Mapping Gas Hydrate using Electromagnetic Methods

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- Sponsored by Statoil
- Sponsored by Paradigm
- Scripps Institution of Oceanography, Seafloor Electromagnetic Methods Consortium
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GLOBAL BUSINESS

An Energy Coup for Japan: ‘Flammable Ice’

By HIROKO TABUCHI  MARCH 12, 2013

TOKYO — Japan said Tuesday that it had extracted gas from offshore deposits of methane hydrate — sometimes called “flammable ice” — a breakthrough that officials hope will help the country reduce its dependence on imports of costly liquefied natural gas.

Gas flames being expelled from a burner in a deep-sea drilling vessel in the Pacific off Japan. Jogmec, via European Pressphoto Agency
Hydrate: the What, the Where, and the Why
Laboratory studies of hydrate electrical conductivity
Marine EM methods
Hydrate Ridge experiment
The Vulcans
2015 San Diego Trough tests
Concluding remarks
Where:
Why:

It is a hazard to drilling and infrastructure
It is viewed by some as a potential energy source
Methane release may play a role in climate change
Is a significant part of the global carbon cycle
Hydrate may play a role in marine CO2 sequestration
It can confound interpretation of marine EM for exploration
There is a lot of it
A lot, but, global volume is highly uncertain:

First Observations of Gas Hydrate in the Marine Environment

Boswell and Collett, 2011, and Milkov 2004
The hydrate resource pyramid.

Boswell and Collett, 2011
Quantification of hydrate volume using seismic methods is difficult.

BSR shows free gas at edge of stability field but provides no indication of hydrate above.

Blanking zones, show hydrate or gas near the seafloor but little below.

Ken Sleeper
The BSR reflection is associated with small amounts of free gas - similar to the “fizz-gas” problem in hydrocarbon exploration.
Hydrate is electrically resistive, and so is a target for electromagnetic methods.

On the resource evaluation of marine gas hydrate deposits using sea-floor transient electric dipole-dipole methods

R. Nigel Edwards*

Logs from Walker Ridge 313-H, from Boswell et al.,
Fire In the Ice Summer 2009
Hydrate/gas concentrations have to be high to generate an electrical signature - EM is a good tool to find the top of the pyramid.
Laboratory studies of hydrate conductivity
Apparatus to synthesize methane hydrate in a conductivity cell.
Synthesis of Methane Hydrate:

\[
\text{CH}_4 \cdot n\text{H}_2\text{O} + \text{CH}_4 \text{ (g)}
\]

Cryo-SEM is used to assess grain characteristics and phase distribution.

100 vol% CH₄ hydrate

50 vol% CH₄ hydrate: 50 vol% Sand

50 vol% CH₄ hydrate: 50 vol% glass beads

100 vol% CH₄ Hydrate

50 vol% ice: 50 vol% sand

10 vol% ice: 90 vol% sand

Du Frane et al., 2015
Impedance spectroscopy and equivalent circuit models allow removal of electrode effects:

Du Frane et al., 2011
Pure hydrate conductivity is 3-4 times lower than ice and well fit by Arrhenius model.

\[ \sigma = \sigma_o e^{-A/kT} \]

Du Frane et al., 2011
Mixed with silica sand, hydrate conductivity goes up until a percolation threshold is reached. We think that impurities from the sand, probably K$^+$ and Cl$^-$, increase the charge carriers available in the hydrate.

Du Frane et al., 2015
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Du Frane et al., 2015

50/50 hydrate and sand is about 2,000 $\Omega\, m$
Marine CSEM Methods
Controlled-source electromagnetic (CSEM) sounding:

Field amplitude and phase is measured as a function of frequency and source/receiver position.
With frequency domain CSEM, the entire air-sea-seafloor system is illuminated continuously. Energy propagates preferentially in resistive rocks.
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Amplitude and phase of the magnetic/electric fields on the seafloor can be used to infer geological structure to depths of several km.
The resolution of EM induction is between wave propagation and potential fields:

<table>
<thead>
<tr>
<th>High frequency (megahertz)</th>
<th>Wave equation: Resolution ~ wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar</td>
<td>$\nabla^2 \mathbf{E} = \mu \sigma \frac{\partial \mathbf{E}}{\partial t} + \mu \varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2}$</td>
</tr>
<tr>
<td>Seismscs</td>
<td>$\nabla^2 u = \varepsilon \frac{\partial u}{\partial t} + \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2}$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Mid frequency (0.001 - 1000 Hz)</th>
<th>Diffusion equation: Resolution ~ size/depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductive EM</td>
<td>$\nabla^2 \mathbf{E} = \mu \sigma \frac{\partial \mathbf{E}}{\partial t}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zero frequency</th>
<th>Laplace equation: Resolution ~ bounds only</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Resistivity</td>
<td>$\nabla^2 \mathbf{E} = 0$</td>
</tr>
<tr>
<td>Gravity/Magnetism</td>
<td>$\nabla^2 U = 0$</td>
</tr>
</tbody>
</table>

$\sigma = \text{electrical conductivity } \sim 3 \times 10^{-6} \ \text{S/m}$

$\mu = \text{magnetic permeability } \sim 10^{-4} - 10^{-6} \ \text{H/m}$

$\varepsilon = \text{electric permittivity } \sim 10^{-9} - 10^{-11} \ \text{F/m}$
Instrumentation:
The many uses of marine CSEM:

Mid-ocean ridges

Subduction zones

Oil and gas exploration

MacGregor et al., GJI, 2001


Myer et al., Geophysics, 2015
Hydrate Ridge Experiment
2004 pilot study at Hydrate Ridge

Weitemeyer et al., GJI, 2011
2D inversion, using Schlumberger’s finite difference code

Hydrate above BSR

Free gas below BSR

Weitemeyer, et al., GJI, 2010; 2011
High resistivity below the BSR corresponds to low seismic velocities -> free gas, while high resistivity above the BSR suggests hydrate.

Weitemeyer, Constable and Tréhu, 2011
Comparison of inversion resistivities with well logs

Gas/hydrate saturations.

Resistivities

Shipboard Scientific Party Leg 204 (2003)

Weitemeyer, Constable and Tréhu, 2011
The Hydrate Ridge project was a success, but ...

There are a number of limitations with deployed seafloor receivers:

• Closely spaced receivers are costly in ship time and instruments
• Navigation errors increase with short source-receiver offsets
• There are still, inevitably, gaps in data coverage

This argues for a towed system.
The Vulcans
Bottom-dragged systems exist but

- Source-receiver offsets are limited
- Noise is high
- Equipment losses are frequent
- Only inline data are possible

Schwalenberg, et al., 2010

The alternative is to fly an array above the seafloor.

But, noise induced by lateral motion of cable in Earth’s magnetic field

\[ \mathbf{E} = \mathbf{v} \times \mathbf{B} \]

\( Goto, \ et \ al., \ 2009 \)
Our modeling also showed that it would be worth recording the vertical component of the electric field.

At lower frequencies, vertical field data can carry more information than horizontal.

0.5 Hz, 500 m offset, 50 m altitude
In 2007, we developed “Vulcan” for fixed offset frequency sounding.
MC 118, Gulf of Mexico using seafloor instruments and towed receiver:

- 24 OBEM
- 500 m spacing
- 10 CSEM tows with towed receiver at a height of 65 m and 300 m offset.

- Active, in proximity to super-saline waters
- Inactive clam graveyard
- Active, out-cropping hydrate
MC118 Vulcan apparent resistivity frequency sections are in good agreement with OBEM pseudosections.
Under Fugro funding in 2011 we developed Vulcan Mk II

- Real-time depth telemetry
- Real-time data samples
- 3-axis accelerometer
- 1000+ meter offsets
- Timing pulse from transmitter
Voltage noise is comparable to our seafloor instrument. (But, dipoles are 5-10 times shorter.)
2015 Southern California Tests
A tale of two seeps

Work carried out by Peter Kannberg and supported by OFG and BOEM
We have carried out two surveys, one targeting a known methane vent called the Del Mar seep, and one covering most of the Santa Cruz Basin.
The Del Mar seep is a methane vent in the San Diego Trough, studied by Scripps students. It is in a pop-up structure bounded by two strands of the San Diego Trough Fault.
Ryan et al. discovered this feature, in about 1,000 m water depth, and predicted fluid or methane venting, since confirmed by ROV dives and acoustics.

Maloney et al., 2015

Ryan, et al., BSSA, 2012
We also obtained an uncalibrated signal on a Contros methane sensor during an earlier CSEM test.
In March 2015 we towed across the vent with a 500 m Vulcan array, made a turn, and towed over it again.
Navigation and stability of the receiver system is important.
Line 1 inversion shows a uniform seafloor except in the seep area.
Frequencies of 1.5, 3.5, 6.5 Hz were fit for 3 Vulcans. Ey fits to 1% amplitude and 0.6° phase. As predicted, there is a strong low-frequency signal in Ez.
Addition of the vertical electric field data removes what appears to be a layering artifact and brings out a conductor that may be fluids feeding the vent.
Anisotropy (ratio of vertical to horizontal resistivities) is very high in the northern part of the region inferred to be gas hydrate.
Using Archie’s Law, resistivity can be converted to hydrate saturation. Integrating saturation provides an estimate of 2 billion cubic meters of methane, or 0.07 tcf.

\[ S_h = 1 - \left( \frac{a R_w}{\phi m R_t} \right)^{\frac{1}{n}} \]

where \( a=1, \ n=2, \ m=3, \ \phi=0.5 \)

\( R_w = 0.3 \Omega m, \ R_t = \) model resistivity

*after Collet and Ladd, 2000*
Santa Cruz Basin study: 21 seafloor receivers and 6 Vulcan tow lines. Water depths are over 2,000 m.
Highest resistivities appear to be on the flanks of the basin.
It looks as though we have discovered another seep.
~8 Ωm resistor lies entirely above the BSR, while a resistor to the east lies under (gas?)

Line 4 seep.
Hydrate potential
- 10 degree dipping beds crossing the BSR
- seismic polarity reversal
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Over 1,000 line-km of Vulcan survey have been carried out off Japan as part of a national assessment of gas hydrate resources.
Inversion of the CSEM data will provide a better estimate of resource potential than is possible with seismic/acoustic data alone.

Research Consortium for Methane Hydrate Resources, Japan, 2015
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