Technology Status Assessment: Geophysical Exploration Methods for Gas Hydrates

November 2006

Author:
John A. Dunbar
Baylor University
Department of Geology

DOE Award Number:
DE-FC26-06NT42959

Submitting Organization:
Baylor University
One bear Place 97354
Waco, Tx 76798

Acknowledgment: "This material is based upon work supported by the Department of Energy under Award Number DE-NT42959."

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List of Acronyms

3D	Three-dimensional
4D	Three-dimensional in space, plus time
AVO	Amplitude versus offset
BSR	Bottom simulating reflection
DC	Direct current
CSEM	Controlled source electromagnetic
DCR	Direct current resistivity
EM	Electromagnetic
MC118	Mississippi Canyon Block 118

Background: The path to commercial gas hydrate exploration

In a recent special issue of *The Leading Edge* dealing with gas hydrates, Johnson and Max (2006) reviewed the current status of potential gas hydrate exploration and production methods and outlined a path to commercial hydrate production. They identified seven remaining problems, the solution of which is essential to expanding industry interest in commercializing this resource. The first problem on their list, which they describe as the "Holy Grail" of commercial hydrate exploration, is developing geophysical methods that can accurately and consistently identify commercial gas hydrate deposits. The goal is not only to detect the presence of gas hydrates, but also to map concentration levels. Experience in the conventional petroleum industry shows that nothing enhances the economics of a prospect as much as having a reliable geophysical indication of a commercial deposit.

The main focus on developing geophysical methods for gas hydrate exploration has been on adapting conventional seismic methods used in the petroleum industry. This makes sense. The companies involved in petroleum exploration have considerable experience in seismic exploration and marine gas hydrates were first recognized by their association with bottom simulating reflections (BSR). However, there is a growing consensus that additional geophysical information in the form of sub-bottom electrical resistivity data is needed to confirm the presence and constrain the concentration of gas hydrates (Dillon et al., 1993; Hyndman and Dallimore, 2001). The question is: what kind of electrical method will be most applicable to future hydrate exploration needs?

It is likely that electrical methods for hydrate exploration will follow a highly accelerated development path similar to that followed by marine seismic methods over the last 40 years. During that time, few completely new methods were developed for marine seismic exploration. Instead, equipment and methods originally developed in academics for marine crustal studies and established land seismic methods were modified, scaled, and otherwise adapted to the marine exploration application. If the development history of marine seismic methods is any guide, elements of existing marine and land electrical methods that can be adapted to produce high spatial resolution, 3D sub-surface images, and 4D time-lapse images will be the elements that contribute to future hydrate exploration.

Technologies

Both seismic and electrical methods are currently being investigated as potential tools in gas hydrate exploration. Seismic methods would exploit contrasts in density and elastic moduli associated with the presence of gas hydrate within sediment pore spaces versus saline pore fluid or free methane gas (Chand, et al., 2004). Similarly, electrical methods would exploit contrasts in electrical conductivity or its inverse, resistivity. Gas hydrate, like pure water ice, is essentially an insulator, which contrasts sharply with saline pore fluids with resistivities on the order of 1 ohm-m or less.

In terms of gas hydrate exploration, seismic and electrical data are expected to be complementary, rather than in direct competition. Experiments under controlled conditions indicate a marked transition in both P- and S- wave velocity occurs at saturations levels as low as 3 to 5%, as the initial hydrate formation cements the sediment grains together and increases matrix stiffness (Priest et al., 2005). In contrast, the electrical resistivity of hydrate-bearing sediment is controlled by ion mobility and shows a gradual decrease with saturation, followed by more drastic changes as the saturation approaches 100% (Santamarina, et al., 2004). Hence, seismic methods may ultimately prove more sensitive to the presence of hydrate and therefore useful for hydrate detection and electrical methods may prove better for determining hydrate saturation and delineating sites of high hydrate saturation.

Benefits and Inadequacies of Current State-of-the-Art

BSR and AVO effects

BSRs are the most commonly used seismic indicator of marine gas hydrate deposits. They are particularly useful for defining the base of the hydrate stability zone. However, ODP results from the Blake Outer Ridge indicate that BSRs can occur at hydrate saturations as low as 3 to 6%. In other regions, such as the Gulf of Mexico, BSRs are largely absent or more subtle and hard to identify. In these cases augmentation with amplitude versus offset (AVO) analysis can make their identification more reliable (Carcione and Tinivella, 2000; Rajput et al., 2005). The limitation of BSR detection is that, while it may be an indicator of the presence of hydrate, it does not produce quantitative estimates of hydrate saturation within the stability zone.

Seismic velocity inversion

To gain information from seismic data about the distribution and saturation of gas hydrate it is necessary to determine sub-bottom seismic velocities. Biot-type models are then used to predict the relationship between the seismic velocities and the properties of the sediment matrix, gas hydrate and pore fluids. Two approaches have been used. Seismic inversion is based on finding reflection coefficient sequences that explain reflection amplitudes on near-vertical seismic traces and then inverting the reflection coefficient sequences to get seismic velocities (Zhang and McMechan, 2006). Because near-vertical traces are used, this method holds the promise of high spatial resolution, but at the expense of robustness. The alternate approach is reflection tomography, in which seismic travel times from a wide range of offsets are inverted to produce sub-bottom velocities (Bunz et al., 2005; Carcione et al., 2005). This is generally done using ocean bottom seismic receivers designed for crustal studies and surface towed seismic sources.

Controlled source electromagnetic profiling

The controlled source electromagnetic method (CSEM) uses low frequency radio waves (from less than 1 Hertz to several tens of Hertz) to probe the subsurface. CSEM sources generate carefully controlled, low-frequency electromagnetic (EM) signals. The receivers measure the amplitude and phase of those signals at different distances from the source. These data are inverted to determine sub-bottom variations in electrical conductivity or resistivity in a manor analogous to that used in reflection tomography. The equipment and methods used in marine CSEM studies were developed originally for academic crustal studies (Young and Cox, 1981; Chave and Cox, 1982; Evans et al., 1991; Nobes et al., 1992; Constable and Cox, 1996; MacGregor et al., 2001).

Edwards (1997) and Weitemeyer et al. (2006) described the use of the CSEM method for characterizing marine gas hydrate concentration. For hydrate investigations, CSEM systems, consisting of a single source and a series of receivers, have been linked in a linear array by a cable and towed along the bottom from a survey ship. Source-receiver offsets of only a few hundred meters are needed to characterize near-bottom hydrate concentrations. These studies show that resistivity profiling by bottom-towed instruments works in the deep-marine environment and that it provides data useful for detecting and constraining the concentration of gas hydrates. However, it is not clear that the EM approach will ultimately lead to resistivity profiling systems needed to support commercial exploitation of gas hydrates.

Why a New Approach is Required?

For both seismic and electrical methods, the equipment used to study gas hydrates to date was originally designed for lager-scale applications. In the case of CSEM, its principle advantage in marine applications over other electrical methods is that the source and receivers do not have to be in electrical contact. This allows more flexibility in source-receiver offset and makes the many kilometers of offset required for crustal studies logistically feasible. However, large offsets are not required in the gas hydrate problem, where objective depths are measured in hundreds of meters, as apposed to tens of kilometers. Hence, this flexibility is of no particular advantage.

The price paid for the flexibility of the CSEM method in source-receiver offset is complexity. Because the signals travel at the speed of light, the source and receivers must be synchronized to high precision to produce useful information. This is usually accomplished using atomic clocks in both source and receiver instruments. The fact that the roles of the source and receiver elements are fixed and cannot be interchanged in the EM method means that many more elements are needed to achieve the same spatial resolution and coverage compared to other electrical methods, such as direct current resistivity (DCR). At the same time, the individual EM elements are more complex and expensive than the simple electrodes used in the DCR method. Hence, extending current EM systems to achieve high-resolution, and 3D and 4D coverage would be more complex and expensive than would be the case using the DCR method.

Development Strategies

The goal of this project is to demonstrate the applicability of the DCR method to gas hydrate exploration. The DCR method is based on injecting DC current into the ground or seafloor and then measuring the resulting potential difference (voltage) between electrode pairs at different distances from the source electrodes. The beauty of the DCR method is its simplicity. A modern DCR system is little more than a computer controlled current source and digital voltmeter connected to an array of electrodes (Griffiths et al., 1990). Land DCR systems with 56 to 112 electrode arrays are widely used to collect 2D and 3D resistivity data in mining exploration for conductive metallic ores or non-conductive aggregates, in engineering studies to map depth to bedrock, determine ground electrical properties for grounding purposes, in hydrogeology to map conductive groundwater and to detect leaks in water reservoirs, and in environmental applications to monitor non-conductive contaminate spills (e.g. Draskivita and Simon, 1992; Maillol et al., 1999; Yaramanci, 2000; Giao et al., 2003; Chambers et al., 2004). There are likely several thousand land DCR systems in use around the world in such applications. Similar systems are available for continuous DCR profiling in shallow marine environments. Shallow marine DCR systems are equipped with electrode-array streamers that can be towed near the water surface, behind a survey vessels or laid on the water bottom in a few tens of meters of water depth. There are much fewer shallow marine systems in use, perhaps only 10 to 20 worldwide. They have been used to explore shallow coastal areas for placer mineral deposits (Wynn, 1988) and to map the fresh-water/saline-water interface is coastal bays and estuaries (Day-Lewis et al., 2006).

In each of these applications, the DCR method is preferred because the target materials are associated with electrical resistivities that are distinct from their host materials and lie at depths of only few tens or hundreds of meters below the surface. Marine gas hydrate exploration represents the same situation, since highly resistive hydrate-bearing sediments will stand out as resistivity highs in contrast to the surrounding sediments containing saline bore waters and the hydrate stability zone extends only a few hundred meters below the seafloor. The only difference in the gas hydrate application is that gas hydrate deposits are found in deep marine environments, which will necessitate placing the electrode array on the seafloor at depths of 1 km or more.

The strategy used for this demonstration project will be to repackage the electronic components of a commercial shallow marine DCR system in a pressure housing and couple it to a gel-filled electrode array, for use on the seafloor at a water depth of 1 km. The reuse of commercial components will keep the prototype development costs low. The prototype system will have 8 channels reading a 56-electrode, 880-m long array. A DCR system with these characteristics is expected to achieve penetration depths of 200 m sub-bottom, with a spatial resolution of 8 m. The prototype system will not be optimally configured for commercial exploration in terms of the number of channels and length of the receiver array. However, it will be of sufficient capability for an initial test of the use of the DCR method for the gas hydrate application.

The prototype seafloor DCR system will first be used to conduct a reconnaissance survey in an area of known seafloor gas hydrate occurrence in Mississippi Canyon Block 118 (MC 118). The goal of this survey is to demonstrate that the DCR method can be used to delineate regions of high hydrate concentration. This will simulate the use of the DCR method in continuous 2D or 3D profiling in gas hydrate exploration. Once this initial survey is complete, the system will be reconfigured and deployed for long-term monitoring at the site. The goal of this phase is to demonstrate the applicability of the DCR method to 4D operations that could be used in monitoring commercial hydrate production.

Problems to Address in this Research Project

The main problems addressed in this project will be in instrumentation and logistics. The project will involve reconfiguring a commercial DCR system designed for manual operation at the surface for both remote and autonomous operation on the deep seafloor.

Future development

Barriers to be Overcome

The penetration and spatial resolution of DCR systems is controlled by the length of the electrode array, the power of the current source, and the spacing of the electrodes along the array. The prototype system developed in this project will be based on an existing design intended for engineering applications. A system specifically designed for gas hydrate exploration would likely have an array that is two to three times longer (1760 to 2640 m), have two to three times more power (4 to 6 amp), and electrodes spaced half as far apart (8 m). The prototype system will read 8 channels simultaneously over a period of 4 s, requiring approximately 30 s to read the entire 56-electrode array. A system used in commercial hydrate exploration would require hundreds of channels to achieve practical data acquisition rates. Efficient 3D acquisition would require configurations with multiple electrode arrays towed in parallel. There are no recognized barriers to this development path. It is the same development path followed by marine reflection seismic systems over the last four decades.

Further development will also be required in DCR data processing to meet the needs of future gas hydrate exploration. A commercial-scale gas hydrate DCR system would generate massive amounts of data, which for optimum results, would require full 3D inversion. Currently available commercial DCR inversion software handles 2D profiles several kilometers in length and small 3D patches, but could not invert large 3D data sets. This is not a theoretical barrier, 3D inversion algorithms suitable for large data sets have been recently described (e.g. Pain et al., 2002; Marescot et al., 2006). There has been a lag by DCR firms in shifting to large-scale, cluster-based processing, as is used in the seismic industry. This is changing and within one to two years commercial, cluster-based software will be available for large-scale 3D DCR processing.

Potential Impact on gas hydrate exploration

The value of electrical methods in gas hydrate studies has already been shown with the CSEM method. The DCR method has the potential of providing comparable information and is more easily extendable to the form and scale needed for commercial gas hydrate exploration. If this potential is shown by the initial experiments in this project, the DCR method could fill a role in gas hydrate exploration comparable to that of the 3D seismic reflection method in conventional petroleum exploration.

Deliverables

This project will produce a prototype seafloor DCR resistivity system, a reconnaissance survey of the sub-bottom gas hydrate distribution to a depth of 200 m, over a 1 km^2 area centered on active methane vents in MC 118, and continuous monitoring results along one profile across the site for a period of one year. Although future DCR reconnaissance surveys for gas hydrates may require greater capabilities than the prototype DCR system, this system would be ideal for further long-term monitoring studies, either at the MC 118 site or elsewhere.

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