A rendezvous with controlled source electromagnetics (CSEM)

The seismic method is the best-known technology when it comes to oil and gas exploration. The interpretation results help to decide the prospective locations for drilling hydrocarbon targets based on the range of geological probability of success. However, like any other method, the seismic method also has some limitations. There comes the CSEM method for rescue, which is based on entirely different physics. This is not the first time a technology based on different physics is used. For example, gravity and magnetics which have been used for ages, but the utility is only in the reconnaissance survey and depth to the basement. On the other hand, the usage of CSEM has a wide spectrum. This technique can be used anywhere from reconnaissance to 4D seismic to the new kid on the block, i.e., CO_2 monitoring.

So why such a promising technique does not find its way into the workflow of oil companies as a routine? Let us discuss the pros and cons of this technique, but a bit of physics first.

One of the first things which should be noted is that this technique is neither new nor has the capability to replace seismic. Previously known as seabed logging, this technique complements seismic very well and hits the seismic where it hurts the most, i.e., fizz gas. Even a small amount of gas in the reservoir can generate a huge amplitude anomaly on the seismic, which is not the case with CSEM. Unless the reservoir is saturated with over 60-70% hydrocarbon, no significant CSEM anomaly will be generated. Figure 1 by Hesthammer et al., 2010, explains this phenomenon.

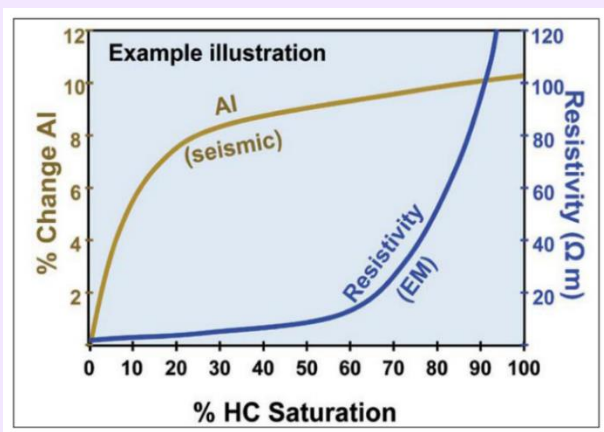

Figure 1: The change in acoustic impedance and resistivity as a function of the change in hydrocarbon saturation. (Hesthammer et al., 2010)

The seismic method is based on sound waves, whereas, as the name suggests, CSEM is based on electromagnetic (EM) waves and depends heavily on the Maxwell equations. The technology is a remote resistivity sensing method that exploits the fact that hydrocarbons are electric insulators, and consequently, the hydrocarbon-filled reservoirs are normally more resistive than surrounding water-filled sediments. This approach uses an electromagnetic-sounding method that exploits the resistivity differences between a reservoir containing highly resistive hydrocarbons and one saturated with conductive saline fluids. This

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frequency domain CSEM sounding provides the existence or otherwise of hydrocarbon-bearing layers that can be determined, and their lateral extent and boundaries can be quantified. Such information provides valuable complementary constraints, i.e., complements seismic on reservoir geometry and characteristics obtained by seismic surveying.

History

Professor Chip Cox of Scripps Institution in California is hailed as the first person, along with his team, to have initially developed the first marine source and receiver systems in the 1970s to investigate volcanic fluid systems in the crust and mantle. The potential of electromagnetics as a geophysical tool has been known to mankind since the early eighties when Exxon saw the potential for hydrocarbon exploration and filed a patent for this technology for oil and gas in 1981; however, the commercialization of EM as CSEM only started with a 'proof of concept' cruise in November 2000. This history is well documented (Whaley, 2008; Cooper and MacGregor, 2020. A CSEM survey in offshore Angola in the year 2000 was funded by Statoil (now Equinor). Such a survey requires a source and a receiver (like any other survey); however, in this case, the receivers came from Scripps (California) and the CSEM source utilized was developed by the team at Cambridge University (UK). This survey campaign was led by Professor Martin Sinha and Dr. Lucy MacGregor, with geoscientists from Statoil, researchers from the University of Southampton (Cambridge), and Scripps Institute of Technology, all of whom had been researching different aspects of the technology. The target was to locate a hydrocarbon reservoir using CSEM, and the campaign was successful in locating it.

After the successful completion of this survey campaign, the Norwegian team founded Electro-Magnetic GeoServices (emgs), the Southampton University (Cambridge) team formed Offshore Hydrocarbon Mapping (OHM), and Scripps collaborated with AOA geophysics to form AGO (later sold to SLB's WesternGeco). PGS acquired the University of Edinburgh spin-out MTEM, along with its marine EM technology, and developed this into a new CSEM system in which both the source and receivers are towed behind survey vessel (like seismic acquisition). This was quite an innovative development since Chip Cox's original surveys (1970), which allowed high-quality marine CSEM data acquisition.

Basics

The propagation and attenuation characteristics of low-frequency electromagnetic (EM) signals in a conductive environment can be elucidated through formulas derived from classical Maxwell's equations. These formulas reveal that the velocity and dampening of such signals depend on two primary factors, namely, the resistivity of the medium and the frequency of the EM signal. When examining a specific frequency, a reservoir filled with high-resistivity hydrocarbons will manifest as a significant positive electric impedance contrast, thereby causing both reflections and refractions.

Like seismic waves, which exhibit distinct behaviours as SH (shear horizontal component) and SV (shear vertical component) modes in layered sediments, EM waves also exhibit specific transverse magnetic (TM) transverse electric (TE) modes. Like their seismic counterparts, these modes display unique responses in various scenarios.

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Furthermore, TE and TM modes react differently when encountering a resistive layer, such as a hydrocarbon-filled reservoir. This distinctive response is harnessed in the processing and interpretation of CSEM data. Like any other technology, CSEM also has certain advantages and certain limitations, which are listed in Table 1.

Table-1: Benefits and limitations of CSEM technology

BENEFITS:	LIMITATIONS:
The technology has following advantages: 1. De-risking prospects due to its ability to distinguish between the brine and hydrocarbon saturated reservoirs. 2. Different physics (resistivity) complements seismic (velocity and density).	The technology has two big limitations. 1. Applicable only in marine environments and not onland. Though, transient domain EM (TDEM) is used exclusively for onland environments. 2. Since carbonate reservoirs are high in resistivity, separating the background resistivity (carbonate matrix) from the oil/gas resistivity becomes difficult. So, only applicable to the clastic depositional environment.

Methodology

Marine electromagnetic surveying uses the same principles as formation evaluation to map resistivity in the subsurface. Crystalline and volcanic rocks primarily derive their resistivity from the matrix, while a combination of porosity, tortuosity, and the resistivity of the pore fluid influences sedimentary rock resistivity. Oil and gas are predominantly highly resistive when contrasted with background or brine-filled sediments and exhibit a resistivity anomaly that can be mapped using the EM method. This provides a rare insight when integrated with seismic and/or well data.

Unlike seismic API, CSEM has AIII (Acquisition, Inversion, Interpretation, and Integration). Secondly, the CSEM acquisition is done mostly along the 2D seismic lines or 3D prime/infill lines. This has the unique advantage of co-rendering the seismic and CSEM resistivity information together as part of the integration of data sets. A strong amplitude anomaly on seismic and a strong/weak anomaly on CSEM enhances/reduces the chance of success of a costly well many times.

CSEM and MT data acquisition

Before going for acquisition, a feasibility modelling is done considering the expected resistivity, size, thickness, and burial depth of the reservoir. The 2D/3D EM acquisition vessels are built for purpose and can handle a large number of receivers. The frequency spectrum is customised for each survey, and the sources can

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illuminate hydrocarbon targets through more than 3.5 km of rock (3.5 km from mudline) at water depths down to 3.5 km. EMGS's new source, "deep blue", claims for even deeper penetration (Figure 2).

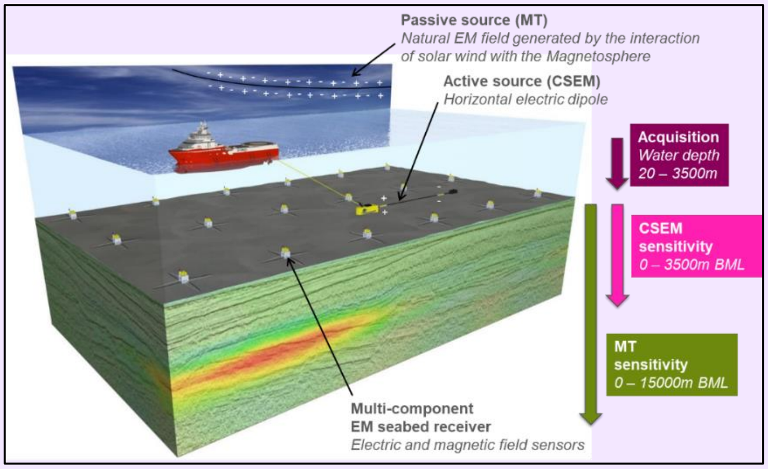

Figure 2: CSEM and MT acquisition with depth tolerances. (Joshi et al., 2015)

CSEM, along with MT data, can be acquired in both 2D and 3D survey geometries with the laying of the receivers on the seabed (like OBC) and towing the source behind the vessel a few meters below the water (like seismic). The source is a horizontal electric dipole (HED) that transmits a discrete EM signal frequency to the array of seafloor receivers. The receiver has four antennas on four sides for recording two orthogonal components of the horizontal electric field at the seafloor. At the bottom of the receiver is a heavy biodegradable base, and both the receiver and base, tied with a special rope, are dropped in water (free fall). Because of the free fall, there is no control over placing the receiver at its designated position on the seabed (unlike OBC nodes placed accurately by ROV). Hence, a tolerance area (which depends on water depth), say a square area of two (2) meters by two (2) meters, is defined. If the receiver lands anywhere within this square, then fine; otherwise, the receiver is pulled up to the vessel and dropped again until it lands within that square. Once the survey is over, an acoustic pulse is given from the vessel, and the special arrangement in the rope burns it, leaving the biodegradable base at the bottom and the receiver floating to the surface of the water due to its buoyant design.

The magneto telluric (MT) data is very low-frequency and recorded concurrently with the CSEM; however, the MT source is not controlled but natural. The receivers are left at the bottom of the sea for a few days for the MT recording. Those years when the solar activity is high are the best years for MT data acquisition.

The 2D layouts are like seismic, typically applied in frontier basins, and frequently acquired as long regional lines, mostly along existing 2D seismic lines. In 3D full-azimuth CSEM data, a receiver grid is laid out on the seabed before the source is towed over the grid. This allows to register signals for various azimuth angles with high data coverage. Such an acquisition provides improved depth and spatial resolution of the resistivity distribution in the subsurface and provides higher confidence in anomaly interpretation. The variation in the amplitude and phase of the received signal as the source is towed through the array of receivers can be used to determine subseafloor resistivity structure at scales that range from a few tens of meters to several kilometres.

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CSEM, MT and joint inversion

The CSEM inversion is a standard tool to reconstruct the subsurface resistivity distribution that explains the CSEM data and its geological meaning for regional exploration, prospect evaluation, reservoir characterization, structural imaging, etc. while accounting for VTI and TTI anisotropy in the subsurface. It can integrate seismic and well-log data into imaging workflow and has flexibility for applying different types of regularization and constraints available as a priori information. The inversion results are delivered in SEG-Y format for easy integration with other geophysical and geological data.

Similar to CSEM, MT data is also subjected to inversion; however, being very low-frequency data, its usage in locating hydrocarbon is much less. It is well-suited for mapping and interpreting regional geology, salt/basalt settings, depth to basement/deepest layer/boundary and crustal understandings. Both MT and CSEM possess distinct sensitivity patterns and varying depths of penetration. Joint inversion leverages the complementary nature of these data sets and produces comprehensive subsurface resistivity images, particularly in geologically complex settings.

Interpretation and integration

As with any analytical method, CSEM surveys are susceptible to yielding a range of outcomes, including true positives, true negatives, false positives, and false negatives. Among these outcomes, the true negative result, i.e., "absence of CSEM anomaly meaning the absence of hydrocarbon", is the most dependant and exceptionally valuable conclusion that CSEM can provide, saving millions of dollars. CSEM data is sensitive to resistivity, which is a very independent earth property because the physics behind the propagation of EM fields is quite different. Unlike the seismic and gravity data, which share a common property (density), seismic and CSEM do not have anything in common; however, there is a huge unity within this diversity i.e., they complement each other to get a complete picture.

Integration of the data has already shown its mettle in the entire value chain, from frontier exploration (wildcat well) to development fields (reservoir extent and volumes), which helps in making an informed choice about exploration/appraisal/development well placement. (Chakraborty and Joshi, 2016).

Usage of CSEM and MT data

CSEM has applications in all stages of the upstream value chain. Out of the three (3) elements of the petroleum system, seismic is most suited for trap identification but not so for reservoir fluids. Well logs are very good at detecting fluids and mineralogy but heavily under-sampled. CSEM can detect fluids and can integrate with seismic and well logs for a complete subsurface picture. (Table 2). The usage of CSEM is in a wide array of oil and gas value chains. A brief snippet of these is given below.

Reservoir detection and de-risking- Because of resistive hydrocarbon and conductive brine solutions, CSEM data can distinguish between hydrocarbon versus brine-filled reservoirs. The Hesthammer et al. (2010) concept of over 60-70% hydrocarbon saturation for generating significant CSEM anomaly helps de-risk AVO and seismic amplitude-driven prospects/drilling targets. Integration can find the actual volume of saturated reservoir rock, resulting in better hydrocarbon volume estimates, further de-risking the target (Joshi et al., 2015).

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Table 2: Capabilities of various data sets in prospect evaluation.

	CSEM	Seismic	Well Data
Imaging structure	X	Yes	X
Detecting fluids	Yes	X	Yes
Determining mineralogy	X	X	Yes
What may go wrong?	Measures resistivity, not hydrocarbons.	AVO and amplitude anomalies may be due to lithology variations. (DHI issues). Saturation is difficult to determine mostly.	Severely under-sampled laterally.

Geobody characterization, volumetrics, and PoS/CoS- In the prolific clastic basins like the Kutai basin (Indonesia), where ENI recently made a five (5) tcf gas discovery, the main challenge before drilling is size quantification. Provided the reservoir is in the detection range of CSEM, the inverted results can accurately estimate the areal extent of the geo-body and accordingly estimate PoS/CoS (Joshi et al., 2016 and Joshi et al., 2017). Basin floor fans, which are more resistive than their surrounding shale, are particularly well suited for geobody detection by CSEM. (Chan et al., 2016).

The major factors in the uncertainty of volume are (1) the areal extent and (2) net thickness. Interestingly, CSEM data is inherently sensitive to these two parameters and hence well placed to estimate the volumes better and predict PoS/CoS. (Baltar and Roth, 2013). To embed 3D CSEM in an evaluation workflow, a set approach is followed, elaborated in length by Baltar et al., 2015.

Appraisal, 4D and CO_2 monitoring-The first movers with CSEM data acquisition, especially in the Barents Sea and the Gulf of Mexico, are investing in CSEM for appraisal well planning, e.g., Pingvin discovery in Bjørnøya Basin, Barents Sea (Baltar et.al., 2015). Another usage of CSEM is 4D. Time-lapse CSEM enables monitoring of the changes in reservoir saturation, highlighting undrained compartments and providing data for the operator to make informed decisions. Finally, CO_2 monitoring, the new kid on the block. CO_2 is resistive and hence can, therefore, be used to monitor the injection and increase in saturation of CO_2 in the reservoir used for CO_2 storage.

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Endpoint

Resistivity is an important rock property for hydrocarbon exploration since hydrocarbon-charged reservoirs are characterized by high resistivity. Furthermore, structures that can be difficult to image reliably with seismic, like salt, basalt, and basement, are typically associated with a high resistivity contrast, making EM methods an excellent complementary measurement to seismic for structural imaging and geological model building. EM methods are widely used in the onshore mining industry and are expected to play a leading role in the emerging marine hydrocarbon exploration industry.

CSEM is a proven technology that should be routinely considered to help solve certain classes of exploration and production challenges, especially when seismic data alone cannot provide a satisfactory answer. In areas where seismic data already exists, CSEM data can be added to provide additional information that helps define the presence and quality of hydrocarbons. In such areas, CSEM and legacy seismic data may be more cost-effective than new seismic data acquisition and may offer a lower environmental footprint.

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