Gas Hydrate Characterization from a 3D Seismic Dataset in the Eastern Deepwater Gulf of Mexico

D. McConnell (Fugro)

Introduction.

The presence of a gas hydrate petroleum system and seismic attributes derived from 3D seismic data are used for the identification and characterization of gas hydrate deposits in the deepwater eastern Gulf of Mexico. In the central deepwater Gulf of Mexico (GoM), logging while drilling (LWD) data provided insight to the amplitude response of gas hydrate saturation in sands, which could be used to characterize complex gas hydrate deposits in other sandy deposits. In this study, a large 3D seismic data set from equivalent and distal Plio-Pleistocene sandy channel deposits in the deepwater eastern Gulf of Mexico is screened for direct hydrocarbon indicators for gas hydrate saturated sands.

Insights from GC955 in the Gulf of Mexico.

Important gas hydrate exploration concepts were hypothesized, tested, and confirmed at GC955 in the Gulf of Mexico. A gas hydrate petroleum system requires gas migration into sediment with the appropriate pressure and temperature conditions, and for potential economic deposits, the gas must migrate into reservoirs into which gas hydrate can accumulate.

Furthermore it was suggested that:

- A BSR did not need to be present.
- A “leading peak” amplitude anomaly in a deepwater clastic sand could be a direct hydrocarbon indicator (DHI) for gas hydrate.
- Determining the presence or quantity of gas below gas hydrate would not be straightforward.

Rock physics models of for sand reservoirs with high saturation gas hydrate coupled over medium to low saturation gas, high saturation gas hydrate coupled over high saturation gas, and only high saturation gas hydrate with no gas beneath suggested that, for all cases, for exploration seismic frequencies, the gas hydrate would show as a “leading peak” and that it would be difficult to determine whether large amount of gas, a low to moderate amount of gas, or if no gas at all underlay the high saturation gas hydrate deposit (Figure 1).

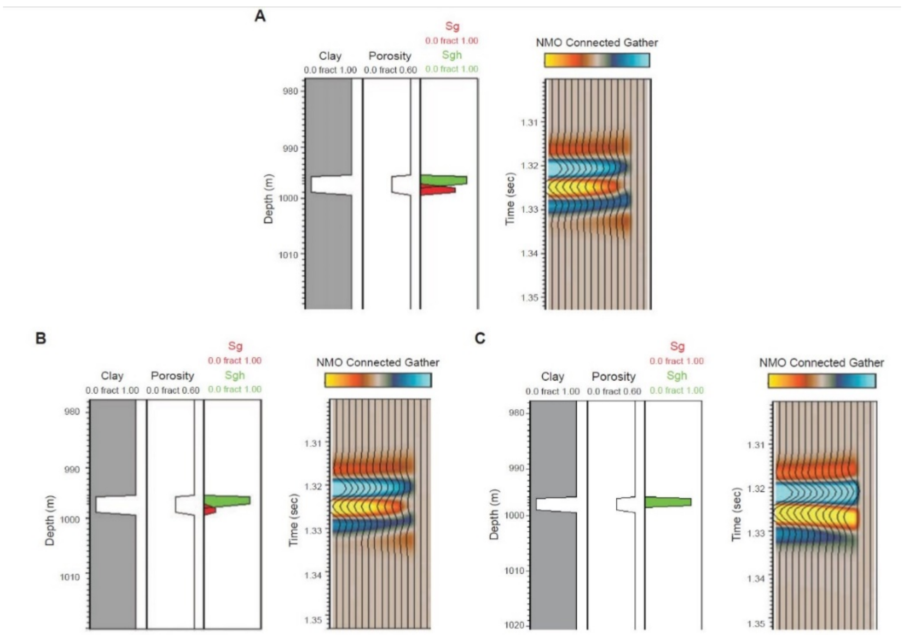

Figure 1. Synthetic gathers showing response of various concentrations of gas hydrate (green) over gas (red) as might be found at the base of gas hydrate stability (modified from Nur and Dvorkin, 2008).

These rock physics concepts, primarily, that in young clastic deepwater deposits a high saturation gas hydrate sand would show as a strong leading peak (in North American Polarity convention, an increase in impedance, positive, to the right) supported prospective gas hydrate deposits that were identified by LWD and later confirmed with core samples.

At GC955, extensional faults extending from a shallow salt body into the gas hydrate stability zone were interpreted to be conduits for fluids, including gas, to move through the shallow sediments. A small mud volcano and near seafloor faults suggested fluid flow from faults to the seabed. The gas hydrate petroleum system was first interpreted by the apparent dimming of gas bright spots along these faults that penetrated interpreted sandy channel sediments (Hutchinson et al., 2009).

The Chevron-DOE Gas Hydrate JIP Leg II field campaign confirmed the gas hydrate deposits by logging while drilling (LWD). The GC 955-H well targeted an anomalous seismic peak over strong trough in the interpreted sand facies. Seismic inversion analysis indicated high potential for gas hydrate of at least 50% saturation in an area at least 450 m by 850 m in size. (Hutchinson et al., 2009). The LWD drilling at the H location indicated approximately 30 m of up to 80% high saturation gas hydrate corresponding with the seismic target (McConnell et al, 2009). In 2017, a close twin to the H location (approximately 15 meters SW of the LWD hole) cored high saturation gas hydrate sands corresponding to the target (Flemings, 2017).

The results from gas hydrate exploration drilling at GC955 and elsewhere around the globe suggested that there is a linear relation between seismic amplitude and gas hydrate saturation, in contrast to gassy sediments where high amplitude is associated with gas presence but not saturation (Boswell et al., 2015).

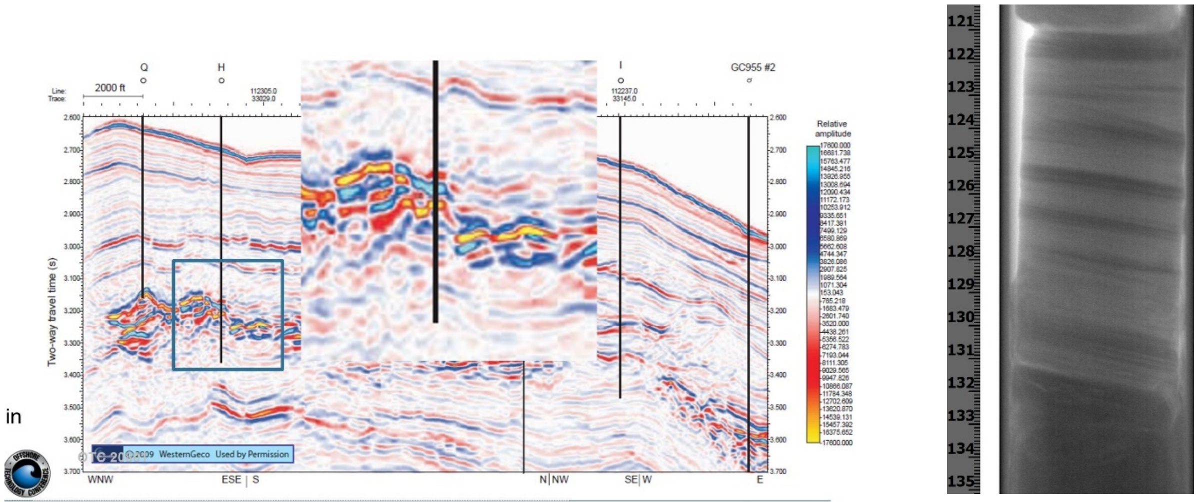

Figure 2. Seismic section showing the GC955 H gas hydrate target (with inset), left, and X-ray of gas hydrate bearing sands corresponding to a portion of the GC955 H seismic target, right Modified from McConnell et al. 2009 left, and Flemings 2017, right.

Available Data.

The data consist of a 3D prestack time migration cube, a prestack depth migration cube, and an interval velocity cube. No angle gathers were provided. The data were shot with 4200 m^3 airgun at a source depth of 7.5 m using 10 streamers of 9,000m length at a depth of 9 m, and a group interval of 12.5 m with separation of 120m between streamers. Processing included preprocessing statics correction and noise removal. A velocity model was built for a Kirchhoff TTI anisotropic depth migration with post processing before final output.

Geologic Setting in the Eastern Deepwater GoM

The Eastern Gulf of Mexico, here, refers to the area bounded on the west by approximately longitude 88.25 projecting south from where the modern distal Mississippi River discharge, on the north by the North American continental shelfs off Mississippi, Alabama, and Florida, to the east by the carbonate reef comprising the Florida escarpment, and the Yucatan shelf and the Straits of Florida to the south and southeast, respectively.

In contrast to the Western and Central regions, where the subsurface geology is strongly influenced by thick sediment loading onto Jurassic salt, the Eastern region is less characterized by salt tectonics and instead by simpler thick, up to 15 km, of Cenozoic sedimentation over Cretaceous sediments that were deposited over the rifted Jurassic section.

These thick clastic sediments were deposited in abyssal fans both mud and sand rich from the Eastern and Central Mississippi River Deltas. The MCAVLU (named for the Mississippi Canyon, Atwater Valley, and Lund protractions areas) is a sand rich Miocene submarine fan that deposited in the Eastern GoM. Late Pliocene slope bypass deposits were followed by thick sand rich Pleistocene Mississippi fan and Eastern Mississippi fan deposits. The modern deepwater Mississippi fan comprises the modern seafloor over the Eastern GoM. As a result, the Eastern GoM has an unusually thick section of sandy channel and potential sandy reservoirs.

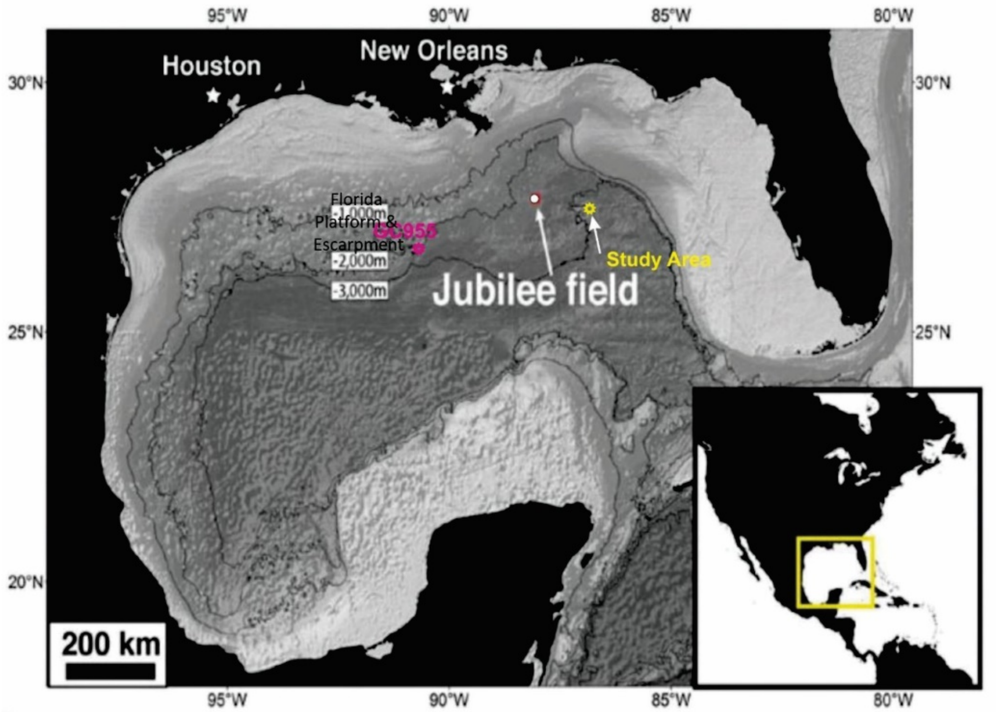

Figure 3. Location map showing the study area, Jubilee gas field, and GC 955 in the Gulf of Mexico

There has been no deepwater oil and gas exploration in the eastern GoM because of a long-standing oil and gas drilling moratorium. The nearest commercial oil and gas discovery to the study area is the Shell Jubilee Gas Field about 120 km to the west northwest where gas is being produced from upper Miocene high-density turbidites with a mass transport deposit top-seal. Sediments within the gas hydrate stability zone in the study area are similar in depositional style but are younger (Pleistocene). The nearest scientific drilling to the study area is at site 616 from ODP leg 96 where thick sandy facies were cored (Shipboard scientific party, 1986). Thick sequences of turbiditic frontal fan splays of the Mississippi channel and fan system are within the gas hydrate stability zone in the study area. The data show many meandering channels and channel lobes separated by mass transport complexes and inter-lobe clays. The thick Miocene to Pliocene channel fill in the deep eastern GoM basin has produced flat-lying sediments that have largely buried the deeper structures.

Whereas the central GoM has pervasive hydrocarbon migration structures caused by salt buoyancy displacing and piercing the sediments (elements that are present at the GC955 gas hydrate deposits), similar vertical fluid migrations structures are far fewer in the eastern GoM. A basin-ward arcuate north-south trending deep-seated fault trend is, however, in the western part of the 3D study area. These faults extend from basement through the Cretaceous and penetrate into the thick Neogene fan deposits providing a conduit for fluid and gas migration into sandy reservoirs at the base of the gas hydrate stability field. Locally focused high amplitude anomalies, both peak-dominant and trough-dominant, are coincident with these localized vertical migration conduits. The velocity cube used for the time and depth migrations indicates a vertical low velocity field associated with the interpreted conduits for vertical fluid and gas migration.

Gas Hydrate Petroleum System in the Eastern GoM.

The study contains the elements required for emplacing gas hydrates in sand- a migration path for gas and ample sands within the gas hydrate stability zone. The water depth is 3120 m at the study location and over the principal gas hydrate target. The base of gas hydrate stability at this water depth is controlled by the local geothermal gradient but could, in general, range from approximately 500 m to 1000 m below seafloor for methane for sediments in the GoM. Sandy sediments are interpreted within the gas hydrate stability zone. Time slices through the data reveal highly channelized Mississippi Fan sediments (Figure 4). Channels show a range of sinuosity. The smaller channels are approximately 0.5 km wide and 50m thick. The larger channels shown on Figure 4 are 1 to 1.5 km wide and are approximately 90m thick. Layers in the abyssal fan sediments are thinner than can be resolved with 50 Hz seismic and thus comprise composite thin-bed reflections.

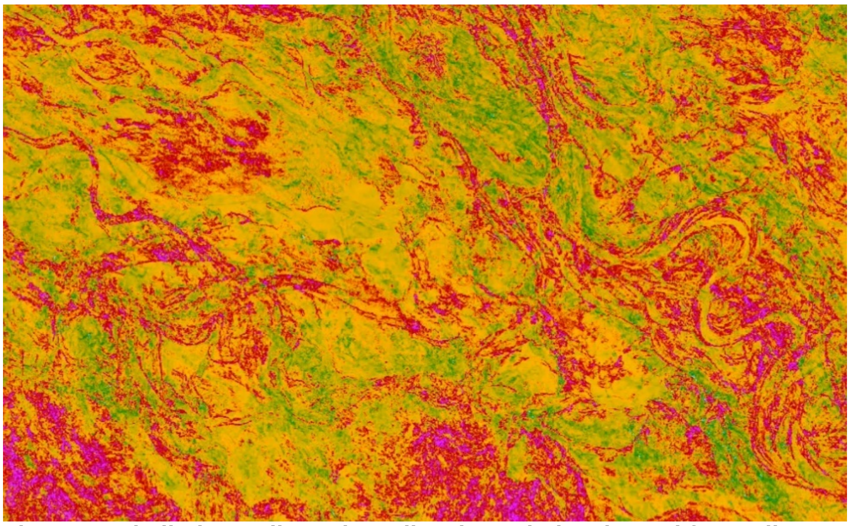

Figure 4. Similarity attribute time slice through the channel fan sediments containing the interpreted gas hydrate deposit. Channel dimensions range from 0.5 km to 1.5 km in width.

No bottom-simulating-reflector (BSR) is seen in the data, nor is there a BSR proxy such as an unambiguous depth to top-most free gas present (Figure 5a). A leading peak anomaly in channel deposits is underlain by interpreted gas where fluids have migrated along a (reactivated?) fault associated with the deep rifted structures in the basin. The seismic anomaly is suggestive of a gas hydrate filled sand (Figures 5a and 5b).

The topmost gassy sediments can be used to estimate geothermal gradients. In the study area, however, a geothermal measurement of 41 mW/m^2 or 36° C/km was taken approximately 40 km south of the gas hydrate target shown on Figures 5a and 5b. Gas hydrate stability calculations (CSMHYD software; Sloan, 1990) indicate that where the water depth is 3120 m, a geothermal gradient of 36° C/km produces a base of gas hydrate stability at 3630 m. Water temperature at the seafloor is assumed at 4° C. The gas hydrate target depth is 3630 m in the prestack depth migration volume and matches the phase boundary calculation.

Geophysical Indicators of Gas Hydrate.

Synthetic seismic wedge models at GC955 show that with 50Hz seismic data, a 40% saturation of a Plio-Pleistocene GoM sand in the hydrate stability zone with no subjacent gas can produce a phase change (negative to positive) with a strong correlation between amplitude and hydrate saturation. The synthetic seismic response is more complicated if the gas hydrate filled sediments overlie gassy sediments and hydrate (or gas) saturation in thin beds enhances the amplitude response (Zhang et al., 2012).

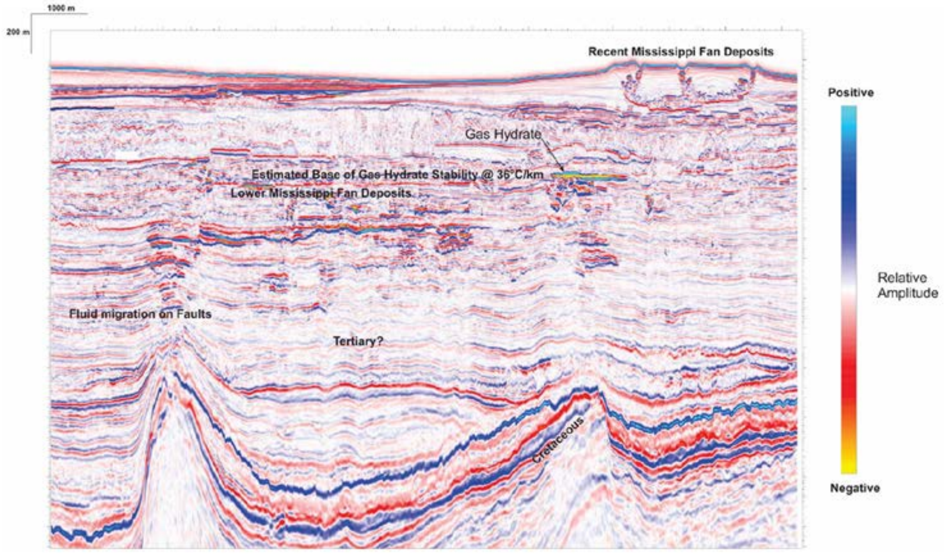

Figure 5a. Seismic section showing fluid migration pathways, and interpreted gas hydrate deposit in Lower Mississippi Fan deposits.

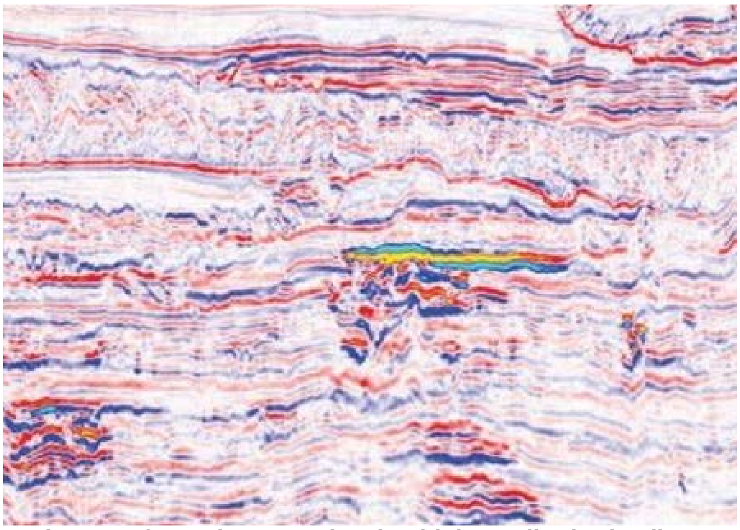

Figure 5b. Inset from Figure 5a showing high amplitude "leading peak" amplitude anomaly at interpreted gas hydrate deposit within Lower Mississippi Fan channel deposits. The "leading peak" DHI is the high amplitude showing as cyan over yellow in the center of the figure.

In the study area, with spectral decomposition, the gas hydrate (and gas deposits) are not seen at low frequencies. The gas hydrate (and gas) deposits begin to illuminate at 34Hz and are best illuminated at the higher frequencies 43Hz, 55Hz, and 70Hz with amplitude increasing in the target deposits in the higher frequency bands (Figure 6).

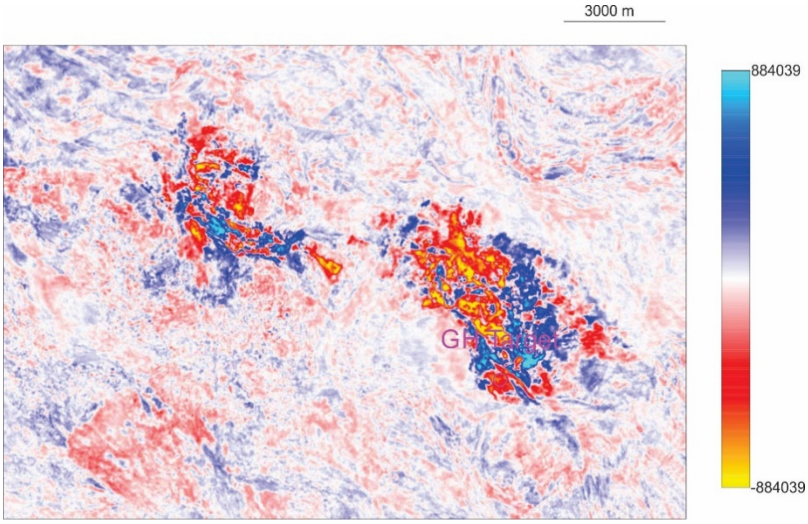

Figure 6. Time slice through interpreted gas hydrate deposits in 70Hz band spectrally decomposed data.

Gas hydrate deposits can be best distinguished from gassy sediments and non-hydrate bearing sediments by their high velocity. The high velocity of gas hydrate saturated sediments causes the diagnostic peak over trough response in a clastic deepwater sand in exploration seismic data when saturation exceeds 40% saturation. Velocities measured in high saturation gas hydrate sands are up to twice as fast as the as the non-hydrate bearing sands (Guerin and Goldberg, 2002; Lee, 2007; McConnell et al., 2009; among others). However, unlike the velocity profiles produced by Ojha and Sain, 2009, and others, where the gas hydrate stability zone can be characterized with high velocities, high velocities associated with a single loop reflector may not show in velocity profiles if gas hydrate deposits are not concentrated more widely within the gas hydrate stability zone. In the study area, no high velocity ledges are associated with the gas hydrate deposit. However, a low velocity column of 300m is apparent beneath the gas hydrate anomaly. This low velocity column is consistent with gas migration to the base of the gas hydrate stability zone.

Other seismic attributes besides seismic amplitude may prove to be useful (Taner and Sheriff, 1977) to indicate gas hydrate saturation. Shown in figures 6, 7, and 8 are three attributes: the 70 Hz amplitude- a wavelet attribute from spectral decomposition, the 2nd derivative of the envelope- a physical instantaneous attribute, and instantaneous Q, also a physical instantaneous attribute. The spectral decomposition attributes (Figure 6) should help determine deposit thickness and saturation. High spectral amplitude at high frequencies may correspond to multiple gas hydrate interfaces. Energy attributes such as envelope attributes are related to acoustic impedance, here shown was 2nd derivative of the envelope which corresponds to the all reflecting interfaces within the bandwidth and shows the sharpness of the envelope peak. This attribute can help determine edges and gas hydrate saturation distribution by imaging multiple hard interfaces found in gas hydrate deposits (Figure7). The instantaneous Q attribute is associated with attenuation. Attenuation is difficult to discern in post-stack data and the relative attenuation of gassy sediments and gas hydrate saturated sediments is not understood yet. Both gassy sediments and gas hydrate are expected to attenuate the propagating seismic energy (Guerin and Goldberg, 2002; Lee, 2007). The large area of low instantaneous Q can be related to attenuation in this setting (Figure 8).

Further work to help identify gas hydrate deposits will take advantage of the linear relationship of seismic amplitude and gas hydrate saturation in sand. Attributes from frequency cubes derived from spectral decomposition, energy, and attenuation attributes when combined with seismic inversion, AVO, and other amplitude attributes should aid in determining gas hydrate presence and saturation in deepwater sands.

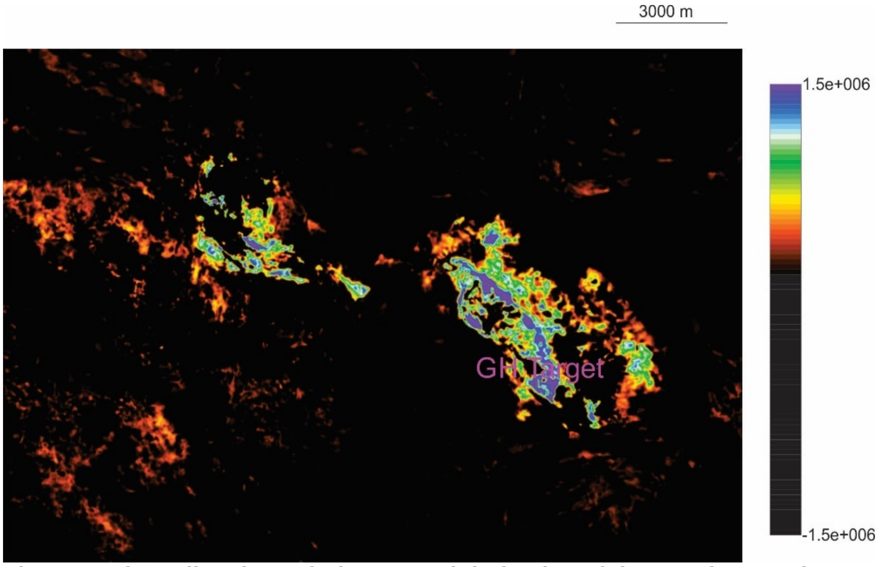

Figure 7. Time slice through the second derivative of the envelope at the interpreted gas hydrate deposit. High values can define extents and edges of gas hydrate deposits.

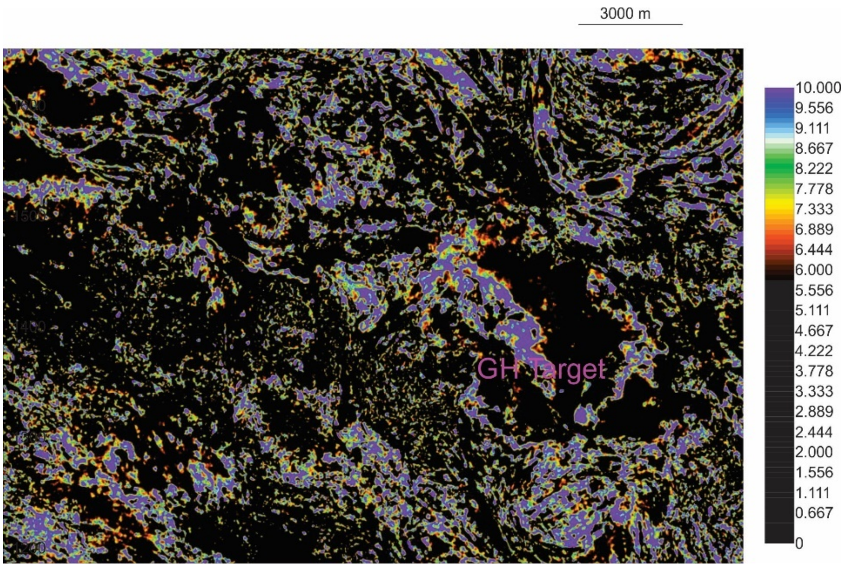

Figure 8. Time slice through the instantaneous Q attribute at the interpreted gas hydrate deposit. Low values are associated with energy attenuation.

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