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SEISMIC MAPPING OF GAS HYDRATE DEPOSITS IN THE KRISHNA-GODHAVARI BASIN OFFSHORE INDIA

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ABSTRACT

The India National Gas Hydrate Program (NGHP) Expedition 01 discovered gas hydrate deposits in numerous geologically complex areas in Indian Offshore. This study utilizes 3-D seismic data and seismic attribute analyses to delineate the gas hydrate occurrences in two distinct geologic settings in the Krishna-Godhavari (KG) Basin. Investigations at Site NGHP-01-10 showed a complex fractured reservoir with gas hydrate occurring in veins and fractures in fine grain mud. Seismic coherency analyses were used to delineate the special extent of the fractured gas hydrate occurrence and showed a strong linkage to a nearby north-trending fault system and an underlying conventional gas reservoir. Site NGHP-01-15, ~40 km north of Site NGHP-01-10, is instead dominated by conventional slope-related channel cut-and-fill sequences. A channel cutting through the sediments around Site NGHP-01-15 was identified, characterized by bright amplitude anomalies within the levee sequences (identified through seismic sweetness attribute).

Keywords: NGHP, 3-D seismic, coherency attributes, channels, fractured reservoirs

INTRODUCTION

During the India National Gas Hydrate Program (NGHP) Expedition 01 gas hydrate was discovered in numerous complex geologic settings along the eastern margin of India [1]. Pre-drilling seismic interpretation for site-selection and safety assessment was based on a widely-spaced grid of 2D lines in the Krishna-Godhavari (KG) basin. Within the KG Basin, a total of 12 Sites were visited (Sites NGHP-01-2, 3, 4, 5, 6, 10, 11, 12, 13, 14, 15, 21). In this study we utilize a 3-D seismic data set consisting of several vintages of smaller-scale 3-D data blocks acquired in the KG basin. The merged 3-D seismic data cover an area of over 1000 km^2. We selected two smaller areas for special analyses focusing on Sites NGHP-01-10 (including delineation Sites NGHP-01-12, -13, and -21) in the southern KG basin and Site NGHP-01-15 in the northern KG basin (Figure 1). Around each drill site, a sub-cube of 10 km by 10 km size

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was selected for detailed seismic attribute calculations.

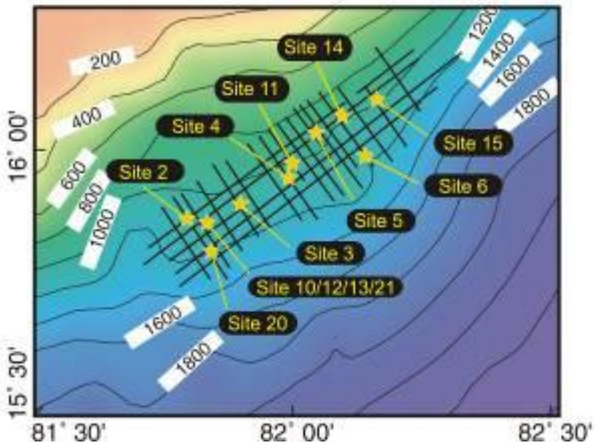

Figure 1: Map of drill sites in the KG basin on the eastern India Margin. This study uses 3-D seismic data around Sites NGHP-01-10 and NGHP-01-15.

mud [1]. Logging-while-Drilling (LWD) data showed numerous fractures dipping at various angles and orientations throughout the four drill sites in this area [2]. Similarly, X-ray images of pressure cores taken at these four sites showed gas hydrate occurring in many forms and sizes, and typically along fractures and veins [3]. Gas hydrates are present at Site 10 below a cover of a ~20 m thick debris flow unit. The top of gas hydrates is seen as a sharp increase in electrical resistivity in the LWD data. Seismic data acquired across the area through the four drill sites show a large-amplitude anomaly associated with a deep free-gas reservoir as well as a weak bottom simulating reflector (BSR) as shown in Figure 2. The seismic character around the four drill sites is dominated by chaotic reflections, typically a few hundred meters in length. Small-scale faults offset the reflection elements from each other and likely represent conduits for the migration of gas into the gas hydrate stability zone from below. This reflection character is different from most of the northern portion of the survey area, where seafloor-parallel reflections are dominant associated with mass-transport deposits (MTD). Four of these MTD units can be identified on the seismic section shown in Figure 2. The extent of the MTD units and the strong contrast with the chaotic reflections at Site NGHP-10 is well observed on time slices of the reflection amplitude through the 3-D seismic data (Figure 3).

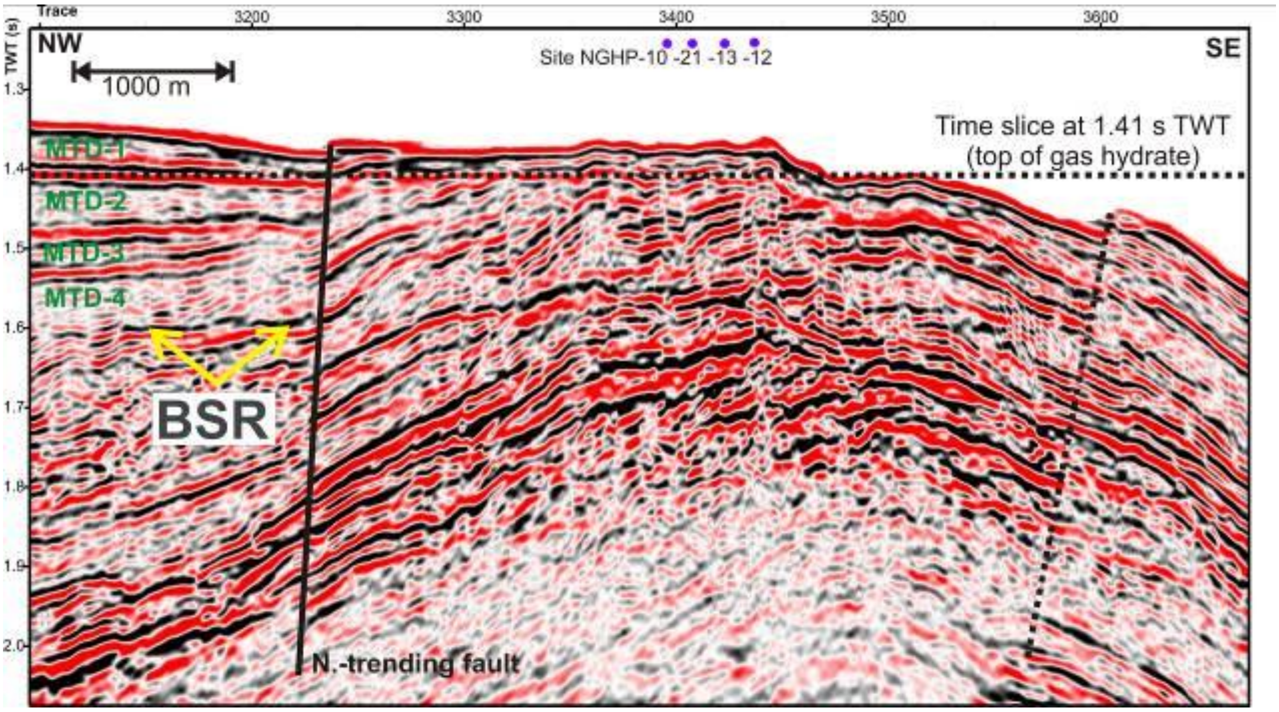

Figure 2: Seismic section (part of Inline 2342) from 3-D data block around Site NGHP-01-10 showing strong reflection amplitude associated with deeper free gas occurrence.

SITE NGHP-10: FRACTURED RESERVOIR

Site NGHP-01-10 (and delineation drill sites NGHP-01-12, -13, -21) showed the largest gas hydrate concentrations of all Sites visited during NGHP-Expedition 01. Massive gas hydrate pieces as well gas hydrate in fractures, small veins and fissures were recovered, embedded in fine-grained

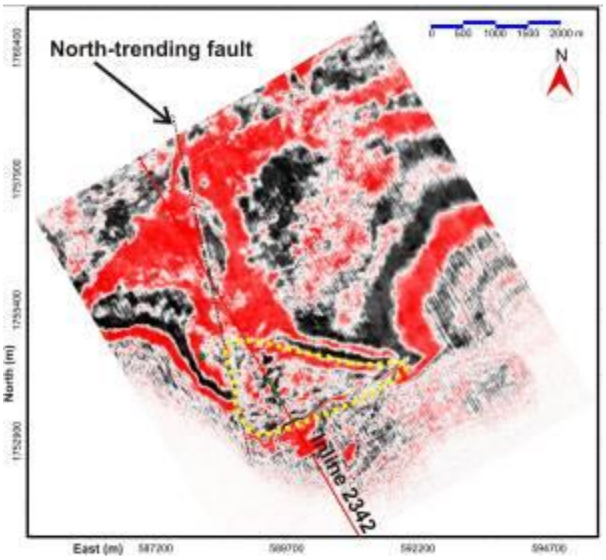

Figure 3: Time slice at 1.41 seconds (top of gas hydrates) of reflection amplitude (positive amplitude in red, negative amplitude in black). The outlined triangular-shaped area is dominated by chaotic reflections in contrast to the MTD units to the north.

In order to further characterize the nature of the fractured reservoir, we calculated seismic coherency from the reflection amplitude data [4]. Before attribute calculation, we conditioned the seismic data by applying a band pass filter with a maximum frequency of 100 Hz and performed f-x deconvolution to reduce some of the apparent foot-print of the seismic data seen as striations in the time-slices. The f-x deconvolution did not improve the data quality significantly and a foot-print is still present in the data. Therefore complete re-processing of the 3-D data from the pre-stack gathers will be performed at a later stage to ultimately improve image quality. However, seismic coherency images obtained so far already showed a distinct lateral confinement of the area of incoherent data, i.e. the area most affected by small scale fractures and faults (Figures 4, 5). The nature of the incoherent events in the seismic data is not yet fully understood. The incoherent events can either be interpreted as small-scale faults (red arrows in Figure 5), or they can be seen to form small-scale channel-like features of several hundred meter length (orange lines in Figure 5). Both interpretations are possible but more detailed seismic processing is required for a more sophisticated interpretation. The channels are a few tens of meters wide and up to 600 m long but do not form a coherent pattern.

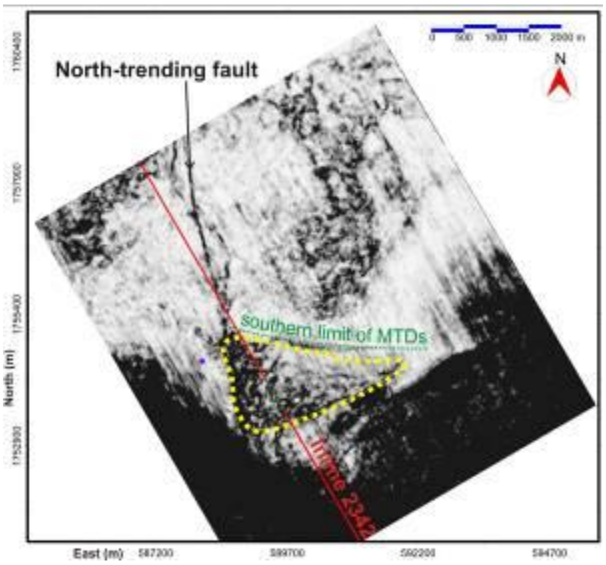

Figure 4: Time slice at 1.41 seconds (top of gas hydrates) of seismic coherency attribute through the 3-D seismic data block (black = incoherent, white = coherent) highlighting faults and fractures in the vicinity of Site NGHP-01-10. The outlined triangular-shaped area is characterized by many short-lived faults (see Figure 5 for detailed image) and is bound on the western edge by the large-scale north-trending fault.

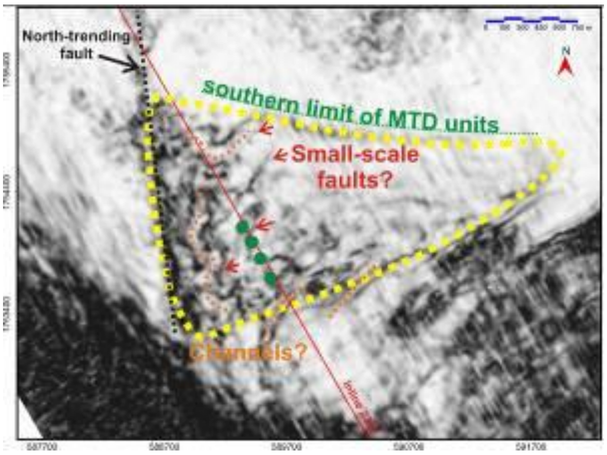

Figure 5: Detailed image of area with strong incoherency around Site NGHP-01-10. Several small-scale faults or short channel systems can be identified (see text for details). No dominant orientation of these faults or channels can be identified.

SITE NGHP-01-15: CHANNEL-SEQUENCES

Site NGHP-01-15 is located ~40 km North-East of Site NGHP-01-10 in the KG basin. The sediments cored at Site NGHP-01-15 were predominantly fine-grained mud with some silt and sand occurrences. Gas hydrate was found at this site only at 75 – 80 mbsf associated with a sandy formation. Chlorinity freshening, electrical resistivity and sonic log data suggest up to 50% gas hydrate saturation of the pore space within this unit [1]. The seismic data in the general area of Site NGHP-01-15 suggests deposition on a typical passive-margin slope where individual basins are separated by margin-parallel faulting creating step-wise drops in the seafloor bathymetry. This compartmentalization of the basins also results in a discontinuity of deeper depositional events that are cut by these faults (Figure 6). The BSR around Site NGHP-01-15 forms many bright-spots (Figure 6) and often it is only identifiable through the upward truncation of gas-brightened reflections.

The nature of some of the apparently random bright spots of the BSR can be better understood on a time slice of instantaneous amplitude or envelope (Figure 7).

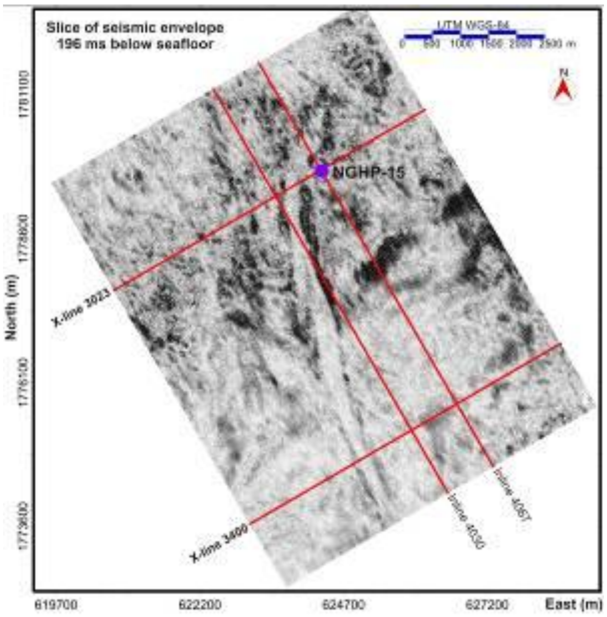

Figure 7: Time-slice (196 ms below seafloor) of instantaneous amplitude showing a channel cutting through the study area of Site NGHP-01-15.

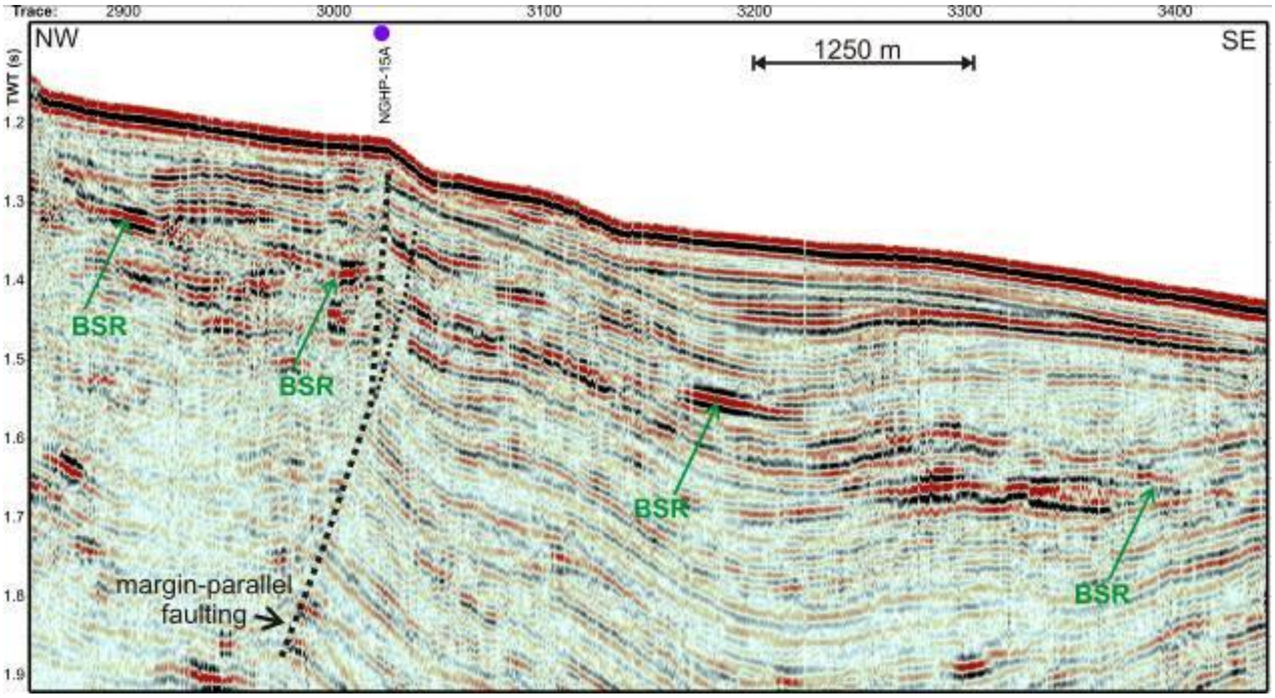

Figure 6: Example of seismic section along inline 4067 of the 3D seismic data block through site NGHP-01-15. The drill site is very close to one of the margin-parallel faults. The BSR forms several bright spots in this area.

Several of the BSR bright-spots seen on the seismic data (Figure 6 and 8) are along the rims of this channel, probably highlighting strata of the levee deposits that are coarser grained and host relatively more free gas below or gas hydrate above. The channel is imaged well seismically and can be easily picked up on crosslines through the 3D data block (e.g. Figure 9, 10) as discontinuous sequence cutting through the regular sediments.

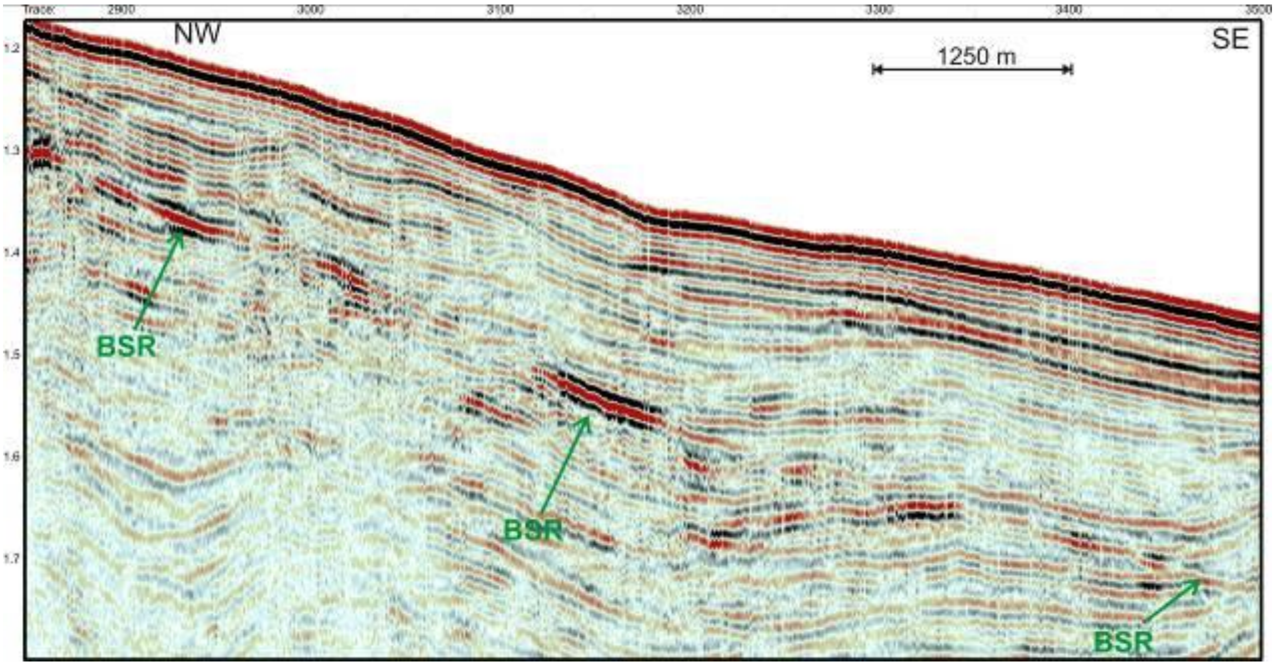

Figure 8: Seismic section of inline 4030 through the channel system, which is cut at an oblique angle by this seismic line. The two bright spots in the BSR are along the edges of the channel levee deposits.

The channel lies in the northern portion of the study area almost entirely below the gas hydrate stability field, especially near the drill site NGHP-15 (Figure 9). Further downslope to the south, the channel is well within the gas hydrate stability zone (Figure 10). At the drill site NGHP-01-15, gas hydrate was found within sands at 75-80 mbsf, which is above the identified level of the channel and potential sand-rich levee deposits. However, a nearby fault suggests that the seafloor around the drill site was uplifted by ~30 m (average change in seafloor bathymetry). If the fault is entirely post-depostional to the channel levee that additional depth added to the depth of the hydrate deposit projects the sand-rich and hydrate-bearing portion of the core well into the depth-range of the levee deposits associated with the channel system. The seismic character of the channel fills and levee-deposits was further analyzed using the seismic attribute sweetness, which is instantaneous amplitude divided by instantaneous frequency. Seismic sweetness is often used to identify shale sequences (low sweetness) in contrast to hydrocarbon-filled sand deposits (high sweetness). We have used this attribute for the area of Site NGHP-01-15 and generated a time slice parallel to the seafloor at the average channel depth (Figure 11). The channel fills are seen as low-sweetness areas (likely shale) and the sweetness decreases down-channel, suggesting a relative increase in finer-grained material. Further south along the channel, the seismic character of the channel fill has changed from chaotic to laminate.

Seismic coherency was used to define structural elements around Site NGHP-01-15 (Figure 12). Due to the original oblique angle of data acquisition of the seismic data around NGHP-01-15 and subsequent forcing into a rectangular grid rotated by ~40 degrees resulted in many trace-misalignments. These trace-misalignments result in large values of seismic incoherence making data interpretation of this type of attribute challenging. The mis-alignment is clearly seen on the time slice shown in Figure 12 as a spot-like striation of high incoherence. However, early analyses already hint at a very complicated and faulted nature of the sediments in the northern half of the sub data cube used around Site NGHP-01-15 (Figure 12). Gas hydrate bound to sand-rich strata is very unlikely to be within a well-established and laterally

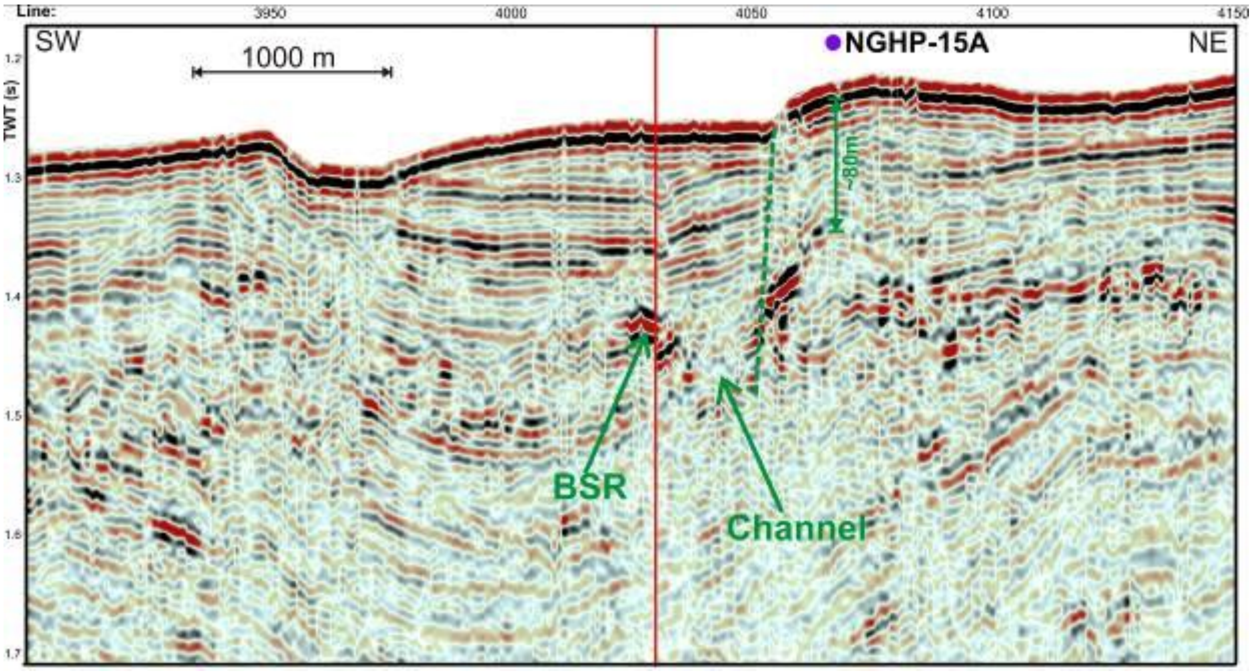

Figure 9: Seismic X-line 3023, showing the channel with edges enhanced in reflection amplitude at the BSR level. The nearby fault may have uplifted some of the hydrate-bearing sand-rich levee deposits, which were found at ~80 mbsf at Site NGHP-01-15.

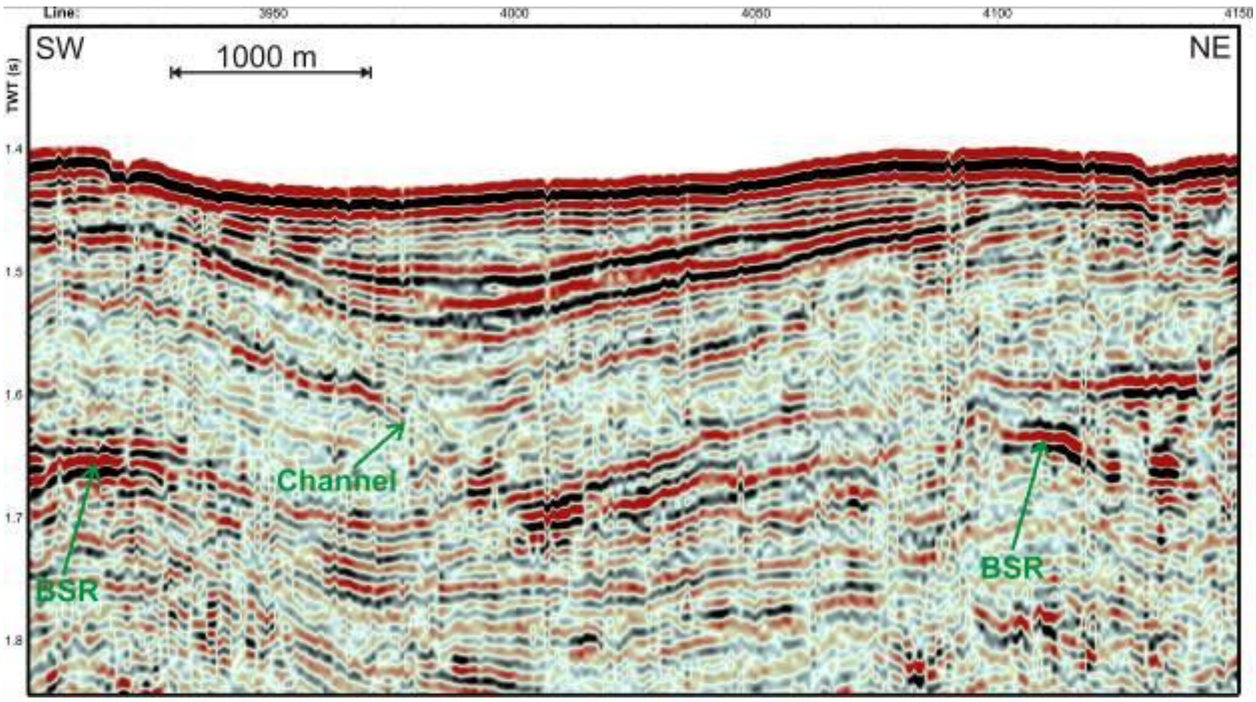

Figure 10: Seismic X-line 3400 showing the channel well within the gas hydrate stability field (BSR ~0.22 s TWT below seafloor). The seismic character of the channel fill indicates more lamination, compared to the more chaotic nature in the northern half.

coherent deposit around Site NGHP-01-15. Future re-processing of the data along the original orientation of data acquisition will be carried out, to obtain more reliable images of seismic coherency and allowing for more detailed interpretations.

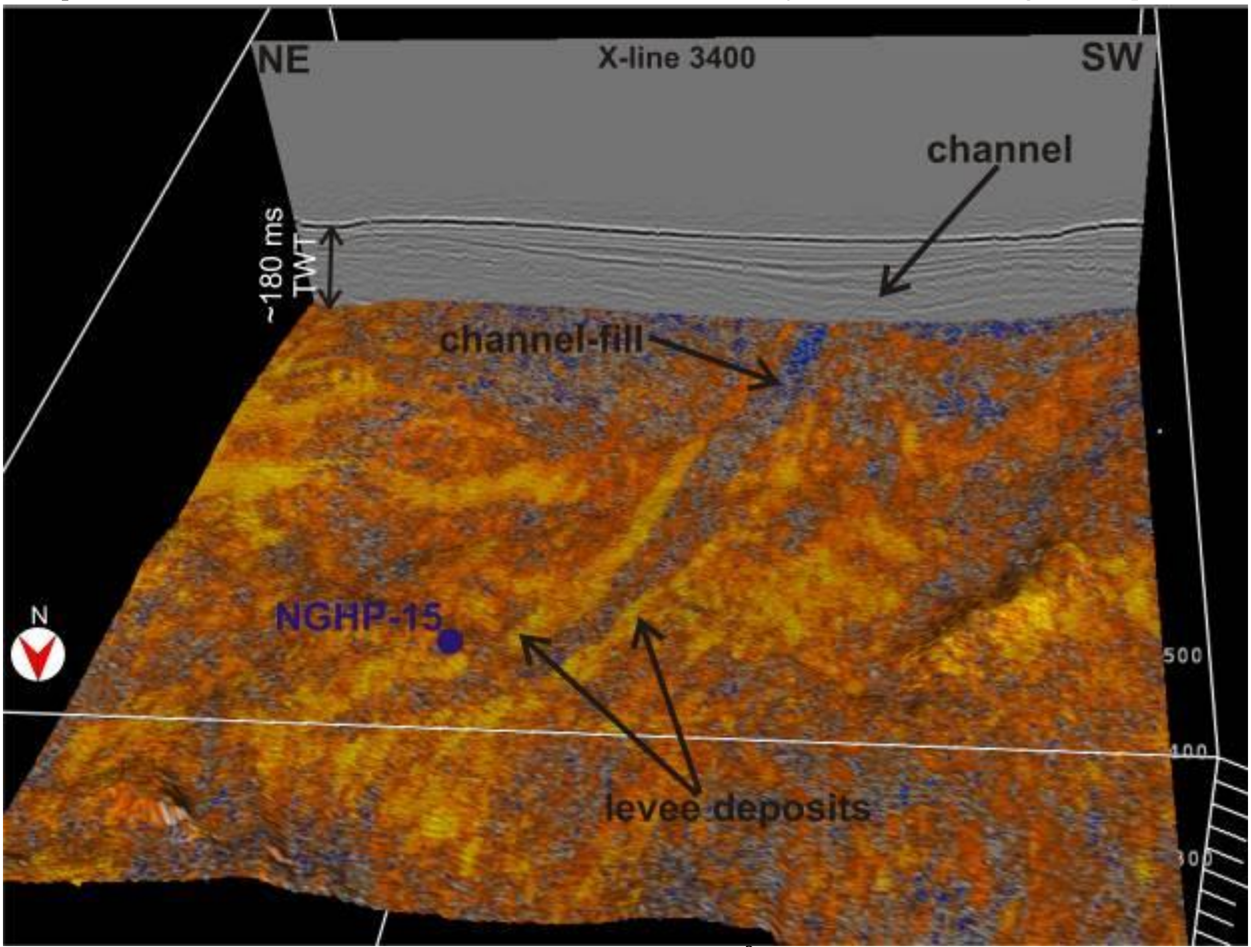

Figure 11: Image showing time slice of seismic attribute sweetness (~180 ms below seafloor along the channel depth) combined with seismic cross line 3399 (shown in Figure 10). High sweetness values are in yellow/orange, low sweetness values are in blue colors. The channel fill appears to gradually decrease in sweetness attribute, suggesting an increase in shale content.

CONCLUSIONS

3D seismic data across most of the KG basin was used to describe the depositional environment around the drill sites NGHP-01-10 and NGHP-01-15. Site NGHP-01-10 is a typical fractured reservoir with extremely large gas hydrate concentrations [1]. LWD and pressure core data show a complicated, chaotic network of gas-hydrate filled fractures of various sizes and dips. Seismically the zone around Site NGHP-01-10 (and delineation sites NGHP-01-12, -13, and -21) also shows high seismic incoherence. The top of the gas hydrate occurrence around these four sites is laterally confined to a triangular-shaped area of ~3km^2. Several faults or small-scale channel features oriented in many directions dominate this triangular-shaped zone confirming the observations made by the LWD data. Further statistical analyses of the fault orientation and comparisons to the LWD results will be performed in the future.

Site NGHP-01-15 in contrast is dominated by passive-margin type channel cut-and-fill deposits. A large channel has been identified cutting through regular deposits. The fill sequences appear shale-dominated, based on the seismic attribute sweetness, with the levee deposits being predominantly sand-rich. The channel edges are also seismically enhanced in their reflection amplitude, often marking the base of the gas hydrate stability field. Seismic coherency calculated for the same data show significant faulting in the northern half of the study area, especially around the drill site NGHP-01-15. Thus, gas hydrate that was seen bound to sand-rich strata is very unlikely to occur within a well-established and laterally coherent deposit around Site NGHP-01-15, but rather in patchy pockets.

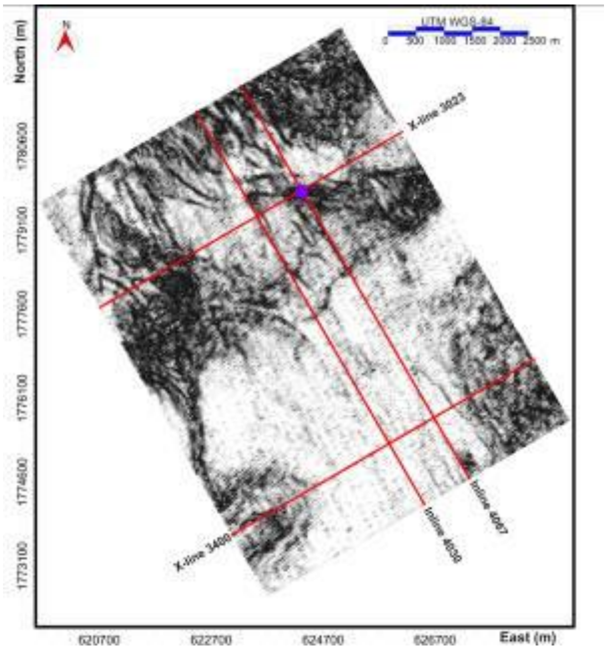

Figure 12: Time slice of seismic coherency at 50 ms TWT below seafloor showing faulting in northern half of survey area. The faulting provides a challenge to define a laterally continuous reservoir for gas hydrate to form.

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