The future of marine CSEM

To great fanfare in 2002 the Norwegian company Electromagnetic Geoservices (EMGS) was established to market the newly introduced concept of marine controlled source electromagnetic surveys for hydrocarbons exploration. Now almost 10 years later, Jens Danielsen, vice president geology and geophysics solutions, and Bekker,* CEO, discuss how the company, its technology, and its vision have evolved in the light of commercial experience.

Nearly a decade has passed since the first commercial marine controlled-source electromagnetic (CSEM) survey. The new method, then named seabed logging or SBL, won a host of awards and was frequently described in the trade press as being 'revolutionary' and 'groundbreaking', words that are often too readily applied to new ideas. So, has the method lived up to the early expectations?

There is perhaps the perception that the potential of marine CSEM surveying was oversold during the first few years, although the survey results have always been carefully and conservatively presented. Statistical reviews of those CSEM surveys for which there are well data leave no doubt that the method works. The challenge lies in retrieving the value it can add to exploration, particularly in combination with seismic and other data. In this article, we report on the current state of the method, describe recent developments, and set out the EMGS vision for the future of marine CSEM surveying.

Widespread adoption

Because it can provide sub-surface resistivity information, which is largely influenced by pore-fluid resistivity, marine CSEM surveying is often presented as being the perfect partner for seismic surveys, which primarily measure rock structure. It is no secret that the vision of the marine CSEM pioneers was to see the method used routinely alongside seismic surveys. After all, why would an explorationist drill without first examining resistivity, which has been the oil and gas industry's primary hydrocarbon indicator since the 1920s? So is the method widely used?

We can only speak from our own experience. EMGS has now performed in excess of 500 commercial marine CSEM surveys, which have involved placing and recovering over 21,100 receivers and towing sources for more than 74,000 km (Figure 1). More than 40 oil and gas companies, including national oil companies, majors, and independents have used our services, as have national regulators. We have also performed several successful multi-client campaigns covering a combined area of 20,000 km^2.

Surveys have been carried out in all the world's marine oil and gas provinces, and in all geological settings, from the Arctic to Australia, for applications ranging from lead generation in frontier regions to pre-abandonment evaluation in mature basins, and in water depths from 30 m to more than 3400 m.

More and more companies are recognizing the advantages of marine CSEM surveying. Over the last six months in particular, there has been a buzz about CSEM methods that is reminiscent of the early excitement of 2005/2006. Several companies use the method regularly in their workflows, particularly to rank and de-risk prospects before fulfilling drilling commitments.

The rapid transition from 2D to 3D CSEM data, which can be more usefully related to 3D geology and 3D seismic data, has helped to accelerate the technique's adoption. Importantly, several companies have developed internal marine CSEM expertise and built up confidence in its use through experience and internal research. Several more companies are close to achieving this level of confidence.

Indeed, large energy companies are beginning to take ownership of the technology by backing joint-industry projects (JIP). For example, Shell and EMGS have a JIP to plan and design the next generation of 3D marine CSEM source, receiver, and positioning system. This project aims to provide a step change in CSEM surveying's depth of penetration and resolution. The hope is that the next-generation system will at least double the number of hydrocarbon prospects that can be evaluated with CSEM.

Adoption will continue if companies can see the advantages of integrating CSEM, seismic, well log, and other data for de-risking exploration and for development, appraisal, and evaluation applications.

Proving its worth

Survey data and drilling results are commercially sensitive. This makes assessing the impact of new technology difficult. However, nearly a decade after the first commercial survey, information from 50 wells drilled through prospects after marine CSEM data acquisition is available for review; see, for example, the review by Fanavoll et al., 2010. Numerous parameters were unknown to the paper's authors and no effort was made to interpret any of the data apart from identifying any simple, observable normalized anomalous amplitude

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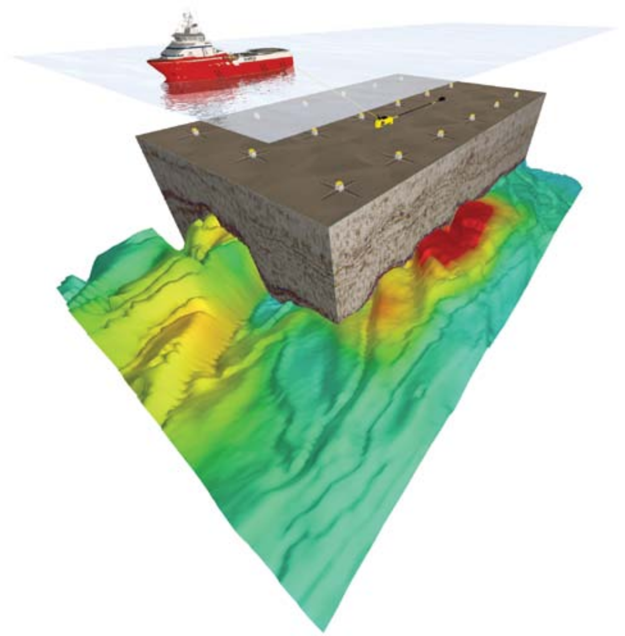

Figure 1 The CSEM method: a survey vessel tows a high-power electromagnetic (EM) source. Sensitive seafloor receivers detect the EM energy that has been guided by electrically resistive bodies, including hydrocarbon reservoirs, in the subsurface.

response in the electric field at the fundamental frequency. This optimized the consistency when comparing the different datasets. A normalized anomalous response (NAR) considers the resistivity response of something that is anomalously resistive in the subsurface with respect to the background resistivity.

Of the 50 marine CSEM surveys reviewed by Fanavoll et al., 30 had NARs of more than 15%, which indicated, in the absence of full analysis, that drilling was more likely to encounter hydrocarbons. Of these 30 likely prospects, 21 were classed as discovery wells – a drilling success rate of 70% compared with the 35% drilling success rate for NARs of less than 15%. Although it is clear that marine CSEM surveys do not eliminate risk, studies like this show that they can significantly reduce it when they are applied correctly.

3D is survey of choice

Owing to many advantages, 3D marine CSEM methods have almost completely replaced 2D surveys. Over the last two years, over 95% of EMGS's revenue has been from 3D work. During this time, we launched two purpose-built 3D CSEM vessels with the capacity to efficiently handle the large numbers of receivers required for 3D surveys (Figure 2). Each vessel can deploy a dense array of receivers, which has greatly enhanced 3D survey productivity. Our operational statistics show that each vessel can acquire more than 1000 km^2 of 3D CSEM data a month.

Marine CSEM surveying for hydrocarbon reservoirs using 3D grids rather than 2D line geometry has significantly expanded the method's application. In a 3D survey, receivers both on (inline) and off (broadside) the source towing line record data. The benefits of 3D acquisition include better resolution and better lateral and vertical delineation, which give improved volume estimates for appraisal and increased target confidence through enhanced understanding of background resistivity trends and anisotropy. For example, information about resistive-body thickness is contained in broadside CSEM data, so 3D data acquisition improves hydrocarbon reservoir thickness resolution in anisotropic inversion.

The rapid rise of 3D CSEM methods has, perhaps, been driven by the fact that the data is easier to use. In most cases, before the significance of an anomalous response can be assessed, the CSEM survey must be set into the appropriate geological and geophysical contexts. Acquiring and processing 3D data offers better, more robust understanding of the background response, which is important if interpreters are to identify anomalies. Trends in the CSEM data, which are also observed in the seismic data, help to validate background models. In 2D surveying, there are many more uncertainties relating to the background response, and small anomalies do not have the benefit of having been measured repeatedly.

Improved integration

There are two different, equally important aspects of integration: first, co-rendering and eyeballing of multiple datasets and, second, using two datasets in a processing algorithm. The former benefits from the latter, but the benefit and value of the first approach are very much experience driven. Skilled, open-minded interpreters can create much value simply by cross-plotting and co-visualizing seismic and CSEM attributes.

While processing and modelling have become more sophisticated over the last few years, marine CSEM data has become easier to integrate and interpret. Models and 3D resistivity cubes are provided in standard SEG-Y formats, and Petrel plug-ins, such as Bridge Electromagnetics from Blueback Reservoir, jointly developed with EMGS (Figure 3), and EM-Connect from WesternGeco, are now available.

CSEM data must become part of a prospect's story, a story that explains the presence or absence of an EM anomaly, just

Figure 2 Up to 200 receivers can be kept aboard EMGS's high-capacity 3D EM surveying vessels. More receivers means larger and more complex surveys, and more data points per km^2 for improved 3D data coverage.

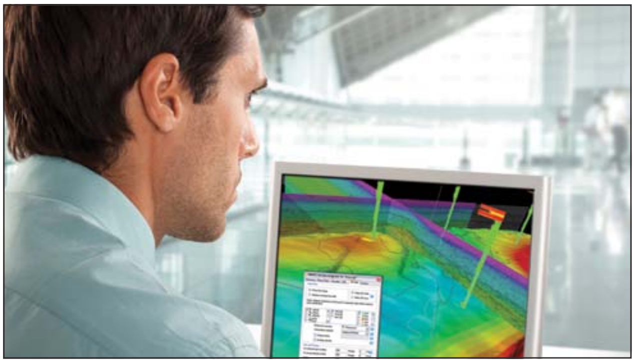

Figure 3 *A screenshot from the Bridge Electromagnetics Petrel plug-in showing integrated CSEM, seismic, and well data.*

as it must be consistent with seismic and other data, and have a geologically credible hydrocarbon source rock, migration route, and cap rock. The responsibility for interpreting this story lies with the energy company's geology and geophysics group. Although many oil and gas companies still rely on expertise in geophysical companies, we believe that this situation is changing as they gain experience of CSEM data integration and interpretation.

The second, algorithm-based, approach to integration is more geophysically driven and is built on modelling and inversion of CSEM data. Aside from data quality and acquisition efficiency, this is where the battle for technology leadership among CSEM contractors is being fought. Full 3D inversion is a costly process and has more in common with full waveform seismic inversion than with seismic depth migration. It requires weeks of preparation and computation time, which is why at EMGS we have dedicated so much effort to developing efficient algorithms.

The importance of considering anisotropy is demonstrated by an example from South East Asia. The interpretations based on isotropic and anisotropic 3D inversions differed, with the former unable to fit the broadside data and the latter both fitting the data and agreeing with the pre-survey geomodel. The final interpretation using the anisotropic 3D inversions suggested that the hydrocarbon charge was restricted to one-third of the original prospect area. This reduced its potential significantly and indicated that the most promising drilling location was not on the highest point of the structure, see figures 4a and b (Mohamad et al., 2010). In this case, performing anisotropic 3D inversion enabled the client to update its prospect ranking and decide whether to move drilling location or change drilling priorities.

Our algorithms and computing power enable us to routinely depth-convert large EM datasets into anisotropic resistivity volumes. The element of integration is introduced by including seismically derived structural, well log resistivity and other information. The inversion is then re-run while honouring the added information. By adding seismic data, the separate structural and resistivity models can then be combined into

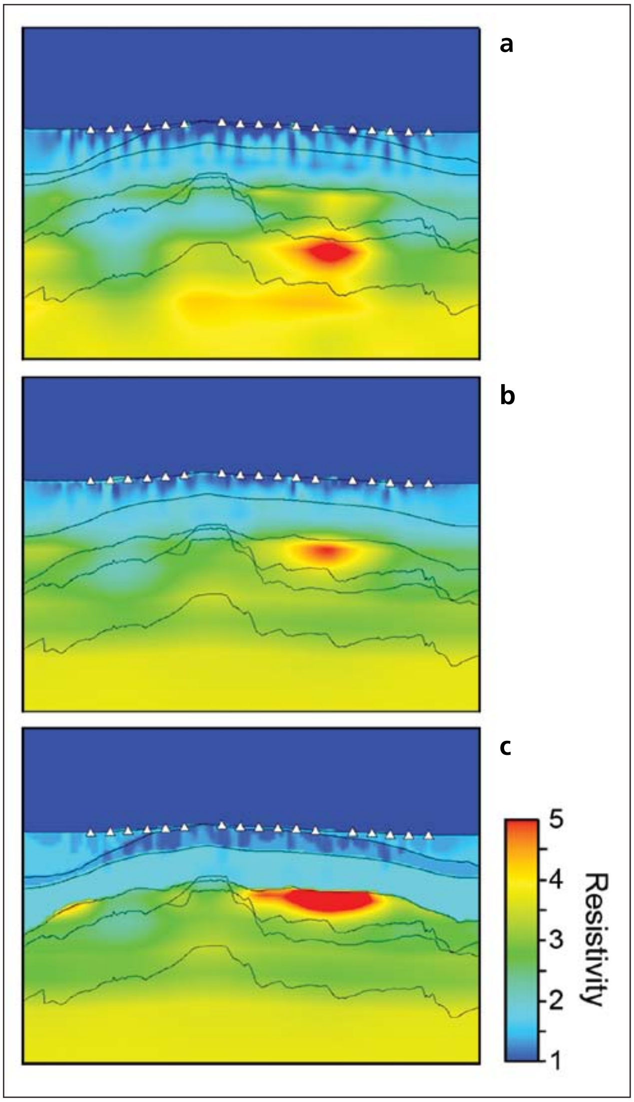

Figure 4 *Isotropic (a), anisotropic (b), and structurally constrained anisotropic (c) 3D inversion results for the full 3D dataset. The improved interpretation changed the client's perception of the value of the prospect.*

one structure–resistivity model, see Figure 4c (Mohamad et al., 2010).

The ultimate integrated processing tool would be joint inversion, particularly of seismic and CSEM data. The real value of joint inversion lies not with the addition of structural constraints, which are already being routinely incorporated, but when the acoustic impedances from seismic inversion are combined with pore fluid resistivity information from CSEM inversion. The more quantitative processing results from joint inversion would be particularly important for reservoir appraisal and evaluation applications.

Integration with seismic, well log, and other data is vital for extracting the maximum value from marine CSEM surveys. We have observed that incorporating information from seismic data in a joint interpretation could increase the resolution capabilities. Conversely, integration can also be important for getting maximum value from seismic data. Although seismic methods are the backbone of exploration and have greater resolution than CSEM methods, they tell us little about the saturation of a potential hydrocarbon-charged reservoir. Integration with CSEM data can help to reduce the risk of drilling reservoirs of an uneconomic scale.

Additionally, CSEM data can help seismic interpreters to focus on the most promising areas of the detail-rich seismic dataset. Mapping anticline structures is a key part of seismic interpretation, but sometimes, in the Niger Delta for example, thick reservoir sands may be associated with channels and fans and do not necessarily coincide with deformational, structural closures. Good reservoirs can be associated with stratigraphic traps, which are often difficult to identify on seismic data. CSEM data are equally sensitive to structural and stratigraphic traps. In this scenario, the integration of CSEM and seismic data could help the seismic interpreter to look for stratigraphic traps in the seismic data and to answer the basic question of whether or not a seismically identified pinch-out structure has retained its hydrocarbon charge.

Expanding the EM application window

Although much progress has been made in expanding the marine CSEM application window, particularly in increasing the range of water depths, today's marine CSEM method has a narrower application window than seismic methods. Inevitably, some targets cannot be identified using current CSEM technology because they are too deep or too small, or below salt or basalt, etc. Continuing to expand the application window is one of the most important tasks for geophysical contractors like us as they seek to expand their addressable market.

Water depth

Marine CSEM has been perceived as a deepwater technology because of the strong airwave interference in shallow waters. Recent developments, in particular 2.5D and 3D anisotropic inversion schemes, can now cope with the additional complexity of the data measured in shallow waters. Several successful surveys have been performed in waters less than 100 m deep. Within the last year, we have delivered five surveys undertaken in less than 100 m of water.

A novel deployment setup in which the electrodes of a conventional CSEM source are suspended from two GPS-positioned buoys and towed 10 m below the sea surface has now been fully commercialized. This setup offers better control of the source position and orientation, along with improved speed and maneuverability.

The consequence of these and other developments is that the minimum water depth of surveys is now only limited by safe vessel operating requirements. The maximum water depth is also increasing. We have a deepwater source-towing depth record of 3449 m while surveying for PEMEX in the Gulf of Mexico.

Salt and basalt

Most CSEM surveys have been run to de-risk prospects and assess if they contain significant hydrocarbon volumes. However, another application is emerging, whereby EM and other data are combined to examine regional geology. This is particularly applicable for geological environments where seismic interpretation, or imaging of seismic data, is complicated by the presence of high-impedance salt or volcanic rocks.

Statoil has demonstrated the use of CSEM data for salt imaging in the Barents Sea, and we have seen that small targets, confirmed by drilling results, were resolvable using 3D CSEM data in a salt province in the Gulf of Mexico.

Marine magnetotelluric (MT) data can be particularly valuable for understanding regional geology where salt and volcanics are present. Marine MT surveys are acquired inherently during CSEM surveys. We will acquire a large marine EM survey, with emphasis on CSEM and MT data, this year in the Red Sea, predominantly to assist in velocity model building for imaging of wide-azimuth seismic data.

End of field life

Prospect ranking and de-risking are established marine CSEM applications. However, the method has also been applied at the end of a field's production life in an effort to locate bypassed reserves. For example, marine CSEM surveying was used to locate and quantify the stranded gas thought, from history matching and the original estimates, to remain in the North Sea Frigg field, as well as bypassed pay in segmented reservoir compartments.

The survey offered challenges, such as pipeline effects, that are less common in frontier exploration surveys. For a survey of this nature, the collection of 3D CSEM data in a grid with all the receivers recording azimuthal data gave a clear advantage over 2D acquisition. Seabed pipelines caused cultural interference, particularly when the source towing line and the pipelines were parallel.

The 3D survey geometry meant that there was good coverage from azimuthal data, even where significant amounts of data had to be removed. Post-acquisition 3D modelling confirmed that the survey had retained sufficient coverage in the inline direction, after editing to remove cultural interference, to interrogate the structures of interest.

4D monitoring applications

Marine CSEM methods also have potential reservoir monitoring applications. At EMGS, we have investigated the technical feasibility of 4D (time-lapse) CSEM surveys, with constraints from seismic and/or well data, for quantitatively mapping resistivity within larger reservoirs. Time-lapse surveys for production and waterflood monitoring, including distinguishing between the different flood shapes, is already technically feasible, and improvements in navigation and processing are likely to increase survey repeatability.

4D marine CSEM surveys also have application for carbon dioxide sequestration monitoring. Studies have shown that 4D CSEM surveys for monitoring a carbon dioxide injection plume for sequestration in the North Sea Sleipner Øst gas field are technically feasible. As with oil and gas exploration, CSEM and seismic methods are complementary for this application, with the former being sensitive to the bulk volume of a resistor and the latter offering superior structural resolution. With the International Energy Authority (2010) highlighting carbon capture and storage as central to climate change mitigation, the need for this application is likely to expand.

Appraisal and monitoring applications tend to require more quantitative interpretations. Hydrocarbon saturation volumes can be created by integrating porosity information derived from seismic inversions with water saturation data from CSEM inversions, both constrained by well logs.

The more quantitative the results, the more important it is that they are derived from good quality 3D datasets, both seismic and CSEM, with robust inversion algorithms. Any large uncertainties in the data and the depth conversion will go straight into the rock properties volumes. EMGS has worked with Fugro-Jason to produce 3D rock property volumes based on CSEM and seismic inversions, and petrophysical analyses. The results will be released soon.

Smaller targets, greater depth

Increasing the marine CSEM method's resolution and penetration depth requires improvements in the fundamentals: data quality and the basic processing steps. The former, in particular, requires significant investment so that more accurate data, with higher signal-to-noise ratios, can be acquired.

Non-exclusive applications

The use of non-exclusive seismic data in exploration is a well established business model. EMGS has carried out CSEM in a multi-client setting and has acquired several large 3D campaigns over the last 2–3 years. Today, our library consists of more than 20,000 km^2 of 3D CSEM acreage in India, the Gulf of Mexico, and Norway, and we are planning several new projects.

Resistivity information is particularly useful in combination with 2D and 3D seismic data to high-grade prospective acreage and gives exploration companies a competitive advantage in licensing rounds. During Norway's 20th and 21st licensing rounds, our extensive CSEM data coverage in the Barents Sea was actively used by several exploration companies and gave some of them their first inexpensive experience of using CSEM data.

Key to the success of these non-exclusive CSEM campaigns has been the ability to acquire extensive, wide-azimuth 3D data cost-effectively. We expect that the multi-client business model will continue to develop and will become a key mechanism by which the worldwide adoption of CSEM data will expand.

The future

At EMGS, our vision remains unchanged in that we would like to see marine CSEM surveying becoming a standard hydrocarbon exploration and appraisal tool, one that routinely provides value for energy companies by helping them to find hydrocarbons more efficiently and with less environmental impact so they can make better informed exploration or production decisions and reduce risk. We see also new applications such as aiding seismic imaging in problem areas; reservoir monitoring and evaluation; and carbon sequestration monitoring.

In the short term, we hope to see the technology becoming established in shallow waters through dedicated shallow water sources and real-time data quality control. The developments will be backed up by improved inversion schemes. Interpretation platforms will continue to improve, and we will see the first large-scale, fully commercial use of marine CSEM and MT data for seismic velocity model building.

In the longer term, we see marine CSEM and MT data being used in combination as the default, even for large 3D surveys. More robust seismic-and CSEM-driven rock property volumes and significantly improved inversion algorithms will also be developed.

When people speak of CSEM technology development, interpretation is the aspect that is often ignored, not the inversion techniques, rather the human factor of a geoscientist trying to make sense of detailed datasets. As for seismic data, the maxim that the best interpreters are those who have seen the most data holds true. Geophysical contractors will become better at presenting and conveying information, helped by technological advances, and oil company interpreters will steadily increase their experience base.

With a few exceptions, marine CSEM companies currently perform much of the integration and interpretation work for oil and gas companies. As energy companies develop expertise and become confident in the use of marine CSEM data, they will routinely integrate and interpret the data as part of their standard exploration and production workflow. When that happens, the EM surveying market is surely bound to take off.

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