Geophysical methods to quantify gas hydrates and free gas in the shallow subsurface: Review and Outlook

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Introduction

Gas hydrates and free gas linked to gas hydrate systems account for 500 to 12000 Gt of carbon – most likely around 3500 Gt (Buffett und Archer, 2004; Kvenvolden, 1993; Milkov und Sassen, 2002). Gas hydrate is an ice-like compound consisting of water-captured gas molecules. Predominantly, natural gas hydrate contains methane that is produced by biological degradation of organic matter. With sufficient water- and of free gas-supply gas hydrate forms in sediment basins all over the world. As gas hydrate is stable only at high pressure and low temperature it occurs at water depth of more than 300 m. The exact depth depends on bottom water temperature and other environmental circumstances such as pore water salinity and the precise composition of the captured gas. Within the sediment the depth of the gas hydrate stability field is further controlled by the geothermal gradient.

Because the amount of carbon stored in gas hydrate and associated with gas hydrate is so substantial gas hydrates are an important part of the Earth system. Gas hydrates have been discussed as a possible driver for climate variations and as an important control for submarine slope stability. Throughout the past two decades also their potential as a future energy resource has been seriously investigated. Countries like the US, Japan, Canada, Taiwan, South Korea, and China run major research programmes to evaluate ways of using gas hydrate as a new energy source and assess technologies for its exploitation. Determining the distribution and concentration of gas hydrate are fundamental requirements for using them as an energy resource.

The first objective of this paper is to review the different geophysical approaches that have been used and tested for gas hydrate mapping and quantification. The second objective is to assess these methods critically and attempt a prediction what current developments may mean for future field campaigns.

Rock physics background

Understanding which geophysical methods may work for quantification and mapping of gas hydrate requires a familiarity with the basic physical properties of sediments bearing a gas hydrate system. Chand et al. (2004) review the effect of gas hydrate on the elastic properties of sediments. Different effective medium theories are capable of reproducing the effects of gas hydrates on P- and S-wave velocity and attenuation to different degrees when compared to bore hole and laboratory measurements. As there are natural variations in the way that gas hydrates fill the pore space, i.e. cementing or not cementing, which depend on hydrate concentration and lithology this is a difficult problem to tackle. In the study of Chand et al. (2004) the best fit between theory and observations was obtained by using a self-consisting approximation/differential effective medium theory. Apart from increasing P-wave and to some extent S-wave velocity and lowering attenuation with increasing gas hydrate concentration, the presence of gas hydrate also has a strong effect on the bulk resistivity of hydrate bearing formations, because they replace electrically conductive pore water with non-conductive hydrate. This effect has been observed in bore holes (Lee und Collett, 2008) and can be used to quantify gas hydrate saturation.

Reflection seismology

Reflection seismology was the first geophysical method that was used to detect gas hydrate and in fact the basis for recognizing that gas hydrate actually exists in the sedimentary basins on continental margins (Shipley et al., 1979). Although the effect of gas hydrate on the acoustic impedance is not very different from naturally occurring velocity variations due to lithological variatons, the association of gas hydrate with free gas causes a conspicuous seismic reflection, called the bottom-simulating reflector (BSR). It is the result of the acoustic impedance contrast between gas hydrates at the base of the gas hydrate stability zone and free gas underneath. Although concentrations of gas hydrate and free gas are typically only 10% and 4% respectively, the free gas fraction causes a strong decrease of P-wave velocity of several hundreds of m/s. The resulting seismic reflector is one of the few seismic events that cross-cut primary stratigraphic reflectors (Berndt et al., 2004). It generally mimics the seafloor because it depends on the pressure and temperature conditions that control hydrate stability. Because it is easy to identify in standard reflection seismic data mapping the BSR is still an important method to determine the distribution of gas hydrate. With 3D reflection seismic data (Figure 1) becoming more readily available also to academic institutions (Planke et al., 2009) this method is widely employed.

However useful this method may be, it also has its shortcomings because it depends on the presence of free gas underneath gas hydrate accumulations, which is not always the case. Therefore, additional seismic constraints are required for a more detailed assessment of gas hydrate concentration and distribution. As discussed above both the elastic properties and the electrical properties of gas hydrate bearing sediment differ from sediment without gas hydrate. The effect of gas hydrate on the seismic velocity can be detected with surface-towed seismic streamers. In particular, using advanced inversion methods on long-offset data can produce a high-resolution, high-sensitivity velocity field for the top 500 m of sediments where gas hydrate is found. Delescluse et al. (2011) applied waveform tomography to a 12 km-long streamer data set from the Scotian Margin and were able to predict gas hydrate distribution also in areas with very weak BSR. Principally, this method could also be extended to modelling amplitude variations with offset to include the effects of P-S conversions, but this is notoriously marred by large uncertainties.

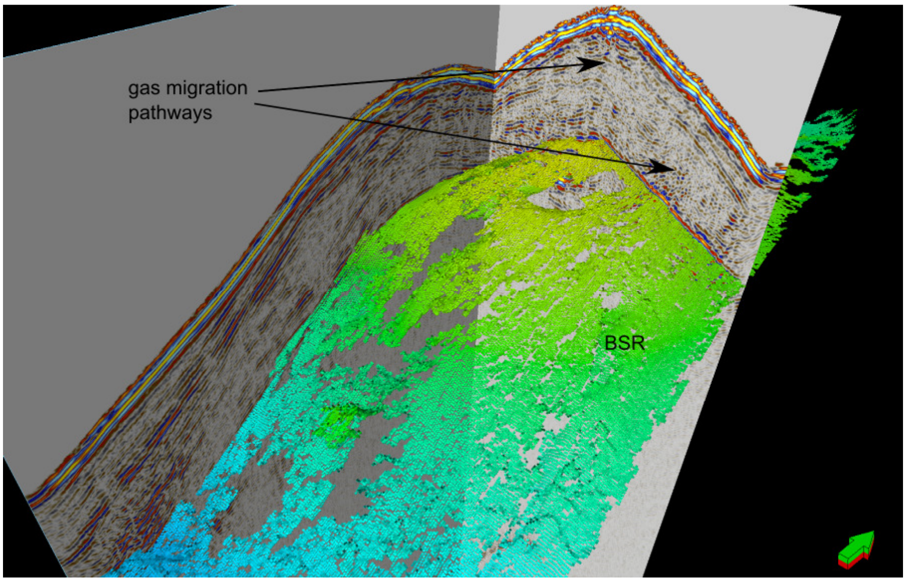

Figure 1 *P-Cable 3D seismic image of the gas hydrate stability zone at Hydrate Ridge, Oregon demonstrating imaging capabilities of modern reflection seismic technology.*

Ocean bottom seismometer experiments

In order to make full use of the independent information on hydrate concentration available from S-wave properties, it is necessary to record P-S converted wave arrivals. This can only be done at the sea floor. Two methods have been used in the past.

Ocean bottom seismometer recordings have been evaluated for 1D P- and S-wave velocity depth functions (Bünz und Mienert, 2004). Such experiments require high-resolution (200-300 Hz) seismic recordings in order to get meaningful information on gas hydrate concentration. Also, attempts have been made to combine a three-dimensional grid of ocean bottom seismometers to invert for a three-dimensional velocity depth field through tomographic methods (Carcione et al., 2005; Plaza-Faverola et al., 2011; Westbrook et al., 2008).

The second approach that has been taken is the use of ocean bottom cables. A single experiment has been carried out so far in a gas hydrate province (Bünz et al., 2005). It resulted in a very high-resolution 2 km-long two-dimensional P- and S-wave velocity transect and constitutes the so far most reliable hydrate concentration and distribution estimates from geophysical methods. Obviously, the use of ocean bottom cables is very resource demanding and therefore this method has not become common practice.

Controlled source electromagnetic experiments

Another way to determine gas and gas hydrate concentration that was pursued during the past decade is electromagnetic sounding. This method involves the deployment of electromagnetic receivers at the sea floor and towing of a powerful low-frequency antenna either on the seabed or just above in the water column. As electromagnetic soundings are very sensitive to the strong electrical resistivity anomalies caused by gas and gas hydrate this method should be a useful tool for gas hydrate quantification. It has been tried off Oregon (Weitemeyer et al., 2009) and off New Zealand (Schwalenberg et al., 2010) with some success resulting in series of 1D resistivity-depth functions. The challenge with these methods is to improve the spatial resolution and several research groups are working on joint inversion of seismic and electromagnetic data to make use of the high resolution of seismic data and the high sensitivity of the electromagnetic data to gas and gas hydrate concentration changes (Hu et al., 2009).

Integration of fluid flow modelling

The integration of seismic data with modelling fluid flow and gas hydrate formation can be a powerful tool to assess the spatial distribution and concentration of gas hydrate (Hornbach et al., in press). Here, fluid flow modelling predicts were gas hydrate should form. This is integrated with observed travel time to the BSR variations caused by the presence of various amounts of gas hydrate in the overlying sediments. Comparison of these predictions with measured gas hydrate concentrations in boreholes has shown that this method can produce reliable estimates of bulk gas hydrate occurrence.

Conclusions and outlook

Quantification and mapping of gas hydrate and shallow free gas become more important as several countries develop plans for using gas hydrate as a future energy source. Many different geophysical techniques are being used for gas hydrate and free gas quantification. The most promising results so far have been obtained with ocean bottom cables, but this method has not become a standard because it is costly. Alternative technologies were investigated and good results can be obtained with long-offset high-resolution reflection seismic data and waveform tomography. Also, controlled source electromagnetic data and ocean bottom seismometer data show promise, but each has its shortcomings, i.e. labour intensiveness and low-resolution respectively. Other methods for gas hydrate mapping and quantification include sea floor compliance to tidal forces and prediction of gas hydrate based on geochemical background information and distribution of gas seeps as they are imaged in the water column, but these are not commonly used. The combination of several methods such as geological modelling and seismic data evaluation or the joint inversion of seismic and electromagnetic data seems to be promising ways forward.

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