[GC]Marine EM Methods*

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General Comments

In the space of just a few years a new geophysical technique has appeared on the scene -- marine controlled source electromagnetic (CSEM) sounding, also known as Seabed Logging by Statoil and R3M by ExxonMobil. Such a rapid rise is bound to create some confusion, and so here I will try to explain just what CSEM methods are and what they can do for the exploration geologist.

First, what is it?

Marine CSEM is one of two electromagnetic techniques applied to offshore exploration (Figure 1). The first technique, the marine magnetotelluric (MT) method, is, to a good approximation, simply the marine implementation of a method well known on land (see, for example, Karen Christopherson's January 1999 Geophysical Corner--http://www.searchanddiscovery.net/documents/geophysical/christopherson/index.htm). The application of MT in the marine environment is very much the same as for on land (the mapping of gross geological structure), and the method has been used successfully to map:

- Base of salt in the Gulf of Mexico.
- Extent of carbonate in the Mediterranean.
- Thickness of basalt in the North Atlantic.

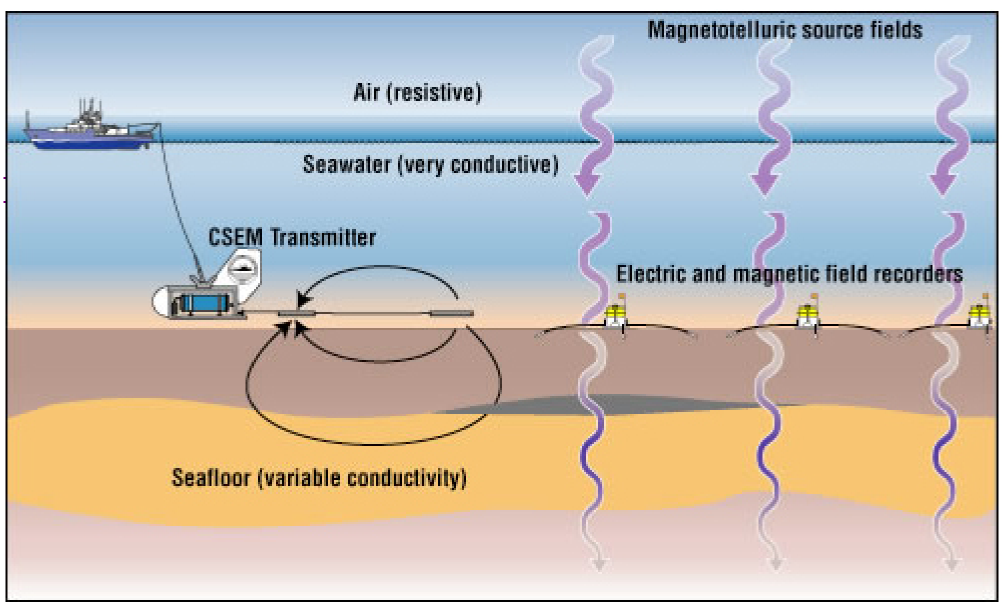

Figure 1. Field schematic for two electromagnetic techniques applied to offshore exploration--magnetotelluric (MT) and marine controlled source electromagnetic (CSEM) sounding.

Marine CSEM, however, behaves very differently than EM used on land, a feature that I will discuss below.

Actually, marine CSEM is not that new; Charles Cox of Scripps Institution of Oceanography proposed the method in the 1970s to compensate for the loss of MT signal at the deep ocean seafloor. By towing an EM transmitter close to the seafloor, EM energy couples well to seafloor rocks but, like the MT signal, gets absorbed quickly by seawater.
The most important concept in any EM method is skin depth. EM energy decays exponentially in conductive rocks over a distance given by the skin depth:

Skin depth = 500 meters x square root (resistivity/frequency).

At a period of one second, the skin depth in seawater is about 270 meters; this means that over each 270 meters the amplitude of EM energy decays another 37 percent. In 1000 Ohm.m basalt, at the same period the skin depth is nearly 16 kilometers; so energy will propagate from the transmitter to the seafloor receivers mostly through seafloor rocks, making the method sensitive mainly to seafloor geology.

This behavior, because it looks a little bit like seismic refraction, has caused some confusion. Seismic waves decay geometrically as they spread, but retain a resolution that is proportional to wavelength no matter how far they travel. EM signals decay exponentially as conductive rocks absorb energy (and get heated by electromagnetic induction!) and have a resolution that is proportional to the depth of the target.

This is not quite as bad as it sounds, since the skin depth provides an intrinsic depth measure; potential field methods (gravity, magnetics, DC resistivity) have no depth resolution other than that associated with spatial geometry. However, a target does need to be about as big as it is deep to be visible by EM methods.

"Discovery" and Use of Marine CSEM

So why, if the method has been around for 30 years, has the exploration community just "discovered" marine CSEM? There are at least two reasons:
1. If the water depth is shallow compared with skin depth, EM energy from the transmitter reaches the atmosphere, where it becomes a true wave and propagates geometrically. This "air wave" rapidly becomes the dominant signal at the seafloor receivers and removes the sensitivity to seafloor geology that we have in deeper water. Thus, until hydrocarbon exploration moved to water around 1,000 meters deep, it was difficult to take advantage of the marine CSEM method.

2. It has long been known that the marine CSEM method is preferentially sensitive to resistive rocks (compared with MT methods, which are most sensitive to conductive rocks), and thin resistive horizons in particular. However, it was not until Statoil and ExxonMobil demonstrated that the method works with horizons as thin as oil and gas reservoirs that it became clear that marine CSEM could be used to discriminate resistive drilling targets from conductive ones. Of course, because oil and gas are resistive compared to sand and shale, this appears to provide direct detection capabilities.

One should caution that evaporites, volcanics, and carbonates are all also resistive; so the method is less a hydrocarbon detector and more a resistor detector.

Figure 2 shows how the method can detect hydrocarbon reservoirs. The CSEM transmitter is assumed to be over the left edge of reservoirs one, two, three, four and five kilometers wide, buried one kilometer deep. For seafloor receivers over the reservoirs, the EM fields are much larger than if the reservoir were not there (indicated by the broken line labeled "1D halfspace"). An infinitely thick reservoir is indicated by the line labeled "1D layer." The vertical scale is logarithmic, so the fields associated with the five kilometer disk are 100 times larger than they would otherwise be; clearly, given the right conditions, the marine CSEM method can provide an unambiguous indication of resistive targets. However, these calculations neglect the electrical conductivity associated with geological complexity in the host rocks, such as resistive shallow gas hydrates or shallow carbonates, for example.

The calculations represented in Figure 2 are quite complicated. To interpret real data without such modeling, it has become practice to divide the measured electric fields by the 1D background response (similar to using a reduced travel time in seismics), or even to simply normalize by the response of an instrument assumed to be positioned off target. Resistive features then stand out as anomalies in the data.

Since resistors anywhere in the section can produce such anomalies, one needs to be very cautious in using this simplified approach. Additional data are always important, and so, for example, MT data can be used to provide background conductivities (even the relatively large reservoir shown in Figure 2 is invisible to the MT method), or other frequencies and geometries of CSEM data can be used. Figure 2 shows only the radial, or in-line, geometry of the CSEM method; the azimuthal, or broad-side, geometry behaves somewhat differently.

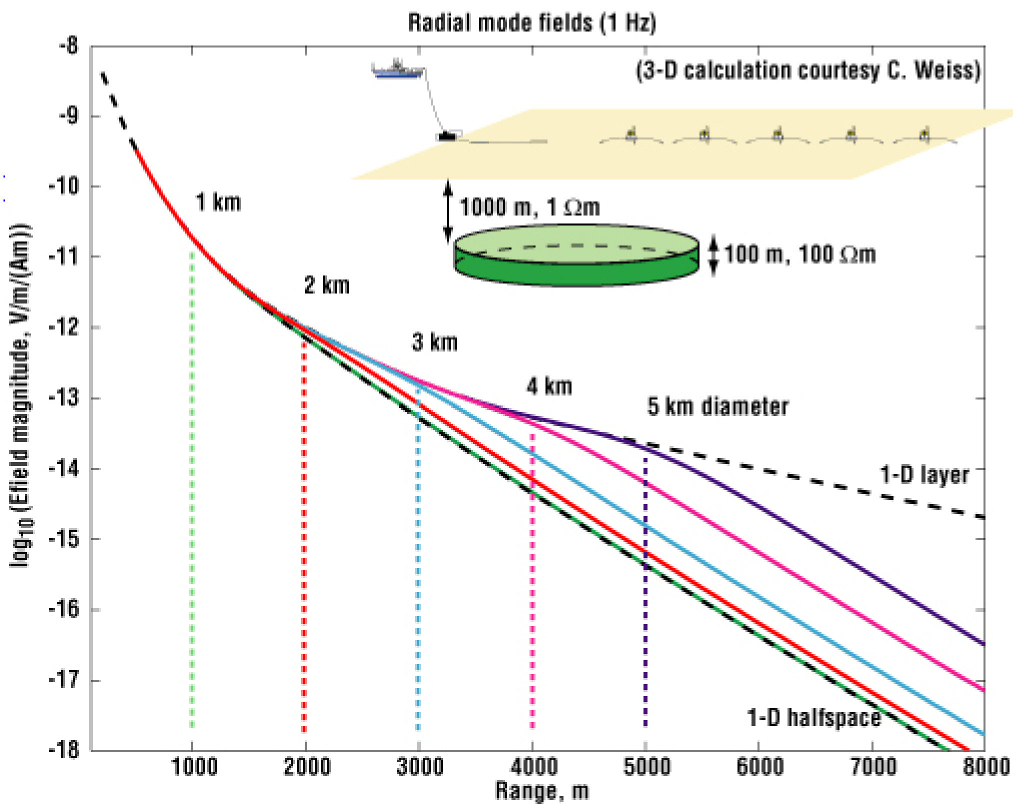

Figure 2. CSEM--how the method can detect hydrocarbon reservoirs.

Figure 2 also shows only one frequency (1 Hz), but other frequencies -- having other skin depths -- will help resolve ambiguities in the interpretation. As in any geophysical interpretation, taken alone CSEM data will not yield a single unambiguous model.

It can be seen from Figure 2 that at short ranges there is no sensitivity to the target. At larger ranges where the target is manifest the electric fields are very much smaller, and so the noise floor of the transmitter-receiver system determines how deep a target can be detected. The vertical axis is in units of electric field at the receivers (in volts per meter) divided by the transmitter dipole strength, given in turn by its antenna length (meters) times zero-to-peak transmission current, in amperes. Typical transmission currents are hundreds of amps; typical antenna lengths are hundreds of meters; and typical receiver sensitivity is hundreds of picovolts per meter.

Another factor of 10 can be obtained by stacking, giving a total noise floor around -15 log units. Figure 3 shows the amplitude and phase of real CSEM data stacked into two-minute and 10-minute data frames. The phase varies over a smaller range than the amplitude but does not contain any independent information.

Does marine CSEM work?

Undoubtedly yes, for big enough targets in relatively deep water. However, even though the method has been around for 30 years in the academic communities, the intensive application to continental shelf exploration is very new, and there is still a lot of work yet to be carried out to develop the interpretational skills and experience to get the most out of this method.

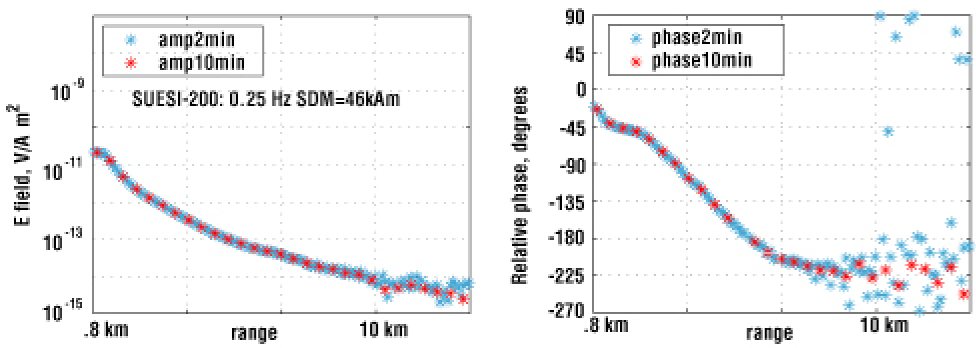

Figure 3. Amplitude and phase of real CSEM data stacked into two-minute and 10-minute data frames.

Take-home points

- The marine CSEM method is not new, but the application to hydrocarbon detection is.
- The method detects resistors, not hydrocarbons per se.
- Resolution decreases with depth of investigation, and targets must be relatively large.
- The method is best suited to deep water. Shallow water eventually destroys sensitivity.
- Frequency, and thus skin depth, must be chosen for target depth and host rock resistivity.
- Interpreting amplitude anomalies can be dangerous; if possible, do the modeling.
- More is better; MT data and other CSEM geometries and frequencies will aid interpretation.
- Resolution for EM methods is worse than for seismics, but better than for potential fields.
- Total noise floor is a combination of transmitter, receiver, and processing characteristics.