

METHOD FOR TRANSFORMATION AND IMAGING OF ELECTROMAGNETIC SUR-
VEY DATA FOR SUBMARINE HYDROCARBON RESERVOIRS

The invention relates to a method for the analysis, process-
ing and transformation of electromagnetic field data with the
aim of mapping earth formations including hydrocarbon reser-
voirs. One application of the invention is the imaging and
inversion of electromagnetic field data measured during ma-
rine surveying by the use of TEMP-VEL/OEL hydrocarbon pros-
pecting systems.

TEMP-VEL (= Transient Electromagnetic Marine Prospecting -
Vertical Electric Lines) and TEMP-OEL (= Transient Electro-
magnetic Marine Prospecting - Orthogonal Electric Lines) hy-
drocarbon prospecting systems are described in NO patent
323889 and NO application 20065436, respectively, incorpo-
rated herein by reference in their entirety.

Existing methods of Controlled Source Electromagnetic (CSEM)
hydrocarbon surveying are typically based on a simplified,
qualitative form of presentation and visualization of field
data, in which hydrocarbon reservoirs are discriminated as a
local anomaly. When imaging and mapping marine hydrocarbon
survey results or when inverting and interpreting the data,
the researchers sometimes confine themselves through general
words like: "...analysis includes comparing the results of the
measurements taken with the results of a mathematical simula-
tion model based on the known properties of the reservoir and

overburden conditions" (Eidesmo et al. 2006 (US 7,026,819)).

Srnka (1986 (US 4,617,518)) proposed to make measurements of an electric field with electrodes separated by some distance, at two or more frequencies, and to use them to determine an average resistivity of a portion of the region located within different depths from the sea floor. This is a virtual description of a common method, VES, which is widely used on shore.

Eidesmo et al. (2002); Ellingsrud et al. (2002); Amundsen et al. (2004); Johansen et al. (2005) etc. used the simplest transformation as the electromagnetic field response measured along some profile at some frequency was normalized to the response measured at some reference point located outside the region in which a subterranean hydrocarbon reservoir was assumed or known to exist. This method has the advantage that it excludes the configuration of the transmitter and the intensity of the transmitter current, but the anomaly value in this method depends, to a great degree, on the response at the reference point and may sometimes be very coarse because of the small amplitude of the electric field at the reference point. In addition, this transformation has low resolution and describes the survey results expressed in dimensionless values for the electric field instead of the natural parameters for electric prospecting, namely resistivity and depth.

Wright et al. (2006 (EP 1 425 612)) proposed in their invention "... to make multichannel transient measurements (MTEM)... of impulse response of the earth and display it or to make transformation of such impulse responses, to create representation of resistivity contrasts". There is no description of a possible transformation in the invention.

Apparent resistivity is often used to transform the field

data of the field measured. The apparent resistivity has substantial advantages with respect to electromagnetic field because it provides sufficient perception of the seabed structure.

- 5 The value of apparent resistivity is normally determined as the resistivity of a homogenous half-space having (with a given transmitter/receiver setup) the same impulse response as that registered in field trials.

For marine applications, Edwards et al. (1984) have proposed
10 the MOSES method with data imaging in the form of apparent

resistivity as $\rho_\alpha = \rho_0 \frac{Id}{2\pi r^2 H_\phi}$, in which ρ_0 is sea water resis-

- tivity, d is sea depth, I is electrical current from transmitter, r is the distance between the transmitter and receiver, H_ϕ is the azimuth component of the magnetic field
15 measured on the sea floor. This formula is valid with some limitations, namely: the length of the vertical transmitter line equals the sea depth, the ratio between the average resistivity of the first crust layer and that of the sea water is larger than 10, so this formula is valid only for shallow
20 water and does not give a good approximation in deep sea.

Another formula for apparent resistivity was proposed by

Wolfgram et al. (1986): $\rho_\alpha = \rho_0 \cdot \frac{I}{2\pi H_\phi} \cdot \frac{d}{\sqrt{d^2 + r^2}} - \rho_0$. This formula

assumes that the upper electrode is at infinity, and is valid for shallow sea only, that is when $d/r < 10$.

- 25 Chen and Oldenburg (2006) substantially improved both Edward's and Wolfgram's formulas and considered a more common 1D earth reference model consisting of a two-layer structure excited by a semi-infinite electrode. Their formulas are based on a semi-analytical term for the magnetic field and

can be used for both shallow and deep water.

It has been found in electric prospecting that the methods operating in the time domain provide higher resolution with respect to hydrocarbon targets than the direct current or alternating current methods. In what follows, we confine ourselves to assessing EM sounding in the time domain, more particularly by TEMP-VEL/OEL methods (Barsukov et al. 2007 (WO 2007/053025)). As proposed here, after some modifications, the method and algorithm can be used for both sounding in the frequency domain and direct current.

In the time domain, the response for a homogenous half-space is calculated analytically for any time τ if it is possible, or by using asymptotic formulas for late or early times (Kaufmann and Keller, 1983; Spies and Frischknecht, 1991; Wilt and Stark, 1982; etc.) For a transient electric dipole-dipole setup, Edwards (1997) has proposed the formula

$$\rho_a = E_r \frac{2\pi r^3}{I \Delta l} \text{ which transforms the electric field response into}$$

apparent resistivity. Here, E_r is the in-line component of the electric field measured by a receiver placed at a distance r from the electric dipole transmitter, $I \Delta l$ is the moment of the transmitter. This formula does not consider the sea depth, real length of line, time delay, as it assumes that the ratio between the average resistivity of the first crust layer and that of the sea water is larger than 10. These conditions evidently limit the possibilities of such transformation.

The 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 in the description below and in the claims that follow.

A method for fast imaging and inversion of marine CSEM survey data based a 1D two-layer reference model excited by arbitrary current and measured by an arbitrary receiver is proposed here.

- 5 In a first aspect the invention relates, more specifically, to a method for imaging, transforming and mapping electromagnetic data from marine hydrocarbon surveying, the method being characterized by including the following steps:
- a) carrying out a marine survey by and measurements of electromagnetic response excited in the earth by a controlled
 - 10 source;
 - b) analysing said electromagnetic response, approximation of the measured response by a smooth curve;
 - c) determining first derivatives of said electromagnetic re-
 - 15 sponse;
 - d) transforming said approximation and first derivatives into a graph of resistivity versus depth;
 - e) using said graph for imaging and mapping earth formations, including hydrocarbon reservoirs;
 - 20 f) using said graph when constructing a base model for inversion.

The electromagnetic response may be measured in the time domain.

Additional information and constrains may be used in the procedure for the approximation of the measured time response by

25 a smooth curve.

Additional information and constrains may be used in the procedure for determining first time derivatives.

A graph of apparent resistivity versus time may be constructed in addition to a graph of resistivity versus depth.

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Both the graph of apparent resistivity versus time and the graph of resistivity versus depth can be used for imaging and mapping earth formations, including hydrocarbon reservoirs.

5 The graph of resistivity versus depth and first derivatives can be used when a base model for inversion is constructed.

Electromagnetic response may be measured and first derivatives calculated and used when a base model for inversion in the frequency domain is constructed.

10 In a second aspect, the invention relates to a computer apparatus characterized by having installed machine-readable instructions for implementing the method for imaging, transforming and mapping electromagnetic marine hydrocarbon survey data in accordance with the method described above.

15 In what follows is described an example of a preferred embodiment which is visualized in the accompanying drawings, in which:

Figure 1 shows the structural plan of a curve of apparent resistivity;

Figure 2 demonstrates mapping of apparent resistivity;

20 Figure 3 illustrates the transformation of TEMP-VEL response into apparent resistivity; and

Figure 4 shows the results of a mapping of the Troll region received from 3D simulated response functions (voltage) transformed into resistivity versus depth
25 in accordance with the proposed method. Rectangles in both pictures show the geometries of real reservoirs. The upper picture presents the section in a "logging" manner and the lower picture in an "imaging" manner.

The method for visualization and inversion is carried out in two phases.

Phase 1: constructing a curve of apparent resistivity $\rho_a(t)$. This phase consists of three sequential steps.

5 Step 1: Approximation of the measured electromagnetic response and calculation of first derivatives.

This procedure is unstable and needs stabilizing. Some constraints and additional information should be used for stabilization; for example approximation of the field by superpositioning of exponential functions (Barsukov, Svetov, 1984):

$$E(t) = \int_0^{\infty} E(s)e^{-st} ds \quad (1)$$

Here, $E(s)$ is the exponential spectrum which is determined from the measured data. First derivatives are calculated from $E(s)$ and (1).

15 After the approximation of field data by a smooth curve, it is appropriate to present the field response in the form of a curve of apparent resistivity versus time - step 2.

Step 2: Presentation of the response in the form of a curve of apparent resistivity versus time.

20 To begin with, we use an asymptotic formula describing the behaviour of electromagnetic fields in the near or far zone, in full-space or half-space or two-layer models, to build a first approximation of apparent resistivity.

For the TEMP-VEL/OEL method the presentation of the response function based on the calculation of apparent resistivity according to the asymptotic behaviour in the last stage of electric fields across a two-layer structure is quite practi-

cal for the calculation of the first approximation of apparent resistivity:

$$\rho = \left\{ \mu_0^{5/2} * P * h_0^2 / (20 * \pi^{3/2} * U) * \left[t^{-5/2} - (t + pulse)^{-5/2} \right] \right\}^{2/3} \quad (2)$$

Here, $P = TR_len * REC_len$ (m x m); TR_len and REC_len are
 5 the lengths of the transmitter line and receiver line, respectively; $h_0 = \text{sea depth} - TR_len/2$ (m); t is the time (in seconds); $pulse$ is the pulse current duration (in seconds); U is the signal normalized to pulse current (V/A); $\mu_0 = 4\pi \times 10^{-7}$ H/m. Figure 1 (smooth-lined "field data" marked
 10 with triangular field dots) shows an example of a curve of apparent resistivity for a two-layer model shown in the upper right-hand corner of the figure.

Step 3: Transformation of the response function into apparent resistivity $\rho_a(t)$.

15 The use of asymptotic formulas which are valid in the late stage for the transformation of the measured voltage (electric field) into apparent resistivity, loses information in an early stage of the response function (shallow depth), whereas the use of asymptotic formulas which are valid in the
 20 early stage loses information on the deep-lying structure in the section.

These drawbacks are absent when formulas which are accurate for the full transient process are used. In some simple cases it is possible to find accurate formulas for the full transient process. In the normal case (two-layer structure excited by a sloping electric line arbitrarily submerged in the
 25 sea and recorded by an arbitrarily submerged, sloping electric receiver line) accurate formulas are absent, and only numerical methods can be used.

In this case, apparent resistivity is determined by solving the non-linear equation $p(t)=F(t, h_1, \rho_1, \rho_2)$. Figure 1 illustrates the solving process. The resistivity ρ_2 at the time t giving the same response (Ωm) as field data (circles) is accepted as apparent resistivity ρ_a at the time t . In inversion and mapping the time scale is replaced with the depth scale. Surface depth is considered as the effective (apparent) sounding depth h_a : $h_a = \sqrt{2\rho_a t / \mu_0}$.

The curve of apparent resistivity found for all delays contains information about the entire process. Such a curve of apparent resistivity can be used for imaging and mapping field data versus time and be utilized as the base curve for the transformation (inversion) of these data into the curve $\rho_{tr}(h_a)$.

Figure 2 illustrates an application of the method described above for the inversion and mapping of TEMP-VEL modelling data calculated for a square target. $E_z(t)$ - "field" data was simulated by a 3D program. Parameters of the model are as follows: sea depth is 1 km, its resistivity equals 0.28 Ωm . The square measurement, 4 x 4 km in size, is located at the depth $h = 1$ km below the sea floor and has a transversal resistance $T = 2000 \Omega m^2$ (thickness of 40 metres and specific resistivity of 50 Ωm). The map was constructed in accordance with the algorithm described, with a time delay of $t = 6$ s. As it can be seen, the location, size and shape of the target are determined correctly.

Phase 2: Transformation (inversion) of apparent resistivity $\rho_a(t)$ into resistivity $\rho_{tr}(h_a)$.

The proposed transformation algorithm is as follows.

Define as $v = v(t)$ the logarithmic derivative of apparent resistivity:

$$v = \frac{t}{\rho_a(t)} \frac{d\rho_a(t)}{dt} = [\ln \rho_a(t)]', \quad |v| < 1$$

Let the gain $k(t)$ be

$$k(t) = \frac{1}{(1-v)^m}, \quad m = 3/2$$

Then the transformed apparent $\rho_{tr}(t)$ resistivity of any time delay t is:

$$\rho_{tr}(t) = k(t) \rho_a(t)$$

The gain $k(t)$ and coefficient $m = 3/2$ is used to correct the extra increase in rising branches of the curves of transformed apparent resistivity and the extra decrease in falling branches. The effective (apparent) depth h_a for any time t is calculated as:

$$h_a = \sqrt{\frac{t\beta(res)}{\mu_0}}, \quad \mu_0 = 4\pi 10^{-7} \text{ H/m}$$

$$\ln(\beta(res)) = \ln(\rho_a) + \frac{\ln(\rho_{tr}) - \ln(\rho_a)}{10} * res, \quad 0 \leq res \leq 10$$

The function $\beta(res)$ is analogous to resistivity, has the dimension $[\Omega m]$ and is inserted into the algorithm to control the resolution of transformation. The $\beta(res)$ value may be changed within the range from $\rho_a(t)$ ("non-transformed" apparent resistivity) to $\rho_{tr}(t)$ and substantially alter the shape of the curve of apparent resistivity $\rho_{tr}(h_a)$. $\beta \rightarrow \rho_{tr}$ in the case of a low-contrast medium, $\beta \rightarrow \rho_a$ for a high-contrast medium and $\beta = (\rho_{tr} \rho_a)^{1/2}$ in a medium-contrast medium. The relationship between

ρ_{tr} and ρ_a in $\beta(res)$ is adjusted by the special parameter "res" - "resolution of transformation".

The method described transforms the measured voltage response into an electrical cross-section - resistivity versus depth and actually yields a solution to an inverse problem. It provides a simple and quick tool for visualizing and mapping earth formations which include hydrocarbon reservoirs.

Figure 3 shows the result of a transformation of TEMP-VEL signals, namely voltage versus time, into apparent resistivity versus depth. Parameters of the model: $h_1 = 300$ m, $\rho_1 = 0.28$ Ω m, $h_2 = 1400$ m, $\rho_2 = 1$ Ω m, $h_3 = 40$ m, $\rho_3 = 100$ Ω m, $\rho_4 = 2$ Ω m.

As it can be seen, the transformed curve represents the model section qualitatively correctly.

Figure 4 illustrates an application of the proposed method for mapping hydrocarbon targets. 3D voltage response for a TEMP-VEL setup was calculated for a simplified model of the Troll region (Johansen et al., 2005) and then transformed into resistivity versus depth.

It is obvious that the proposed method for mapping yields the correct location, size and depth of the target; some reflection underneath the target is the result of the approximation of a small, thin target layer as the continuous function of depth.

The model constructed can be used as a good base model for 3D inversion.

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P a t e n t c l a i m s

1. A method for imaging, transforming and mapping electromagnetic data from marine hydrocarbon surveying, characterized in that it includes:
 - 5 a) marine surveying by and measurements of electromagnetic response excited in the earth by a controlled source;
 - b) analysis of said electromagnetic response, approximation of the measured response by a smooth curve;
 - 10 c) determination of first derivatives of said electromagnetic response;
 - d) transformation of said approximation and first derivatives into a graph of resistivity versus depth;
 - e) application of said graph for the imaging and mapping of earth formations, including hydrocarbon reservoirs;
 - 15 f) application of said graph when constructing a base model for inversion.
2. The method as described in claim 1, characterized in that the electromagnetic response is measured in the time domain.
- 20 3. The method as described in claim 1 or 2, characterized in that additional information and constraints are used in the procedure for the approximation of the measured time response by a smooth curve.
- 25 4. The method as claimed in claim 1, 2 or 3, characterized in that additional information and constraints are used in the procedure for the determination of first derivatives.
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5. The method as described in claim 1, 2, 3 or 4,
c h a r a c t e r i z e d i n that a graph of appar-
ent resistivity versus time is constructed in addition
to a graph of resistivity versus depth.
- 5 6. The method as described in claim 1, 2, 3, 4 or 5,
c h a r a c t e r i z e d i n that both the graph of
apparent resistivity versus time and the graph of re-
sistivity versus depth are used for imaging and map-
ping earth formations, including hydrocarbon reser-
10 voir.
7. The method as described in claim 1, 2, 3, 4, 5 or 6,
c h a r a c t e r i z e d i n that the graph of re-
sistivity versus depth and first time derivatives are
used when a base model for inversion is constructed.
- 15 8. The method as described in claim 1, 2, 3, 4, 5, 6 or
7, c h a r a c t e r i z e d i n that the electro-
magnetic response is measured and first derivatives
are calculated and used when a base model for inver-
sion in the frequency domain is constructed.
- 20 9. Computer apparatus, c h a r a c t e r i z e d i n
that it has installed machine-readable instructions
for implementing the method for imaging, transforming
and mapping electromagnetic marine hydrocarbon survey
data in accordance with any one of claims 1 to 8.