Faculty of Natural and Applied Sciences Journal of Applied and Physical Sciences
Print ISSN: 3026-9857
www.fnasjournals.com
Volume 2; Issue 1; September 2024; Page No. 99-115.

A Review of the Applications of Marine CSEM Method in Offshore Resource Exploration and Environmental Studies

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Abstract
A review of the applications of marine Controlled-Source Electromagnetic (mCSEM) method in offshore resource explorations and environmental studies is undertaken in this paper. Initially revisited for offshore hydrocarbon exploration, CSEM has expanded its utility beyond this to other application in the offshore industry such as production monitoring, environmental studies, and even sub-seafloor groundwater mapping, due to its ability to isolate high resistive layer below the mudline. This study looks into the fundamental principles of CSEM, including electromagnetic induction and wave propagation, and delves into its instrumentation, survey design, and data interpretation processes. Key concepts such as shared earth modeling, seabed isotropy, resistivity variations, and attribute analyses are examined to enhance the understanding of CSEM's effectiveness in mapping subsurface conductivity. Significant advancements in CSEM technology and methodologies have addressed challenges associated with marine environments, making it a reliable and cost-effective tool for offshore exploration. The study highlights the potential impact of CSEM on various industries, including energy and mining, and underscores its importance in the ongoing evolution of geophysical exploration techniques.

Keywords: Marine CSEM, Offshore Exploration, Innovative Applications, Resource Exploration, Environmental Studies

Introduction

Offshore resource exploration plays a crucial role in identifying and extracting valuable natural resources such as oil, gas, and minerals from beneath the seabed. The increasing demand for energy and raw materials has driven the need for more sophisticated exploration techniques. Simultaneously, environmental studies have gained importance due to the potential ecological impacts associated with offshore resource extraction. Understanding the marine environment, assessing the impact of resource extraction, and ensuring sustainable practices are essential components of offshore environmental studies. Traditional exploration methods, such as seismic surveys, have been widely used, but they often face limitations in complex geological settings and in assessing the environmental impact of resource extraction (Smith, 2018). The Marine Controlled-Source Electromagnetic (CSEM) method has emerged as a promising geophysical technique for offshore exploration and environmental studies. This method involves transmitting electromagnetic fields through the seafloor and measuring the resulting signals to infer the subsurface electrical conductivity. The CSEM method offers several advantages over traditional seismic techniques, particularly in detecting and characterizing hydrocarbon reservoirs in challenging environments. Its ability to provide complementary data to seismic surveys has made it an essential tool for reducing exploration risks and enhancing resource evaluation accuracy (Jones & Brown, 2019; Folorunso, 2015). Recent innovations in the Marine CSEM method have expanded its applications beyond traditional resource exploration to other applications such as to delineate complex reservoirs, particularly in deepwater and ultra-deepwater environments, environmental studies, such as monitoring carbon capture and storage (CCS) sites, assessing the impact of resource extraction on marine ecosystems, reservoir production monitoring, mapping of an offshore freshened groundwater system and studying the electrical properties of marine sediments (Ellingsrud et al., 2002; Weitemeyer et al., 2006a; Lien & Mannseth, 2008; Liang et al., 2012; Folorunso et al., 2015; Micallef et al., 2020, Fawad & Mondol, 2021; Folorunso 2022). These applications demonstrate the versatility of the Marine CSEM method in addressing both resource exploration challenges and environmental concerns in offshore settings (Williams & Clark, 2020).

Cite this article as:
Ofubu, E.E., Folorunso, A.F., & Chukwusa, F.O. (2024). A review of the applications of Marine CSEM method in offshore resource exploration and environmental studies. *FNAS Journal of Applied and Physical Sciences, 2*(1), 99-115.

Marine Controlled Source Electromagnetic (mCSEM) Method

Marine Controlled-Source Electromagnetic (mCSEM) surveying has become a game-changerin hydrocarbon exploration and other subsurface imaging purposes over the past few years (Constable, 2010). By examining the variations in these fields, CSEM allows for the detection and characterization of subsurface structures, such as hydrocarbon reservoirs, gas hydrates, and mineral deposits (Constable & Weiss, 2006). The principles of electromagnetism underpin CSEM, where changes in subsurface electrical conductivity result in corresponding alterations in the measured electromagnetic fields. Through precise control of source signals and careful analysis of the received data, CSEM surveys can map subsurface structures in detail, providing valuable insights into the distribution, composition, and geometry of geological formations (Constable & Weiss, 2006). The development of marine CSEM began with academic research in the 1980s, initially focusing on deepwater, frequency-domain, electric dipole-dipole methods (Constable & Srnka, 2007). Instrumentation for marine magnetotelluric and controlled-source electromagnetic soundings has been extensively reviewed, highlighting the significance of electromagnetic transmitters and receivers in marine settings (Constable, 2013). Data on electrical resistivity obtained from marine CSEM surveys can offer insights into the presence and volume of gas hydrates within sub-seafloor sediments (Schwalenberg et al., 2020). Finite element modelling has been used to simulate marine CSEM responses across various conductivity structures, demonstrating the method's effectiveness in mapping offshore hydrocarbon reservoirs (Li & Dai, 2011).

Marine CSEM is particularly sensitive to the lateral extents and thicknesses of resistive bodies within conductive hosts, making it a powerful tool for subsurface mapping (Zhdanov et al., 2014). The use of optimal transmitter waveforms, such as square waves, is commonly employed in marine CSEM surveys to improve data quality (Mittet &Schaug-Pettersen, 2008). Additionally, the application of marine CSEM has been extended to the detection of gas hydrates offshore, as shown by surveys conducted at Hydrate Ridge, Oregon (Weitemeyer et al., 2006b). The 3D marine controlled-source electromagnetic method plays a critical role in exploration geophysics, aiding in the detection and characterization of gas hydrates and other sub-seafloor features (Castillo-Reyes et al., 2018). Significant advancements in CSEM technology and methodologies have addressed many challenges associated with marine environments, including seawater conductivity, seafloor topography, and signal propagation characteristics. These developments have made CSEM increasingly reliable and cost-effective for marine exploration efforts (Constable & Weiss, 2006). This seminar provides an in-depth review of the Marine Controlled-Source Electromagnetic (CSEM) method, covering its principles, applications, advantages, and challenges in marine environments. By drawing on existing literature and case studies, this paper aims to highlight the evolving role of CSEM in offshore resource exploration and its potential impact on industries ranging from energy to mining.

Principles of CSEM in Marine Environments

Electromagnetic (EM) methods are geophysical exploration techniques that utilize electromagnetic fields to study the Earth's subsurface properties, such as electrical conductivity, permittivity, and magnetic susceptibility (Mittet & Morten, 2013). These methods are rooted in the principles of electromagnetic induction and wave propagation.

A. Electromagnetic Induction: Electromagnetic induction occurs when an electromagnetic field generates electrical currents in conductive materials. The strength and distribution of these induced currents provide valuable information about subsurface properties, as explained by Faraday's Law of induction. This law states that a time-varying magnetic field produces a voltage that drives an electric current. These induced currents can appear as in-phase or quadrature sinusoidal waves and can be measured in both frequency and time domains (Mittet & Morten, 2013).

B. Electromagnetic Wave Propagation: Electromagnetic waves, typically in the form of alternating currents, are transmitted into the Earth's subsurface. The subsurface response, characterized by induced currents and secondary electromagnetic fields, is measured to infer subsurface properties. Maxwell's equations, which describe the behavior of electromagnetic fields in various media, govern the propagation of EM waves. As these signals penetrate the Earth, they propagate through diffusion, where the time-varying magnetic field induces an oscillating electric current. As these currents flow, energy is dissipated as heat, causing the amplitude of the EM signal to decrease exponentially with distance (Mittet & Morten, 2013). Electromagnetic methods generate and measure electromagnetic fields to infer subsurface properties. These methods, including Magnetotellurics (MT), Controlled-Source Electromagnetics (CSEM), Frequency-Domain Electromagnetics (FDEM), Time Domain Electromagnetic Method (TDEM), Ground Penetrating Radar (GPR), Electromagnetic Induction (EMI), and Transient Electromagnetics (TEM), are used for various applications such as mineral exploration, groundwater studies, environmental investigations, oil and gas exploration, engineering assessments, and archaeological investigations (Constable & Weiss, 2006; Mittet & Morten, 2013).

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C. Electromagnetic Methods in Marine Exploration

I. Magnetotellurics (MT): MT surveys measure natural variations in the Earth's electromagnetic fields caused by solar and cosmic radiation. These variations are influenced by subsurface conductivity structures, allowing researchers to infer the electrical properties of geological formations. MT is particularly effective for investigating large-scale geological features and deep-seated structures, making it valuable for regional studies in marine geophysics (Egbert & Booker, 1986).

II. Controlled-Source Electromagnetics (CSEM): CSEM surveys involve the transmission of controlled electromagnetic signals from a seabed source into the subsurface. The induced electromagnetic fields are captured by seafloor receivers, providing insights into variations in subsurface conductivity. CSEM is especially useful for detecting hydrocarbon reservoirs and mineral deposits beneath the seafloor due to its sensitivity to changes in electrical conductivity associated with these formations (Constable & Weiss, 2006).

III. Frequency-Domain Electromagnetics (FDEM): FDEM surveys employ electromagnetic signals at varying frequencies to investigate subsurface conductivity variations. By analyzing the responses of electromagnetic fields at different frequencies, FDEM surveys can delineate geological structures and detect mineral deposits beneath the seafloor.

IV. Time Domain Electromagnetic Method (TDEM): Also known as Transient Electromagnetics (TEM), TDEM is a geophysical survey technique designed to detect subsurface conductivity variations. It involves generating a primary electromagnetic field by transmitting a current through a loop or wire. When the current is suddenly turned off, the decaying magnetic field induces eddy currents in the subsurface (Vignesh et al., 2015). These secondary fields are measured over time, providing data on the subsurface resistivity distribution. TDEM is effective for mapping subsurface features to considerable depths and delivers high-resolution data for hydrogeological investigations, environmental studies, and mineral exploration (El-Kaliouby & Abdalla, 2015).

Fundamentals of Controlled Source Electromagnetic (CSEM) Technique

The Controlled Source Electromagnetic (CSEM) technique has become a highly effective geophysical method for subsurface imaging, especially in marine settings. This section offers a detailed examination of the key aspects of the CSEM technique, including its principles, instrumentation, survey design, and data interpretation.

Principles of CSEM: The CSEM technique is grounded in the principles of electromagnetism, which it uses to investigate variations in subsurface conductivity. This method involves the controlled transmission of electromagnetic signals from a seabed source into the Earth's subsurface. As these signals interact with subsurface geological formations, they induce secondary electromagnetic fields. The technique operates on the principle of electromagnetic induction, where the transmitted electromagnetic field generates eddy currents within the subsurface (Figure 1). These eddy currents, in turn, generate secondary electromagnetic fields that can be measured and analyzed to determine the subsurface's electrical conductivity. This conductivity is linked to geological characteristics such as porosity, permeability, and fluid content, making CSEM an invaluable tool for both hydrocarbon exploration and environmental monitoring (Constable & Weiss, 2006).

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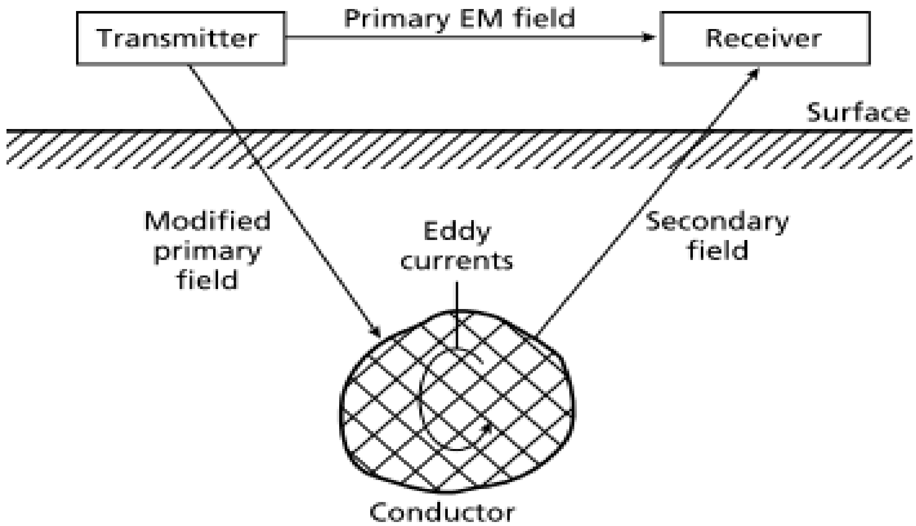


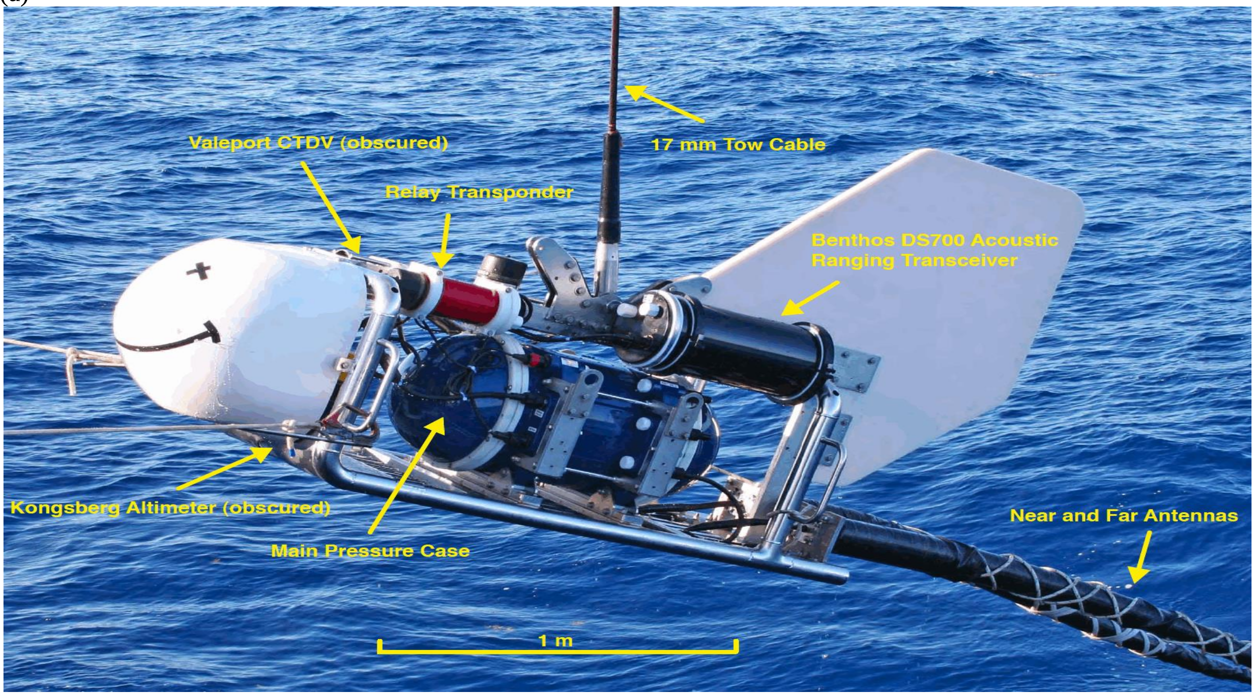
Fig 1: General principle of Electromagnetic Surveying (Kearey et al.,2002).

Instrumentation

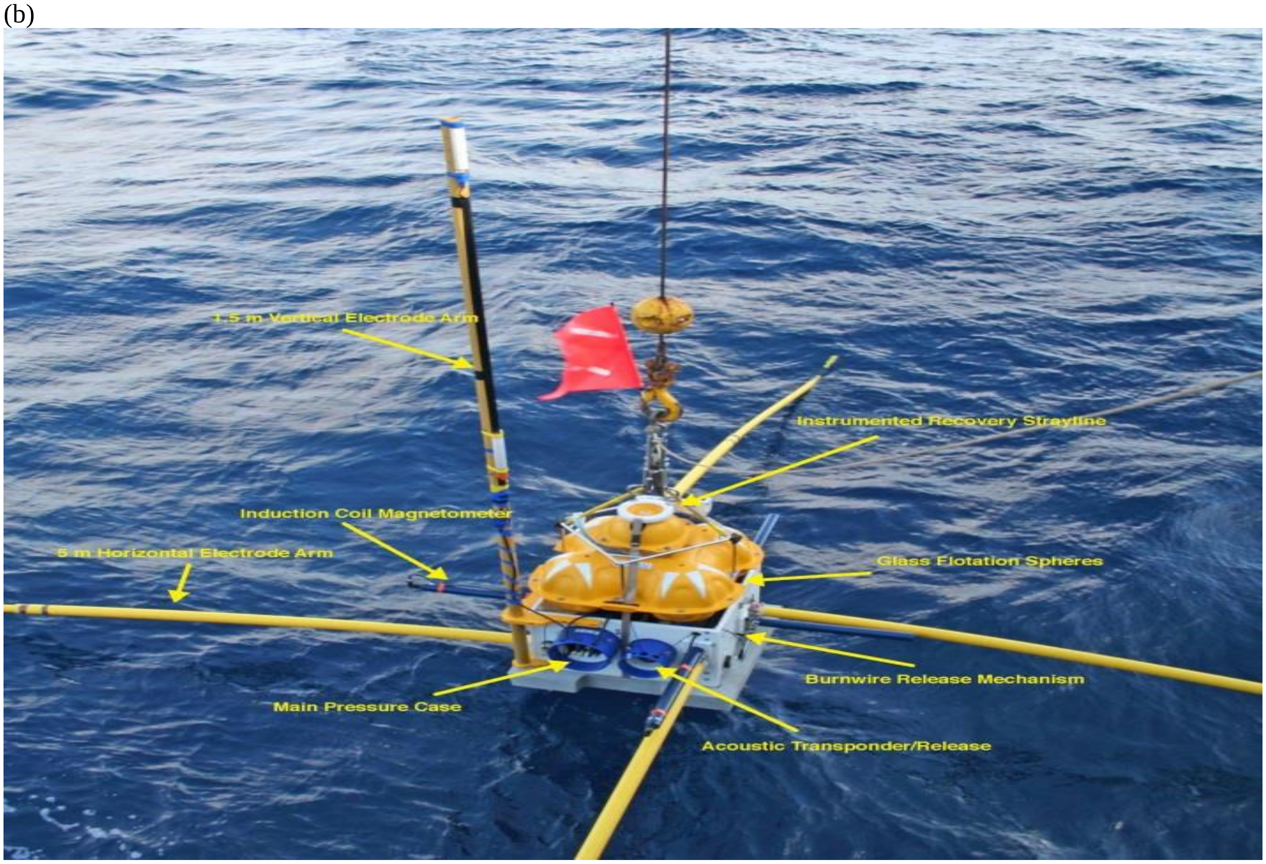
The major instruments needed in marine CSEM surveys consist of a deep-towed transmitter (**the source**) and ocean bottom electromagnetic (OBEM) **receivers.** The source is usually an electric dipole antenna or a horizontal electric current source (Figure 2a). It consist of a horizontal electric dipole (HED) transmitter towed 25–100 meters above the seafloor and a horizontal dipole antenna, usually 50–300 meters long, transmitting EM signals at preset frequency (frequency ranging from 0.01 – 10 Hz) (Constable 2010, Folorunso 2015). The seabed source transmits controlled electromagnetic signals into the subsurface.

The ocean bottom electromagnetic (OBEM) receivers are self-contained, battery powered and completely autonomous seafloor data logging system, having high accurate clocks for timekeeping, even when towed on the sea-floor or in the water column behind a transmitter (Figure 2b&c). The OBEM receivers capture the resulting induced electromagnetic signals emanating from the subsurface or sub-seafloor (Key and Constable, 2021; Folorunso, 2022). These receivers are arranged in a grid pattern on the seafloor to gather data across a broad area (Constable & Weiss, 2006).

(a)


Valeport CTDV (obscured)
17 mm Tow Cable
Relay Transponder
Benthos DS700 Acoustic
Ranging Transceiver
Kongsberg Altimeter (obscured)
Main Pressure Case
Near and Far Antennas
1 m

(b)


1.5 m Vertical Electrode Arm
Instrumented Recovery Strayline
Induction Coil Magnetometer
5 m Horizontal Electrode Arm
Glass Flotation Spheres
Burnwire Release Mechanism
Main Pressure Case
Acoustic Transponder/Release

(c) 

Figure 2: (a) mCSEM transmitter (b) mCSEM OBEM receiver (Courtesy of SCRIPPS Institution of Oceanography, USA) and (c) Ocean University of China's OBEM receiver during operation in early 2015.

Other accessories required include long baseline or short baseline acoustic ranging needed to navigate both receivers and transmitters. Compasses and tiltmeters are also needed by the seafloor receivers for additional measurements of orientations. All equipment has to be packaged to accommodate the high pressure (up to 40 MPa) and corrosive properties of the seawater environment (Key, 2011).

Survey Design and Field Techniques

CSEM surveys are carefully planned to enhance data collection and imaging effectiveness. Key parameters like the distance between the transmitter and receiver (i.e. transmitter-receiver offset – Tx-Rx), signal frequency, and the arrangement of the receiver array are strategically selected through rigorous forward modeling to achieve the desired investigation depth and resolution (Myer et al., 2012; Folorunso and Li, 2014; Folorunso,2015 and Folorunso, 2022). The survey layout is also customized to meet the specific goals of the exploration, whether for hydrocarbon detection, mineral exploration, or environmental assessments (Constable & Srnka, 2007).

The field techniques in the marine CSEM survey involve different acquisition methods as depicted in Figure 3. This include horizontal electric dipole (HED) source with seabed receivers, horizontal electric dipole (HED) source with cable towed receivers, and vertical electric dipole (VED) source with seabed receivers (Johansen and Gabrielsen 2015; Folorunso, 2022).

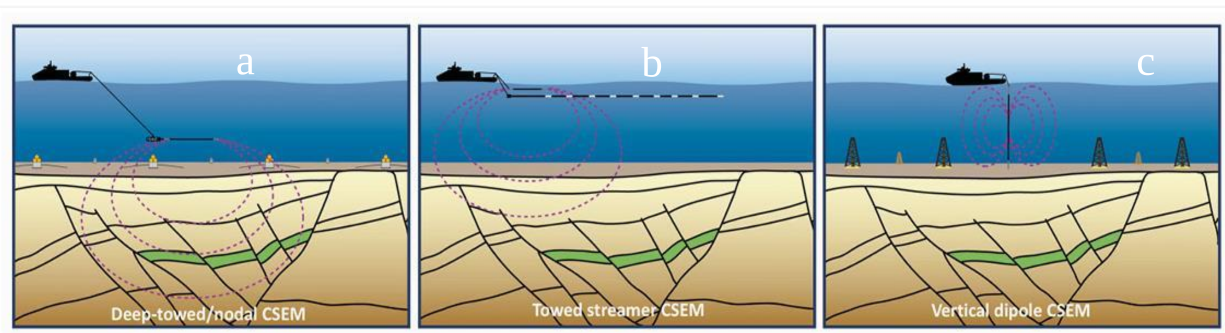


Figure 3. The t**hree different methods for marine CSEM data acquisition** (a) The traditional method involves deploying receivers on the seafloor and using a deep-towed electromagnetic (EM) source to collect data (b): The towed streamer EM system, where both the source and receivers are towed behind the survey vessel, allows for faster data collection. However, this approach is typically effective in water depths of less than about 500 meters. (c) The vertical dipole system employs seafloor-deployed receivers and stationary transmission stations for data acquisition (MacGregor et al., 2019, Folorunso, 2022). Li et al. (2022a) provided a schematic overview of the fundamental mCSEM method and how electromagnetic fields are transmitted as shown in Figure 4. The black arrows represent the reflected and refracted transmission of electromagnetic signals at the seawater–air interface, commonly known as airwaves. The airwave is more predominant at shallow depth, masking the EM signal but reduces significantly at deep and ultradeep water depth (Sasaki, 2011; Folorunso and Li, 2015). In Figure 4, the blue arrows indicate the direct transmission of the source field. Green arrows show the reflection and refraction of electromagnetic signals along the seabed. Red arrows depict the reflected and refracted transmission of electromagnetic signals through a buried high-resistivity layer, such as a hydrocarbon reservoir (Li et al., 2022a). It is this guided EM energy that constantly leaks back to the seafloor that is recorded by the EM receivers.

Typical acquisition vessel with all settings is shown in Figure 5. This figure illustrates the fundamental setup of marine CSEM used in hydrocarbon exploration. The electromagnetic (EM) signal propagates in all directions through seawater, the air–seawater interface, and sediment layers before being captured by EM receivers (Aris et al., 2019).

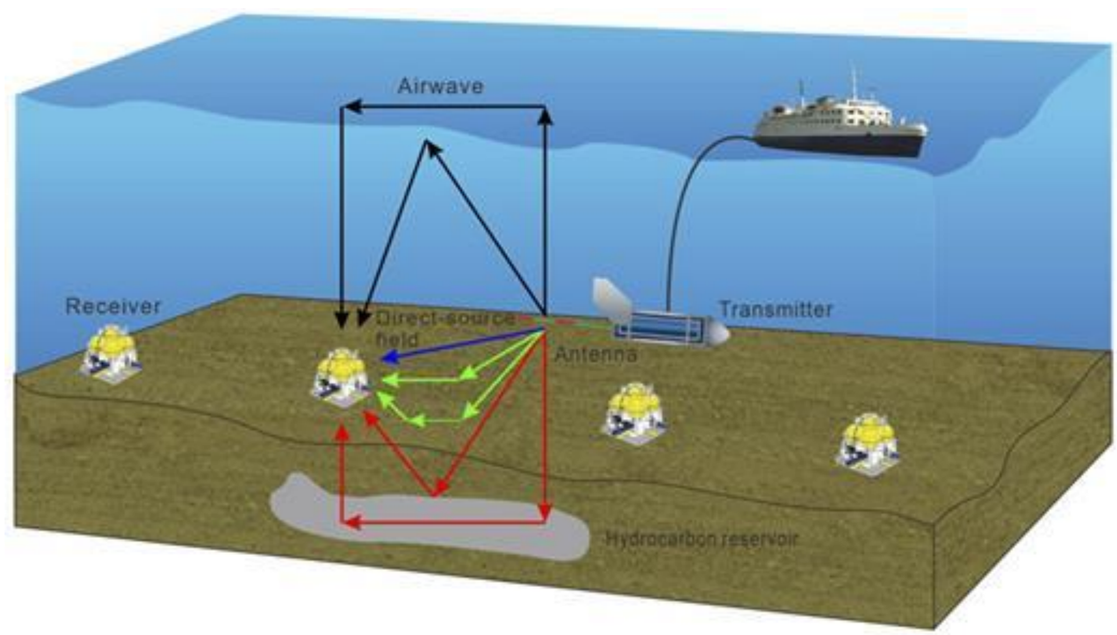


Figure 4:A schematic overview of the fundamental MCSEM method and how electromagnetic fields are transmitted (Adapted from Li et al., 2022a).

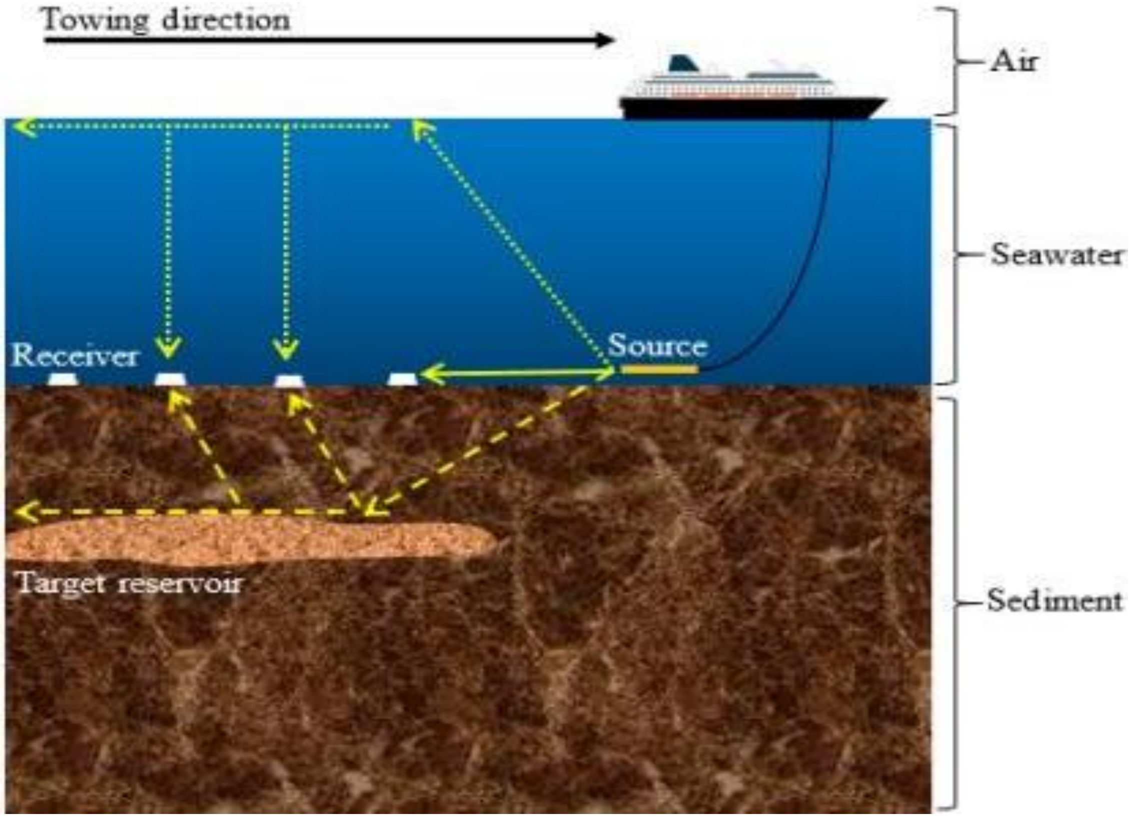


FIG 5: Marine CSEM acquisition field setup used in hydrocarbon exploration (Adapted from Aris et al., 2019).

Data Interpretation: Interpreting CSEM data entails examining the recorded electromagnetic fields to deduce subsurface conductivity structures. Advanced inversion algorithms are utilized to convert raw data into detailed subsurface conductivity models. These models offer valuable insights into geological formations, including hydrocarbon reservoirs, mineral deposits, and fluid migration pathways. Key Parameters and Concepts. Parameters and concepts crucial to understanding and interpreting marine controlled-source electromagnetic (mCSEM) methods include:

i.Shared Earth Modelling: The integration of shared earth modelling is essential for obtaining reliable quantitative interpretations from marine CSEM data (Constable, 2010). Shared earth modelling entails creating a quantitative representation of the subsurface, which can be utilized to determine resource size and predict fluid flow performance. This approach incorporates static and dynamic data from various disciplines into a comprehensive subsurface model that evolves as new data, including marine CSEM data, are collected and integrated. One challenge, known as the 'scale-up' problem, often arises when integrating data obtained at different scales into the shared earth model. Nevertheless, the effectiveness of this approach has been demonstrated in complex geological settings, improving field appraisal and reducing exploration risks (Dell'Aversana et al., 2012). This integrated method, which also incorporates seismic and gravity data, has proven particularly beneficial in shallow water environments (Dell'Aversana, 2007). Additionally, 3D inversion of marine CSEM data can enhance survey design and improve reservoir resolution (Bornatici, 2007). Shared Earth Modelling (SEM) represents a collaborative approach to subsurface modelling, integrating multiple datasets—including seismic, electromagnetic, well log, and geological information—into a unified 3D representation of the Earth's subsurface. This integrated model provides a comprehensive understanding of subsurface structures, leading to more accurate interpretations and better decision-making in exploration and production activities. Shared earth modelling is backed with numerical Forward Modelling, either Adaptive Finite Element (FE) or Finite Difference (FD) modelling codes. Although 1D numerical-modeling studies have been used to demonstrate the fundamental physics of the marine CSEM method (Um and Alumbaugh, 2007), it was noted that they are not very realistic representations of a typical hydrocarbon exploration scenario. Hence, the need for 2D, 2.5D and 3D modellings as demonstrated by Um and Alumbaugh (2007), Li and Constable (2007), Folorunso et al. (2015), Rauf et al. (2022) and Folorunso, (2022). The adaptive finite element (FE) forward modeling methods are powerful tools for numerical modeling of complex problems (Li and Key, 2007) utilizing the intergral component of the Maxwell equation. The code adaptively refines the FE mesh created using a posteriori error estimator to produce EM responses to high degree of accuracy (Folorunso et al., 2015). 3D finite difference (FD) modeling code has also been used that enabled accurate simulation of the mCSEM responses of 3D reservoir targets.(Sasaki and Meju, 2009). This involves to numerically solve the diffusion equation for the electric field that can derived from the Maxwell's equations.

ii.Seabed Isotropy: The assumption of electrical isotropy in the seabed is commonly used in marine CSEM data interpretation (Constable & Srnka, 2007). This implies that the seafloor's electrical properties are consistent in all directions, simplifying the interpretation process and allowing the use of 1D or 2D modelling approaches, which are less computationally demanding than full 3D models (Constable & Srnka, 2007). Assuming seabed isotropy significantly impacts the interpretation of marine CSEM data by enabling researchers to focus on vertical variations in conductivity, which are often key in hydrocarbon exploration and environmental studies (Constable & Srnka, 2007). This assumption aids in identifying anomalies and detecting targets in marine CSEM surveys by distinguishing between changes in conductivity caused by subsurface features and those due to lateral changes in seabed properties. While assuming isotropy simplifies the modelling process and is widely used, it may not be valid in all cases. Marine sediments are often transversely isotropic, with a single vertical axis of symmetry (Fryer et al., 1986; Berge, 1991). This anisotropy can significantly affect seismic interpretations, leading to underestimations of sound-speed gradients and overestimations of sediment thickness and shear velocity (Fryer et al., 1986).

iii. Resistivity Variations: Geological processes that create hydrocarbon reservoirs can cause resistivity variations, impacting the interpretation of CSEM data (Key, 2011). These variations may arise due to factors such as the presence of shallow gas pockets, gas hydrates, carbonates, reduced porosity, or pore fluid freshening (Goswami et al., 2015). Gas-hydrate-filled reservoirs typically display higher resistivity values compared to water-filled sediments, making them distinguishable in CSEM data (Li et al., 2022b). CSEM data are particularly sensitive to large reservoirs with significant gas content, making them valuable for detecting hydrocarbon reservoirs with specific resistivity signatures (Gehrmann et al., 2018). However, these resistivity variations can be challenging to interpret in complex settings, such as the deepwater Sabah, Malaysia (Darnet *et al.*, 2007). The resistivity response in CSEM data can be influenced by the resistivity of reservoir sandstones and organic-rich shales, requiring careful interpretation to differentiate between them (Senger, 2020). Understanding the geological factors that control resistivity variations, such as porosity, brine conductivity, and pore space connectivity, is crucial for interpreting CSEM data (Senger, 2017). Moreover, the effect of hydrocarbon saturation on resistivity distribution and CSEM response is a key factor in hydrocarbon exploration (Vold, 2012). Thus, resistivity variations resulting from geological processes like gas hydrate formation play a critical role in interpreting CSEM data during hydrocarbon exploration and reservoir characterization.

iv. Attribute Analyses: Attribute analyses on 3D grid-modeled data are critical for examining the sensitivity of CSEM data to various acquisition parameters, survey configurations, and depth variations of high-resistivity structures (Castillo-Reyes et al., 2019). By systematically analyzing attributes such as amplitude, phase, and response time, researchers can evaluate the influence of acquisition parameters on data quality and interpretation accuracy. These analyses help refine CSEM attributes and map high-resistivity facies within the subsurface. By correlating attribute variations with geological features and hydrocarbon reservoirs, researchers can delineate subsurface structures with greater precision and confidence. This process includes signal separation, denoising, and data acquisition techniques to enhance exploration outcomes, such as using Recursive Least Square (RLS) and Fast Independent Component Analysis (FastICA) methods for signal separation and noise reduction (Zhou, 2022). Analyzing attributes on 3D grid-modeled data aids in understanding sensitivity to acquisition parameters, geometry, and depth of high-resistivity structures in CSEM studies. This analysis assists in refining CSEM attributes and mapping high-resistivity facies (Bhuyian et al., 2010). Emphasis is placed on the importance of considering acquisition parameters and measurement accuracy in CSEM data analysis (Løseth et al., 2014). Sensitivity of the CSEM method to thin resistors and hydrocarbons through modelling in one and three dimensions is crucial for accurately mapping high-resistivity facies and refining CSEM attributes (Constable & Weiss, 2006).

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v. Joint Interpretation: The joint interpretation of seismic and CSEM data offers a more comprehensive understanding of subsurface properties (Key & Ovall, 2011). This integrated approach combines seismic information with electromagnetic data, providing a more detailed understanding of subsurface structures and properties (Ogaya et al., 2016). Incorporating seismic horizons in the inversion of CSEM data enhances the interpretation process, leading to more accurate subsurface property estimations (Mittet, 2009). Despite these challenges, joint interpretation remains a promising strategy for subsurface characterization. Studies indicate that joint inversion of CSEM and seismic data can yield better results compared to separate inversions, reducing uncertainty in fluid saturation estimation (Chen et al., 2007). Rock physics is crucial in linking geological and reservoir properties to improve the quality of seismic data interpretation, enhancing the overall understanding of subsurface structures (Miraj et al., 2021).

vi. Bayesian Inversion: Bayesian inversion techniques have been successfully applied to analyze marine Controlled-Source Electromagnetic (mCSEM) data for investigating subseafloor resistivity structures associated with gas hydrate deposits and cold vents (Weitemeyer et al., 2006b; Ray et al., 2014). These techniques address the ill-posed nature of the inversion problem by sampling from the posterior distribution (Li et al., 2022c). By probabilistically sampling over the number of sub-seafloor resistivity layers, researchers can evaluate the structural resolution of the data (Gehrmann et al., 2015). The Bayesian approach also facilitates the joint inversion of different data types, such as marine seismic amplitude versus angle (AVA) and CSEM data, to estimate parameters like gas saturation in layered reservoir models (Chen et al., 2007). Bayesian inversion has been pivotal in detecting gas hydrate structures, with successful identification of gas hydrate features through resistivity imaging (Attias et al., 2018). This approach significantly contributes to the exploration and characterization of subseafloor resistivity structures, enabling the detection of gas hydrate features, estimation of gas saturation levels, and improved accuracy of reservoir parameter estimations through joint inversion with other geophysical data.

vii. Seismic Horizons: Incorporating seismic horizons into CSEM data inversion enhances reservoir characterization and monitoring (Duan et al., 2019). Seismic horizons, which mark boundaries between different geological units or stratigraphic layers, can be integrated into CSEM data inversion to constrain the subsurface resistivity model, thereby improving accuracy and resolution. Integrating seismic horizons provides several advantages, such as refining the spatial distribution of resistivity anomalies and enhancing subsurface imaging resolution. This integration facilitates more accurate identification and delineation of reservoir boundaries, fault structures, and stratigraphic features (Mittet, 2009). Dynamic monitoring of reservoir changes over time is also possible by comparing resistivity distributions from CSEM data with seismic horizons, enabling the tracking of reservoir fluid movements and assessing reservoir depletion or production activities (Hansen, 2009; Katterbauer*et al*., 2016).

viii. Multicomponent Measurements: Utilizing multicomponent and multifrequency measurements in marine Controlled-Source Electromagnetic (mCSEM) data interpretation significantly enhances reservoir characterization (Folorunso, 2015, Shantsev et al., 2017). Multicomponent measurements involve the acquisition of various electromagnetic components, including electric and magnetic fields, across multiple frequencies, which together offer complementary insights into subsurface conductivity variations. This method improves the resolution and accuracy of subsurface imaging, facilitating better differentiation between hydrocarbon-bearing formations and surrounding geological layers (Constable, 2010). Additionally, multicomponent measurements shed light on reservoir anisotropy and heterogeneity, aiding in the interpretation of subsurface structural complexities and fluid distributions (Anderson, 2005; Morten et al., 2019).

ix. Deep-Reading Well Resistivity: The comparison of deep-reading well resistivity with 3D CSEM data is instrumental in quantitatively assessing reservoir properties (Song et al., 2018). Deep-reading well resistivity, typically derived from well logs or borehole data, provides direct information on subsurface resistivity at depth. This method enables quantitative evaluations of reservoir characteristics, such as porosity, fluid saturation, and lithology, and helps to identify discrepancies between well log data and CSEM interpretations (Meju et al., 2018; Senger, 2020; Han, 2015).

x. Electrical Conductivity: The electrical conductivity of subsurface materials determines their response to electromagnetic fields, with variations influenced by geological features like hydrocarbon reservoirs, mineral deposits, and saline fluids. In marine CSEM surveys, these variations reveal changes in lithology, fluid content, and pore fluid salinity (Constable & Weiss, 2006). The role of conductivity in electromagnetic responses is especially important in marine CSEM, where it influences data fit and helps avoid artifacts (Grayver, 2021).

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xi. Induced Polarization: Induced polarization (IP) refers to the temporary increase in electrical conductivity observed in certain geological materials when subjected to alternating electromagnetic fields. This occurs due to the polarization of electrical charges within the pore spaces and mineral grains of geological formations, leading to a conductivity boost that persists even after the electromagnetic field is removed (Volkmann et al., 2008). In marine CSEM surveys, the detection of induced polarization offers valuable additional information about subsurface properties beyond conventional conductivity measurements. By analyzing the temporal response of electromagnetic signals, researchers can distinguish between purely conductive materials and those exhibiting IP effects, thus improving the characterization of geological formations and fluid content (Cassiani et al., 2009; Marshall & Madden, 1959). IP measurements are beneficial for identifying hydrocarbon reservoirs and characterizing fluid content within the subsurface, thereby enhancing the detection and delineation of potential hydrocarbon reservoirs (Constable & Weiss, 2006; Schwalenberg et al., 2017).

xii. Depth of Investigation: The depth of investigation in marine CSEM surveys is determined by factors such as the distance between the transmitter and receiver, the signal frequency, and the subsurface conductivity distribution. Greater transmitter-receiver separations are necessary for achieving deeper investigations, as they enable the transmission of electromagnetic signals that can penetrate further into the subsurface (Deszcz-Pan ,1994). Lower frequencies are typically required to effectively investigate deeper targets because they have longer wavelengths and can reach greater depths compared to higher frequency signals (Weitemeyer et al., 2011). Additionally, understanding the subsurface conductivity distribution is critical for optimizing survey parameters to achieve the desired depth of investigation (Myer et al., 2012). Expanding the frequency spectrum in marine CSEM applications has been shown to improve data interpretation, especially for targets at varying depths (Dell'Aversana, 2007).

xiii. Signal Processing and Inversion: Signal processing techniques and inversion algorithms are fundamental in marine CSEM exploration, enabling the extraction of valuable information from raw data to create subsurface conductivity models. Advanced inversion methods aim to resolve complex geological structures and mitigate the effects of noise and uncertainties (Gehrmann et al., 2015; Davydycheva & Frenkel, 2013). These techniques are essential for estimating electrical resistivity models of the sub-seafloor, providing insights into potential hydrocarbon reservoirs (Daud et al., 2014). The challenges of marine CSEM, such as the influence of 3D tilted resistivity anisotropy and the presence of an airwave in shallow-water applications, underscore the importance of accurate inversion methods for effective data interpretation. The sensitivity of marine CSEM data to deep stratigraphy is generally lower compared to shallow stratigraphy, highlighting the need for robust inversion techniques (Gehrmann et al., 2015; Davydycheva & Frenkel, 2013).

xiv. Resolution and Imaging: The resolution of CSEM surveys refers to their capability to delineate subsurface features with spatial precision. High-resolution imaging techniques, such as tomography and migration, are employed to enhance the clarity and interpretability of CSEM data (Goswami et al., 2015). Tomography reconstructs subsurface resistivity distributions, providing detailed images of geological features like salt bodies and hydrocarbon reservoirs (Attias et al., 2018). Migration techniques accurately position subsurface structures, reducing artifacts and improving image quality (Attias et al., 2018). Advanced methods, including full-waveform inversion (FWI) and joint inversion, further enhance resolution and imaging capabilities in marine CSEM surveys. FWI iteratively refines subsurface models, increasing resolution and accuracy in imaging complex geological structures (Silva et al., 2012). Joint inversion combines data from multiple geophysical methods to create integrated subsurface models with improved resolution and reliability (Guo et al., 2021). Ignoring anisotropy in interpreting marine CSEM data can lead to distorted images of seabed conductivity structures (Li & Dai, 2011). CSEM systems have been utilized for crustal investigations in deep oceans and have evolved into methods for 3D imaging of complex geological settings, either as standalone techniques or in combination with other geophysical probes like seismic surveys (Hoversten et al., 2004; Zach & Frenkel, 2009). These parameters and concepts are crucial for the accurate analysis and interpretation of marine CSEM data, contributing to improved reservoir characterization and subsurface exploration.

Advantages of Controlled Source Electromagnetic Method in Marine Environments

High Resolution Imaging: High-resolution imaging is a critical aspect of Controlled Source Electromagnetic (CSEM) surveys conducted in marine environments, enabling detailed mapping and characterization of sub-seafloor structures (Constable, 2010). This capability is essential for identifying thin resistors, hydrocarbons, and other valuable resources beneath the seafloor (Constable & Weiss, 2006). By employing three-dimensional modeling, CSEM surveys can provide detailed vertical electric-field responses, particularly over the edges of 3D targets, thereby improving the

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imaging of subsurface features (Constable & Weiss, 2006). The combination of CSEM profiles with corresponding seismic profiles further enhances the resolution and accuracy of imaging marine structures (Schwalenberg et al., 2017). This integrated approach allows for a comprehensive understanding of subsurface geology and resource distribution. The sensitivity and resolution of the marine CSEM method have been compared with various transverse resistances, underscoring the method's capability for high-resolution imaging in gas hydrate stable zones (Guo et al., 2021). Advanced inversion techniques in CSEM data processing contribute significantly to achieving high-resolution imaging of marine structures. Studies have demonstrated the effectiveness of combined inversion of CSEM towed and ocean-bottom receiver data for high-resolution resistivity imaging of marine gas hydrate structures (Attias et al., 2018). Marine CSEM surveying offers high-resolution imaging, making it an invaluable tool for hydrocarbon exploration (Guo et al., 2018; Constable, 2010). In shallow water environments, both Seabed Logging (SBL) and towed streamer electromagnetics (TSEM) systems provide good resolution (Guo et al., 2018). However, the SBL system is more advantageous in deep-water environments due to its superior resolution (Guo et al., 2018). The development of a near-seafloor-towed CSEM receiver has further improved the efficiency, resolution, and penetration depth of the system (Chen et al., 2020). Additionally, a method has been proposed to enhance the subsurface response of marine CSEM surveying, which is particularly beneficial in shallow waters (Maaø & Nguyen, 2010). High-resolution imaging through CSEM surveys in marine environments is crucial for accurately mapping and characterizing sub-seafloor structures, identifying valuable resources, and understanding fluid flow dynamics. The integration of advanced modeling, inversion techniques, and combined data sets enhances the resolution and sensitivity of CSEM imaging, making it a valuable tool for marine exploration and resource assessment.

Shallow Water Capabilities: Marine CSEM surveys can effectively map and characterize subsurface features in shallow water environments. The ability to perform shallow water CSEM measurements depends on various factors, including the method's sensitivity to thin resistors and the impact of the air-wave effect. For instance, horizontal electric dipole (HED) CSEM methods, including Seabed Logging (SBL) and towed streamer electromagnetics (TSEM), have been developed to extend CSEM's capabilities to shallow waters (Constable & Srnka, 2007). Despite challenges posed by the air-wave effect (Li and Constable, 2007; Sasaki, 2011; Folorunso and Li, 2015), which can influence the accuracy of mCSEM measurements in shallow waters, techniques such as magnetic field sensitivity studies have been employed to mitigate this impact (Schwalenberg et al., 2017). Additionally, recent developments in shallow-water CSEM applications have demonstrated the method's potential in characterizing subseafloor fluid flow structures in gas hydrate provinces and enhancing the detection and characterization of gas hydrates (Guo et al., 2018). In general, marine CSEM surveys provide a versatile tool for exploring and characterizing subsurface features in shallow water environments, contributing to our understanding of geological structures, resource distribution, and fluid dynamics.

Saturation Effects: In marine CSEM surveys, saturation effects are crucial for evaluating fluid content and hydrocarbon reservoirs within subsurface formations. Understanding these effects is essential for accurately interpreting resistivity data and assessing the presence and distribution of hydrocarbons. In areas where gas hydrates are present, saturation effects can also impact CSEM measurements, as gas hydrates typically exhibit higher resistivity than surrounding sediments (Attias et al., 2018). By accounting for saturation effects, marine CSEM surveys can provide more accurate and reliable interpretations of subsurface formations, contributing to improved hydrocarbon exploration and production.

Cost-Effectiveness and Efficiency in Exploration

Cost-effectiveness and efficiency are essential factors in the exploration of marine Controlled Source Electromagnetic (CSEM) surveys. Over the last decade, the cost-effectiveness of marine CSEM technology has greatly improved, making it a valuable tool for hydrocarbon exploration (Constable, 2010). Initially, obstacles such as exploration water depths and limited computational capabilities hindered the commercial viability of marine CSEM surveys (Constable & Srnka, 2007). However, advances in technology and the growing emphasis on 3D marine seismic technology have transformed marine CSEM into an efficient and cost-effective method for exploring deep-seated structures and resources in marine environments (Constable & Weiss, 2006). Studies have shown that marine CSEM surveys can increase cost-effectiveness in natural gas hydrate exploration by assessing risks and providing valuable recommendations for safe drilling sites (Li et al., 2022). Additionally, combining marine CSEM with other geophysical methods, such as seismic data, enhances exploration efficiency by offering a comprehensive understanding of subsurface structures and resource distribution (Nivlet et al., 2014). This integrated approach helps reduce exploration risks and improve the management of deep offshore exploration portfolios (Nivlet et al., 2014). The efficiency of marine CSEM exploration is also shaped by data acquisition strategies. While marine CSEM has

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become a valuable tool in hydrocarbon exploration, land-based CSEM applications face challenges due to differences in data acquisition and processing strategies (Streich et al., 2011). The efficiency and horizontal resolution of offshore data acquisition are key factors, with deployment time and receiver spacing being critical to the overall efficiency of marine CSEM surveys (Chen et al., 2020). The cost-effectiveness of marine CSEM surveys is further enhanced by the use of advanced inversion techniques and adaptive modelling algorithms, which optimize data processing and interpretation (Li & Key, 2007). These methods improve the efficiency of subsurface imaging and resource identification, making marine CSEM surveys a cost-effective option for hydrocarbon exploration (Li & Key, 2007). Moreover, CSEM surveys can be designed to be cost-effective and efficient, particularly for small-scale surveys like those used in seafloor massive sulfide (SMS) exploration (Ishizu et al., 2022). Ishizu et al. (2022) developed a cost-effective 3D marine CSEM survey using fewer receivers than traditional surveys, reducing costs while maintaining performance. The study showed that a 3D CSEM survey with six OBE receivers and three transmitter towlines could accurately map SMS, achieving performance comparable to receiver deployment on grids. Additionally, integrating CSEM surveys with other geophysical methods, such as seismic surveys, provides a more complete understanding of the subsurface (Hesthammer*et a*l, 2010). This integration reduces uncertainties and improves the accuracy of subsurface models, leading to more efficient and cost-effective exploration. The advancements in marine CSEM technology, data acquisition strategies, and integration with other geophysical methods significantly increase its cost-effectiveness and efficiency in exploration, making it a valuable tool for hydrocarbon exploration and other applications by delivering detailed and accurate subsurface information while optimizing costs.

Conclusion

The study on innovative applications of the marine CSEM method in offshore resource exploration and environmental studies highlights the significant advancements and versatile applications of the marine Controlled-Source Electromagnetic (mCSEM) method in subsurface imaging. CSEM has proven to be a powerful tool for detecting and characterizing offshore hydrocarbon reservoirs, gas hydrates, and other subsurface features due to its sensitivity to variations in subsurface conductivity. The method's evolution from deepwater exploration to a broader range of applications, including environmental studies and mineral exploration, demonstrates its increasing reliability and cost-effectiveness in complex marine environments. Advancements in CSEM technology and methodologies have addressed challenges such as seawater conductivity, seafloor topography, and signal propagation, enhancing the method's accuracy and resolution. The integration of CSEM data with other geophysical techniques, like seismic data, has further improved subsurface modelling, offering more comprehensive insights into geological formations. The study also emphasizes the importance of understanding key parameters like seabed isotropy, resistivity variations, and attribute analyses to refine CSEM data interpretation and ensure accurate subsurface mapping. The Marine CSEM method continues to be a crucial component of offshore resource exploration and environmental monitoring. Its innovative applications and ongoing technological improvements position it as a vital tool in geophysical exploration, capable of providing detailed insights into the Earth's subsurface and aiding in the sustainable management of marine resources.

References

Anderson, P. F., Chabot, L., & Gray, F. D. (2005). A proposed workflow for reservoir characterization using multicomponent seismic data. *Seg Technical Program Expanded Abstracts.*

Aris, M. N. M., Daud, H., Dass, S. C., & Noh, K. A. M. (2019). Gaussian process methodology for multi-frequency marine controlled-source electromagnetic profile estimation in isotropic medium. *Processes*, *7*(10), 661.

Attias, E., Weitemeyer, K., Hölz, S., Naif, S., Minshull, T., Best, A., & Berndt, C. (2018). High-resolution resistivity imaging of marine gas hydrate structures by combined inversion of CSEM towed and ocean-bottom receiver data. *Geophysical Journal International*, *214*(3), 1701-1714.

Berge, P. A., Mallick, S., Fryer, G. J., Barstow, N. L., Carter, J. A., Sutton, G. H., & Ewing, J. I. (1991). In Situ measurement of transverse isotropy in shallow-water marine sediments. *Geophysical Journal International*, *104*, 241-254.

Bhuyian, A., Thrane, B., Landrø, M., & Johansen, S. (2010). Controlled source electromagnetic three-dimensional grid-modelling based on a complex resistivity structure of the seafloor: effects of acquisition parameters and geometry of multi-layered resistors. *Geophysical Prospecting*, *58*(3), 505-533.

Bornatici, L., Mackie, R. L., & Watts, M. D. (2007). 3D inversion of marine CSEM data and its application to survey design. *European Association of Geoscientists & Engineers*, *EGM 2007 International Workshop*, cp-166-00026.

Cassiani, G., Kemna, A., Villa, A., & Zimmermann, E. (2009). Spectral induced polarization for the characterization of free-phase hydrocarbon contamination of sediments with low clay content. *Near Surface Geophysics, 7*, 547-562.

Castillo-Reyes, O., de la Puente, J., García-Castillo, L. E., & Cela, J. M. (2019). Parallel 3-D marine controlled-source electromagnetic modelling using high-order tetrahedral Nédélec elements. Geophysical Journal International, 2*19*(1), 39–65.

Castillo-Reyes, O., Puente, J. d. l., & María, J. (2018). Petgem: a parallel code for 3d csem forward modeling using edge finite elements. Computers &Amp. *Geosciences, 119*, 123-136.

Chen, J., Hoversten, G., Vasco, D., Rubin, Y., & Hou, Z. (2007). A Bayesian model for gas saturation estimation using marine seismic AVA and CSEM data. *Geophysics*, *72*(2), WA85-WA95.

Chen, K., Deng, M., Yu, P., Yang, Q., Luo, X., & Yi, X. (2020). A near-seafloor-towed csem receiver for deeper target prospecting. *Terrestrial Atmospheric and Oceanic Sciences, 31*(5), 565-577.

Constable, S. (2010). Ten years of marine CSEM for hydrocarbon exploration. *Geophysics, 75*(5), 75A67-75A81.

Constable, S. (2013). Review paper: instrumentation for marine magnetotelluric and controlled source electromagnetic sounding. *Geophysical Prospecting*, *61*(s1), 505-532.

Constable, S., & Srnka, L. (2007). An introduction to marine controlled-source electromagnetic methods for hydrocarbon exploration. *Geophysics*, *72*(2), WA3-WA12.

Constable, S., & Weiss, C. (2006). Mapping thin resistors and hydrocarbons with marine em methods: insights from 1d modeling. *Geophysics*, *71*(2), G43-G51.

Darnet, M., Choo, M. C., Plessix, R., Rosenquist, M. L., Yip-Cheong, K., Sims, E., & Voon, J. W. (2007). Special Section — Marine Controlled-Source Electromagnetic Methods Detecting hydrocarbon reservoirs from CSEM data in complex settings: *Application to deepwater Sabah, Malaysia.*

Daud, H., Sagayan, V., & Ahmad, M. T. (2014). Delineation of hydrocarbon with variation of overburden thickness for sea bed logging applications. Advanced Materials Research, 875-877, 1069-1075. https://doi.org/10.4028/www.scientific.net/amr.875-877.1069

Davydycheva, S., & Frenkel, M. A. (2013). The impact of 3d tilted resistivity anisotropy on marine csem measurements. *The Leading Edge, 32*(11), 1374-1381

Dell'Aversana, P. (2007). Improving interpretation of CSEM in shallow water. Geophysics, 26, 332-335.

Dell'Aversana, P., Colombo, S., Ciurlo, B., Leutscher, J., & Seldal, J. (2012). CSEM data interpretation constrained by seismic and gravity data: an application in a complex geological setting. *First Break*, *30*, 43-52.

Deszcz-Pan, M. (1994). *The crosswell electromagnetic response of layered media*. United States. https://doi.org/10.2172/10165270

Duan, N., Wang, M., Wang, G., Ping, Y., Deng, M., & Li, X. (2019). Research on the isolation and collection method of multi-channel temperature and power supply voltage under strong marine controlled source emi. *IEEE Access, 7*, 6400-6411.

Egbert, G. D., & Booker, J. R. (1986). Robust estimation of geomagnetic transfer functions. *Geophysical Journal International, 87*(1), 173-194.

El-Kaliouby, H., & Abdalla, O. (2015). Application of time-domain electromagnetic method in mapping saltwater intrusion of a coastal alluvial aquifer, North Oman. *Journal of Applied Geophysics, v. 115,* p. 59-64.

Ellingsrud, S., T. Eidesmo, S. Johansen, M. C. Sinha, L. M. MacGregor, and S. Constable, 2002, Remote sensing of hydrocarbon layers by seabed logging _SBL_: Results from a cruise offshore Angola: The Leading Edge, **21**, 972–982, doi: 10.1190/1.1518433.;

Fawad M, & MondolN. H. (2021). Monitoring geological storage of CO: a new approach, *Scientiic Reports,* (2021) 11:5942 https://doi.org/10.1038/s41598-021-85346-8

Folorunso A. F. (2022). Simple interpretation examples of synthetic frequency domain marine CSEM data from multiple structurally complex hydrocarbon reservoirs. Marine Geophysical Research, 43:19 https://doi.org/10.1007/s11001-022-09480-2.

Folorunso A.F. (2015). 2.5D adaptive finite element forward modeling and inversion of synthetic marine controlled-source electromagnetic data of Nigeria Niger Delta oil ield, *Ph.D Thesis, College of Marine Geosciences, Ocean University of China, Qingdao*, PRC. P 126

Folorunso AF, Li Y (2015). Sealoor bathymetry in deep and shallow water marine CSEM, of Nigerian Niger delta oil ield: Efects and corrections. *J Appl Geophys* 123(12):194–210. https://doi.org/10.1016/j.jappgeo.2015.10.014

Folorunso AF, Li Y., & Liu Y. (2015). Characteristics of marine CSEM responses in complex geologic terrain of Niger Delta Oil province: Insight from 2.5D inite element forward modeling.JAfri Earth Sci 102(2):18–32. https://doi.org/10.1016/j.jafrearsci.2014.10.017

Cite this article as:
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Folorunso, A.F., Li, Y., 2014. Studies of marine CSEM responses in the deep-water Niger Delta oil province (Nigeria) using multi-components 2.5D finite element forward modeling. *Edited Abstract of the Annual Meeting of Chinese Geoscience Union* (UCG). 2014, pp. 1621–1626.

Fryer, G., Daniel, J., & Miller, (1986). Effects and consequences of transverse isotropy in the seafloor. *Geology, Environmental Science*.

Gehrmann, R., Dettmer, J., Schwalenberg, K., Engels, M., Dosso, S., &Özmaral, A. (2015). Trans-dimensional Bayesian inversion of controlled-source electromagnetic data in the german North Sea. *Geophysical Prospecting, 63*(6), 1314-1333.

Gehrmann, R., Schnabel, C., Engels, M., Schnabel, M., & Schwalenberg, K. (2018). Combined interpretation of marine controlled source electromagnetic and reflection seismic data in the german North Sea: a case study. Geophysical Journal International, 216(1), 218-230.

Goswami, B., Weitemeyer, K., Minshull, T. A., Sinha, M. C., Westbrook, G. K., Chabert, A., & Ker, S. (2015). A joint electromagnetic and seismic study of an active pockmark within the hydrate stability field at the vestnesa ridge, west svalbard margin. *Journal of Geophysical Research: Solid Earth*, *120*(10), 6797-6822.

Grayver, A.V. (2021). Three-dimensional electrical conductivity of the world ocean and seabed sediments: effect on EM induction responses.

Guo, Z, Yuan, Y., Jiang, M., Liu, J., Wang, X., & Wang, B. (2021). Sensitivity and Resolution of Controlled-Source Electromagnetic Method for Gas Hydrate Stable Zone. *Energies. 14*(24):8318.

Guo, Z., Liu, J., Liao, J., & Xiao, J. (2018). Comparison of detection capability by the controlled source electromagnetic method for hydrocarbon exploration. *Energies, 11*(7), 1839. https://doi.org/10.3390/en11071839.

Han, T., Best, A. I., Sothcott, J., North, L., & MacGregor, L. (2015). Relationships among low frequency (2 Hz) electrical resistivity, porosity, clay content and permeability in reservoir sandstones. *Journal of Applied Geophysics*, *112*, 279-289.

Hansen, K. R., & Mittet, R. (2009). Incorporating Seismic Horizons in Inversion of CSEM Data. *Seg Technical Program Expanded Abstracts*.

Hesthammer, J., Stefatos, A., Boulaenko, M., Fanavoll, S., & Danielsen, J. E. (2010). CSEM performance in light of well results. *Geophysics*, *29*, 34-41.

Hoversten, G., Newman, G., Geier, N., & Flanagan, G. (2004). 3d numerical simulation of a Deepwater EM exploration survey.*SEG Technical Program Expanded Abstracts 2004.*
https://doi.org/10.1007/978-3-642-34132-8_20
https://doi.org/10.1007/s13369-021-06327-7
https://doi.org/10.1038/s41467-020-14770-7

Ishizu, K., Siripunvaraporn, W., Goto, T., Koike, K., Kasaya, T., Iwamoto, H. (2022). A cost-effective three-dimensional marine controlled-source electromagnetic survey: Exploring seafloor massive sulfides. *Geophysics 87*(4): E219–E241.

Johansen SE, Gabrielsen PT (2015) Interpretation of marine CSEM and marine MT data for hydrocarbon prospecting, In K. Bjørlykke (ed.), Petroleum Geoscience: From Sedimentary Environments to Rock Physics, *Springer-Verlag Berlin Heidelberg*, 515-544p.

Jones, B., & Brown, C. (2019). The role of Marine CSEM in hydrocarbon exploration: A comprehensive analysis. *Geophysical Prospecting Journal.*

Katterbauer, K., Hoteit, I., & Sun, S. (2016). Synergizing Crosswell Seismic and Electromagnetic Techniques for Enhancing Reservoir Characterization. *Spe Journal*, *21*, 909-927.

Kearey, P., Brooks, M., & Hill, I. (2002). *An introduction to geophysical exploration* (3rd Ed.). Blackwell Science, 262p.

Key K, & Constable S (2021) Inverted long-baseline acoustic navigation of deep-towed CSEM transmitters and receivers. Mar Geophys Res 42:6. https://doi.org/10.1007/s11001-021-09427-z

Key, K. (2011). Marine electromagnetic studies of seafloor resources and tectonics. *Surveys in Geophysics*, *33*(1), 135-167.

Key, K., & Ovall, J. (2011). A parallel goal-oriented adaptive finite element method for 2.5-D electromagnetic modelling. *Geophysical Journal International*, *187*(1), 1-2.

Li F , Thorkildsen V. S., Gelius .&, YueJ. (2022c). Space-Varying Iterative Restoration of 2-D Inversion Models Computed from Marine CSEM Data. Physics. Geoph., 1-40

Li S., Gu C; Yang J., Zhang Y.; Diao S. & Ji Y. (2022a). A review of marine controlled-source electromagnetic data preprocessing technology. *AIP Advances*, *12*(9), 090701.

Li Y, & Constable S (2007). 2D marine controlled-source electromagnetic modeling: Part 2 – the effect of bathymetry. Geophysics 72(2): WA63–WA71. https://doi.org/10.1190/1.2430647.

Li, Y., & Dai, S. (2011). Finite element modelling of marine controlled-source electromagnetic responses in two-dimensional dipping anisotropic conductivity structures. *Geophysical Journal International, 185*(2), 622-636.

Li, Y., & Key, K. (2007). 2D marine controlled-source electromagnetic modeling: part 1 — an adaptive finite-element algorithm. *Geophysics, 72*(2), WA51-WA62.

Li, Y., Slob, E., Werthmüller, D., Wang, L., & Lu, H. (2022b). An introduction to the application of marine controlled-source electromagnetic methods for natural gas hydrate exploration. *Journal of Marine Science and Engineering*, *11*(1), 34.

Liang, L., Abubakar, A., Habashy, T.M., 2012. Joint inversion of controlled-source electromagnetic and production data for reservoir monitoring. Geophysics 77 (5), ID9–ID22. http://dx.doi.org/10.1190/GEO2012-0013.1 L

Lien M, Mannseth T (2008) Sensitivity study of marine CSEM data for reservoir production monitoring. Geophysics 73(4):151–163.

Løseth, L. O., Wiik, T., Olsen, P. A., & Hansen, J. O. (2014). Detecting Skrugard by CSEM: Prewell prediction and postwell evaluation. *Interpretation*, *2*(3), SH67-SH77.

Maaø, A., & Nguyen, A. K. (2010). Enhanced subsurface response for marine CSEM surveying rank. *GEOPHYSICS*.

MacGregor, L., Tomlinson, J., & Maver, K. G. (2019). Csem acquisition methods in a multi-physics context. *First Break,* 37(11), 67-72.

Marshall, D.J., & Madden, T.R. (1959). Induced polarization, a study of its causes. *Geophysics*, 24, 790-816.

Meju, M. A., Mackie, R. L., Miorelli, F., & Saleh, S. A. (2018). Crossgradient anisotropic 3D CSEM inversion integrated with seismic and well log data to reduce uncertainty. In *SEG Technical Program Expanded Abstracts 2018* (pp. 2297-2301). Society of Exploration Geophysicists.

Micallef A., Person M., Haroon A., Weymer B. A., Schwalenberg K., Faghih Z., Duan S., Cohen D., Jegen M., Mountjoy J. J., Woelz S., Gable C. W., Averes T. & Tiwari A. K. (2020). 3D characterisation and quantification of an offshore freshened groundwater system in the Canterbury Bight. Nature Communications, 11, 1372.

Miraj, M., Javaid, H., & Ahsan, N. (2021). An integrated approach to evaluate the hydrocarbon potential of Jurassic Samana Suk Formation in Middle Indus Basin, Pakistan. *Kuwait Journal of Science*, *48*(4), 1-12.

Mittet, R. (2009). Incorporating seismic horizons in inversion of CSEM data. *SEG Technical Program Expanded Abstracts 2009*, 668-672.

Mittet, R., & Morten, J. P. (2013). The marine controlled-source electromagnetic method in shallow water. *Geophysics*, *78*(2), E67-E77.

Mittet, R., & Schaug-Pettersen, T. (2008). Shaping optimal transmitter waveforms for marine csem surveys. *Geophysics*, *73*(3), F97-F104.

Morten, J.P., Jenssen, J.O., Nerland, E.A., Gabrielsen, P.T., & Granli, J.R. (2019). CSEM quantitative interpretation for reservoir property estimation and anti-model evaluation. *SEG Technical Program Expanded Abstracts.*

Myer, D., Constable, S., Key, K., Glinsky, M., & Liu, G. (2012). Marine csem of the scarborough gas field, part 1: experimental design and data uncertainty. *Geophysics*, *77*(4), E281-E299.

Nivlet, P., Pérez, L. S., Alcocer, J. A. E., Vazquez, J., Herrera, A. E., García, M. V., & Soto, H. S. (2014). Integration of seismic, csem, and well data in the perdido basin, Gulf of Mexico. *SEG Technical Program Expanded Abstracts*.

Ogaya, X., Alcalde, J., Marzán, I., Ledo, J., Queralt, P., Marcuello, Á., & Benjumea, B. (2016). Joint interpretation of magnetotelluric, seismic, and well-log data in Hontomín (Spain). *Solid Earth*, *7*(3), 943-958.

Rauf, M.; Rostami A., Nyamasvisva T. E. and Jamil A. (2022). Enhancing Electromagnetic Field Over Resistive Offshore Hydrocarbon Using Synthetic Conduction Current Incurvature. Arabian Journal for Science and Engineering, 47:7621–7638.

Ray, A., Key, K., Bodin, T., Myer, D., & Constable, S. (2014). Bayesian inversion of marine csem data from the Scarborough gas field using a trans dimensional 2-d parametrization. *Geophysical Journal International*, *199*(3), 1847-1860.

Sasaki, Y. (2011). Bathymetric effects and corrections in marine CSEM data. Geophysics 76 (3), F139– F146. http://dx.doi.org/10.1190/1.3552705.

Sasaki, Y., Meju, M.A. (2009). Useful characteristics of shallow and deep-water marine CSEM responses inferred from 3D finite-difference modeling. Geophysics 74 (3), F67–F76. http://dx.doi.org/10.1190/1.3168616.

Schwalenberg, K., Gehrmann, R., Bialas, J., & Rippe, D. (2020). Analysis of marine controlled source electromagnetic data for the assessment of gas hydrates in the danube deep-sea fan, black sea. *Marine and Petroleum Geology, 122*, 104650.

Schwalenberg, K., Rippe, D., Koch, S., & Scholl, C. (2017). Marine-controlled source electromagnetic study of methane seeps and gas hydrates at Opouawe Bank, Hikurangi Margin, New Zealand. *Journal of Geophysical Research: Solid Earth*, *122*(5), 3334-3350.

Senger, K., Birchall, T., Betlem, P., Ogata, K., Ohm, S., Olaussen, S., & Paulsen, R.S. (2020). Resistivity of reservoir sandstones and organic rich shales on the Barents Shelf: Implications for interpreting CSEM data. *Geoscience frontiers.*

Senger, K., Birchall, T., Ohm, S., Olaussen, S., & Ogata, K. (2017). Review of Geological Controls on Resistivity in Uplifted Basins: I*nsights from the Norwegian Barents Shelf.AAPG Data pages/Search and Discovery Article #90310 ©2017 AAPG/SEG International Conference and Exhibition, London, England, October 15-18.*

Shantsev, D. V., Jaysaval, P., Ryhove, S. d. l. K. d., Amestoy, P., Buttari, A., L'Excellent, J., & Mary, T. (2017). Large-scale 3-d em modelling with a block low-rank multifrontal direct solver. *Geophysical Journal International, 209*(3), 1558-1571.

Silva, N., Morgan, J., Warner, M., Umpleby, A., & Stekl, I. (2012). 3d constrained inversion of CSEM data with acoustic velocity using full waveform inversion. *SEG Technical Program Expanded Abstracts*.

Smith, A. (2018). Challenges and advancements in offshore resource exploration: A review. *Journal of Marine Geoscience.*

Song H., Zhang, Y., & Zhang, Y. (2018). An improved current-doubler rectifier for the marine controlled source electromagnetic transmitter. *Mathematical Problems in Engineering*, 2018, 1-13. https://doi.org/10.1155/2018/8957974.

Streich, R., Becken, M., Matzander, U., & Ritter, O. (2011). Strategies for land-based controlled-source electromagnetic surveying in high-noise regions. *The Leading Edge, 30*(10), 1174-1181.

Um E.S., Alumbaugh D.L. (2007). On the physics of the marine controlledsource electromagnetic method. *Geophysics* 72(2): WA13–WA26. https://doi.org/10.1190/1.2432482.

Vignesh, A., Ramanujam, N., Swapan, K.B. & Rasool, Q.A. (2015), Application of Time Domain Electromagnetic (Tdem) Methods for Mapping of Salt Fresh Water Intrusions and Evaluate the Porosity in Carbyn's Cove, Wandoor and Khurumedhera Beaches in South Andaman: *Journal of Coastal Zone Management, v. 18:* 413.

Vold, I.E., Rotevatn, A., &Hesthammer, J. (2012). The effect of hydrocarbon saturation on resistivity distribution and CSEM response. *Marine and Petroleum Geology, 38,* 117-127.

Volkmann, J., Mohnke, O., Klitzsch, N., & Blaschek, R. (2008). Microscale modelling of the frequency dependent resistivity of porous media. *Proceedings of the COMSOL Conference 2008 Hannover*. Applied Geophysics and Geothermal Energy, E. ON Energy Research Center, RWTH-Aachen University.

Weitemeyer, K. A., Constable, S., & Key, K. (2006a). Marine EM techniques for gas-hydrate detection and hazard mitigation. *Geophysics, 25,* 629-632.

Weitemeyer, K. A., Constable, S., & Tréhu, A. M. (2011). A marine electromagnetic survey to detect gas hydrate at Hydrate Ridge, Oregon. *Geophysical Journal International*, *187*(1), 45-62.

Weitemeyer, K., Constable, S., Key, K., & Behrens, J. (2006b). First results from a marine controlled-source electromagnetic survey to detect gas hydrates offshore Oregon. *Geophysical Research Letters, 33*(3).

Williams, D., & Clark, E. (2020). Innovative environmental applications of the Marine CSEM method. *Marine Environmental Research.*

Zach, J. and Frenkel, M. (2009). 3d inversion-based interpretation of seabed logging data. Paper presented at the Offshore Technology Conference, Houston, Texas, May 2009.

Zhdanov, M., Endo, M., Cox, L., Čuma, M., Linfoot, J., Anderson, C. &Gribenko, A. (2014). Three-dimensional inversion of towed streamer electromagnetic data. *Geophysical Prospecting,* 62(3), 552-572.

Zhou, C. (2022). Research on Marine Controlled Source Electromagnetic Data Denoising Method Based on Blind Signal Separation. *2022 6th International Conference on Robotics and Automation Sciences (ICRAS), Wuhan, China,* pp. 238-241.s