

## Sea Bed Logging (SBL), a new method for remote and direct identification of hydrocarbon filled layers in deepwater areas

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In this paper we describe a technique called Sea Bed Logging (SBL), an application of marine CSEM sounding, which can be applied to detect and characterize hydrocarbon bearing reservoirs in deep water areas. The basis of the approach is the use of a mobile horizontal electric dipole (HED) source and an array of seafloor electric field receivers. The transmitting dipole emits a low frequency electromagnetic signal both into the overlying water column and downwards into the seabed. The array of sea floor receivers measures both the amplitude and the phase of the received signal that depend on the resistivity structure beneath the seabed. A survey consisting of many transmitter and receiver locations can be used to determine a multidimensional model of sub-seafloor resistivity. In deep water areas the geological strata are generally dominated by shale or mud rocks with rather low resistivity. A hydrocarbon reservoir can have resistivity perhaps 10–100 times greater. With an in-line antenna configuration the transmitted electric field enters the high resistive hydrocarbon layer under a critical angle and is guided along the layer. Electromagnetic signals constantly leak from the layer and back to the seafloor. The guiding of the electric fields significantly alters the overall pattern of current flow in the overburden layer. A broad-line antenna configuration does not generate guided waves, and thus the two antenna configurations have different sensitivity to thin buried resistive layers. This so-called ‘split’ effect that is diagnostic for buried resistive layers is verified by 1-dimensional modelling. 1- and 2-dimensional modelling and real data acquired offshore West Africa also demonstrate that by careful positioning of transmitter tow tracks and receivers relative to a suspected hydrocarbon bearing structure, the SBL technique can provide detailed information on the presence and lateral extent of the hydrocarbon reservoir.

### Introduction

Measurements of electrical resistivity beneath the seafloor have traditionally played a crucial role in hydrocarbon exploration and reservoir assessment and development. In the oil and gas industry, sub-seafloor resistivity data has, in the past, been obtained almost exclusively by wire-line logging of wells. However, there are clear advantages to developing non-invasive geophysical methods capable of providing such information. Although inevitably such methods would be unable to provide comparable vertical resolution to wire line logging, the vast saving in terms of avoiding the costs of drilling test wells into structures that do not contain economically recoverable amounts of hydrocarbon would represent a ma-

ior economic advantage. Several electromagnetic methods for mapping sub-seafloor resistivity variations have been developed (e.g. Sinha *et al.* 1990; Chave *et al.* 1991). Here we concentrate on marine controlled source electromagnetic (CSEM) sounding in the frequency domain. This technique has been successfully applied to the study of oceanic lithosphere and active spreading centres (Young & Cox 1981; Evans *et al.* 1994; Constable & Cox 1996; MacGregor *et al.* 1998, 2001). In this paper we describe a technique called Sea Bed Logging (SBL), developed by Statoil (Eidesmo *et al.* 2000; Ellingsrud *et al.* 2001), an application of marine CSEM sounding which can be applied to the problem of detecting and characterizing hydrocarbon bearing reservoirs in deep water areas.

### Method

The basis of the approach is the use of a mobile horizontal electric dipole (HED) source and an array of seafloor electric field receivers. The transmitting dipole emits a low frequency (typically a few tenths to a few tens of Hz) electromagnetic signal that diffuses outwards both into the overlying water

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column and downwards into the seabed. The rate of decay in amplitude and the phase shift of the signal are controlled both by geometric and by skin depth effects. Because in general the seabed is more resistive than seawater, skin depths in the seabed are longer. As a result, electric fields measured at the seafloor by a receiving dipole at a suitable horizontal range are dominated by the components of the source fields that have followed diffusion paths through the seabed. Both the amplitude and the phase of the received signal depend on the resistivity structure beneath the seabed. A survey consisting of many transmitter and receiver locations can therefore be used to determine a multidimensional model of sub-seafloor resistivity.

The method relies on the large resistivity contrast between hydrocarbon-saturated reservoirs, and the surrounding sedimentary layers saturated with aqueous saline fluids. Hydrocarbon reservoirs typically have a resistivity of a few tens of  $\Omega\text{m}$  or higher, whereas the resistivity of the over and underlying sediments is typically less than a few  $\Omega\text{m}$ . In the following sections it will be demonstrated that this resistivity contrast has a detectable influence on SBL data collected at the sea bed above the reservoir, even though the hydrocarbon bearing layers are thin compared to their depth of burial. The effect of the reservoir is detectable in SBL data at an appropriate frequency, and if the horizontal range from source to receiver is of the order of 2–5 times the depth of burial of the reservoir in typical situations.

### Geometric considerations

One of the most crucial factors for the success or otherwise of the SBL technique in practical applications related to hydrocarbon reservoirs is related to survey geometry. As a simple illustration of this in the context of hydrocarbon surveys, consider a case in which the subsea-bed structure can be represented by a simple stack of horizontal layers (a useful first approximation for many situations in sedimentary basins). The upper layer represents sediments above a reservoir (the overburden). The middle layer, corresponding to a hydrocarbon reservoir, has resistivity perhaps 10–100 times greater, due to a high saturation of non-conducting hydrocarbon occupying much of the pore spaces (normally a mix with formation water). The deepest layer, below the reservoir, again has low resistivity due to its similarity to the overburden layer.

The relationships between the electric currents flowing in two adjacent regions of space are determined by both galvanic and inductive effects. Since charge is conserved, the current leaving one volume of the subsurface and that arriving in an adjacent volume along the direction of current flow are related to each other by a galvanic mechanism. On the other hand, if two volumes are close together but separated from each other along a direction orthogonal to current flow, then the coupling between the currents flowing in the two volumes

will be primarily inductive. For conducting media, Ohms Law yields the conduction current density  $J$  (Stratton 1941):

$$J = \sigma E, \quad (1)$$

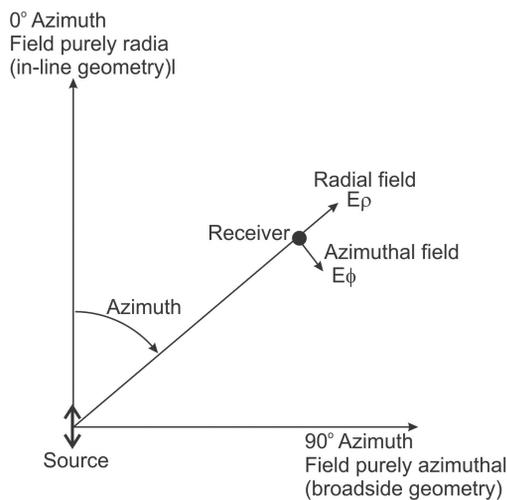
Where  $\sigma$  is the conductivity and  $E$  the electric field (E-field). As seen in equation 1 the current is proportional to the E-field.

Applying this to our model of a sub-seafloor structure containing a thin but resistive hydrocarbon reservoir, we can infer that the effect of the reservoir on the survey results will depend strongly on the direction of flow of the currents generated by the transmitter or the direction of the E-fields. If the survey generates significant vertical components of electric current flow in the overburden layer, then galvanic effects along the current path will be strongly affected by even a thin resistive hydrocarbon layer. For the galvanic case the magnetic field will be polarized transverse to the resistive hydrocarbon layer and we denote this as a transverse magnetic mode, TM mode. In the TM mode the electric field enters the resistive hydrocarbon layer under a critical angle and propagates along the layer. Due to lower conductivity than in the surrounding sediments the E-field will be attenuated less and be guided along the layer. EM energy or currents constantly leak from the layer and back to the seafloor. This guiding of the electric fields will significantly alter the overall pattern of current flow in the overburden layer. In this case, the presence of the hydrocarbon will significantly influence the outcome. The detection of the guided energy is the basis of SBL (Ellingsrud *et al.* 2001).

In contrast, if the current at the base of the overburden layer is dominantly horizontal, inductive effects will dominate the coupling between this layer and the deeper layers. Then the E-fields are transverse to the resistive layer, which we define as the TE-mode. In the TE mode E-fields will only be reflected from the layer, and the reflected energy will die off as a function of offset. At a certain offset the E-fields or the currents from the in-line configuration will dominate the energy contribution at the sea floor.

It is therefore important in designing a practical survey approach for detecting buried hydrocarbon reservoirs to distinguish between source and receiver geometries in which coupling between layers is largely inductive in which case the survey has little sensitivity to the presence of the reservoir. For those in which a significant component of vertical current flow occurs, then the survey is strongly sensitive to its presence.

A horizontal electric dipole source excites both galvanically and inductively coupled modes (Walker & West 1992), and the response of a given resistivity structure depends on the interplay between the galvanic and inductive effects, which tend to work in opposition. Because the fields of a horizontal electric dipole are 3-dimensional in nature, the relative



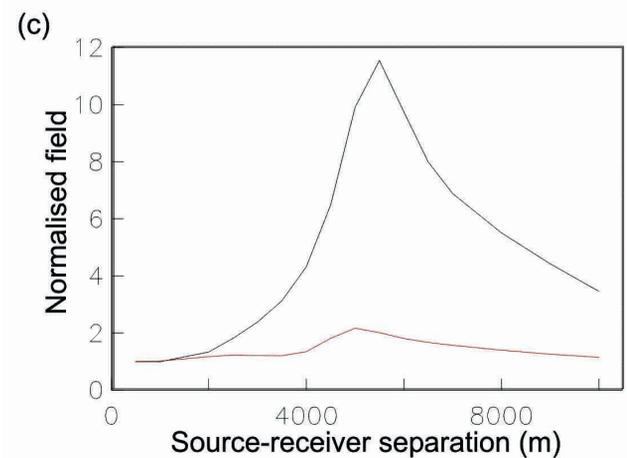
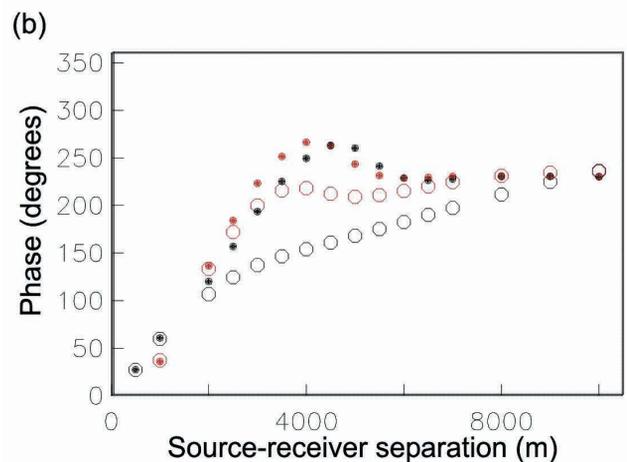
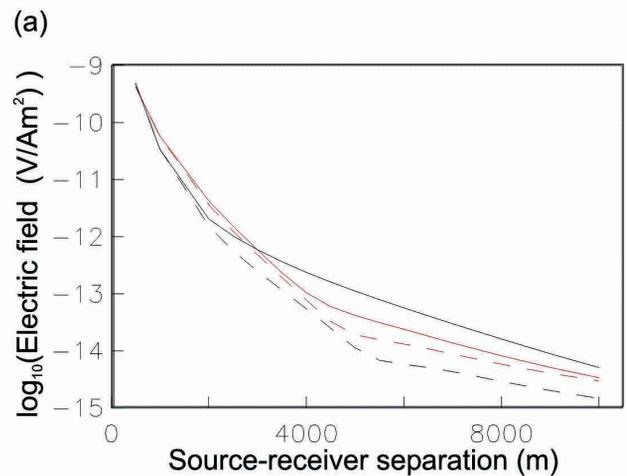
**Figure 1** Source-receiver geometry can be expressed in terms of the azimuth, defined as the angle between the axis of the source dipole and the line joining the source and receiver. Two extreme geometries can be considered: At an azimuth of 0° (the in-line geometry), the fields are purely radial (parallel to the line joining the source and receiver). In the orthogonal direction (broadside geometry), the fields are purely azimuthal.

magnitude of each mode depends on the source-receiver geometry. The geometry can be expressed in terms of the source-receiver azimuth, defined as the angle between the dipole axis and the line joining the source and receiver (Fig. 1). At an azimuth of 90° (broadside geometry) inductive effects dominates and the observed response can in general be explained in terms of attenuative effects governed by electromagnetic skin depth. At an azimuth of 0° (in-line geometry) galvanic effects are much stronger (MacGregor & Sinha 2000).

**1-dimensional modelling**

To illustrate this geometric effect, Fig. 2 shows the in-line and broadside response of a 1-dimensional structure consisting of

**Figure 2** The response of a 1-dimensional model comprising a 100 Ωm, 100 m thick layer (representing a hydrocarbon bearing reservoir), embedded at a depth of 1 km below the seafloor in a 1 Ωm half-space. The model is overlain by an 800-m thick seawater layer. The source is a 0.5 Hz HED at the seafloor. (a) The electric field strength as a function of range for the in-line (solid black line) and broadside (solid red line) geometries. For comparison the dashed black and red lines show the corresponding in-line and broadside responses (respectively) of a 1 Ωm half-space. The effect of the 'airwave' caused by fields travelling up through the water, through the air and back to seafloor, starts to dominate the half-space response at a range of approximately 5 km from the source. The in-line (0° azimuth) response shows a marked increase in amplitude caused by the presence of the hydrocarbon layer. The effect on the broadside response is much smaller. (b) The phase of the in-line and broadside signal (black and red open circles, respectively). For comparison the black and red dots show the in-line and broadside phases (respectively) of a 1 Ωm half-space. The effect of the



'airwave' can be seen at ranges greater than about 5 km, when the phase lag shows no further variation with range. The effect of the thin resistive layer is to advance the phase in both geometries relative to the half-space value, however, as in the amplitude response, the effect is much larger in the in-line response. (c) The electric field strengths in (a) normalized by the corresponding half-space values for the in-line (black) and broadside (red) geometries, respectively. This highlights the effect on the response of the hydrocarbon layer. It is clear that whilst the amplitude of the in-line component is increased by over an order of magnitude, the effect on the broadside response is minimal.

a 100-m thick, 100 Ωm layer representing a hydrocarbon reservoir, embedded at a depth of 1 km below the seafloor in a 1 Ωm half-space. An 800 m thick seawater layer overlies the seafloor model. For comparison the amplitude and phase response of a simple 1 Ωm half space overlain by an 800 m seawater layer is also shown. The source is a 0.5 Hz HED located at the seafloor.

In shallow water depths, it is possible for signals from the transmitter to follow a propagation path upwards through the water column to the surface, horizontally through the air (which has a very high resistivity), and back down through the water column to a seafloor receiver. This airwave component contains no information about the sub seafloor resistivity, and tends to dominate the received signal in shallow water and at long source receiver offsets. The effect of the airwave on the amplitude and phase can be seen in Fig. 2, where the break in slope on the plot of electric field as a function of range to a distinctly shallower gradient indicates the emergence of the airwave as the dominant signal at the receiver. This occurs at about 5 km range in the responses for a 1 Ωm half-space. The phase beyond this point remains almost constant, because the air has such a high resistivity that the phase lag caused by the portion of the path through it is negligible. The total phase lag between the source and receiver therefore depends only on water depth, which in this 1-dimensional case does not vary with increasing range. Table 1 shows the range at which the airwave starts to dominate the response of a 1 Ωm half space for a range of water depths and transmission frequencies.

The range at which the airwave dominates the response, and information on seabed resistivity is lost, increases with

decreasing frequency and increasing water depth. The effect of the airwave can therefore be minimized by choosing appropriate transmission frequencies, and by targeting surveys on prospects in deep water and in which the target is at a relatively shallow depth below the seabed.

Figure 2 demonstrates that the effect of the thin resistive layer on the response depends on the source-receiver geometry. The in-line geometry results in a significant contribution to the observed field at the seafloor by the vertical component of current flow (cf. Chave *et al.* 1990). The broadside geometry results in fields at the sea floor which are more dependent on the contribution of inductively coupled currents flowing in horizontal planes. As a result, the presence of the thin resistive reservoir layer produces a significant increase in the in-line fields, while having virtually no effect on the broadside fields. This effect on thin resistive layers buried in a conductive media (e.g. sediments in exploration basins) has been shown experimentally with scaled measurements ( $\approx 50$  kHz) in a big water tank ( $8 \times 9 \times 9$  m) filled with salt water ( $\approx 0.3$  Ωm). The resistive layer was a waterbed mattress filled with tap water ( $\approx 150$  Ωm). The different effect on the in-line and broad-line antenna configurations was evident. The E-field from the in-line transmitter antenna entered the layer as guided energy, which was not the case for the broad-line configuration. The difference could be measured as a function offset between transmitter and receiver antennas (Ellingsrud *et al.* 2002).

This effect of a thin buried resistive layer has also been demonstrated by a full-scale experiment offshore West Africa (Ellingsrud *et al.* in press). The full-scale test was run in November 2000 and carried out from the research ship *RRS Charles Darwin*, in an area with proven hydrocarbon reserves. The survey was a collaboration between STATOIL, the Scripps Institution of Oceanography, USA, and the Southampton Oceanography Centre, UK. The objective of the survey was to demonstrate that the SBL technique could be used in a practical situation to directly detect hydrocarbon filled layers in the subsurface in deep water areas (Eidesmo *et al.* 2000; Ellingsrud *et al.* 2001).

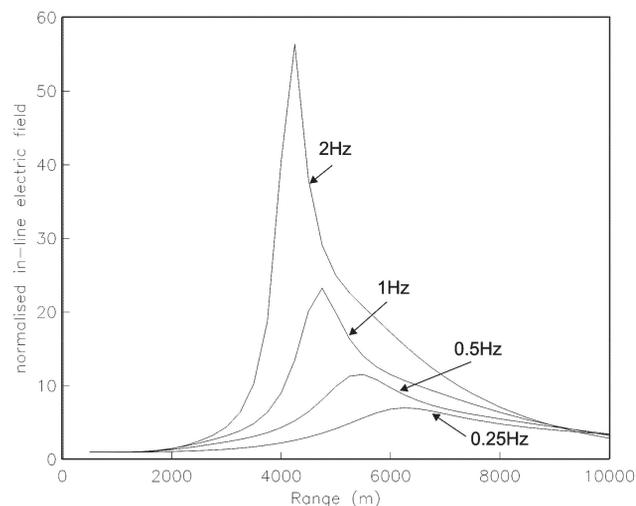
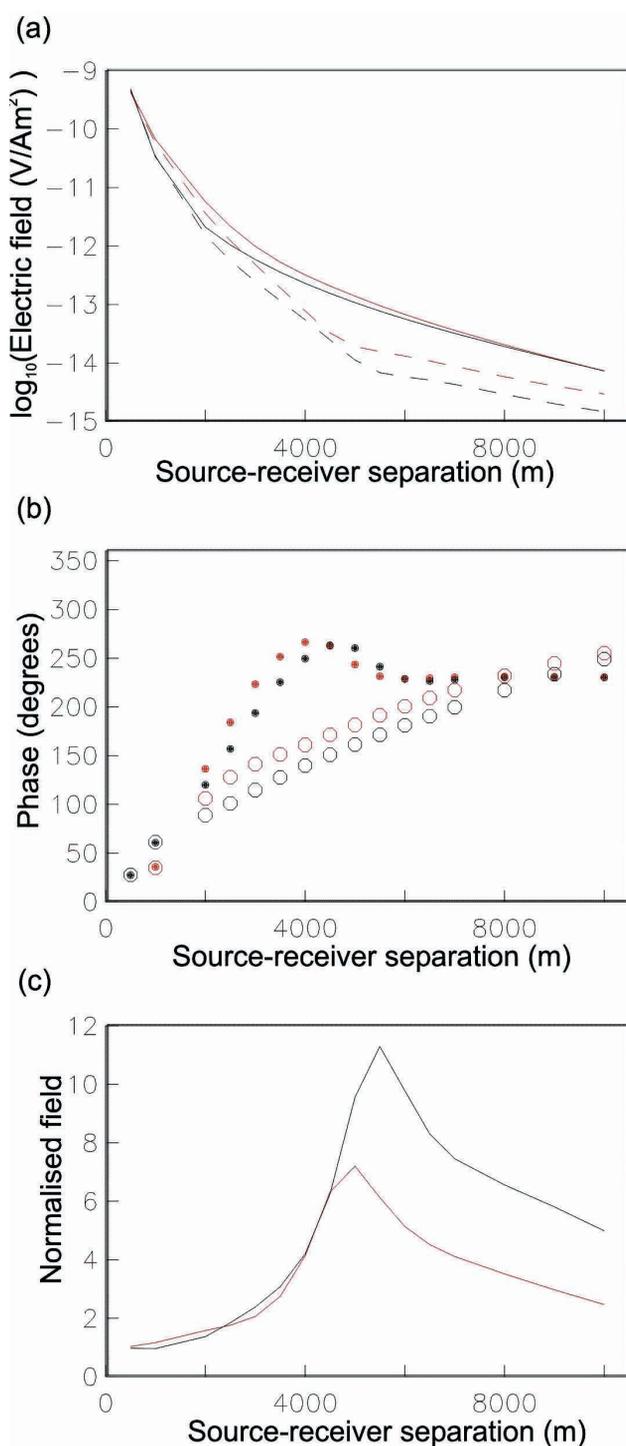
The ‘splitting’ of amplitudes between the two modes, has also been observed on a very different geological model. In this model the resistivity first increases and then decreases with depth (MacGregor *et al.* 1998; MacGregor & Sinha 2000).

It can be seen in Fig. 2a that the signal amplitude varies by several orders of magnitude over the useful set of source-receiver offsets, while the phase lag of the received signal also increases steadily with increasing offset. In order to visualize more clearly the effects of buried structure on SBL signal properties, it is convenient to normalize the observed signals with respect to some reference model. The simplest model to use consists of a water layer above the survey of the true depth, and a homogeneous isotropic half space representing the seabed below the survey. If appropriate, and if the rel-

**Table 1** The distance from the source (in km) at which the airwave (the part of the signal travelling up through the water column, through the air above, and back to the seafloor) starts to dominate the overall response, as a function of water depth and signal frequency. When the response is dominated by the airwave, the information about sub-seafloor resistivity structure is masked by the airwave

| Water depth (m) | Frequency |        |        |        |
|-----------------|-----------|--------|--------|--------|
|                 | 0.25 Hz   | 0.5 Hz | 1.0 Hz | 2.0 Hz |
| 500             | 4.8       | 4.0    | 3.4    | 3.0    |
| 600             | 5.2       | 4.3    | 3.9    | 3.5    |
| 700             | 5.7       | 4.7    | 4.3    | 3.8    |
| 800             | 6.1       | 5.0    | 4.6    | 4.1    |
| 900             | 6.5       | 5.4    | 4.9    | 4.5    |
| 1000            | 6.9       | 5.8    | 5.4    | 4.9    |
| 1200            | 7.6       | 6.7    | 6.1    | 5.6    |
| 1400            | 8.5       | 7.5    | 6.8    | 6.2    |
| 1600            | 9.3       | 8.3    | 7.5    | 7.1    |
| 1800            | 10.1      | 9.0    | 8.3    | 7.8    |
| 2000            | 11.0      | 9.8    | 8.9    | 8.4    |

evant *a priori* information is available, a more complex reference model may be used, although it is desirable to use the simplest reference model that can broadly represent the large-scale background properties of the seabed. Figure 2c illustrates the effect of normalizing the response shown in Fig. 2a with a uniform 1  $\Omega\text{m}$  half-space, overlain by an 800 m



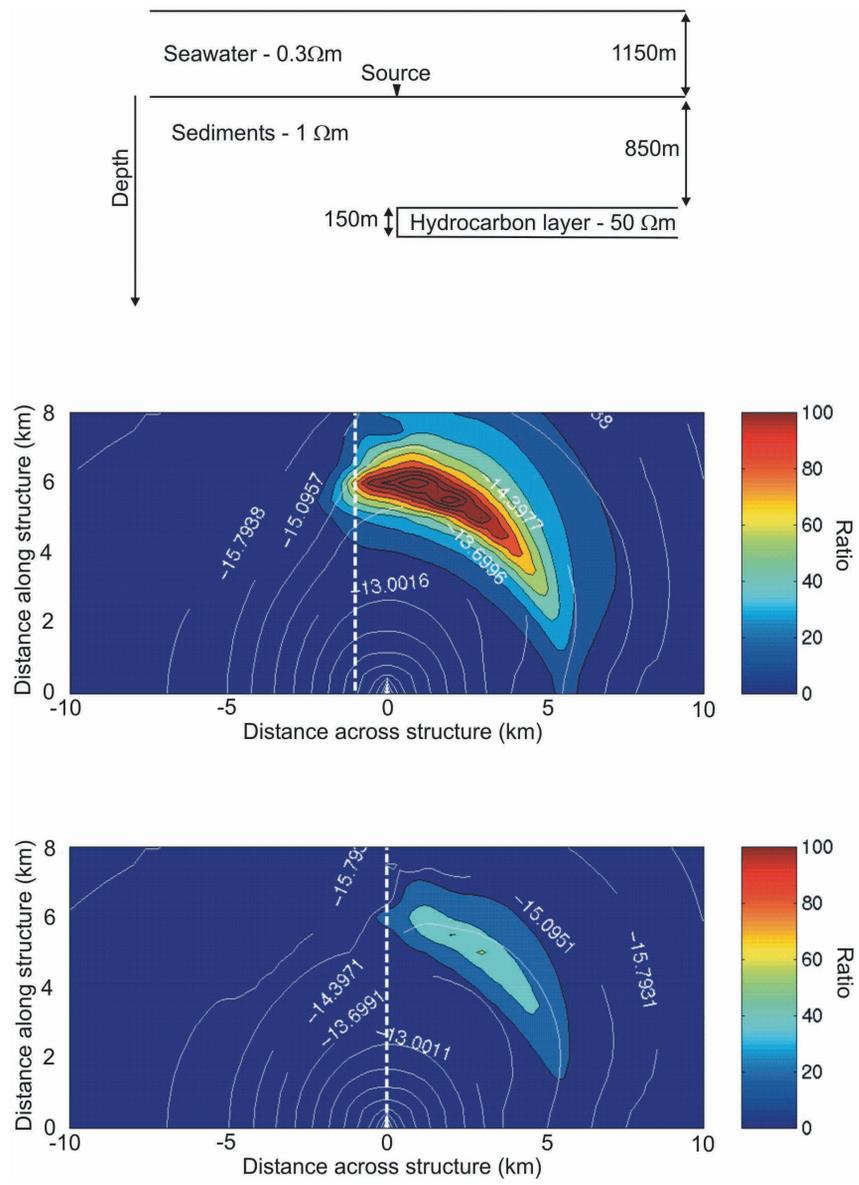
**Figure 4** Normalized in-line fields for the 1-dimensional model containing a resistive reservoir layer described in Fig. 2, for four different transmission frequencies. The response of the 1-dimensional structure has been normalized by that of a 1  $\Omega\text{m}$  half-space. The effect of the resistive layer increases with increasing frequency. See text for discussion.

seawater layer. The effect of the presence of the hydrocarbon layer is clear. At short ranges the response is only sensitive to the overburden, and therefore the difference between it and the half-space response (for both in-line and broadside geometries) is small. At ranges of 4–6 km the amplitude of the in-line response is increased by more than an order of magnitude relative to the model with no hydrocarbon layer. In contrast the broadside response is only marginally altered. At long range the effect of the airwave in the half-space response causes the magnitude of the normalized fields to fall again.

The lack of sensitivity in the broadside response to the presence of thin resistive layers might argue in favour of survey geometries that concentrate on the collection of in-line data. However, in order to unambiguously resolve the pres-

**Figure 3** The amplitude and phase response of a simple 1-dimensional model in which resistivity increases steadily from 1  $\Omega\text{m}$  at the seafloor to 20  $\Omega\text{m}$  at a depth of 3 km. (a) Amplitude response of the in-line (black) and broadside (red) geometries. Dashed lines show the responses for a 1  $\Omega\text{m}$  half-space for comparison. (b) Corresponding phase response. Symbols as in Fig. 2. (c) The amplitude response in (a) normalized by the corresponding response of a 1  $\Omega\text{m}$  half-space. Comparing this with Fig. 2c, it can be seen that the in-line response on its own cannot distinguish between a model in which the resistivity increases steadily with depth, and one containing a thin resistive layer. Only by including the broadside response can the ambiguity between the possible (and equally plausible in many situations) models be removed.

**Figure 5** (a) Vertical section through a 2-dimensional resistivity structure constructed to demonstrate the effect of a resistive hydrocarbon layer of finite lateral extent. The structure is invariant perpendicular to the plane of the page. The source is a 1 Hz HED with its axis aligned parallel to the structure invariant direction, and is placed at or close to the edge of the resistive layer. (b) The electric field at the seafloor for the case when the source is over the resistive layer and 1 km from its edge (shown by the dashed white line). The source is at the origin with its axis aligned parallel to the structure invariant direction (up and down the page). White contours show the magnitude of the electric field parallel to the maximum axis of the polarization ellipse. Colours represent the normalized field values, defined as the electric field in the presence of the 2-dimensional structure, normalized by the corresponding fields for a 1  $\Omega\text{m}$  half-space. Electric field strengths are enhanced by more than two orders of magnitude between 5 and 7 km range from the source, relative to the case with no hydrocarbon layer. However the effect is only seen in the region above the hydrocarbon. (c) The electric field at the seafloor for the case when the source is located above the edge of the hydrocarbon layer (again shown by the white dashed line). Other parameters as in (b). In this case the effect of the hydrocarbon layer is much smaller.

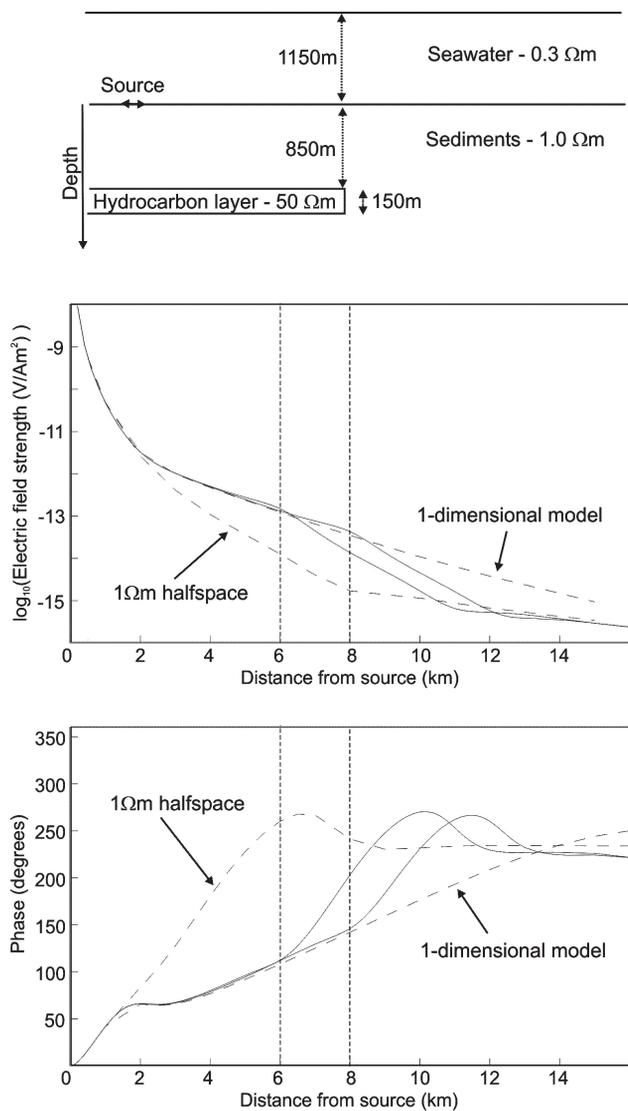


ence of hydrocarbon layers, both in-line and broadside data should be collected.

The theoretical subsurface model in Fig. 3 illustrates this point clearly. In this 1-dimensional model the resistivity increases steadily with depth, from 1  $\Omega\text{m}$  at the seafloor to 20  $\Omega\text{m}$  at a depth of 3 km. The in-line response is similar in both magnitude and phase to that seen in Fig. 2. However, in this case because the skin depth in the seafloor is longer and hence attenuation lower, the broadside response also exhibits an increase in amplitude and decrease in phase lag. For this situation there is no 'split' between in-line and broadside responses.

This second model is probably not realistic in the subsur-

face. The overburden sediments are a matrix of minerals with the pore volume filled with formation fluids. The formation fluids are comparable with seawater (dependent on the depositional environment); an electrolyte with salts dissociated in an aqueous solution. According to Ohm's law (Barrow 1979), the resistivity of an aqueous solution in a conductivity cell is proportional to the length of the cell and inversely proportional to the area and the specific conductance (conductance of a cube with unit dimensions). In the sediments the pore structure is the 'conductivity cell' and the resistivity in sediments are controlled by parameters such as porosity, pore sizes, tortuosity, formation water salinity, pressure and temperature.



**Figure 6** (a) Vertical section through a 2-dimensional resistivity structure demonstrating the effect of a resistive hydrocarbon layer when the axis of the source dipole is perpendicular to the edge of the reservoir. The source is a 1 Hz HED. (b) The in-line ( $0^\circ$  azimuth) electric field strength as a function of distance from the source when the edge of the resistive layer is 6 km (solid black line) and 8 km (solid red line) from the source. In each case the vertical dashed lines indicate the location of the edge of the resistive reservoir layer. For comparison, the black dashed curves show the electric field in the case of an infinite hydrocarbon layer (a 1-dimensional structure) and a simple  $1 \Omega\text{m}$  half-space. (c) The phase of the electric fields shown in (b) as a function of distance from the source. Other parameters as in (b). The effect on both the amplitude and phase of the resistive hydrocarbon layer falls off rapidly outside with distance from the boundary.

Shales and mud rocks are generally the dominant part of the overburden sediments in hydrocarbon prospective basins. Shales have also a certain inherent conductivity due to the adsorbed cat ions in the diffuse double layer on the pore surfaces (Van Olphen 1977). The porosity in shales is reduced from around 50% at the sea floor to approximately 10% at a burial depth of 3 km due to pressure compaction. The tortuosity is also increasing with depth. Those two factors should increase resistivity as a function of depth. However, the conductance of electrolytes increases with temperature (Korium & Backris 1951) and counteracts the effects of pressure compaction. The normal thermal gradient in the North Sea, for example, is approximately  $30^\circ\text{C}$  for each km of depth.

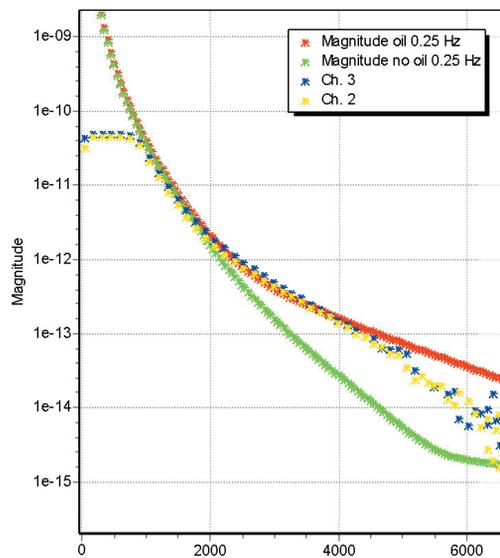
Typical resistivity well logs, logged from the sea floor and several km down in the underground tends to show a reduced resistivity with depth rather than the opposite. This indicates that the temperature effect is stronger than the compaction effects. For these reasons it is unlikely to find a dramatic resistivity change from 1 to  $20 \Omega\text{m}$  from the seafloor and down to 3 km. Designing a survey in such a way that different parts of the resulting data are more or less sensitive to the presence of certain key features is still essential for removing ambiguity in the interpretation.

The effect of transmission frequency on the response of a 1-dimensional model containing a thin resistive layer is illustrated in Fig. 4, which shows the normalized in-line electric fields at four frequencies. The effect of the thin resistive layer increases with increasing frequency, and the range at which the maximum effect is seen decreases. However as the frequency increases the magnitude of the field measured at a given distance from the source decreases. If the frequency is increased too far, then the signal falls below the noise level and can no longer be detected in practical surveys. Careful modelling is therefore needed prior to a survey in order to optimize the survey parameters for the target of interest.

### 2-dimensional modelling: edge effects

In many practical applications it is not only the presence of hydrocarbon that is of interest, but also the lateral extent of the reservoir. The effect of a resistive hydrocarbon body of finite extent can be investigated using 2.5-dimensional modelling (an HED source whose fields vary in 3-dimensions, over a 2-dimensional resistivity structure), using the finite element modelling code of Unsworth *et al.* (1993).

Figure 5a illustrates a model in which the resistive hydrocarbon layer is of finite extent and the source is placed at or close to its edge with the dipole axis parallel to the edge. Figure 5b,c show the normalized electric field at the seafloor for two source locations. In Fig. 5b, the transmitter lies over the reservoir and 1 km from its edge. In Fig. 5c, the transmitter lies directly above the reservoir edge. In the first case, at ranges of 5–7 km from the source and azimuths of  $0^\circ$ – $45^\circ$ , the



**Figure 7** Electric field as a function offset. The blue and yellow stars show the measured data from two channels acquired by one of the receivers positioned at the central part of the oil field. The data are compared with a 1-dimensional model, based on a resistivity well log from the overburden and the oil zone. The red solid line is the response from a model with hydrocarbons present and the green line is the response with no hydrocarbons present. At the left part of the figure the data are almost horizontal and do not follow the model trend due to receiver saturation. An interpreted edge effect is observed at an offset of approximately 4500 m east of the receiver where the data falls off from the oil trend towards the water trend. (See text and Ellingsrud *et al.* in press) for detailed discussions of field test results)

magnitude of the electric field is enhanced by more than two orders of magnitude relative to the case without a hydrocarbon layer. In the second case the effect of the resistive layer is much smaller. In both cases the asymmetry in the sub-seafloor structure is reflected in the fields at the seafloor. These figures show clearly that the reservoir structure causes substantial increases in the fields at geometries close to in-line, provided that the source and receiver are both over the reservoir. If either the source or receiver is off the reservoir, then the amplitude increases are weak. At receiver locations close to broadside geometry, the effect of the resistive layer is minimal as in the 1-dimensional case, even if both source and receiver are over the reservoir. This figure illustrates that the amplitude splitting effect should be observable over reservoirs of finite size, as well as over 1-dimensional (layered) structures.

The marked difference between the response on and off the resistive structure shows that the observed fields are extremely sensitive to the location of the transmitter with respect to the edge of the reservoir. In the upper panel, the marked asymmetry of the fields about the  $y$ -axis shows that provided the

transmitter is over the reservoir, the observed fields are also highly sensitive to the location of the receiver with respect to the edge of the reservoir.

Figure 6 shows the effect of a hydrocarbon layer of finite lateral extent when the axis of the source dipole is perpendicular to the edge of the reservoir. The in-line electric field amplitude and phase (measured along the dipole axis) are shown, along with the responses of a simple half-space structure, and the response when the resistive layer is infinite in lateral extent (the 1-dimensional case). When the source and receivers are over the hydrocarbon layer, then as in the 1-dimensional case the effect of the layer is to increase the magnitude of the in-line electric field and advance the phase with respect to the response of a model with no hydrocarbon layer. However for receiver positions outside the reservoir boundary, the effect on both the amplitude and phase dies off rapidly with distance from the edge.

This edge effect is also interpreted to be present in the real data from the West Africa survey. Figure 7 shows an example of data acquired by one of the receivers positioned at the central part of the oil field. The transmitter was towed over the receiver from west to the east and the electric field was measured as a function of offset. Blue and yellow stars show the measured data from two channels. The data are compared with a 1-dimensional model, based on a resistivity well log from the overburden and the oil zone. The red solid line represents a model with hydrocarbons present and the green line represents a model with no hydrocarbons present. The measured data follows the hydrocarbon model to approximately 4500 m east of the receiver. Then the data 'falls' towards the model with no hydrocarbons present. This edge effect is interpreted to correspond to the OWC determined from seismic data. For detailed results from the full scale field survey see Ellingsrud *et al.* (in press).

These examples demonstrate that by careful positioning of both transmitter tow tracks and receivers relative to a suspected hydrocarbon bearing structure, the survey method described here can provide detailed information on the lateral extent of the hydrocarbon, as well as on its existence or otherwise.

## References

- Barrow, G.M. [1979] *Physical Chemistry*, 4th edn. McGraw-Hill Co.
- Chave, A.D., Constable, S. and Edwards, R.N. [1991] Electrical exploration methods for the seafloor. *Electromagnetic Methods in Applied Geophysics* (ed. Nambighian, M.N.), Vol. 2, pp. 931–966, Society of Exploration Geophysicists.
- Chave, A.D., Flosadottir, A.H. and Cox, C.S. [1990] Some comments on the seabed propagation of VLF/ULF electromagnetic fields. *Radio Science* 25, 825–836.
- Constable, S. and Cox, C. [1996] Marine controlled source electromagnetic sounding – II: The PEGASUS experiment. *Journal*

of *Geophysical Research* **97**, 5519–5530.

Edwards, R.N., Law, L.K., Wolfgram, P.A., Nobes, D.C., Bone, M.N., Trigg, D.F. and DeLaurier, J.M. [1985] First results of the MOSES experiment: sea sediment conductivity and thickness determination, Bute Inlet, British Columbia, but magnetometric offshore electrical sounding. *Geophysics* **50**, 153–160.

Eidesmo, T., Ellingsrud, S., Kong, F.N., Westerdahl, H. and Johansen, S. [2000] Method and apparatus for determining the nature of subterranean reservoirs. *Patent application number WO 00/13046*, filed August 1998.

Ellingsrud, S., Eidesmo, T., Kong, F.N. and Weterdahl, H. [2001] Reservoir identification using refracted wave, *Patent application number WO 01/57555*, filed February 2000.

Ellingsrud, S., Eidesmo, T., Pedersen, H.M. and Schaug Pettersen, T. [2002] Method for electric dipole configuration on the seabed, *International patent application (PCT) GB01/03473*, priority date 14.08.2000.

Ellingsrud, S., Sinha, M., Constable, S., Eidesmo, T., MacGregor, L. and Johansen, S. [in press] Remote sensing of hydrocarbon layers by Sea Bed Logging (SBL): results from a cruise offshore. *West Africa*, in press.

Evans, R.L., Sinha, M.C., Constable, S. and Unsworth, M.J. [1994] On the electrical nature of the axial melt zone at 13°N on the East Pacific Rise. *Journal of Geophysical Research* **99**, 577–588.

Kortum, G. and Backris, J.O.M. [1951] *Textbook of Electrochemistry*, Vol. 1. Elsevier, Amsterdam.

MacGregor, L.M., Constable, S.C. and Sinha, M.C. [1998] The RAMESSES experiment – III: Controlled source electromagnetic sounding of the Reykjanes Ridge at 57°45'N. *Geophysical Journal International* **135**, 773–789.

MacGregor, L.M. and Sinha, M.C. [2000] Use of marine controlled source electromagnetic sounding for sub-basalt exploration. *Geophysical Prospecting* **48**, 1091–1106.

MacGregor, L.M., Sinha, M.C. and Constable, S.C. [2001] Electrical resistivity structure of the Valu Fa Ridge, Lau basin, from marine controlled source electromagnetic sounding. *Geophysical Journal International* **146**, 217–236.

Sinha, M.C., Patel, P.D., Unsworth, M.J., Owen, T.R.E. and MacCormack, M.G.R. [1990] An active source electromagnetic sounding system for marine use. *Marine Geophysical Research* **12**, 29–68.

Stratton, J.A. [1941] *Electromagnetic Theory*. MacGraw-Hill.

Unsworth, M.J., Travis, B.J. and Chave, A.D. [1993] Electromagnetic induction by a finite electric dipole over a 2-dimensional earth. *Geophysics* **58**, 198–214.

Van Olphen, H. [1977] *An Introduction to Clay Colloid Chemistry*, 2nd edn. John Wiley & Sons, New York.

Young, P.D. and Cox, C.S. [1981] Electromagnetic active source sounding near the East Pacific Rise. *Geophysical Research Letters* **8**, 1043–1046.