Seismic amplitudes from gas hydrates

A real seismic-stack profile from an offshore hydrate reservoir is matched with a synthetic gather produced on a simplified earth model to determine hydrate presence.

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Gas hydrates are solids where gas molecules are locked inside cage-like structures of hydrogen-bonded water molecules. The physical properties of hydrates are remarkably close to those of pure ice: the compressional and shear (P and S) wave velocity in methane hydrate may reach 3.60 and 1.90 km/s, respectively, while its density is 0.910 g/cc. The corresponding values for ice are 3.89 and 1.97 km/s, and 0.917 g/cc, respectively. As a result, sediment with hydrate in the pore space, similar to frozen earth, is much more rigid than sediment filled solely by water.

However, unlike ice, methane hydrate can be ignited. A unit volume of hydrate releases about 160 unit volumes of methane (under normal conditions). Also, unlike ice, hydrate can exist at temperatures above 31°F (0°C), but not at room conditions — it requires high pore pressure to form and remain stable.

Such stability conditions are abundant on the Deep Shelf: high pressure is supported by the thick water column, while the temperature remains fairly low (but above 0°C) at depths of several hundred feet below the seafloor because temperature increase with depth starts at a low level, just a few degrees at the bottom of the ocean. Hydrates also exist onshore below the permafrost, which acts to lower temperature at depth where the hydrostatic pressure is already high. Needless to say, favorable pressure and temperature are necessary but not sufficient for hydrate generation. Its molecular components, water and gas, have to be available at the same place and time.

Once all these conditions are in place, the elevated rigidity of sediment with hydrate makes it discernable in a seismic reflection volume. Relatively high P-wave impedance of this sediment stands out in the low-impedance background of shallow and unconsolidated deposits. Its seismic response is a positive reflector which runs parallel to the seafloor, the so-called bottom-simulating reflector (BSR).

BSRs are abundant in the ocean. Dozens of research wells directly confirm that these reflectors are due to methane hydrate. Therefore, hydrates arguably form a gigantic pool of methane.

The implications for society are at least threefold: (1) a hydrate reservoir is a source of fuel; (2) variations in sea level and earth temperature may release methane from destabilized hydrate and vent it into the ocean and atmosphere, thus affecting the global climate; and (3) sediment with hydrate can become a geohazard if disturbed by engineering activity. These factors drive governmental and industrial interest in understanding and quantifying methane hydrate in earth, the latter mostly by means of geophysical remote sensing. Domestically, such interest is manifested by large funds provided by the US Department of Energy through its National Energy Technology Laboratory (NETL) Methane Hydrate program.

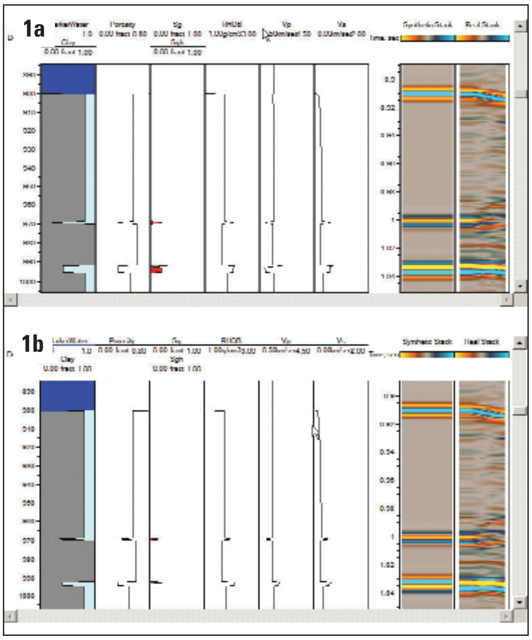

Figure 1. Each of the two frames contains a real stack (far right) at the Hydrate Ridge offshore Oregon. To the left of it is a synthetic stack produced by ray tracing. The elastic inputs (density and P- and S-wave velocity) are displayed in the third to sixth frames, respectively. They are computed from the clay content, porosity, and hydrate (green) and free gas (red) saturation displayed in the first three frames. In figure 1a, the three main seismic events matched at the sea bottom (the upper reflection), a thin free-gas layer (the middle reflection), and hydrate with underlying free gas layer (the lower reflection). Figure 1b shows the same model but without free gas beneath the hydrate. The frames are produced in iMOSS. (Images courtesy of Stanford University)

Hydrate quantification is, in principle, no different from traditional hydrocarbon reservoir characterization. Similar and well-developed remote sensing techniques can be used, seismic reflection profiling being dominant among them. Thus, the questions are: What properties and conditions of a methane hydrate reservoir and surrounding sediment can produce the observed seismic reflection? How to quantify seismic ampli-

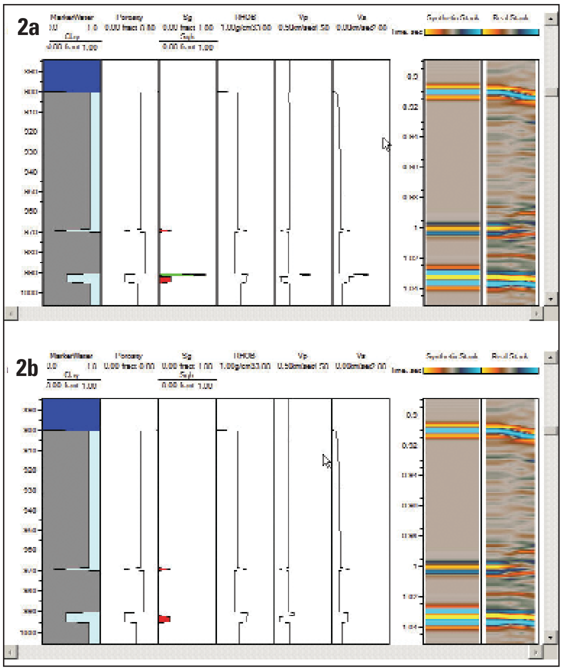

Figure 2. Same as Figure 1 but with a thicker hydrate layer with high hydrate saturation (2a) and without hydrate (2b).

tudes in terms of hydrate volume?

Seismic response of the subsurface is determined by the spatial distribution of the elastic properties. The elastic properties depend on porosity, lithology, texture and hydrate content. These two links connect seismic response to the reservoir properties and conditions, namely porosity and hydrate saturation. One approach to addressing the questions posed is: (a) create a geologically plausible earth model; (b) assign porosity, mineralogy and hydrate saturation to the layers in this model; (c) calculate the velocity and density from porosity, mineralogy and hydrate saturation; (d) generate synthetic seismic traces using these elastic parameters; and (e) match this synthetic seismogram to real data.

The key hypothesis that underpins this approach is that if synthetic traces match real traces, the properties and conditions in the subsurface used to produce the former are the same as the actual properties and conditions that produced the latter. The key element of this approach is relating porosity, mineralogy, stress and hydrate saturation to the elastic properties of the sediment. Rock physics delivers this element.

Rock physics and hydrate detection

A versatile software tool designed to implement this workflow is iMOSS provided by Rock Solid Images in Houston. Its arsenal contains essentially all available rock physics models combined with rigorous synthetic seismic generators. The motto of this tool is, "Model before interpret."

As an example, we attempt to match a real seismic-stack profile from an offshore hydrate reservoir with a synthetic gather produced on a simplified earth model. Drilling indicates that the actual reservoir contains small amounts of hydrate occupying pore space in sand embedded in unconsolidated shale. Free gas is possibly present directly below the hydrate.

First we construct a layered earth model with sea water and three sand bodies within a shale background. The porosity and mineralogy are assigned based on the well measurements from a location within the seismic stack. The user can vary the saturations of hydrate and free gas in the sand and calculate the corresponding elastic properties according to the rock physics transform, proven to work for several other hydrate reservoirs. Finally, a 1-D synthetic seismic stack is generated from this elastic profile. The sea-bottom reflection is used to calibrate the amplitudes of the synthetic and real stacks (Figure 1).

A satisfactory synthetic-to-real match at the dominant seismic events is achieved by placing a small amount of free gas in the first sand layer, a small amount of hydrate in the second layer and free gas in the third sand layer immediately underneath the hydrate (Figure 1a).

The next task is to explore the robustness and uniqueness of this interpretation by varying the hydrate and gas amounts. One hypothetical scenario is the absence of free gas below the hydrate. Figure 1b shows that free gas has to necessarily be present in the system because in its absence even a qualitative match between the synthetic and real stacks is impossible.

Let us then leave free gas in the model and explore the sensitivity of the amplitude to the quantity of methane hydrate by increasing it and also increasing the thickness of the host sand layer. Figure 2a indicates that the hydrate amount has to be small: setting its saturation at 80% makes the synthetic event discernibly different from the real one.

Finally, let's ask ourselves whether the real stack can be matched without any hydrate in the system. We compute the synthetic stack for the configuration used in Figure 2a and observe that it does not visibly change (Figure 2b). This result means that the presence of free gas is the feature that dominates the response. It also exposes the non-uniqueness of the seismic response to actual conditions in the subsurface. This non-uniqueness is not model-imposed but rather physics-imposed, which means that it is real and cannot be resolved mathematically.

A way out is by venturing beyond mathematical and physical modeling and considering geologic factors. For example, after obtaining these discouragingly non-unique results, one may wonder whether free gas can exist alone within the hydrate stability window. An answer is that it is not very likely because gas may escape if a seal naturally composed by the hydrate that plugs the pore space and strongly reduces the relative permeability to gas is absent. Geology and common sense have to necessarily complement any mathematical reservoir quantification.

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