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SUBSURFACE CHARACTERIZATION OF THE HYDRATE BEARING SEDIMENTS NEAR ALAMINOS CANYON 818

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ABSTRACT

Gas hydrate has been identified by drilling in Alaminos Canyon block 818, within the Perdido Fold Belt, outboard of the Sigsbee Escarpment, in approximately 2750 meters (9000 feet) of water. At the location of the AC818 #1 ("Tigershark") well, the gas hydrate occurs within the top 20 m (65 feet) of an approximately 90 meter (300 feet) thick Oligocene Frio sand, a volcaniclastic sandstone rich in lithic fragments, feldspar, and volcanic ash. The Frio reservoir is folded into a 4-way closed anticline. At the crest of the anticline, the sand is partly eroded and is unconformably overlain by 450 m (1500 feet) of Pleistocene shale and sand. The unconformity surface is also in a 4-way closed geometry and defines the top of the hydrate reservoir at the well. The rock is poorly consolidated and has porosity as high as 42% from log data. LWD logs indicate that the hydrate zone has high resistivity and high P-velocity (2750 mps: 9000 fps). The underlying wet sand at the base of the gas hydrate stability zone (GHSZ) has low resistivity and P-velocity (Vp: 1500 mps: 5000 fps). The very low Vp indicates the presence of low-saturation free gas ("fizz gas"). The large velocity contrast creates a strong response in seismic data which was inverted into a 3D gas hydrates saturation (Sgh) volume. Elsewhere in the GHSZ, seismic

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character was used to predict predominant sediment facies. Relative high stand facies, which are more clay-rich, will generally be characterized by more continuous and parallel seismic reflectors. In contrast, relative low stand facies, which have more sand content, will be characterized by more hummocky, discontinuous seismic character and will often lie on erosional surfaces, particularly in uncompacted sediments. Understanding the stratigraphy throughout the section is important, since sand will often provide beneficial reservoir conditions, while clay will provide more impervious sealing qualities. The seismic interpretation also identifies migration pathways, such as faults and gas chimneys, and the presence of available gas, which are necessary to charge reservoirs within the HSZ.

Keywords: gas hydrates, alaminos canyon, gulf of mexico

INTRODUCTION

Pore-filling methane hydrate was encountered in the top 20 meters of a 100-meter thick sandstone during drilling of the Chevron Alaminos Canyon (AC) Block 818 #1 "Tiger Shark" well in the Perdido Fold Belt of the deep-water Gulf of Mexico. The well and associated data acquisition were designed for evaluation of a deeper oil prospect. However, the AC818 hydrate occurrence provides unique documentation of the presence of pore-filling gas hydrates in a porous, permeable sand reservoir, the effect of the hydrates on petrophysical properties and the signature of hydrates on modern "exploration grade" 3-D seismic data.

Regional Setting

The AC818 well is located in the Perdido fold belt of the Southwestern Gulf of Mexico, approximately 200 miles south of Galveston, TX (Figure 1). The Perdido fold belt is a series of southwest-trending box folds. Most of the folds lie beneath the Sigsbee Salt Escarpment, but several of the southwestern-most folds lie outboard of the salt [1, 2]. The folds outboard of salt have been the subject of active oil and gas industry exploration throughout the current decade [3]. Oil and gas discoveries in the Eocene Wilcox and Oligocene Frio formations are being commercially developed in the Great White (AC 857), Silvertip (AC 815) and Tobago (AC 859) fields. Additional discoveries, not yet commercially developed, have been made at the Tiger Shark (AC 818) and Trident (AC 903) prospects. Formation of the Perdido folds occurred primarily in early Oligocene time and strata from Mesozoic through Oligocene age were subject to extensive compressional deformation.

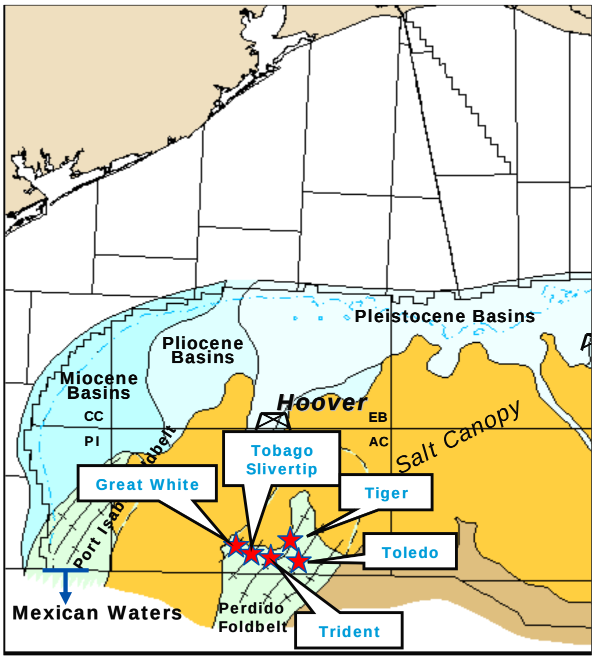

Figure 1: index map showing location of the Perdido Fold belt and Eocene-Oligocene oil and gas discoveries.

SUBSURFACE CHARACTERIZATION

Hydrates in the AC818#1 well

The AC818 #1 well was an exploration well targeting Eocene and Paleocene Wilcox sands. Seismic data indicated an anomalously strong reflector roughly 460 meters below the sea floor (mbsf; or 1,500 feet) that was interpreted to approximate the depth of: 1) the Oligocene Frio sands, a secondary regional oil and gas reservoir and 2) the base of gas hydrate stability zone (GHSZ). During drilling of the AC 818 #1 well, the Frio sand was first encountered as expected at a depth of 3,212 meters below sea level (mbsl; or 10,537 ft), at which time a return flow ("kick") of 246 bbl drilling fluid was observed. Drilling fluid weight was increased from 8.7 to 9.1 ppg in order to control the flow. Mud log data from above the Frio sand had indicated less than 50 units (one percent gas in air), and below 3,212 mbsl (10,537 ft), mudlog gas content increased to 500-1000 units (10-20%) and persisted to a depth of 3,225 mbsl (10,580 ft). Below this depth, gas content decreased steadily from about 5% immediately below the hydrate to 2% at the base of the Frio sand at 3,304 mbsl (10,840 ft.). Gas content then returned to the low levels (at or below 1% in both sand and shale intervals) to 3,475 mbsl (11,400 ft). To determine the nature of this seismic event, a full suite of well logs were acquired through this shallow interval. This was the first full suite of high-quality well logs from within the gas hydrate stability zone in the Gulf of Mexico [4].

Geology of the AC818 hydrate occurrence

At the location of the AC818 well, the water depth is 9004 feet (2744 meters). In the area of Alaminos Canyon block 818, the late Oligocene compressional folding uplifted one of the Oligocene Frio sands to within 1500 feet (460 meters) of the seafloor, placing it partly within the hydrate stability zone (Figure 2). Sidewall cores taken from the AC818 well show that the Frio sand containing the hydrate is a poorly-consolidated volcanigenic litharenite containing abundant volcanic glass shards, feldspar, and rock

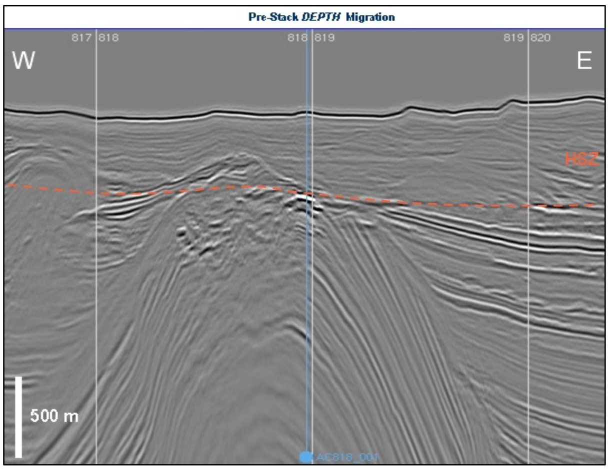

Figure 2: Regional seismic line showing Perdido fold drilled by Well AC818#1(blue line). The interpreted base of the GHSZ is shown by the red dashed line. Note that bright spots occur beneath the base GHSZ. Offshore block boundaries (white lines) are about 5km apart. Pre-stack depth migration courtesy of WesternGeco.

fragments (Figure 3). The fresh, unrounded glass shards indicate a significant volcanic airfall component that must have been only minimally reworked. Erosion due to the structural uplift has removed the top of the sand unit; the preserved thickness is 314 feet (96 meters) but the original thickness is unknown.

Figure 3. Photomicrograph of a typical Frio sand sidewall core from the AC 818 well within the hydrate interval. The sand is porous, poorly consolidated, and contains abundant volcanic glass shards. Courtesy Chevron.

The unconformity surface overlying the Frio sand has a four-way closure geometry (Figure 4) and is overlain by a Plio-Pleistocene section dominated by mudrock. Three of the components necessary for hydrocarbons to accumulate, reservoir, trap, and seal, are therefore present. The source of the methane forming the AC818 gas hydrate deposit has not been positively identified, but it seems likely that it is the accumulation of oil and gas discovered by the AC818 well in Eocene sands approximately 600 meters deeper. Seismic data indicates a network of small normal faults connecting the Eocene sands with the Frio reservoir; these faults could have acted as conduits for the methane. There are no obvious BSRs in this area so the base of the GHSZ is inferred by the upper most occurrences of "bright spots" caused by low velocity contrast due to (at least) a small amount of free gas trapped beneath the GHSZ. Gas charge is indicated on the seismic data by gas effects such as high amplitude bright spot events particularly concentrated at the crest of the anticline and additionally by absorption, or the loss of high frequency content, to the west of the structure.

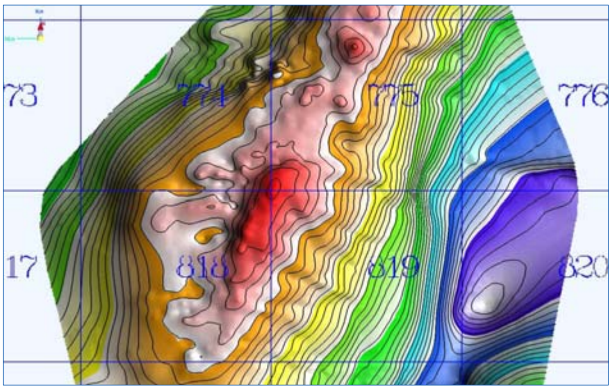

Figure 4. Structure contour map on the post-Oligocene unconformity. Contour interval is 200 feet (61 meters). Blue squares are 3 by 3 mile (4.8 by 4.8 km) OCS lease blocks. Courtesy Chevron.

Petrophysical properties

The petrophysical properties of the hydrate-bearing Frio sand will be discussed in a future publication and will be summarized briefly here. For purposes of understanding the seismic response, the relevant lithologies are the Plio-Pleistocene shale overlying the Frio sand, the hydrate-bearing portion of the Frio sand, and the underlying brine-saturated portion of the Frio sand. The Plio-Pleistocene shale unconformably overlying the Frio is a massive layer approximately 60 meters thick. Its petrophysical properties are not unusual for an unconsolidated mudrock. V_p is about 1800 m/s and V_s is about 565 m/s, giving a Poisson ratio of 0.44. Density is 1.87 g/cm^3.

The hydrate-bearing Frio sand is a high-impedance, low Poisson's ratio rock. V_p is about 2700 m/s and V_s averages 1200 m/s, giving a Poisson's ratio of 0.3. Density is 1.85-1.89g/cm^3, about the same as the overlying shale (Figure 5). The hydrate sand also has anomalously high resistivity, 20-40 ohm-m, compared to 1 ohm-m for the brine sand. The properties of the hydrate-saturated sand are quite different from the expected properties of a free gas-saturated sand of similar lithology. High resistivity would be expected in both cases, but compared to a brine sand a free gas sand would have lower density, much lower P-velocity, and about the same S-velocity. Compared to a brine sand, the gas hydrate-bearing sand has about the same density, and much higher P- and S-velocities.

The brine sand that constitutes most of the thickness of the Frio reservoir has very low

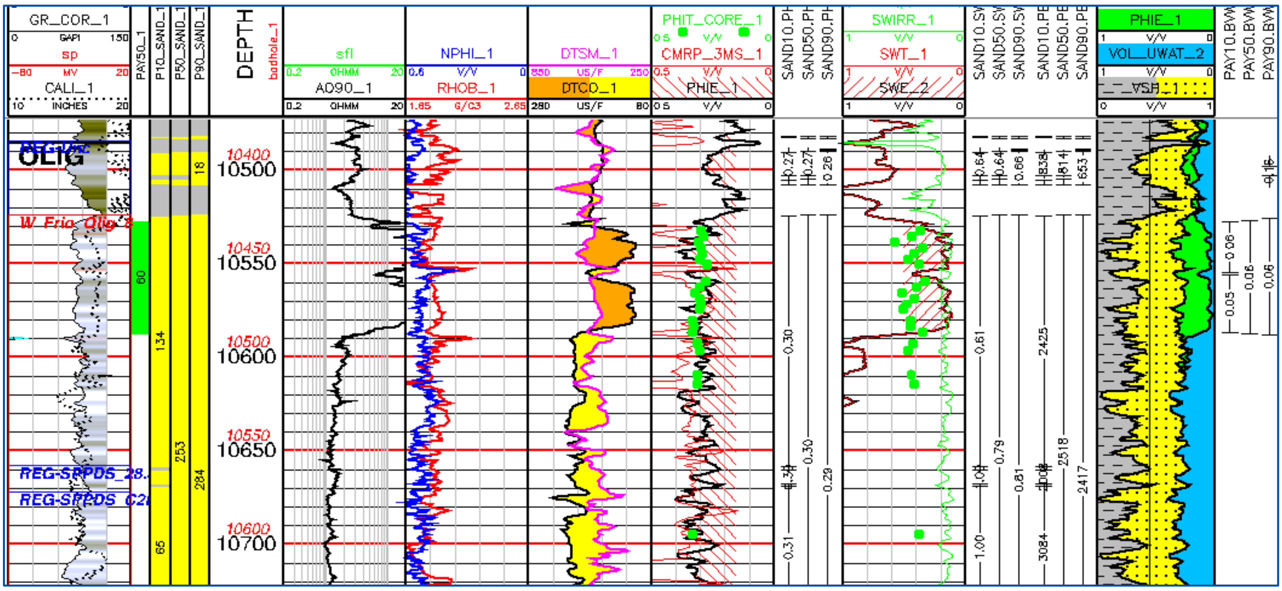

Figure 5: Log response of Frio sand. The full thickness of the sand extends below the bottom of the figure. Key curves shown are gamma (GR_COR_1), resistivity (sfl), neutron porosity (NPHI_1), bulk density (RHOB_1), shear velocity (DTSM_1), P-velocity (DTCO_1), and log porosity (PHIE_1). The colored track on the right indicates relative volumes of shale (gray), sand (yellow), hydrate-filled pore space (green), and brine-filled pore space (blue). The hydrate zone is characterized by high resistivity, and high velocity, but density is essentially the same as for the brine sand below.

impedance and high Poisson's ratio. V_p is about 1500-1700 m/s and V_s is about 500 m/s, giving a Poisson ratio of 0.4. Density is 1.87g/cm^3, essentially the same as the hydrate sand. The dominant pore fluid in the deeper part of the sand is brine, but the anomalously slow p-velocity, only slightly faster than seawater velocity, may indicate presence of low-saturation, or "fizz" gas. As will be described below, the low-saturation gas interpretation may be corroborated by the seismic response.

Modeled and observed seismic response

An elastic forward model of the seismic response to the shale – hydrate sand – brine sand section was constructed in order to aid in interpretation of the observed seismic response (Figure 6). The model used the compressional and shear sonic logs and the density log. Logs were blocked over the hydrate interval and kept at a uniform 2 millisecond sample rate elsewhere. Amplitudes were calculated using the Aki-Richards approximation [5]. The wavelet and CDP gather geometry used match those of the real seismic data.

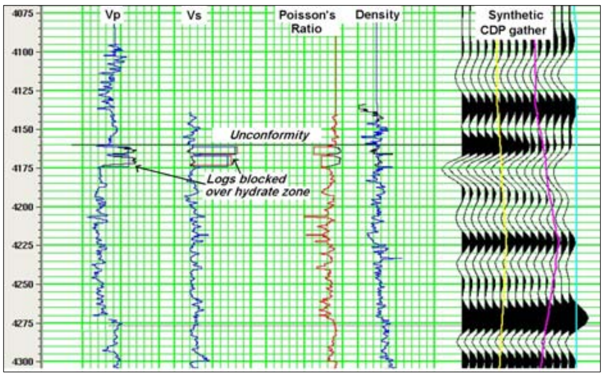

Figure 6. Elastic forward seismic model. Shown are compressional sonic (Vp), shear sonic (Vp), Poisson's ratio, density, and synthetic CDP gather. Courtesy Chevron

The shale over hydrate sand interface produces a strong peak with amplitude *decreasing* with offset and the hydrate sand over wet (fizz gas?) sand interface produces a very strong trough with amplitude *decreasing* with offset. The decrease of amplitude with offset is the opposite of what would be observed in the case of a free gas sand, and may be diagnostic of pore-filling hydrates in porous sands.

We also investigated an additional case, not illustrated here, of shale directly over the wet or low-saturation gas Frio sand with no intervening hydrate. In that case, the predicted response is a strong trough with amplitude *increasing* with offset, a response that is indistinguishable from free gas-saturated sand, a phenomenon all too well known by exploration geophysicists.

The real seismic response at the location of the AC818 well is, as predicted, a strong peak at the unconformity surface, representing the interface between Plio-Pleistocene shale and hydrate-filled Frio Sand (Figures 7 and 8). The peak is followed by an even stronger amplitude trough representing the hydrate-water interface, presumably at the base of the hydrate stability zone. Off the crest of the structure, the leading peak disappears and the signature becomes a strong trough alone. We interpret the trough-only response as Plio-Pleistocene shale directly overlying brine or low-saturation gas filled Frio sand, with gas hydrate either absent or thinned below seismic resolution.

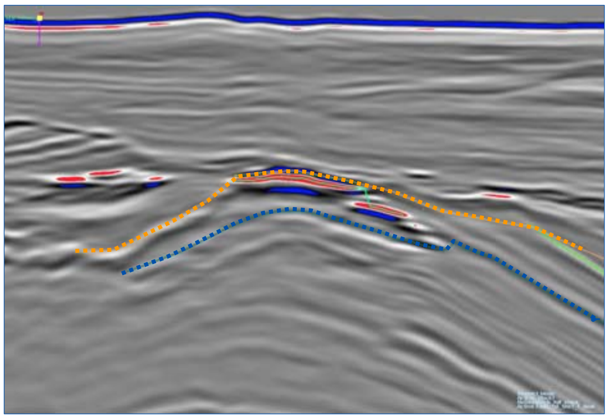

Figure 7: East-West seismic line through the AC 818 well location. High amplitude peaks are in blue and high amplitude troughs are in red. At the well location, the peak over trough signature is interpreted as representing hydrate over water. Courtesy WesternGeco

3-D Inversion

The 3D inversion using an integrated seismic characterization methodology described by Dai et al. [6] was used to estimate Saturation of Gas Hydrates (Sgh) from offset amplitudes in pre-stack

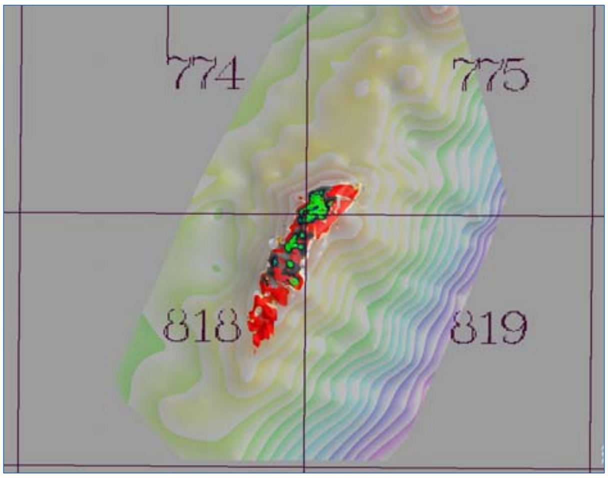

Figure 8: Map view of seismic amplitude overlaid on unconformity structure. Peaks are in green and troughs in red. The leading peak, representing the top of the hydrate, is present only at the crest of the structure. Courtesy Chevron.

3D seismic data. Initially the seismic data was carefully processed to maximize resolution and maintain offset amplitude fidelity. Inversion of the seismic data estimated P impedance (Figure 9), S impedance, and density by analyzing the wavelet

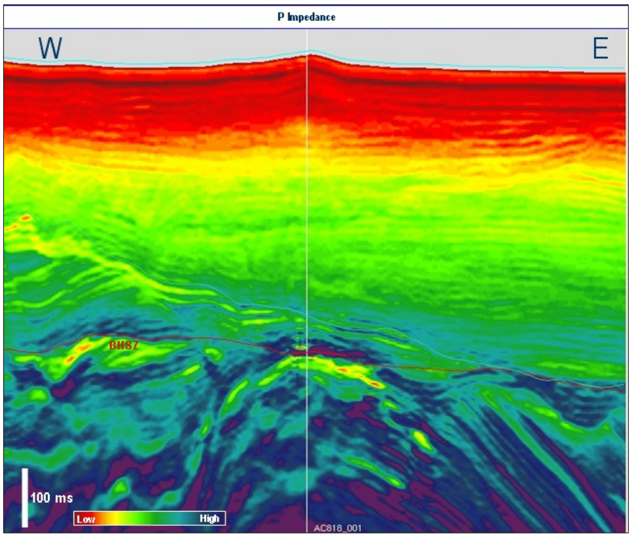

Figure 9: P impedance cross section through well AC818#1 (white line) of the inversion using pre-stack seismic data. Blue and purple colors denote high values. Note the high impedance above the base GHSZ (red line) encountered by the well. Courtesy Schlumberger - Reservoir Seismic Services.

and offset amplitude present in pre-stack seismic gathers. P velocity, S velocity, and density data from available well data are used to define a model for the in situ, hydrate free, lithology in terms of P impedance, S impedance and density. So that when the seismic inverted data is compared to the model, the amount of deviation from the model can be related to Sgh (Figure 10). It is important to

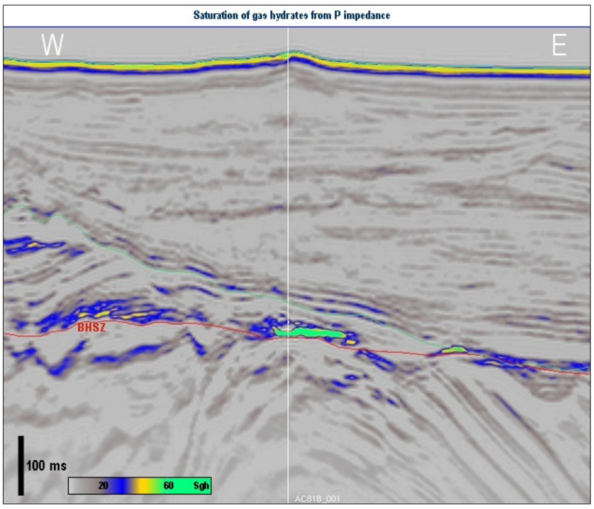

Figure 10: Cross section of saturation of gas hydrates (Sgh) derived from inversion of pre-stack seismic data. Green color shows high concentrations of gas hydrates at well location (white line) and correlates with well log data. Saturations are based on deviations from the model, which was designed with no gas hydrate layers. Courtesy Schlumberger – Reservoir Seismic Services.

note that the model did not contain hydrate layers and allowed the seismic data to independently show where the hydrates occur and to what relative quantity. Care must be taken with the results as lithologic changes can also cause elevated Sgh values, however this can be mitigated by carefully interpreting the data and reviewing the feasibility of the anomalies.

In AC818, the Sgh volume shows an extent of a highly saturated gas hydrate feature as being roughly 2 x 0.5 km in area and on trend with the Perdido 3b fold axis (Figure 11). Additional information on the inversion results can be found elsewhere in this volume [7]. This is interpreted as the area where the excellent reservoir of the Frio sandstone crests above the base GHSZ and is sourced with both gas and water to form the hydrates in high concentrations. Evidence of minor faulting, most likely due to expansion during

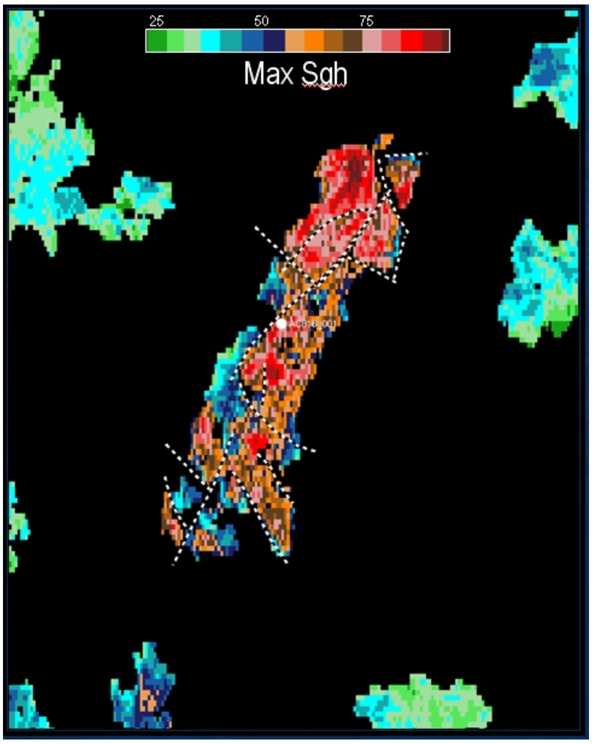

Figure 11: Map of anomalously high values of Saturation of gas hydrates (Sgh) derived from seismic data. Red color shows high concentrations with values greater than 75%. The well location (white dot) is roughly in the center of the approximately 2 x 0.5 km anomaly. Dashed white lines indicate minor faulting that may compartmentalize the reservoir. Courtesy Schlumberger – Reservoir Seismic Services

folding, is apparent. The seismic data indicates an even thicker Frio section, and gas hydrate layer to the north of the well location. The faulting also indicates the reservoir may be partially compartmentalized.

SUMMARY

We have described the geologic setting and geophysical expression of a gas hydrate occurrence in Oligocene Frio sandstone in Alaminos Canyon block 818. The Frio gas-hydrate reservoir lies along the crest of a 4-way closed structure, where it is partly eroded and unconformably overlain by 450 m (1500 feet) of Pleistocene shale and sand. The large velocity contrast between the gas-hydrate-bearing sands and the underlying water-wet Frio (with likely minor free gas saturation) creates a strong response in seismic data which was inverted into a 3D gas hydrates saturation (Sgh) volume. The seismic interpretation also identifies migration pathways, such as faults and gas chimneys, and the presence of available gas, which are necessary to charge reservoirs within the GHSZ.

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