

Electromagnetic Surveying

The present invention relates to electromagnetic (EM) surveying, in particular for seabed logging, and is concerned with providing a system for determining
5 the resistivity or conductivity of subsea strata, especially the upper strata, e.g. at a depth of up to about 100 m or even greater.

Currently, the most widely used techniques for geological surveying, particularly in sub-marine situations, are seismic methods. These seismic
10 techniques are capable of revealing the structure of the subterranean strata with some accuracy. However, whereas a seismic survey can reveal the location and shape of a potential reservoir, it can normally not reveal the nature of the reservoir.

15 It has been appreciated by the present applicants that while the seismic properties of hydrocarbon filled strata and water-filled strata do not differ significantly, their electromagnetic resistivities do differ. Thus, by using an electromagnetic surveying method, these differences can be exploited and the success rate in predicting the nature of a reservoir can be increased
20 significantly.

Consequently, a method and apparatus embodying these principles form the basis of the present applicants' EP-A-1256019.

25 This contemplates a method for searching for a hydrocarbon containing subterranean reservoir which comprises: applying a time varying electromagnetic field to subterranean strata; detecting the electromagnetic wave field response; seeking, in the wave field response, a component representing a refracted or ducted wave; and determining the presence and/or nature of any

reservoir identified based on the presence or absence of a wave component refracted or ducted by hydrocarbon layer.

5 A ducted wave behaves differently, depending on the nature of the stratum in which it is propagated. In particular, the propagation losses in hydrocarbon stratum are much lower than in a water-bearing stratum while the speed of propagation is much higher. Thus, when a hydrocarbon-bearing reservoir is present, and an EM field is applied, a strong and rapidly propagated ducted wave can be detected. This may therefore indicate the presence of the reservoir
10 or its nature if its presence is already known.

Electromagnetic surveying techniques in themselves are known. However, they are not widely used in practice. In general, the reservoirs of interest are about 1 km or more below the seabed. In order to carry out electromagnetic
15 surveying as a stand alone technique in these conditions, with any reasonable degree of resolution, short wavelengths are necessary. Unfortunately, such short wavelengths suffer from very high attenuation. Long wavelengths do not provide adequate resolution. For these reasons, seismic techniques are preferred.

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However, while longer wavelengths applied by electromagnetic techniques cannot provide sufficient information to produce an accurate indication of the boundaries of the various strata, if the geological structure is already known, they can be used to determine the nature of a particular identified formation, if
25 the possibilities for the nature of that formation have significantly differing electromagnetic characteristics. The resolution is not particularly important and so longer wavelengths which do not suffer from excessive attenuation can be employed.

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The resistivity of seawater is about 0.3 ohm-m and that of the overburden beneath the seabed would typically be from 0.3 to 4 ohm-m, for example about 2 ohm-m. However, the resistivity of an oil reservoir is likely to be about 20-300 ohm-m. This large difference can be exploited using EM surveying techniques. Typically, the resistivity of a hydrocarbon-bearing formation will be 20 to 300 times greater than water-bearing formation.

Thus, an EM source such as an electric dipole transmitter antenna on or close to the sea floor induces (EM) fields and currents in the sea water and in the subsurface strata. In the sea water, the EM-fields are strongly attenuated due to the high conductivity in the saline environment, whereas the subsurface strata with less conductivity potentially can act as a guide for the EM-fields (less attenuation). If the frequency is low enough (in the order of 1 Hz), the EM-waves are able to penetrate deep into the subsurface, and deeply buried geological layers having higher electrical resistivity than the overburden (as e.g. a hydrocarbon filled reservoir) will affect the EM-waves. Depending on the angle of incidence and state of polarisation, an EM wave incident upon a high resistive layer may excite a ducted (guided) wave mode in the layer. The ducted mode is propagated laterally along the layer and leaks energy back to the overburden and receivers positioned on the sea floor. The terms "refracted" and "ducted" are used in this specification to refer to this wave mode.

In seabed logging, a signal is emitted from a towed source antenna, parallel to, and close to the sea floor; and the wavefield response detected by a number of stationary receivers, distributed on the sea floor, is recorded. The strength of the emitted signal is proportional to the current I_A delivered to the antenna, and this current is accurately monitored and recorded. [If the current source is very stable, the current would, of course be constant.]

It is an object of the present invention to provide an apparatus and method for detecting and/or determining the nature of a subterranean reservoir.

According to one aspect of the invention, there is provided a method of
5 determining the nature of a subterranean stratum which comprises: deploying
an electric dipole transmitter antenna, preferably with its axis generally
horizontal; applying an electromagnetic (EM) field to the stratum containing
the reservoir using the transmitter; measuring the current and voltage at the
antenna terminals during the EM transmission; and determining the nature of
10 the stratum from changes in the measured voltage.

Changes in the nature of subterranean strata cause changes in the resistivity of
the seabed as a whole beneath the sea floor. Since the resistivity of the source,
antenna and sea water should remain constant, these changes in seabed
15 resistivity alone may cause the voltage at the antenna terminals to vary and so
the variations in antenna voltage will be representative of the of the changes in
the nature of the strata in the seabed.

Thus, analysis of the logged receiver data may reveal the presence of a fast,
20 low attenuation guided wave, and thus the presence of a high resistivity stratum
which may be oil bearing.

High resistivity may, however, occur, not in oil bearing strata only, but also in
strata consisting of e.g. solid salt or rock containing little or no water. In order
25 to determine the nature of the high resistivity stratum, it is generally necessary
to carry out a detailed analysis of the logged receiver data, in order to create a
model, based on the seismic data, in which resistivity values are assigned to
the various strata. From the geological knowledge of the region in question, the
most likely nature of a high resistivity stratum may then be ascertained.

The accuracy of the model is limited by the receiver data, and may be improved by utilising other available information. One means of obtaining such additional information is by monitoring the input impedance of the towed transmitter antenna $Z_A = V_A/I_A$, where I_A is the antenna current and V_A the terminal voltage.

The input impedance of the towed transmitter antenna is determined by the following parameters:

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1. The configuration of the antenna.
2. The conductivity of the sea water
3. The position and orientation of the antenna with respect to the sea floor
4. The topography of the sea floor (plane or otherwise).
- 15 5. The resistivity distribution below the sea floor.

Parameters 1-4 may be separately monitored and accounted for, and the remaining variations of Z_A provide information about the resistivity distribution below the sea floor.

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In one embodiment, the transmitter is located on or close to the seabed or the bed of some other area of water. Preferably, the frequency of the EM field is continuously varied over the transmission period. Preferably, the field is transmitted for a period of time for 3 seconds to 60 minutes, for example, from 25 10 seconds to 5 minutes. Preferably, the method is repeated at different locations.

In a more preferred embodiment, the transmitter is towed over the seabed while the EM field is being transmitted. The transmitter is preferably towed as close

to the sea floor as possible. Preferably, the distance to the sea floor should be much less than the length of the antenna (e.g. 20 m to 200 m), and much less than the wavelength of the frequencies to be used.

- 5 Preferably, the transmitter includes an inertia sensor to sense the difference between a change in the sea floor height and a rise/fall of the transmitter.

In addition, the transmitted signal shape may be modified so that it contains more of the harmonics which are useful for mapping the conductivity. It will
10 be understood that calculation of the conductivity of the upper strata of the seabed as a function of position and depth is also desirable.

Preferably, the method of the invention is carried out during a conventional EM survey using receivers to detect the transmission wavefield response. The
15 method may also be used in conjunction with seismic surveying techniques.

The invention extends to a method for detecting different subterranean strata and is particularly applicable to the detection and identification of hydrocarbon bearing strata.

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Preferably, the wavelength of the transmission is given by the formula

$$0.01h \leq \lambda \leq 30h; \text{ or more preferably,}$$

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$$0.1h \leq \lambda \leq 10h$$

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wherein λ is the wavelength of the transmission through the subsea strata and h is the distance from the seabed to the strata under investigation. Preferably, the transmission frequency is from 0.01 Hz to 1 kHz, for example, from 0.1 to 20 Hz.

The invention extends to a process for the production of a survey report by carrying out a method according to the invention, and a survey report produced in this way.

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The invention may be carried into practice in various ways and an embodiment will now be described by way of example with reference to the accompanying drawings, in which:

10 Figure 1 is a schematic diagram showing how the invention may be carried out in practice.

Figure 1 shows an antenna 11 towed by a vessel 12 at a distance h above the sea floor 13. The antenna 11 emits a wavefield, whose strength is proportional to the current I_A delivered to the antenna 11, and this is accurately monitored and recorded. By also monitoring and recording the voltage V_A at the antenna terminals, the impedance of the antenna, $Z_A = V_A/I_A$, may be calculated. Z_A is a function of the frequency, f , and when a multifrequency signal is employed, this function may be found within a range of frequencies extending from $f = 0$ to a maximum frequency $f_{\max}$, determined by the frequency spectrum of the signal, and the accuracy of the voltage and current measurements. By means of the impedance function, the following important parameters may be calculated, namely, the distance from the antenna to the sea floor, the conductivity of the sea water, and the step in conductivity at the sea floor, and possibly more detail of the conductivity variation immediately below the sea floor.

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Part of the emitted signal is reflected at the sea floor, the reflection coefficient being

$$\rho = \frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2} \quad (1)$$

5 where σ_1 and σ_2 are the conductivities above and below the sea floor 13,
respectively. The reflected signal induces a voltage V_R in the antenna, thereby
altering the voltage and the current at the antenna terminals, thus ultimately
causing a change in the antenna impedance. The amplitude and phase of V_A
vary with the frequency f , and the distance h between the antenna and the sea
10 floor. At sufficiently high frequencies, V_A is negligible, and the impedance
depends only on the frequency, and on the conductivity σ_1 , which may then be
calculated.

Assuming σ_2 constant, the reflected signal may be found from the simple model
15 indicated in Figure 1, as emitted from an image antenna 14 located the distance
 h below the (plane) sea floor, with $\sigma_2 = \sigma_1$. The current of the image antenna is
 ρI_A .

Claims

1. A method of determining the nature of a subterranean stratum which comprises deploying an electric dipole transmitter antenna; applying an electromagnetic (EM) field to the stratum containing the reservoir using the transmitter; measuring the current and voltage at the antenna terminals during the EM transmission; and determining the nature of the stratum from changes in the measured voltage.
2. A method as claimed in Claim 1, in which the input impedance of the antenna is calculated from the measured current and voltage and the nature of the stratum is determined from changes in the impedance.
3. A method as claimed in Claim 2, in which the changes in the impedance are used to calculate the resistivity of the stratum and the nature of the stratum is deduced from the resistivity.
4. A method as claimed in Claim 3, in which the resistivity is combined with existing geological knowledge of the stratum to determine the nature of the stratum.
5. A method as claimed in Claim 4, in which the existing geological knowledge comprises seismic data.
6. A method as claimed in any of Claims 2 to 5, in which the conductivity of the sea water is monitored and changes in sea water conductivity are taken into account in determining the antenna input impedance.
7. A method as claimed in any of Claims 2 to 6, in which the height of the

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antenna above the sea floor is monitored and changes in the antenna height are taken into account in determining the antenna input impedance.

5 8. A method as claimed in any preceding claim in which the transmitter antenna is deployed with its axis generally horizontal.

9. A method as claimed in any preceding claim, in which the transmitter is towed over the seabed while the EM field is being transmitted.

10 10. A method as claimed in any preceding claim in which the transmitter is towed at a distance between 20 m and 200 m from the seabed.

11. A method as claimed in any preceding claim in which the transmitter is towed at a distance from the seabed which is significantly less than the wave
15 length of the frequencies of the EM transmitter.

12. A method as claimed in any preceding claim in which the transmitted signal shape contains harmonics which are used in the determination of the antenna input impedance.
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13. A method as claimed in any preceding claim in which the wave length of the EM transmitter is given by the formula

$$0.01h \leq \lambda \leq 30h,$$

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wherein λ is the wave length of the transmission through the subsea strata and h is the distance from the seabed to the strata under investigation.

14. A method as claimed in any preceding Claim in which the transmission

frequency is from 0.01 Hz to 1 kHz.

15. A process for the production of a survey report which comprises carrying out a method as claimed in any preceding Claim and formulating the
5 voltage and/or impedance changes together with the related conclusions into a report.