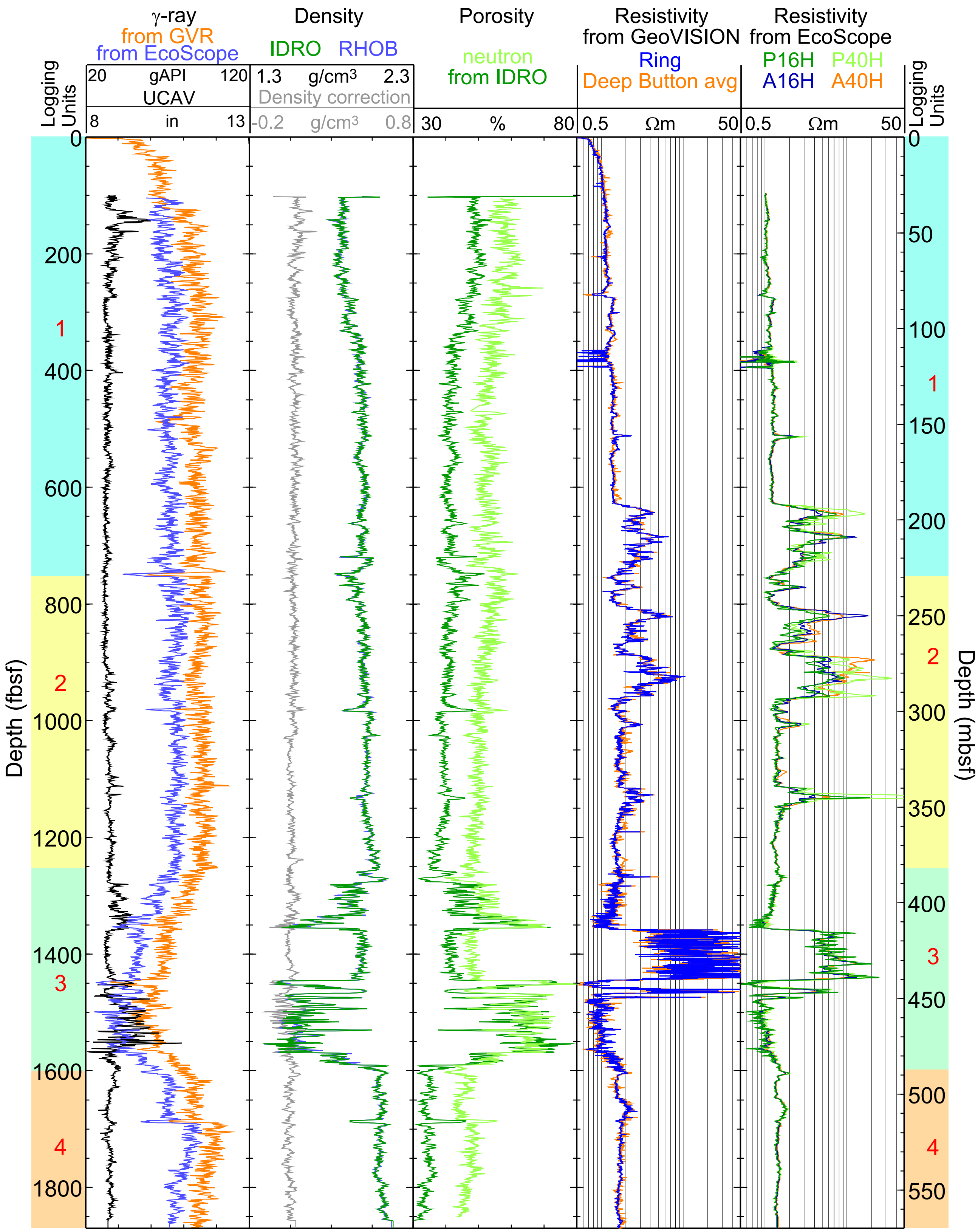

Figure F14: *Summary LWD data display for the GC 955-H well. The target sand (Logging Unit 3) was encountered between 1250 and 1600 fbsf, and contained ~100 feet of gas hydrate at high saturations. See Guerin et al. (2009a) for further information.*

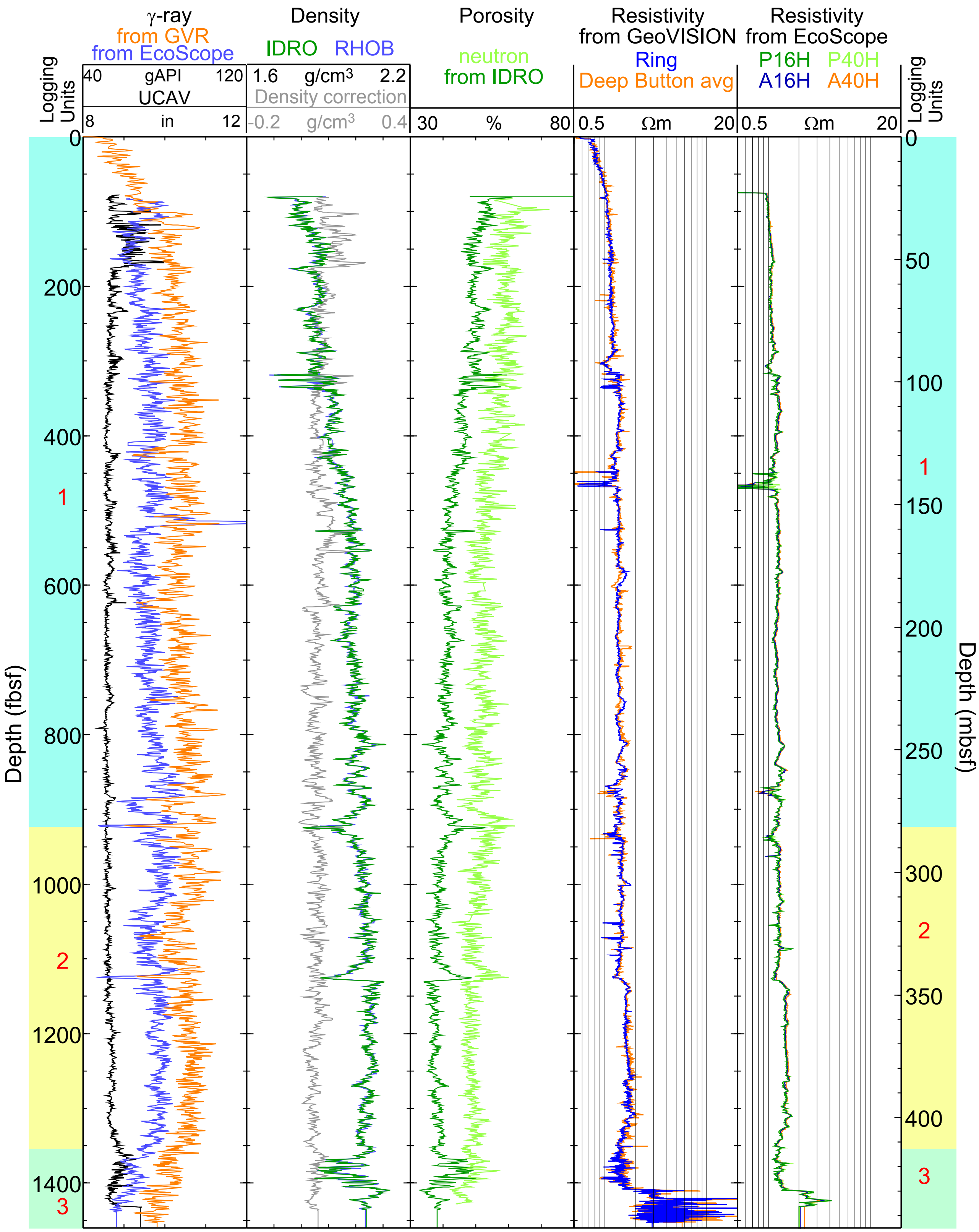

Figure F15: *Summary LWD data display for the GC 955-Q well. The target sand (Logging Unit 3) was encountered below 1350 fbsf, and was gas hydrate-bearing. See Guerin et al. (2009b) for further information.*

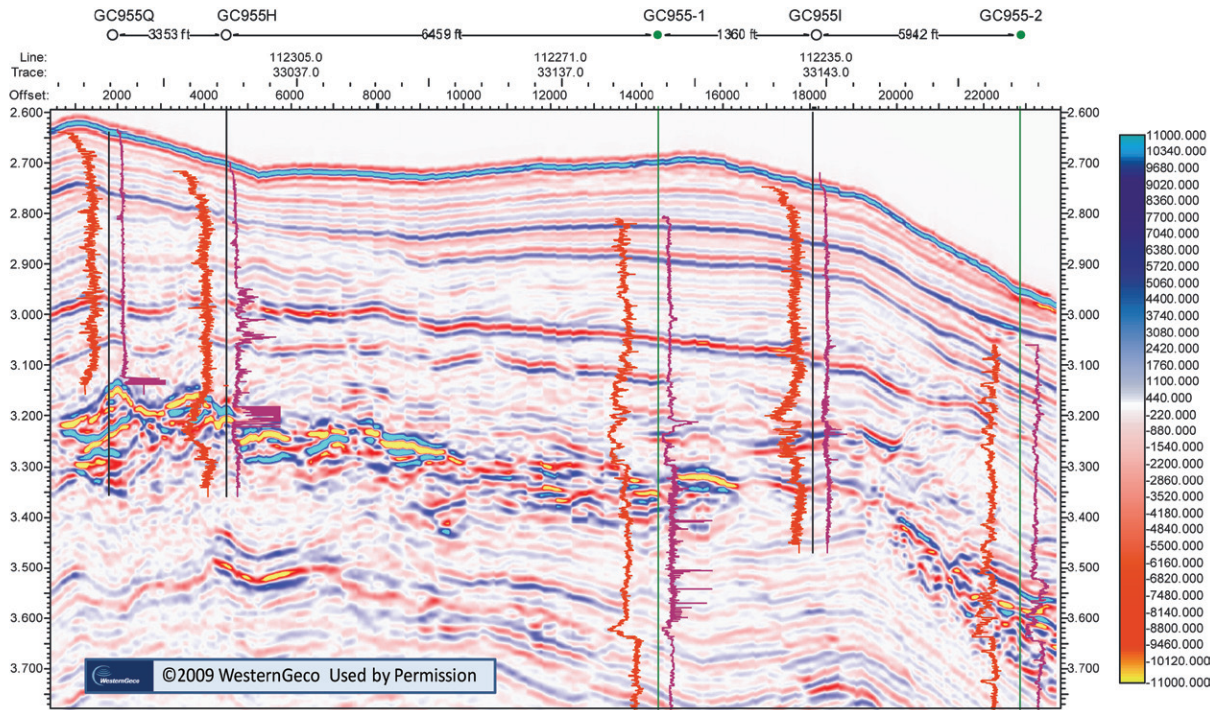

Figure F16: *Preliminary display of seismic data and LWD data in GC 955 site. Synthetic seismic analyses now in progress will further refine the well to seismic ties. Scale at right shows relative amplitude. Seismic data courtesy of WesternGeco.*

Site Summary – Alaminos Canyon Block 21

Review of the initial scientific results of the JIP Leg II LWD operations at the AC 21 site can be found in Frye *et al.* (2009) and Guerin *et al.* (2009b). The following is an overview of key events and findings.

Setting

Proposed JIP Leg II drilling sites in EB 992 and AC 21/65 lie within the Diana sub-basin and target anomalous seismic reflections that occur approximately 600 feet below the seafloor and 800 feet above the inferred base of gas hydrate stability (Figure F17). The two sites, located about 5 miles apart, provided opportunities to test slightly different settings within a single geologic prospect. Two primary features drive the prospectivity of these sites. First, an existing (1995) industry well (the EB 992 #001 "Rockefeller" well) logged a thick and slightly resistive sand at shallow depths (Frye *et al.*, 2009). Log analysis of the LWD resistivity indicated potential gas hydrate saturation ranging from 20 to 40% with some uncertainty due to the potential poor quality of the log data. Second, seismic data showed strong seismic reflectors at both the top and base of this seismic inferred sand, with polarity and amplitude again consistent with low to moderate gas hydrate saturation. However, this interpretation is uncertain, due largely to the limited data on the acoustic nature of shallow, unconsolidated, high-porosity sediments. No pre-drill seismic analyses for gas hydrate saturation were conducted for these sites. However, preliminary seismic mapping of this sand body clearly delineated its extent, and showed wide occurrence through a large portion of the south Diana sub-basin (Frye *et al.*, 2009). Regional mapping of the seismic attributes conducted by the MMS revealed a unit of complex architecture.

Initial interpretation suggests a complex array of laterally-coalescing turbiditic lobe and minor channel complexes that delivered sand-rich sediments from the northeast to the southwest across the Diana sub-basin Drilling sites in both AC 21 and the adjoining AC 65 (where the sand was more laterally extensive) and in EB 992 (where a single sand dendroid occurred) were developed and permitted. This setting is similar to that interpreted for deeper conventional oil and gas-bearing sands within the Diana basin (Sullivan *et al.*, 2004). Throughout the area, the geophysical expression of the target interval is consistent, and shows no clear evidence of gas sources, or any variation in seismic amplitudes that might reflect local variations in gas hydrate saturation due to proximity to gas sources. The sediments

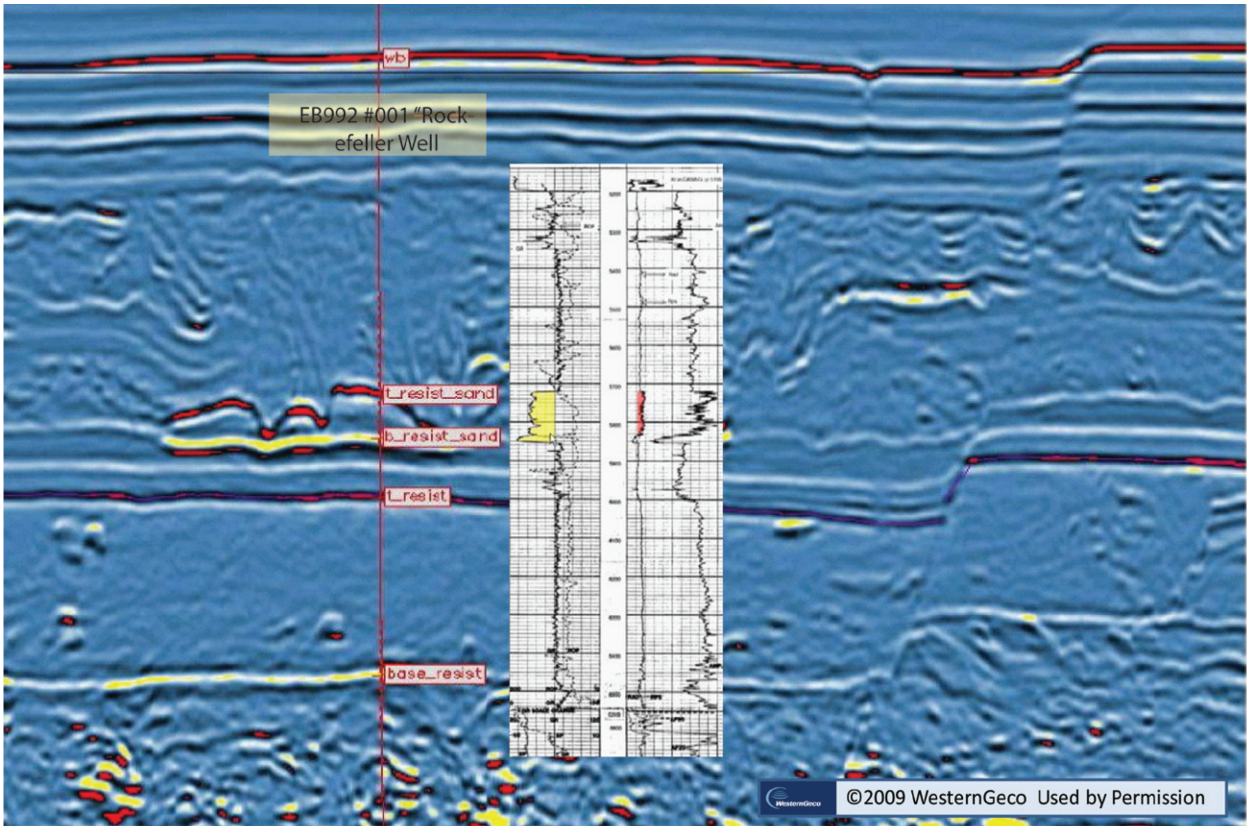

Figure F17: *Seismic data from EB 992 showing relationship between resistive sand seen in the EB 992 #001 well and strong amplitudes seen in seismic data. Red line shows position of EB 992 #001 well. Seismic data courtesy of WesternGeco.*

are also very young, being no more than 440,000 years in age.

The primary hypotheses to be tested at the site included 1) the opportunity to test log and seismic interpretations of low-saturation gas hydrates in reservoir-quality sands – an occurrence that has rarely been observed (Collett *et al.*, 2009a); and 2) the potential that the 1995-vintage LWD resistivity data were degraded, due to poor logging conditions (typical of the shallow portions of large-diameter deep boreholes) or perhaps complex reservoir architecture (such as very-thinly interbedded sands and shales) resulting in a composite low-resistivity "pay".

Drilling Results

Two wells were drilled through the prospective shallow sand facies in AC 21. A third permitted well in AC 65 was not drilled, and none of the permitted wells in EB 992, were drilled. The AC 21-B well targeted a relatively thick occurrence which seismic response typical of the unit throughout the AC 21 and AC 65 region. This well logged a single sand body 125 ft-thick at 520 fbsf. The resistivity of the sand was remarkably consistent at 1.8 to 2.5 Ω-m, slightly more resistive than the bounding shales (1.5 Ω-m). The AC 21-A location, approximately 1.2 nm to the south of the AC 21-B well, featured a more complex geophysical response including a series of four seismic events of higher magnitude than seen elsewhere in the unit's lateral equivalents. This well encountered two sands (at 540 and 570 fbsf) separated by a 15-foot thick shale. As in the AC 21-B well, resistivity in these sands was consistently ~2 Ω-m. No clearly water saturated sands were observed in either well. Log and seismic data summary displays for AC 21-A and AC 21-B are provided as Figures F18, F19 and F20.

Initial interpretation of the AC 21/EB 992 drilling results is that the sands appear to exhibit widespread, and low gas hydrate saturation over a potentially large area. However, lack of data on reservoir mineralogy and pore water geochemistry makes it difficult to assess nature or degree of pore fill with great confidence. Assuming the inferred low concentrations of gas hydrates is correct (~20%; Guerin, *et al.*, 2009b), the limitation on gas hydrate occurrence is

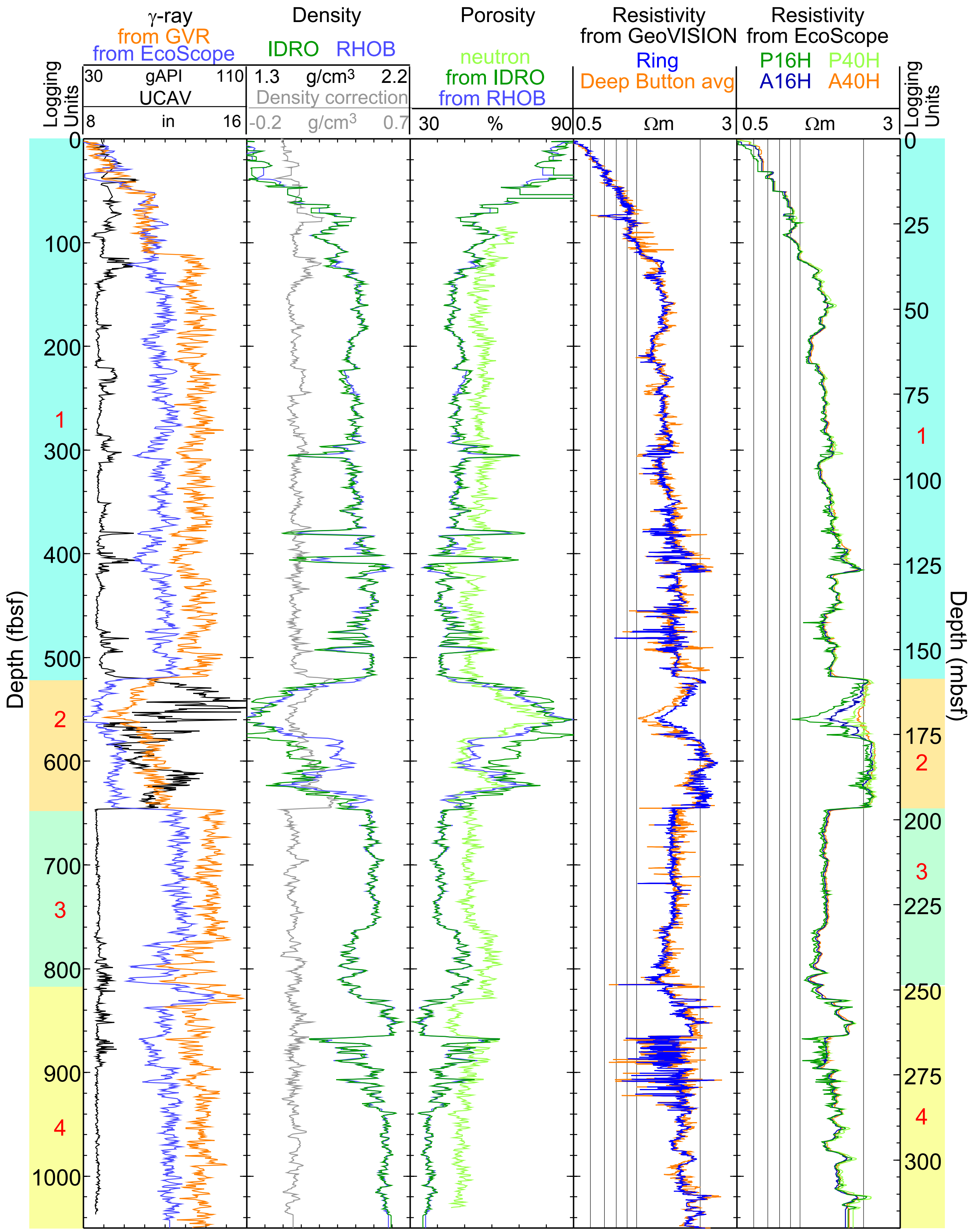

Figure F18: *Summary LWD data display from the AC 21-B well. See Guerin et al. (2009b) for further information.*

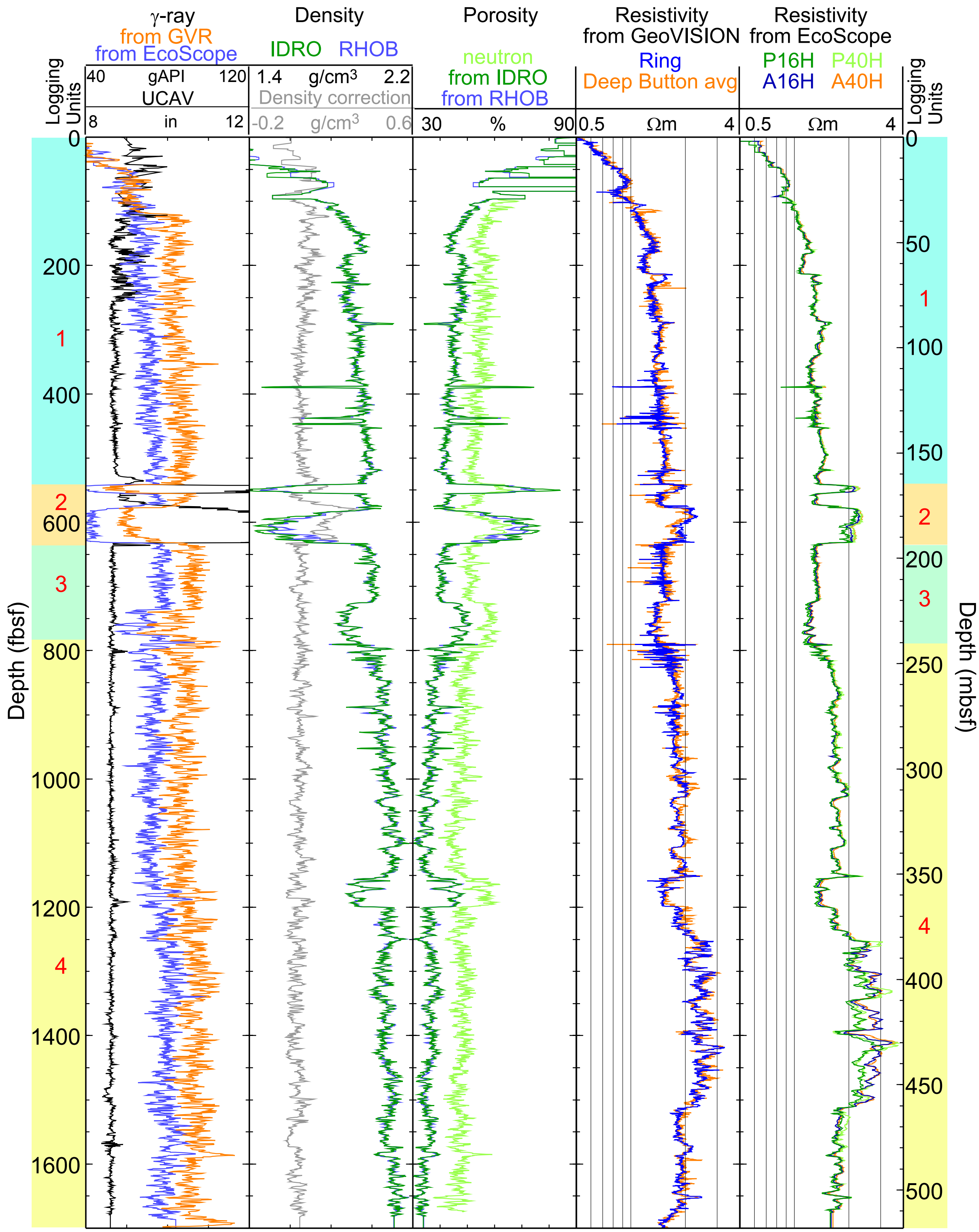

Figure F19: *Summary display of LWD data from the AC 21-A well. See Guerin et al. (2009b) for further information.*

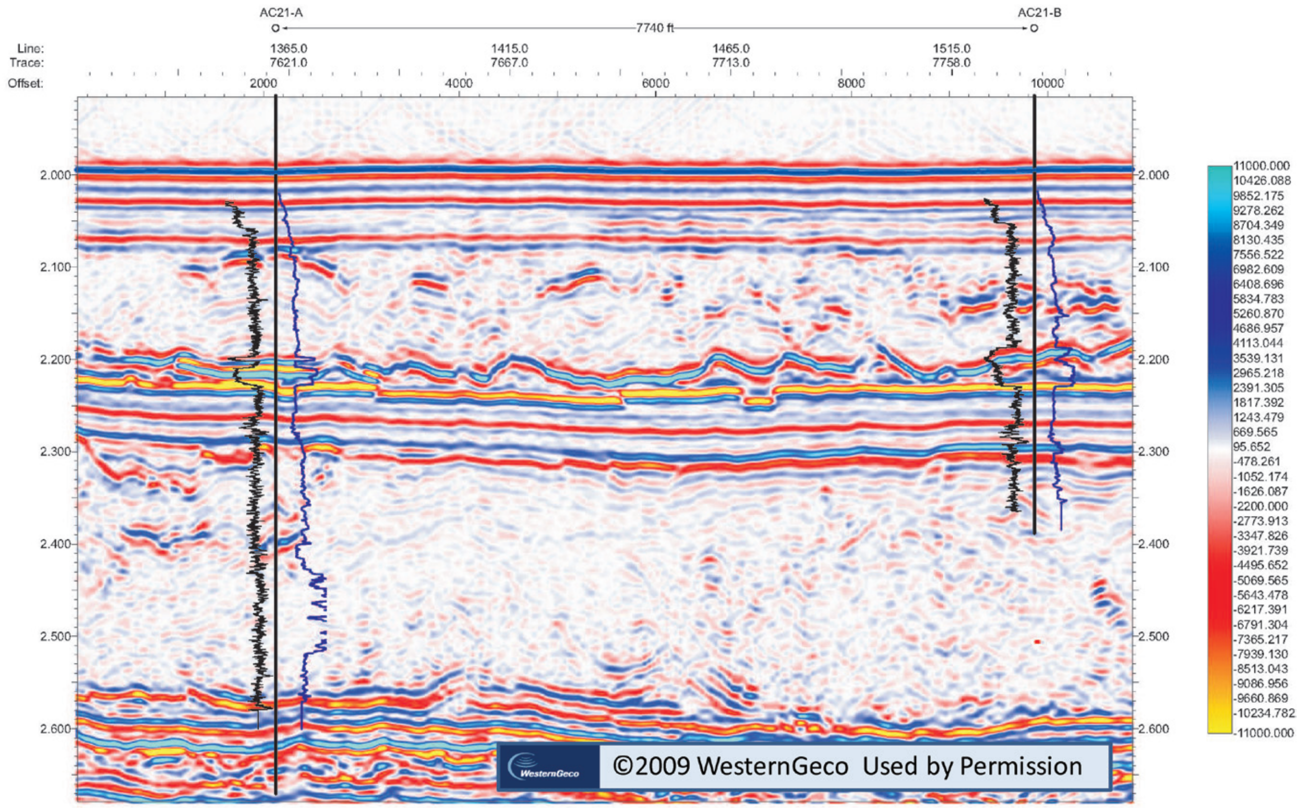

Figure F20: *Preliminary well log to seismic tie for the AC 21 site (Frye et al., 2009). Scale at right shows relative amplitude. Seismic data courtesy of WesternGeco.*

most likely related to the potential lack of gas charge to these shallow sand reservoirs (Frye *et al.*, 2009), due both to the young age of the sediment and the lack of major gas migration pathways into the unit. Further examination of the LWD data should further this interpretation; however, it is likely that recovery of sediment and fluid samples will be needed to fully understand the nature of gas hydrate occurrence in this very large prospect.

Summary

This report provides an initial review of JIP Leg II operations and results. Further work will be required to provide final estimates of the nature of the gas hydrate-bearing units encountered. This work includes analyses of the full LWD data sets, as well as improved calibration between the drilling results and the seismic data.

JIP Leg II set out to conduct LWD operations to confirm the existence of gas hydrate in sand reservoirs in the Gulf of Mexico, and to test existing approaches and technologies for pre-drill appraisal of gas hydrate concentration. Both of these objectives were fully achieved. From a management standpoint, Leg II was extremely successful; being completed on time and under budget, with zero injuries. Operationally, the expedition provides significant new information on the optimal drilling and well control protocols for deep gas hydrate research projects (Collett *et al.*, 2009b). Technically, the operation of the LWD tools was outstanding, without a single incidence of operational time loss due to tool failure (Mrozewski *et al.*, 2009; Cook *et al.*, 2009; Guerin *et al.*, 2009a and 2009b). Scientifically, the expedition was a clear success, yielding extremely valuable and advanced datasets on gas hydrate occurrences ranging from low to high saturation in sands as well as thick sections of fracture-filling gas hydrate in muds. Perhaps most importantly, the expedition validates the integrated geological and geophysical approach used in the pre-drill site selection process, and provides increased confidence in the assessment of gas hydrate volumes in the Gulf of Mexico. It is expected that further evaluation of the complex geology of these sites, including both conventional and pressure coring, will add significantly to the understanding of the nature and occurrence of gas hydrate-bearing sands in the marine environment.

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