First results from a marine controlled-source electromagnetic survey to detect gas hydrates offshore Oregon

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1. Introduction

[2] Natural gas hydrates are a hazard to drilling, infrastructure, and slope stability; hydrates are also considered to play a significant role in global climate change and in the carbon cycle [Kvenvolden, 2000]. The large quantities of methane contained in hydrate found in marine and permafrost regions worldwide, estimated to be $10^{16}$ kg, has generated interest in gas hydrates as a future hydrocarbon resource [Buffett, 2000]. However, there is no reliable method for mapping and quantifying natural gas hydrates in situ. We explore the use of electromagnetic (EM) methods for this purpose.

[3] The common natural gas hydrate consists of a methane molecule encased by a water lattice. High pressures and cool temperatures are required for hydrate stability; at ocean depths greater than 300 m and temperatures around 0°C, methane concentrations in excess of solubility will cause the formation of methane hydrate [Kvenvolden, 2003]. Perturbations in pressure or temperature can cause the rapid release of methane from hydrate.

[4] Seismic methods are often used to detect hydrates; a bottom simulating reflector (BSR) sometimes marks the phase boundary of solid hydrate above and free gas below the BSR [Shipley et al., 1979]. The BSR depth is controlled by the intersection of the hydrate stability field with the local geothermal gradient. While seismic methods are often able to detect the lower stratigraphic bound of hydrate, the diffuse upper bound is not well imaged and there is no seismic reflectivity signature from within the hydrate region. Finally, there are cases where hydrates are known to exist, yet exhibit no BSR [Sloan, 1990].

[5] Other methods for hydrate detection include electrical resistivity measurements both from well logs and from controlled-source electromagnetic (CSEM) methods. Electrical resistivity logs indicate an increase in resistivity from zones containing hydrate when compared with water saturated zones [e.g., Collett and Ladd, 2000]. Although this effect can be modest, it provides a suitable EM target for the detection of hydrates. The EM response increases with an increase in hydrate volume fraction.

[6] The CSEM technique has been developed primarily from academic research [e.g., Chave et al., 1991]. The application for hydrate detection was first considered by Edwards [1997]; he modeled the transient electric dipole-dipole method as a means of estimating hydrate volume and argued for the usefulness of EM methods in augmenting seismic and drilling techniques. Field studies conducted at the Cascadia margin off the west coast of British Columbia [Yuan and Edwards, 2000; Schwalenberg et al., 2005] have demonstrated the merits of this technique by revealing the presence of hydrates when no BSR or other seismic signature exists.

[7] A pilot marine EM study at Hydrate Ridge, Oregon, was conducted in August 2004. The CSEM method we employed is a frequency domain technique described by Chave and Cox [1982] and Constable and Cox [1996], and has recently been extended to hydrocarbon exploration [e.g., Eidesmo et al., 2002]. A horizontal electric dipole source is towed on or close to the seafloor and receivers anchored on the seafloor record the transmitted fields at various ranges and frequencies. Extensive CSEM and magnetotelluric data were acquired for our study; here we present first results from one CSEM transect.

2. Hydrate Ridge

[8] Located 80 km off-shore from Newport, Oregon, Hydrate Ridge is situated on an accretionary ridge, part of the Cascadia subduction zone, and is in water depths of 820–1200 m (Figure 1). Hydrate Ridge has been extensively studied using seismic methods, by the Ocean Drilling
different hydrate proxies from well logs. Concentrations vary from 1% to 8% based on correlation of 2003, 2002. Along the northern flank of SHR the concentrations of hydrates. Generally, hydrates occur in lenses in a region from 45 mbsf to the BSR, at a depth of about 130 meters below seafloor (mbsf). ODP Leg 204 well logs place further constraints on the distribution and concentration of hydrates. Generally, hydrates occur in lenses in a region from 45 mbsf to the BSR, however at the summit of southern Hydrate Ridge (SHR) massive gas hydrate outcrops [Shipboard Scientific Party, 2003; Clague et al., 2001]. Along the northern flank of SHR the concentrations vary from 1% to 8% based on correlation of different hydrate proxies from well logs [Tréhu et al., 2004].

3. Experimental Methods and Data Analysis

Forward modeling studies using a 1-D layered code [Flosadóttir and Constable, 1996] reveal that the hydrate anomaly should exhibit the largest signal in radial mode (when source and receiver dipoles are in line) electric fields at high frequencies (>10 Hz). Fields at these high frequencies attenuate very quickly. To create a wide window of detectable ranges (200–2500 m) associated with the hydrate anomaly we transmitted a lower frequency square wave at 5 Hz and processed both the fundamental (5 Hz) and the first odd harmonic (15 Hz).

Twenty-five seafloor EM receivers [Constable et al., 1998] were placed in a linear west-east array at a 600 m instrument spacing across the northern flank of SHR (Figure 1). This array coincides with four ODP well logs (1244, 1245, 1246, 1252) and seismic line 230 [Tréhu and Bangs, 2001], which sample the ridge and the slope basin to the east. The CSEM transmissions were done using a 90 m antenna with dipole moment 1.15 kA·m. The transmitter was towed 100 m above the seafloor for 10 hours, equivalent to a 20 km line of data. Locations of receivers and transmitter were obtained using long baseline acoustic navigation.

Electric field time series from the receivers are Fourier transformed to the frequency domain within stack frames of 2 minutes and the results are merged with the navigated source–receiver offset. We calculate the major axis of the electromagnetic polarization ellipse (Pmax) for the horizontal electric fields because it is insensitive to receiver orientation and is less sensitive to transmitter orientation [Constable and Cox, 1996]. Figure 2 shows Pmax versus source-receiver offset for the receiver at site 5 (s5). The 5 Hz data are above the instrumental noise floor to a 2.5 km range and the 15 Hz data to a range of 1.5 km. The 5 Hz electric fields are stronger when the transmitter is 2 km west of the receiver, indicative of a resistive feature in the subsurface.

We convert the 5 Hz and 15 Hz electric field data at each receiver and each range into equivalent half-space resistivity using the 1-D layered code [Flosadóttir and Constable, 1996] and obtain values between 1 and 3 Ω-m, which are similar to the four ODP well logs (Figure 3e). To gain an understanding of the subsurface structure without involving the complication of a 2-D inversion we map resistivities to depths in a similar manner to the DC resistivity pseudosection, in essence creating a CSEM apparent resistivity pseudosection. We assume that the resistivities at each range can be mapped into an equivalent depth by means of a common midpoint between the receiver and the transmitter projected at a 45 degree angle from the seabed. This method, while limited, does provide insight into the lateral heterogeneity in the data. However, unlike DC resistivity the depth is not purely geometric.

4. Results

Reciprocity between transmitter and receiver creates a two fold redundancy in the pseudosection from east-side and west-side transmission data. The east-side and west-side transmission data sets are compatible, so we averaged them using a regularized contouring algorithm to obtain a 2-D map of apparent resistivity. The 15 Hz and 5 Hz pseudosections are shown in Figures 3a and 3b. The 15 Hz data are sensitive to shallower sediment than the 5 Hz data. This is reflected by a general agreement of the 15 Hz pseudosection with the shallow part of the 5 Hz pseudosection.

Figure 2. Major axis of the electromagnetic polarization ellipse (Pmax) versus range for site 5 at 5 Hz and 15 Hz.
The pseudosections exhibit significant lateral variations in resistivity. The basin to the east (s18–s25) is more conductive than the ridge (s4–s17), consistent with estimates of higher concentrations of hydrates at the ridge and lesser concentrations of hydrate in the basin [Tréhu et al., 2004]. Below s16 and s17 there is a resistive feature in the 5 Hz data associated with the anticline and possibly reflecting a change in lithologic composition. This feature is barely seen in the 15 Hz data which suggests that it is deeper. The high resistivity seen in the 5 Hz data below s8–s15 could be associated with seismic horizons B and B’, which consist of highly resistive layers as indicated in the logging while drilling data at ODP 1246 (Figure 3e) [Shipboard Scientific Party, 2003]. The largest CSEM resistivities are along the western end of the profile (GH in Figure 3d), consistent with the inference of high hydrate and free gas saturations from seismic velocity inversions [Zhang and McMechan, 2003].

To convert apparent resistivities into an approximate hydrate concentration we follow Collett and Ladd [2000] and ODP Leg 204 Initial Reports [Tréhu et al., 2003] for the calculation of hydrate saturations using the Archie equation:

\[ S_w = \frac{a R_w / \phi^m R_t}{n} \]

Here, \( S_w \) is water saturation; \( R_w \) is resistivity of the formation water (equivalent to seawater = 0.33 \( \Omega \)-m); \( R_t \) is formation resistivity taken from the CSEM pseudo-section; \( \phi \) is porosity of the sediments taken as the average value of 65% for the gas hydrate stability zone [Tréhu et al., 2003, 2004]. The constants \( a \), \( m \) and \( n \) are empirical parameters in Archie’s equation and are given as...
a = 1, m = 2.8, n = 1.9 [Tréhu et al., 2003]. A hydrate saturation is calculated using $S_h = 1 - S_w$. The resulting concentration (Figure 3a) ranges from 0–30%. Our calculations indicate the eastern basin has 0% hydrate concentration at the surface and increased concentration at depth, consistent with reported higher concentrations of hydrates just above the BSR [Shipboard Scientific Party, 2003]. On the ridge we obtain concentrations of 10%–15%, similar to 8% previously estimated [Tréhu et al., 2004]. West of the ridge we obtain concentrations of 30%, a high value which could be the result of a mixture of hydrate and free gas. In general, hydrate concentrations calculated from pseudosections show consistency with those calculated from ODP well logs of 0–30% [Tréhu et al., 2003]. However, EM derived concentrations are subject to any inaccuracies in Archie’s equation and to our assumption of uniform values of $\phi$, $m$, $n$, $a$, and $R_o$ for the region.

[18] The basin structure appears to be one dimensional, so smooth 1-D inversions [Flosdóttir and Constable, 1996] of the data between s22 and s23 were carried out (Figure 3c). The transition from 1 to 2 $\Omega$-m occurs at about 300 m depth in the 15 Hz inversion, and about 500 m in the 5 Hz inversion, providing some control on the depths of the corresponding features in the pseudosection projections. Similar inversions between s9 and s10 near ODP 1246 indicate higher resistivities at the ridge, but are probably not reliable for depth control because this region appears less 1-D in the pseudosections.

5. Conclusions

[19] Analysis of a new, comprehensive data set demonstrates the utility of the CSEM method for hydrate mapping. CSEM provides a more direct measure of bulk hydrate concentration than is possible with seismic reflectivity. The method estimates concentration in situ, in contrast to drilling, where sediments are altered and disturbed. The pseudosection approach developed for DC resistivity is a linear and tightly spaced group of seafloor EM receivers.


References


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