

# Introduction to CSEM

Kjetil Eide<sup>1\*</sup> and Steve Carter<sup>1</sup> present the latest developments in Marine Controlled Source Electromagnetics.

Marine Controlled Source Electromagnetics (CSEM) is the collective term for techniques that can be used to investigate the geological subsurface using electromagnetic signals generated by artificial and controllable source systems operated in a marine setting. This is possible because the various subsurface strata are made up of materials with different electromagnetic properties in terms of their resistivity/conductivity and chargeability. The differences in resistivity between different materials enable us to use electromagnetic signals to map geological formations in the subsurface. When an electromagnetic field propagates through the different formations, it becomes successively influenced and modified by the resistivities of the different strata it encounters.

The fact that hydrocarbons exhibit different resistivities from the surrounding rocks allows CSEM to be used, for example, to determine with high levels of probability whether hydrocarbon-bearing formations are present in the subsurface (Ellingsrud et al, 2002), and to obtain information about the geometry, volume and extent of the reservoir.

## Principles

CSEM belongs to the family of geoelectrical methods, further subdivided into passive and active methods according to the nature of the source of the electromagnetic (EM) signal. An electromagnetic field is a physical phenomenon produced by electrically charged objects. It is made up of an electric field and a magnetic field. In many ways, electricity and magnetism represent two aspects of the same phenomenon. A time-variant electric

field acts as a source for a magnetic field, while a time-variant magnetic field acts as a source for an electric field.

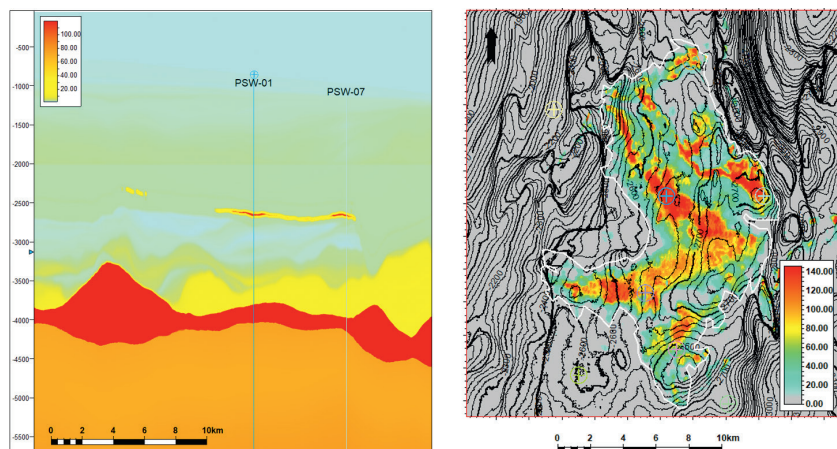
The electromagnetic spectrum categorizes different forms of electromagnetic signal radiation on the basis of signal frequency. For example, radio waves transmit at relatively low frequencies, and visible light at relatively high frequencies. The electromagnetic signals used in marine CSEM typically exhibit very low frequencies.

A field generated by an electromagnetic source will propagate in all directions unless non-conductive insulators intervene to prevent propagation. In a theoretical vacuum, the field will propagate at the speed of light. All material substances, including air, have a given property that counters this propagation, commonly called electrical resistivity. The resistivity of a given material is measured in ohm-meters ( $\Omega\text{m}$ ). Resistivity causes propagation of the field to attenuate the further it travels from the source.

The differences in resistivity between different materials enable us to use electromagnetic signals to map geological formations in the subsurface. When an electromagnetic field propagates through the different formations, it becomes successively influenced and modified by the resistivities of the different strata it encounters.

## Historical development

Marine CSEM techniques have their precursors in measurement methods developed using natural electromagnetic sources. A method known as magnetotellurics (MT) was developed during the 1950s and can be used to investigate the geological subsurface

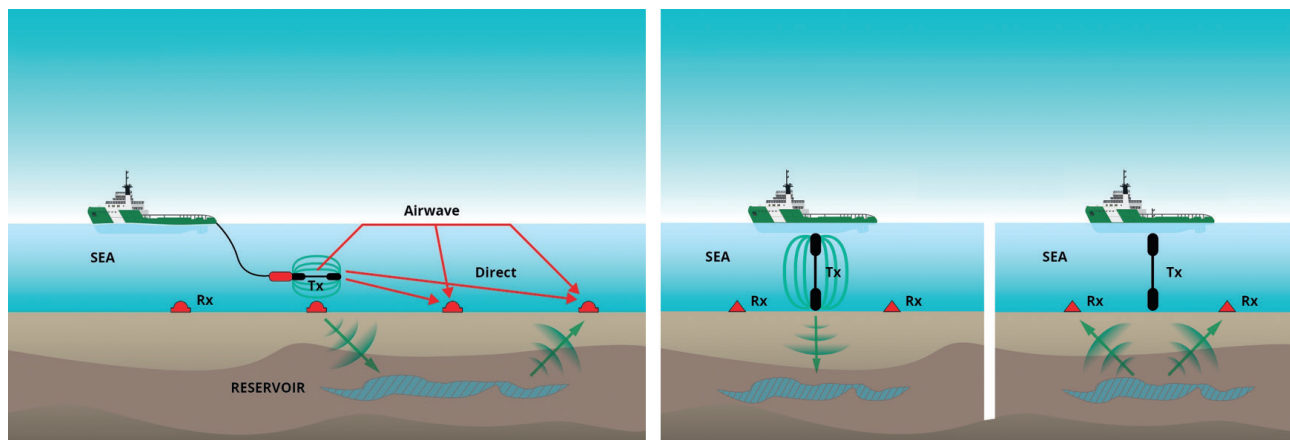


**Figure 1** Example resistivity model from the Marlim oil field offshore Brazil (Correa, 2019). Depth section (left) and top reservoir depth surface (right). Increased resistivity is observed in the oil-charged reservoir, and also in deeper salt and basement formations.

<sup>1</sup> Allfon

\* Corresponding author, E-mail: Kjetil.Eide@allfon.com

DOI: 10.3997/1365-2397.fb2020081



**Figure 2** Controlled source electromagnetic signal propagation through subsurface with towed (left) or stationary source (right).

to depths of about 100 km. MT employs natural sources of electromagnetic radiation such as the sun. The purpose of such methods is to obtain greater insights into the physical structure of the Earth and how the planet has evolved. However, MT is not very suitable for investigations of the oceanic lithosphere because, among other things, natural sources transmit signals at very high frequencies that attenuate rapidly during propagation in water.

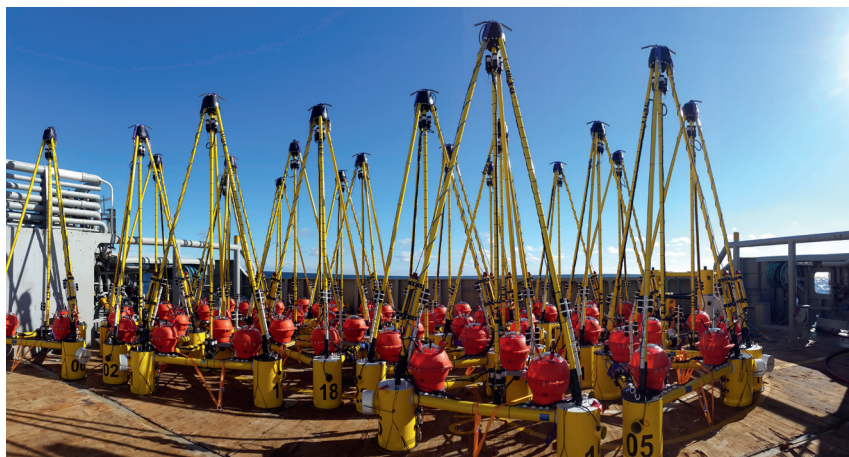
The development of marine CSEM techniques (Chave & Cox, 1982) has been driven by the limitations associated with using MT at sea. Research into such methods was launched in the late 1970s by the Scripps Institute of Oceanography in California. Natural electromagnetic sources were replaced by artificial and controllable devices that made it possible, among other things, to control the frequency components of transmitted electromagnetic fields. In the 1980s, development was continued by several academic research groups, but up until the turn of the new millennium marine CSEM remained for the most part an academic discipline, focusing on investigations of the major structures of the Earth's subsurface, and involving a limited number of research scientists.

During the first decade of the 21<sup>st</sup> century commercial applications arose as companies such as EMGS and Ohm took the principles of CSEM to the application of hydrocarbon exploration. The development of marine CSEM for use in the oil and gas sector was partly driven by limitations of the seismic techniques, which primarily provides structural information. CSEM methods

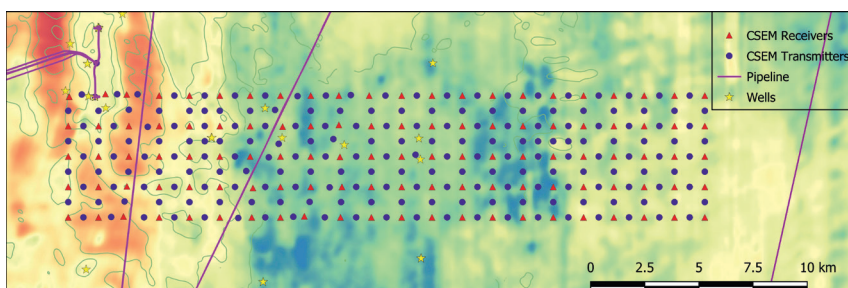
detect contrasts in electrical conductivity, exploiting the fact that the electrical conductivity of hydrocarbon-saturated reservoirs is significantly smaller than in the surrounding sediments, which are saturated with salt water. The contrast is typically a factor 10-100. Hydrocarbons exhibit relatively high resistivities, typically in the range 20 to 100  $\Omega\text{m}$ , while formation brines have relatively low resistivities, typically between 0.25 and 0.3  $\Omega\text{m}$ . There is a considerable difference between the resistivity of a reservoir formation containing hydrocarbons and one containing brine. Thus, CSEM directly measures independent geophysical parameters related to saturation of hydrocarbons and can provide significant reductions in the risks and costs associated with exploration and production when integrated into the exploration toolkit (Constable 2010; Buland et al 2011)

### Marine CSEM surveying

Marine CSEM surveys require an artificial electromagnetic field source, one or more electromagnetic signal receivers, and a vessel to carry the equipment. Standard marine CSEM techniques utilize a dipole source, which can be oriented either horizontally or vertically. Operation of the source involves towing the source submerged behind the vessel or deployment of a stationary source. Similarly, receivers recording components of the electromagnetic field are placed on the seabed in pre-defined patterns or towed behind a vessel. Typically, a single source is used in combination with many receivers in different positions.



**Figure 3** CSEM receivers with dipoles for tri-axial recording of electric field.



**Figure 4** CSEM survey layout for stationary transmitter and receiver positions.

The electromagnetic signals are transmitted with a waveform optimized for the geophysical setting and survey objectives. The waveform contains a signal with alternating polarity, either with continuous transmission or silent periods without transmission. The signals are recorded continuously by the receivers during transmission and inactive periods.

The electromagnetic field will propagate from the source in all directions, both downwards through the water, penetrating the seabed, and upwards into the air. Receivers will record this transmitted field. What is of interest is the measurement of the response to the transmitted field as it propagates through the geological subsurface. These response signals will be influenced and modified by the resistivity of the different subsurface formations it passes through.

### CSEM data processing

The time series signals recorded at the receivers are commonly referred to as the raw data, which needs to be processed and inverted to allow imaging and interpretation of the resistivity distribution in the subsurface. The goal of the processing is two-fold: to improve signal-to-noise ratio in the signal, and to extract the specific information within the signal sensitive to resistivity changes.

While the original recording is in time domain, signal analysis can be performed either in frequency domain or time domain. In the frequency domain, a measured deviation in the form of a stronger and higher velocity signal will typically be the result of transmitted electromagnetic signals having been guided through a resistive body, and frequency and phase content in the recorded signal will contain information on the presence and location of resistivity contrasts. For time domain analysis, the fact that time dependent electrical discharge is directly related to the resistivity distribution is exploited. A resistive feature will cause a faster diffusion process than a low resistive; also, the depth of the resistive feature will be coded in the time domain signal.

A challenge common to all EM technologies is to obtain sufficient signal-to-noise. There are many different noise sources that may affect the measurement and sensitivity (Mittet, 2012). Ambient noise sources independent of the measurement system such as variations in the earth magnetic field will affect the recordings. Other noise sources can be internal, such as electronic noise in the receiver system. Furthermore, additional noise can be caused by interactions of the measurement system with the surroundings, such as motion-induced noise caused by currents in the conductive sea.

The aim of data processing is to enhance the relevant signal information and suppress noise to achieve a broader and more

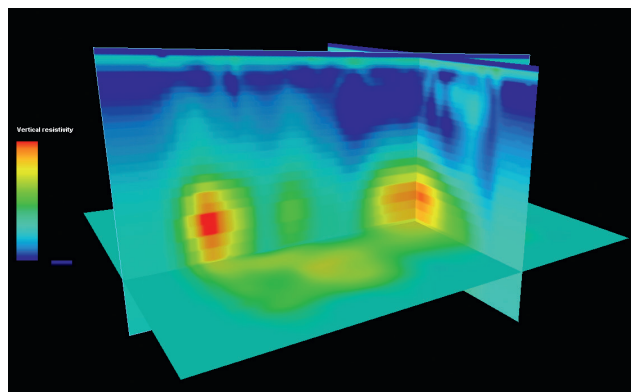
robust basis for further data analysis. It usually involves a process called ‘stacking’ by which data that ostensibly belong together are gathered with the aim of achieving a broader and more robust basis for data analysis. This is carried out in different ways depending on the CSEM technique that has been applied. For example, stacking may be performed based on common frequency, common location or common time.

### Inversion

For interpretation of CSEM data the measurements of electrical voltage on the sea floor are converted to a matching resistivity distribution for the subsurface. The standard process for this is through computational inversion. A forward solver based on the mathematical framework of Maxwell’s equations will calculate a synthetic data set for a specific resistivity distribution. The synthetic data is compared to the field data, and the resistivity model is iteratively updated according to a minimization scheme aimed at reducing the data misfit between field data and synthetic data. This optimization problem is highly non-linear, and small variations in input data can lead to instability for the solution models. Solutions are in general also non-unique, as multiple or even infinite models can explain the observed data.

To obtain stable and unique solutions regularization methods are applied to select appropriate classes of models. Furthermore, constraints can be imposed on the model to implement a priori knowledge about the geology. For example, geometrical constraints known from seismic or resistivity information from well logs can be used to control the inversion. The final output is a spatial resistivity distribution that best matches the field data within data uncertainty.

The significant advances in CSEM acquisition technology have been closely followed by the need for inversion



**Figure 5** 3D resistivity volume from unconstrained inversion.



algorithms which can handle the large-scale data sets. Over the last 15 years sophisticated 3D inversion algorithms have been developed to ensure efficient computation, and inversion code development remains an important research field for the CSEM industry. The 3D codes are usually based on standard minimization methods such as Gauss-Newton, Gradient Descent or Levenberg-Marquardt. In parallel to improvements in numerical performance, forward algorithms have been enhanced to take into account key geophysical features of resistivity. For example, advanced interpretation requires proper handling of anisotropic effects such as Vertical Transverse Isotropy or Tilted Transverse Isotropy. Another active area of development is joint inversion, where the CSEM data is inverted simultaneously with and dependent on other data sets such as MT or seismic data (Johansen et al, 2019).

### Interpretation

Upon completion of the data inversion the final and most important part of the CSEM workflow begins. The output from an inversion workflow gives a resistivity distribution, but these results need to be interpreted and integrated in a geological context. For advanced applications quantitative analysis is necessary and the resistivity distribution needs to be founded on an understanding of underlying rock physics. Seismic data provides structural and stratigraphic information, but often provides less information about fluid content and hydrocarbon volumes. The reservoir geometry from modern seismic data, jointly interpreted with matching high-quality CSEM data, gives a better pre-drill prediction of the reservoir and understanding of the geological model. Quality seismic data is important for an accurate integration with CSEM data

as it allows for improved constraints, especially in a reservoir delineation or monitoring application.

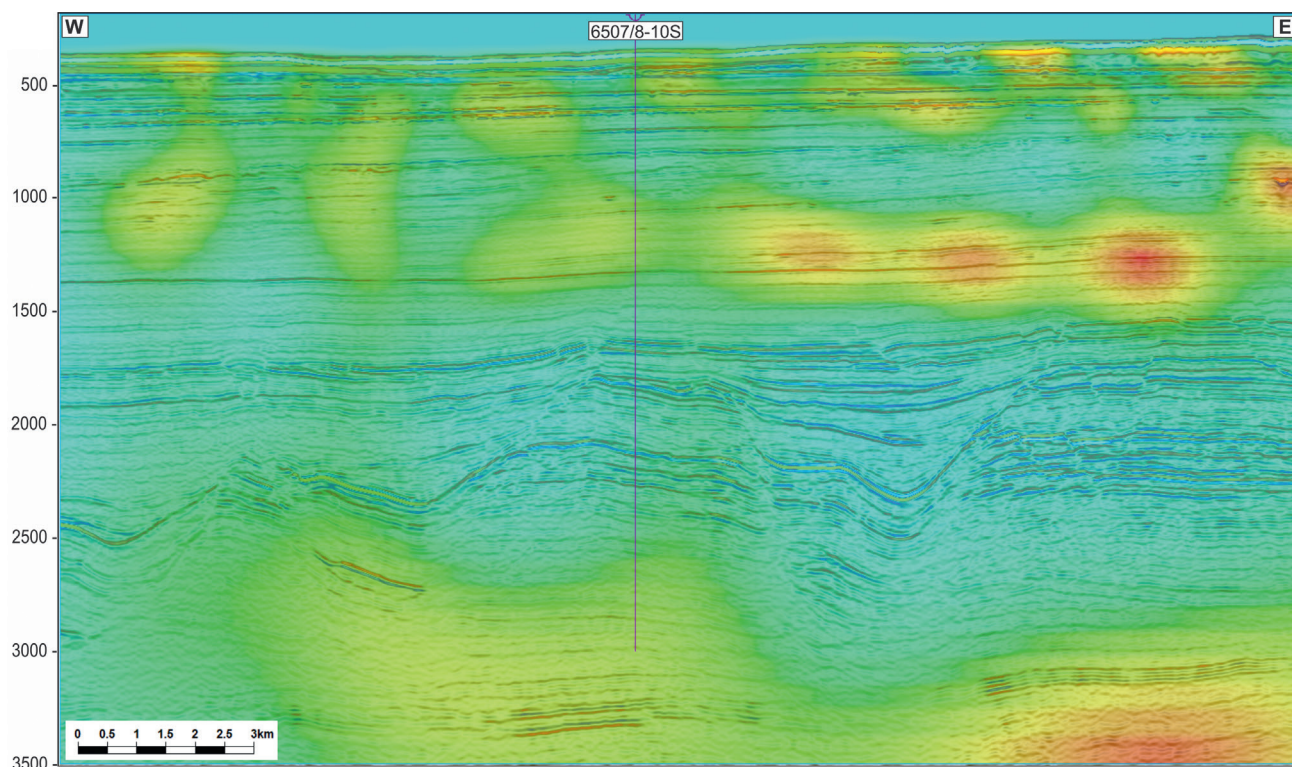
### Grind prospect — a recent application for de-risking

Historically, the main application of CSEM in hydrocarbon exploration has been prospect de-risking. The presence or absence of a resistive anomaly correlating with a prospect defined through seismic investigations can provide valuable independent information and significant risk reduction for a drilling decision. At the same time, a proper geological understanding and data integration is necessary when interpreting CSEM results. A recent case study from the Norwegian Continental Shelf exemplifies the potential of CSEM for de-risking.

In 2017 Allton acquired vertical 3D CSEM for a 500 km<sup>2</sup> multi-client project in the Haltenbanken area, a mature area with several well-known fields such as Heidrun and Midgard/Åsgard complex. The acquisition tied into both discoveries/fields and dry wells, allowing calibration of the CSEM data against the existing resistivity logs. The acquisition utilized a 3D grid with vertical transmitters and receivers deployed with 1700 m spacing. A total of 211 transmitters and 221 receivers were acquired.

The acquisition area covered several exploration targets mapped from seismic data, including the Grind prospect which was drilled in 2020 and proved dry. Grind was a prominent 4-way closure 10 km east of the Heidrun field, making it an attractive prospect close to existing production facilities. The target was a mid-Jurassic play around 2000 m below sea level, and the primary risk associated with the prospect was migration.

Results of synthetic modelling completed prior to acquisition indicated that the area was well suited for CSEM. The sea



**Figure 6** Unconstrained inverted resistivity section co-rendered with seismic at the Grind well location.

depth of approximately 300 m allows both a high signal level from the vertical dipole transmitter, and low ambient noise levels at seabed due to sea shielding effects. From a geological perspective the background resistivities observed from resistivity logs are moderate with typical observed horizontal resistivities below 3  $\Omega\text{m}$ , potentially allowing high resistivity contrast for a hydrocarbon saturated reservoir. The conclusions from feasibility modelling were that a Grind reservoir moderate total transverse resistance would have a strong signature in the CSEM data.

The vertical transmitter-vertical receiver CSEM data was inverted in both 2D and 3D, but inversion did not recover any resistive features in the region associated with the Grind target (Figure 6). The consistent lack of an anomalous structure reduced the likelihood for a hydrocarbon presence, and Allton interpretation predicted a water-filled reservoir. The Grind prospect was drilled in spring 2020, and the dry result confirmed the CSEM prediction.

### Outlook: CSEM repeatability and 4D applications

The maturation of CSEM technologies has seen significant improvements both in instrumentation and for data processing, inversion and interpretation tools. These improvements open new possibilities for more advanced applications of CSEM. In particular, the increased accuracy allows for repeatability or time-lapse applications, where production changes in resistivity are monitored over time.

Since the resistivity is directly linked to hydrocarbon saturation, time lapse measurement can be used to monitor fluid changes caused by the production of a field. The objective is to determine the changes occurring in the reservoir as a result of hydrocarbon production or injection of water or gas into the reservoir by comparing the repeated datasets. While seismic time-lapse applications have been used for a number of years with success, a CSEM application integration adds complementary information based on independent geophysical parameters and can improve the understanding of reservoir behaviour. Oil, gas and water movements can be measured highlighting bypassed or poorly drained portions of a producing field, ultimately leading to optimized well planning, avoiding noncommercial production wells, better artificial lift implementation and increased recoverability.

Sensitivity studies have demonstrated that very high accuracy is necessary to achieve the required resolution for time lapse applications (Orange et al, 2009). In particular, strict requirements are placed on the positioning when measurements are repeated. A stationary acquisition configuration, as provided by Allton, allows for accurate acquisition repeatability after the baseline survey, reducing the acquisition uncertainty. The vertical dipole transmitter can also reduce the coupling with conductive infrastructure such as pipelines and wells in the vicinity of the transmitter, another challenge time-lapse CSEM solves. Development of inversion schemes operating on time lapse data and aimed at resolving changes in resistivity distribution will also be necessary to achieve the resolution required for reservoir management and well intervention in a production setting.

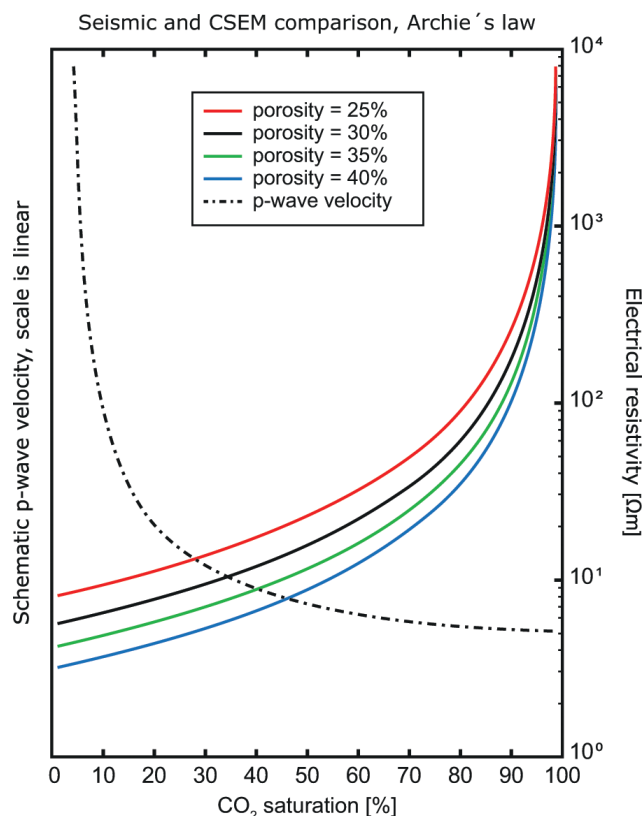


Figure 7 Comparison of p-wave velocity and resistivity as function of CO<sub>2</sub> saturation.

### Carbon capture and storage

Mitigation of the increased concentration of carbon dioxide in the atmosphere is a major political and scientific challenge in upcoming decades. One of the leading mitigation methods under consideration for atmospheric CO<sub>2</sub> reduction is carbon capture and sequestration where carbon dioxide is captured from industrial sources or the atmosphere and injected into an underground reservoir for permanent storage. This opens up a new application for time lapse CSEM, monitoring of CO<sub>2</sub> sequestration in these reservoirs. To ensure the integrity of a carbon storage reservoir the injection will need to fill the storage reservoir as predicted, the CO<sub>2</sub> will need to remain sealed in the reservoir and the risk of leakage through uncertain seals or faults in the reservoir will need to be reduced. One strategy is to monitor and verify CO<sub>2</sub> distribution through time lapse measurements, informing regulators of any CO<sub>2</sub> movement. Such a risk reduction application involving a continuous site monitoring programme would provide public and stakeholder confidence in safe storage. If migration beyond the storage reservoir is detected, injection of further CO<sub>2</sub> could be stopped at an early stage.

The resistivity of an aquifer containing CO<sub>2</sub> is highly dependent on CO<sub>2</sub> saturation, with rock physics models predicting resistivity changes over orders of magnitude as partial saturation increases. CSEM measurements will have great sensitivity to increasing saturation changes while seismic p-waves will not have the same sensitivity to mid-to-high saturation changes. (Figure 7) In addition, the saturated volumes can also have high resistivity contrast to adjacent water-filled formations, allowing accurate lateral imaging.

Monitoring CO<sub>2</sub> storage is a highly complicated geophysical problem which requires an integrated multi-physics approach, and the direct observation of fluid saturation through CSEM measurements can potentially provide a cost-efficient methodology and a telling additional inversion tool to enhance a CO<sub>2</sub> monitoring system if saturation changes lead to a significant resistivity contrast in the reservoir fluids.

CSEM techniques and technology have continuously progressed since the beginning of commercial offerings of marine CSEM in 2002. However, CSEM technology still holds great potential for advancement, especially with applications for 4D oil and gas monitoring and for measurement, monitoring and verification of CO<sub>2</sub> injection sites. Expansion of current CSEM applications will require continued adaptation of the present-day technology in addition to investment in technology improvements for new 4D applications.

## References

- Ayani, M., Grana, D. and Liu, M. [2020] Stochastic inversion method of time-lapse controlled source electromagnetic data for CO<sub>2</sub> plume monitoring, *International Journal of Greenhouse Gas Control*, **100**, 103098.
- Bhuyian, A.H., Landrø, M. and Johansen, S. [2012] 3D CSEM modeling and time-lapse sensitivity analysis for subsurface CO<sub>2</sub> storage. *Geophysics*, **77**, E343-355.
- Buland, A., Løseth, L.O., Becht, A., Roudot, M. and Røsten, T. [2011] The value of CSEM data in exploration. *First Break*, **29**(4), 69-76.
- Cagniard, L. [1953] Basic theory of the magneto-telluric method of geophysical prospecting. *Geophysics*, **18**(3), 605-635.
- Chave, A.D. and Cox, C.S. [1982] Controlled electromagnetic sources for measuring electrical conductivity beneath the oceans 1. Forward problem and modeling study. *J. Geophys. Res.*, **87**, 5327-5338.
- Constable, S. [2010] Ten years of marine CSEM for hydrocarbon exploration. *Geophysics*, **75**, A67-A81.
- Correa, J.L. et al. [2019] Marlim R3D: A realistic model for controlled-source electromagnetic simulations – Phase 2: The controlled-source electromagnetic data set. *Geophysics*, **77**, E343-355.
- Ellingsrud, S., Eidesmo, T., Johansen, S., Sinha, M.C., MacGregor L.M. and Constable, S. [2002] Remote sensing of HC layers by seabed logging (SBL): Results from a cruise offshore Angola. *The Leading Edge*, **21**(10), 972-982.
- Johansen, S.E., Panzner, M., Mittet, R. et al. [2019] Deep electrical imaging of the ultraslow-spreading Mohs Ridge. *Nature* **567**, 379-383.
- Mittet, R. and Morten, J.P. [2012] Detection and imaging sensitivity of the marine CSEM method. *Geophysics*, **77**, E411-E425.
- Orange, A., Key, K. and Constable S. [2009] The feasibility of reservoir monitoring using time-lapse marine CSEM: *Geophysics*, **74**(2), F21-F29.