

METHOD AND DEVICE FOR INDUCED POLARIZATION MAPPING OF SUBMARINE HYDROCARBON RESERVOIRS

The invention describes a method for fast direct mapping of the anomaly zones associated with hydrocarbon reservoirs below the seabed. The method is based on induced polarization effect observed in an electromagnetic field measured by vertical coinciding transmitter/receiver lines moving over sub-sea reservoirs.

At present two approaches are used for detecting and characterizing hydrocarbon-bearing reservoirs in deep-water areas.

The first approach is based on the sounding of a horizontally layered, electrically conductive section lying under a layer of sea water. This section represents the sediments. At some depth in these sediments is embedded a thin resistive reservoir containing hydrocarbons. The powerful transmitter excites alternating electric current in the layer of sea water and the underlying section, and one or multiple electric and/or magnetic recorders located at different sites on or above the seabed record(s) electromagnetic responses from the section. Images of these responses or their inversion and transformations are used, together with seismic data, logging data and other data, for oil and gas exploration as well as for reservoir assessment and development.

This approach has been described in numerous patents and

methods, for example US patent No. 4,617,518 and 6,522,146 of Srnka; 5,563,513 of Tasci; 0052685, 0048105, 6,628,119 of Eidesmo et al.; 2006132137 of MacGregor et al.; EP patent No. 1425612 of Wright et al.; international publication No. WO 03/048812 of MacGregor and Sinha, WO-2004049008; GB publication 2395563, AU publication 20032855 of MacGregor et al. and numerous other publications mentioned in the list of references which follows.

Such an approach can be used in the absence of so-called induced polarization effect (IP) which is capable of distorting the electromagnetic response of the structure containing a reservoir. In addition, this approach has a low resolution compared with seismic prospecting, the effectiveness thereby being relatively low.

The other approach is based on analysis on secondary electric fields arising under the impact of electric current transmitted in the section by a control source. These fields are of an electrochemical nature and are caused by processes in so-called double layers arising at the contact between the solid substance of rocks and interstitial fluids. This effect is called induced polarization effect (IP).

The character of the IP depends on the electrical resistivity of the solid rock. In case hydrocarbons are present at the contact between resistive bearing strata, the IP processes are of an electro-kinetic character. The intensity of the IP effect depends on the electrolyte concentration and on the pore structure and can be used for hydrocarbon exploration.

IP effect is measured in either the time or the frequency domain.

In the time domain the transmitter excites series of electric current pulses of a rectangular shape with pauses between the

pulses and recorders make measurements of the resultant electric fields in pauses between pulses. The IP effect manifests itself as a specific change in the time domain response which is present in the absence of IP effect.

- 5 In the frequency domain the transmitter generates alternating current of different frequencies, and recorders make measurements of responses. IP effect manifests itself as a reduction in voltage against an increase in frequency and a negative shift in voltage phase relative to the exciting current.
- 10 According to Kruglova et al. (1976) and Kirichuk (1976) rocks lying in the reservoir area suffer epigene modifications under the influence of upward migration of hydrocarbons, which lead to changes in the chemical-mineralogical structure and physical properties of the rocks.
- 15 The other mechanism which creates IP effect has been discussed by Pirson (1969, 1976) and Oehler (1982) who explained it as the accumulation of pyrite in a shallow, porous host rock, where the pyrite is distributed within fractures or between original grains with a disseminated or cement-like texture.
- 20

Other models have been proposed for the explanation of IP effect, for example by Schumacher (1969). However, in all models the processes resulting in IP effect embrace huge volumes of rocks and can create anomalies not only in or close to the reservoirs but at different levels of section above the reservoirs.

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Existing methods of hydrocarbon exploration based on the surveying of IP effect and US (Kaufman, 1978; Oehler, 1982; Srnka, 1986; Vinegar, 1988; Stanley 1995; Wynn, 2001; Conti, 2005) and Russian patents (Alpin, 1968; Belash, 1983; Kashik, 1996; Nabrat, 1997; Rykhlinksy, 2004; Lisitsin, 2006) cited

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above have been designed to detect electrochemically altered sediments, that is an alteration zone that may extend far upwards from the pyrite accumulation.

According to Moiseev (2002) a pyrite halo accompanying hydrocarbon deposits can be located at a depth of 300-700 metres independently of the deposit depth itself. Moiseev also noted that according to field investigations, a close relation between enhanced polarizability contours and hydrocarbon reservoir projection has been determined, which is indicative of vertical migration of hydrocarbons and gives the possibility of using this circumstance for hydrocarbon exploration.

At present there is little experience from the application of IP effect for marine hydrocarbon exploration; at the same time on-land experience has demonstrated that the exploration of hydrocarbon reservoirs was successful in seventy out of a hundred boreholes drilled on the basis of IP effect (Moiseev, 2002).

In experimental data the behaviour of the IP effect is usually described via different types of models representing the electric resistivity ρ of rocks as a frequency-dependent parameter. The dependence of the resistivity on frequency is of very great importance for hydrocarbon mapping because it provides a higher resolution with respect to parameters indicative of the existence of hydrocarbons.

An exhaustive review and analysis of existing models describing the dependence of resistivity on frequency, given by Dias (1968; 1972, 2000), demonstrated that IP effect can be appropriately expressed as:

$$\rho = \rho_0 \left[1 - \eta \left(1 - 1/t\omega\tau_1 \left(1 + \frac{1}{\mu} \right) \right) \right], \quad (1)$$

where

$$\mu = \omega\tau + (i\omega\tau_2)^{1/2}, \quad \tau = rC, \quad \tau_1 = (R + R_s)C, \quad \tau_2 = (\alpha C)^2, \quad \eta = (\rho_0 - \rho_\infty) / \rho_0.$$

Here τ , τ_1 and τ_2 are the relaxation times related to the different relaxation modes,

5 ρ is the complex resistivity,

ρ_0 and ρ_∞ are the real values of ρ by direct current and highest frequencies, respectively,

η is the chargeability characterizing the intensity of the IP effect.

10 These 5 parameters (ρ_0 , η , τ , τ_1 , and τ_2) describe the frequency dependence of complex resistivity completely and can be used for petrophysical interpretation (Dias, 2000, Nelson et al., 1982, Mahan et al., 1986). The parameters r , R , R_s , C , and α giving a phenomenological description of IP effect,
15 are resistors, capacitor and some coefficient of equivalent circuit analogues (Dias, 2000). The relaxation times τ , τ_1 and τ_2 are closely connected with the separation between particles (sources of IP).

The well-known and popular Cole-Cole model has 4 parameters
20 and is less precise than Dias's formula.

The complex character of ρ , which is typical of IP effect, considerably increases the sensitivity of electromagnetic fields to hydrocarbon targets and makes the method using IP effect as the indicator of hydrocarbons attractive for hydro-
25 carbon mapping.

Kashik et al. (RU 2069375 C1, 1996), considered here as a precursor of the present invention, uses three vertical lines: one for a transmitter and two for receivers. All three of the lines are placed in different holes made in the ice
30 floe. The transmitter generates pulse-shaped electric cur-

rent, and receivers measure the vertical component of the electric field. The distance between the receiver lines in a horizontal direction is in the order of 1-2 times the prospecting depth. The difference between the amplitude of an
5 electric field measured in two adjacent lines is used as the interpretive parameter. The disadvantage of this invention is the inability to control the movement of the ice floe, which highly decreases its possibilities and productivity; absence of measurements of the vertical component of the electric
10 field at different levels in the sea, which limits the possibilities for noise suppression and interpretation.

The present invention has for its object to remedy or reduce at least one of the drawbacks of the prior art.

The object is achieved through features which are specified
15 in the description below and in the claims that follow.

The present invention provides a fast method of surveying for straightforward and fast determination of IP.

The present invention also provides a method for constructing and contouring an area through characterization by IP effect,
20 thereby increasing the probability of detecting hydrocarbon reservoirs.

In addition, the present invention provides a method which enables the evaluation of some parameters which are useful for the petrophysical interpretation of rocks characteristic
25 of hydrocarbon reservoirs potentially present in the area under surveying.

Further, the invention provides a method for processing the data recorded during surveying, with the aim of determining parameters characterizing the petrophysical properties of the
30 rocks creating the IP effect. These parameters are used for

mapping by plane projection of reservoir edges on the seabed and together with CSEM, seismic, logging and other geological and geophysical methods for interpretation.

In a first aspect the invention relates more specifically to a method for electromagnetic surveying based on the detection of induced polarization effect and evaluation of its characteristics for mapping marine hydrocarbon targets, characterized by the method comprising:

a) deploying vertically in a water body at least one electrical wire forming an electromagnetic transmitter emitting electromagnetic energy which is arranged to excite an electromagnetic field in the water body and underlying medium, the same wire being used as a receiver for measurements of the vertical component of the electric field;

b) providing surveying data as the spatial distribution of the vertical component of the electric field and the medium response in the form of apparent resistivity versus time in the body of water;

c) carrying out a space/time analysis of the vertical component of the electric field and the response for the purpose of detecting induced polarization effect and determining its intensity and relaxation times; and

d) mapping the anomalous zones described by the characteristics perspective of the induced polarization effect for the exploration of an underground hydrocarbon reservoir.

Through the supply of electromagnetic energy, one conductor of a vertically deployed multi-conductor cable is preferably used as an electromagnetic transmitter exciting an electromagnetic field in the body of water and underground medium, and other conductors in the cable, which are of different lengths and are terminated by electrodes, are used as receivers for measuring the medium response.

Advantageously, a plurality of vertically deployed multi-conductor cables, each having one conductor arranged for the supply of electromagnetic energy, are used as the electromagnetic transmitter exciting an electromagnetic field in the body of water and underlying medium, and other conductors in the cables, which are of different lengths and are terminated by electrodes, are used as receivers for measuring the medium response.

Preferably, one or a plurality of the receivers is/are fixed during measurements.

Preferably, one or a plurality of the receivers is/are towed by a vessel.

Preferably, the at least one transmitter emits electromagnetic energy in the time domain as an intermitted series of current pulses of different polarities and with sharp terminations, and at least one receiver makes measurements of time domain responses during time lapses between consecutive current pulses when the response is not masked by the transmitter current.

Preferably, the duration of the current pulses and pauses is specified in such a way that an electromagnetic field penetration depth is provided, exceeding two to three times or more the depth at which the reservoir is located, preferably within a range of 0.1 seconds to 30 seconds.

In a second aspect the invention relates more specifically to a surveying apparatus for the electromagnetic surveying of marine hydrocarbon targets, characterized by one or more generators, which are arranged to generate current pulses of different polarities with sharp terminations, being connected to a submersible system comprising:

at least one electrical wire which is arranged to emit

electromagnetic energy into a body of water and an underlying medium, and is arranged to receive the vertical component of the electric field, at least one of the electrical wires being a vertically deployed multi-conductor cable in which at least one conductor is arranged to excite, when being supplied with electromagnetic energy from a generator, an electromagnetic field in the body of water and the underlying medium, and other conductors of the cable, which are of different lengths and are terminated by electrodes, are arranged to receive the vertical component of the electric field for registration of the medium response.

In a third aspect the invention relates to a surface vessel characterized by it carrying a surveying apparatus in accordance with the appended claim 8.

In a fourth aspect the invention relates to a computer apparatus loaded with machine-readable instructions for the implementation of the method for an electromagnetic survey in accordance with any one of the appended claims 1 to 7.

In what follows is described a non-limiting example of a preferred embodiment which is visualized in the accompanying drawings, in which:

Figures 1a-1c illustrate the possible configurations usable for fast IP mapping of potential hydrocarbon-containing areas;

Figures 2a and 2b present the result of numerical modelling with curves of apparent resistivity versus time for different sections with and without IP effect; and

Figure 3 illustrates the possible strategy for hydrocarbon surveying.

In a first exemplary embodiment a single transmitter mounted on a vessel consists of a vertically deployed, elongated, conductive single-core cable terminated by electrodes, which is submerged in a body of water. The vessel is moving slowly, and the transmitter emits intermittent current pulses which have sharp terminations, while the same cable with electrodes is used for measurements of medium responses in the course of time lapses between consecutive current pulses. This is described further in NO323889 which is incorporated herein in its entirety as reference.

The first exemplary embodiment is illustrated in figure 1a, in which a vessel 1 floating on a water surface 82 is towing a vertical elongated cable 2 terminated by electrodes 4, said cable 2 being submerged in a body of water 8 towards a seabed 81. A generator (not shown) is installed on the vessel 1 and is arranged to emit intermittent current pulses, which have sharp terminations, into the cable 2. The cable 2 with the electrodes 4 is arranged to register the response from an underlying medium 83, that is, the underground structure which is the object of the mapping, in the course of the pause between two pulses. A position monitoring system 6 is used for determining the position of the vessel 1 during the survey.

In a second exemplary embodiment a generator is installed on the vessel and is connected to a vertically deployed, elongated multi-core conductive cable including electrodes, which is submerged in the body of water. The vessel is moving slowly in a horizontal direction and the transmitter emits, on one of the conductors of the cable, intermittent current pulses having sharp terminations, whereas the others of the conductors of the cable, which are of different lengths and are terminated by electrodes, are used for measurements of the medium responses at different distances from a seabed in

the course of time lapses between consecutive current pulses. Such a configuration makes it possible to suppress the influence of local inhomogeneities near the seabed and increase the accuracy of the response determination and its interpretation.

The second exemplary embodiment is illustrated in figure 1b, in which the vessel 1 is towing a vertically elongated multi-conductor cable 3 submerged in the body of water 8. One of the conductors (not shown) of the cable 3, which are terminated by electrodes 4, is connected to a generator (not shown) as a source of intermittent current. Other cable conductors (not shown) terminated by non-polarized electrodes 5 form a recording system for measurements of the responses of the medium at different levels in the water body 8. A position-monitoring system 6 is used for determining the position of the vessel 1 at surveying.

In a third exemplary embodiment a plurality of transmitters are installed on the vessel and on associated buoys behind the vessel 1 in the form of vertically deployed, elongated multi-core conductive cables terminated by electrodes, which are submerged in a body of water, the transmitter cable configuration corresponding to what has been described for the second exemplary embodiment above. The vessel moves slowly in a horizontal direction and each of the transmitters emits, on the core of one cable, intermittent sharp-termination current pulses, whereas each of the other cores of the cables, which are of different lengths and are terminated by electrodes, is used for measurements of the medium responses at different distances from the seabed during the time lapses between consecutive current pulses. Such a configuration gives the possibility of stacking the signals, suppressing the influence of local inhomogeneities near the seabed which produce sepa-

ration of deep-lying IP targets complicated by IP effect, and increasing the accuracy in response determination and interpretation.

The third exemplary embodiment is illustrated in figure 1c, in which the vessel 1 is towing a vertically deployed, elongated first multi-conductor cable 3 which is submerged in the body of water 8. In addition, by means of a towing rope 9 the vessel 1 tows one or more vertical, elongated second multi-conductor cables 3' suspended from buoys 7 and submerged in the body of water 8. One of each of the conductors (not shown) of the multi-conductor cables 3, 3' terminated by electrodes 4 is connected to a generator (not shown) as a source of intermittent current. The others of the conductors (not shown) of the multi-conductor cables 3, 3' are terminated by non-polarized electrodes 5 for measurements of the medium responses at different distances from the seabed and different distances from the vessel 1. A position-monitoring system 6 is used for the determination of the positions of the ship 1 and buoys 7 during surveying.

Figures 2a and 2b illustrate the possibility of distinguishing between IP effects originating from shallow and deep targets. Parameters of the sections are:

Figure 2a: $h_1 = 300 \text{ m},$
 $\rho_1 = 0.3 \text{ } \Omega\text{m (sea water),}$
 $h_2 = 1000 \text{ m},$
 $\rho_2 = 1 \text{ } \Omega\text{m (sediments),}$
 $h_3 = 50 \text{ m},$
 $\rho_3 = 40 \text{ } \Omega\text{m (hydrocarbon layer),}$
 $\rho_4 = 1 \text{ } \Omega\text{m.}$

The curves 1, 2, 3 relate to a model without IP effect and the curves 4, 5, 6 relate to a model with IP effect (charge-

ability $m = 0.1$).

Figure 2b: $h_1 = 300$ m,
 $\rho_1 = 0.3 \text{ } \Omega\text{m}$ (sea water),
 $h_2 = 300$ m,
5 $\rho_2 = 1 \text{ } \Omega\text{m}$ (sediments),
 $h_3 = 50$ m,
 $\rho_3 = 40 \text{ } \Omega\text{m}$ (hydrocarbon layer),
 $\rho_4 = 1 \text{ } \Omega\text{m}$.

The curves 1, 2, 3 relate to a model without IP effect and
10 the curves 4, 5, 6 relate to a model with IP effect (charge-
ability $m = 0.1$).

The length of the transmitter line 2 is 300 m and the re-
ceiver line coincides with the transmitter line 2, 3, 3' and
has a length equalling 1 m. The distance of the receiver line
15 from the seabed is 0 m (curves 1, 4), 100 m (curves 2, 5) and
300 m (curves 3, 6), respectively.

A vertical line 7 marks the beginning of IP effect ($t = 0.6$ s
in figure 2a and $t = 0.11$ s in figure 2b).

In figure 3 the arrows indicate the start and end points of
20 the surveying; and the reference numerals 1-4 are contours of
IP effect intensity anomalies.

According to the first exemplary embodiment of the present
invention only one line is used, forming a vertical, coincid-
ing set-up of the transmitter and receiver (figure 1a). Such
25 a set-up provides maximum sensitivity in the electromagnetic
field with respect to the resistive hydrocarbon target. The
vertical component of the electric field has maximum sensi-
tivity to the resistive targets (reservoirs). In addition the
coincidence of the transmitter and receiver lines provides
30 maximum amplitude in the measured IP fields.

In another configuration of the present invention are used a plurality of receiver lines of different lengths in the form of conductors in the multi-conductor cables 3 which coincide with a single transmitter line (figure 1b). The longer away
5 the receiver lines are from the seabed 81, the less sensitive they are for shallow-lying responding media. A spatial analysis of a vertical electric field measured at different levels gives the possibility of distinguishing between IP effects created by responding media near the seabed and deeper-lying
10 responding media and to estimate the depth of the responding media.

A simple estimation of the depth of the responding media creating IP effect can be made by the use of a time delay t_0 (vertical line 7 in figures 2a and 2b) for the beginning of
15 IP effect: $t_s^{ip} \approx 0.6$ s - see figure 2a, and $t_s^{ip} \approx 0.1$ s - see figure 2b. The penetration depth h of an electromagnetic field in a uniform medium is $h = \sqrt{10^7 \rho t_0 / 2\pi}$ metres; the depth of the model in figures 2a and 2b equals approximately 1000 m, respectively 400 m, close to real values, that is. There
20 are different ways of determining the time delay, for example response measured from the area with IP effect, or construction of the response by the use of independent section parameters characterized by the absence of IP effect.

Still another configuration of the present invention consists
25 of a plurality of vertical transmitter and multi-core receiver lines 3, 3' spaced apart horizontally, deployed at different distances from the seabed (figure 2c), which gives the possibility of suppressing the influence of shallow-lying inhomogeneities creating local IP anomalies. The system of
30 spatially distributed measurements is, in some cases, able to provide information on a depth of the targets creating IP effect.

The preferred configuration of the present invention which provides high performance of surveying is a plurality of transmitters and receiver 3, 3' which are towed by the vessel 1. The vessel 1 is stopped from time to time and/or works in a start-stop regime.

A comparison of the present invention with Kashik et al. (RU 2069375 C1, 1996) shows that the possibility of using coincident lines 3, 3' for the transmitter and receivers and space-time measurements of the vertical component of the electric field simultaneously at different levels and in different locations as the vessel 1 is moving, provides principally new possibilities for mapping promising areas and searching for hydrocarbon areas.

Another advantage of the present invention is the way of determining the interpretation parameters ρ_0 , η , τ , τ_1 , and τ_2 which are inserted into the formula (1). These parameters are determined by a two-step procedure:

- 1) transformation of the measured vertical, electric field into apparent resistivity ρ^e ;
- 2) evaluation of interpretive parameters from minimum of functional

$$\sum_{n=1}^N \sum_{m=1}^M w_{nm} |\rho_{nm}^e - \rho_{nm}^c| \quad (2)$$

Here ρ_{nm}^e is the measured apparent resistivity relevant for the n-th time sample at the m-th location; N and M are the total number of time samples, respectively locations, ρ_{nm}^c is the result of direct problem solution for some electrical model of the medium containing a target producing IP effect; w_{nm} is the weight of the ρ_{nm}^e sample allowing accuracy of data, a priori geological and geophysical information etc.

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C l a i m s

1. An electromagnetic surveying method based on the detection of induced polarization effect and evaluation of its characteristics for mapping marine hydrocarbon targets, c h a r a c t e r i z e d i n that the method comprises:
- 5 targets, c h a r a c t e r i z e d i n that the method comprises:
- a) deploying vertically in a body of water (8) at least one electrical wire (2, 3, 3') forming an electromagnetic transmitter which emits electromagnetic energy which is arranged to excite an electromagnetic field in the body of water (8) and underlying medium (83), the same wire (2, 3, 3') being used as a receiver for measurements of the vertical component of the electric field;
- 10 energy which is arranged to excite an electromagnetic field in the body of water (8) and underlying medium (83), the same wire (2, 3, 3') being used as a receiver for measurements of the vertical component of the electric field;
- b) providing survey data as the spatial distribution of the vertical component of the electric field and the medium response in the form apparent resistivity versus time in the body of water (8);
- 15 b) providing survey data as the spatial distribution of the vertical component of the electric field and the medium response in the form apparent resistivity versus time in the body of water (8);
- c) performing a space/time analysis of the vertical component of the electric field and response with the aim of detecting induced polarization effect and determining its intensity and relaxation times; and
- 20 component of the electric field and response with the aim of detecting induced polarization effect and determining its intensity and relaxation times; and
- d) mapping the anomalous zones described by the characteristics perspective of the induced polarization effect for the exploration of an underground hydrocarbon reservoir.
- 25 effect for the exploration of an underground hydrocarbon reservoir.
2. The method according to claim 1, c h a r a c t e r i z e d i n that one conductor of a vertically deployed multi-conductor cable (3, 3') is used, when supplied with electromagnetic energy, as an electromagnetic transmitter exciting an electromagnetic field in the body of water (8) and underlying medium (83),
- 30 supplied with electromagnetic energy, as an electromagnetic transmitter exciting an electromagnetic field in the body of water (8) and underlying medium (83),

and other conductors of the cable (3, 3'), which are of different lengths and are terminated by electrodes (5), are used as receivers for measurements of the medium response.

- 5 3. The method according to claim 1 or 2, c h a r a c -
t e r i z e d i n that a plurality of vertically
deployed multi-conductor cables (3, 3'), each having
one conductor arranged for the supply of electromag-
netic energy, are used as an electromagnetic transmit-
10 ter exciting an electromagnetic field in the body of
water (8) and underlying medium (83), and other con-
ductors in the cables (3, 3'), which are of different
lengths and are terminated by electrodes (5), are used
as receivers for measurements of the medium response.
- 15 4. The method according to claim 1, 2 or 3, c h a -
r a c t e r i z e d i n that one or a plurality of
the receivers is/are stationary during measurements.
5. The method according to claim 1, 2 or 3, c h a -
r a c t e r i z e d i n that one or a plurality of
20 the receivers is/are towed by a vessel (1).
6. The method according to any preceding claim, c h a -
r a c t e r i z e d i n that the at least one trans-
mitter emits electromagnetic energy in the time domain
as an intermitted series of current pulses of differ-
25 ent polarities and with sharp terminations, and at
least one receiver makes measurements of time domain
responses during time lapses between consecutive cur-
rent pulses when the response is not masked by the
transmitter current.
- 30 7. The method according to any preceding claim, c h a -
r a c t e r i z e d i n that the duration of the

current pulses and pauses is specified in such a way that there is provided a penetration depth for the electromagnetic field exceeding two to three times or more the depth at which the reservoir is located, preferably within a range of 0.1 seconds to 30 seconds.

8. A surveying apparatus for the electromagnetic surveying of marine hydrocarbon targets, characterized in that one or more generators arranged to generate current pulses of different polarities with sharp terminations is/are connected to a submersible system comprising:

at least one electrical wire (2, 3, 3') which is arranged to emit electromagnetic energy in a body of water (8) and an underlying medium (83) and is arranged to receive the vertical component of the electric field, at least one of the electrical wires (3, 3') being a multi-conductor cable (3, 3') deployed vertically, at least one conductor being arranged to excite, when supplied with electromagnetic energy from a generator, an electromagnetic field in the body of water (8) and the underlying medium (83), and other conductors in the cable (3, 3'), which are of different lengths and are terminated by electrodes (5), being arranged to receive a vertical component of the electric field for registration of the medium response.

9. A surface vessel, characterized in that it carries a surveying apparatus in accordance with claim 8.

10. A computer apparatus loaded with machine-readable instructions for the implementation of the method for an

electromagnetic survey in accordance with any one of claims 1 to 7.