Journal of Applied Geophysics 118 (2015) 92–105

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Quantifying the effect of the air/water interface in marine active source EM

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ARTICLE INFO

Article history:
Received 24 September 2014
Received in revised form 27 February 2015
Accepted 31 March 2015
Available online 3 April 2015

Keywords:
Marine CSEM
Airwave
Time-domain
Frequency-domain
Modelling

ABSTRACT

The marine controlled source EM surveying method has become an accepted tool for deep water exploration for oil and gas reserves. In shallow water (<500 m) data are complicated by the signal which interacts with the water–air interface which can dominate the response at the receiver. By decomposing the 1-D response to an impulsive current dipole source in the time domain and frequency domain I separate the response into: (1) an earth response, (2) a direct arrival, (3) a coupled airwave which travels through the air and (4) a surface coupling term which travels through the earth. The last two terms are coupled to the sea surface as well as to the earth resistivity structure but one travels through the air between source and receiver and the other only through the earth. Using a range of simple models I quantify the effect of these four terms in the time domain and the frequency domain. The results show that in shallow water the total response is significantly larger than in very deep water and that a large part of this extra energy comes from surface coupling, which is reflected at the sea surface and does not propagate through the air but through the earth. As a result, this term is highly sensitive to the resistivity of the earth. This means that the sea surface in shallow water not only significantly increases the signal strength of CSEM data but also enhances the sensitivity to subsurface resistivity structure. Compared with the surface coupling term, the coupled part of the airwave contains very little information about the earth, and is limited to the near surface.

Time domain separation of the airwave from the surface coupling response results in greater sensitivity to a deep resistive target than frequency domain separation although there is also reasonable sensitivity in the frequency domain.

1. Introduction

The controlled source electromagnetic method (CSEM) was developed more than thirty years ago for use in academic research in deep water (>500 m) to study the conductivity of the earth's crust (Cox, 1981). The method employs a continuous signal emitted by a horizontal electric dipole (HED) towed about 50 m above the seafloor, and receiver nodes on the seafloor which measure two orthogonal horizontal electric field components and three orthogonal magnetic field components (Sinha et al., 1990).

The source typically emits a signal in the frequency range 0.1–10 Hz (Constable, 2007), although frequencies below 0.1 Hz are now commonly used. An alternative approach is to use a transient source signal in which the source signal is a broad bandwidth signal (Edwards and Chave, 1986). The alternative technique also employs a horizontal electric dipole source and an array of in-line electric field receivers and has been applied in the investigation of gas hydrates (Schwalenberg et al., 2005). Commercialisation of the continuous source CSEM system for the detection of hydrocarbon reserves in deep water was first described by Eidesmo et al. (2002) and Ellingsrud et al. (2002). The technique has now become an accepted tool in the de-risking of expensive deep water exploration wells with more than 50 deep water wells drilled based on the results of CSEM data (Hesthammer et al., 2010). The transient approach has also been commercialised (Ziolkowski et al., 2008) and applied successfully in detecting hydrocarbons in shallow water (Ziolkowski et al., 2010) and within a fully towed system (Anderson and Mattsson, 2010).

A feature of the broad bandwidth transient approach is that the complete causal impulse response of the earth, including coupling with the sea surface, may be obtained from the recorded data using deconvolution. Deconvolution effectively transforms the recorded data into what would have been recorded if all the energy of the source time function had been transmitted as a single impulse of very short duration. In the frequency domain deconvolution is predominantly a change in the phase spectrum, especially if the source time function has a flat amplitude spectrum.

The use of conventional or continuous source CSEM as a predominantly deep water tool has been largely due to the airwave problem in

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http://dx.doi.org/10.1016/j.jappgeo.2015.03.028
0926-9851/

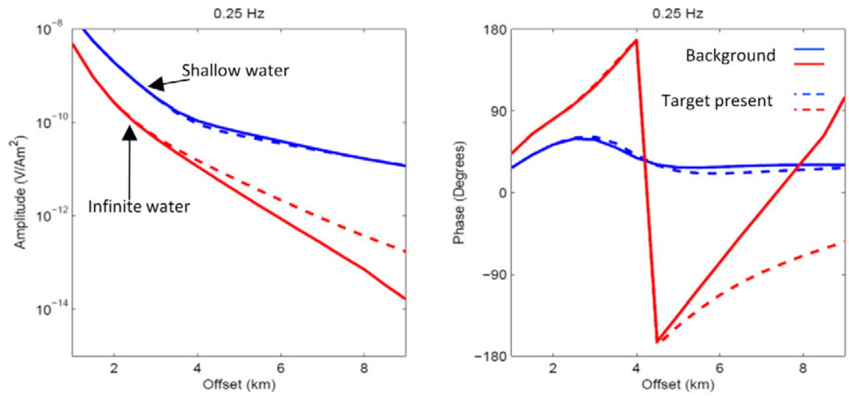

Fig. 1. CSEM response at 0.25 Hz in infinite water (red) and 100 m of water (blue) to a 100 m thick 50 Ω·m resistor 2 km deep (dashed curves) and a uniform 1 Ω·m background (solid curves). Source and receiver are on the seafloor. Left: AVO curve. Right: PVO curve.

shallow water although surveys acquired in water as shallow as 40 m have been reported (e.g. Darnet et al. (2010)). The rise in the commercial use of CSEM coincides with exploration moving into water over 1 km deep and the much greater cost of drilling which makes the use of CSEM attractive (Constable, 2010). The 'airwave problem' results from a large fraction of the energy travelling from the source to the receiver through the air. It is difficult to de-couple this signal from the signal that has propagated through the subsurface. This results in a reduction in subsurface sensitivity and a consequent reduction in the detectability of resistive hydrocarbon-filled layers. The problem has been recognised for over thirty years, with Chave and Cox (1982) illustrating the problem of constructive and destructive interference from sea surface reflections affecting the electric field in shallow water.

Airwave contamination in conventional CSEM data is recognised as a decrease in the slope of the amplitude versus offset (AVO) curve to $1/r^3$, and a flattening of the phase versus offset (PVO) curve, as illustrated in Fig. 1 for a frequency of 0.25 Hz. The red curves are for an infinite water layer (i.e. no surface), the blue curves are for a 100 m water layer, solid lines denote a 1 Ω·m uniform background, and dashed lines are for a target layer 2 km below the seabed 100 m thick with a resistivity of 50 Ω·m. Fig. 1 shows that the response of conventional CSEM at a frequency of 0.25 Hz with the 2 km resistive target distinguishable from the 1 Ω·m half-space response when the water is very deep and the airwave is negligible. When the water is only 100 m deep the two responses are barely distinguishable.

Fig. 2 shows part of the time domain impulse response of the earth at a source–receiver offset of 6 km for the same model as was used in Fig. 1. While there is a very large arrival at early times in the shallow water case due to propagation of energy through the air, the target response is later and actually bigger than the target response for the infinite water layer case. Weiss (2007) showed that in the time domain there is a time window for which the earth impulse response and airwave are largely separated. The limiting case of shallow water is the land case for which the airwave is a delta function which appears synchronously across all receivers, with complete separation from the earth response for a transient system (Ziolkowski et al., 2007).

The differences between the shallow and deep water results in Figs. 1 and 2 are due purely to the presence of the air–water interface. The amplitude of data in shallow water (100 m) is more than an order of magnitude larger than in very deep water. In the argument that follows I will show how different components of the total response contribute to this increased amplitude. I will also show how a significant part of this signal does not actually propagate through the air and can be used to aid the sensitivity to deep resistive layers, particularly in the time domain.

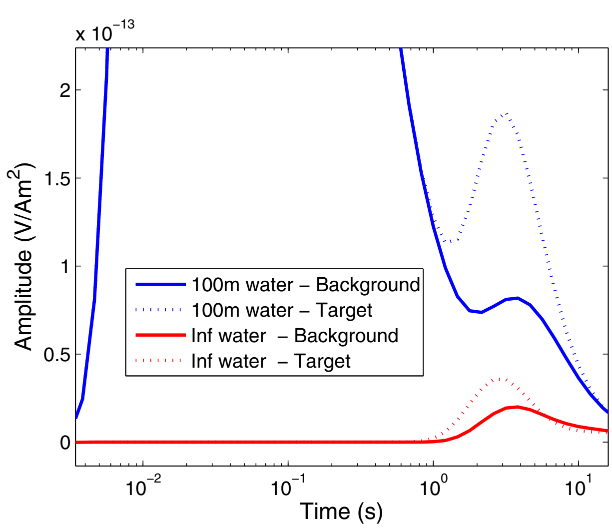

Fig. 2. Part of the impulse response of the earth in infinite water (red) and 100 m of water (blue) to a 100 m thick 50 Ω·m resistor 2 km deep (dashed curves) and a uniform 1 Ω·m background (solid curves). Source and receiver are on the seafloor.

2. Airwave mitigation techniques

The theory of the airwave in the frequency domain was studied in detail initially in the field of subsea communication (Bannister, 1984;

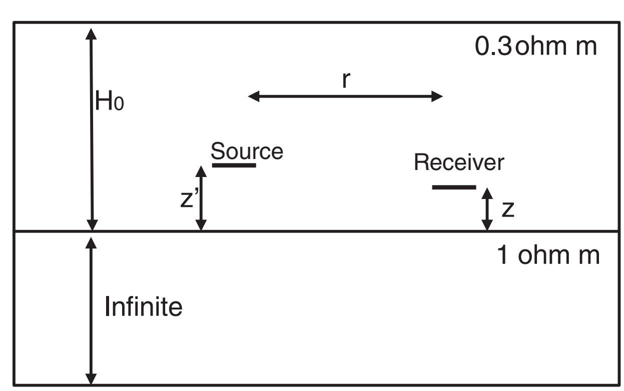

Fig. 3. Field layout for horizontal electric dipole source and an inline receiver. Source distance above the seafloor z' and receiver distance z above the seafloor. The water depth is H_0 and source receiver offset r.