

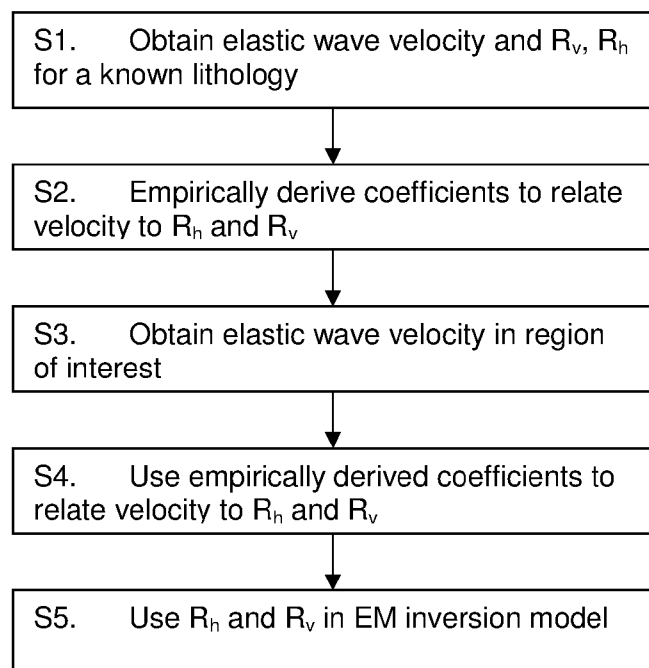


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[Continued on next page]

- (54) Title: ESTIMATING ANISOTROPIC RESISTIVITY OF A GEOLOGICAL SUBSURFACE



(57) Abstract: A method and apparatus for estimating anisotropic resistivity of a geological subsurface in a region of interest. Elastic wave velocity data is obtained for the region of interest. The obtained elastic wave velocity is related to vertical and horizontal components of resistivity for the region of interest using empirically derived coefficients.

Figure 1



Published:

— *with international search report (Art. 21(3))*

Estimating Anisotropic Resistivity of a Geological Subsurface

TECHNICAL FIELD

- 5 The invention relates to the field of estimating anisotropic resistivity of a geological subsurface.

BACKGROUND

- 10 Controlled Source Electromagnetic (CSEM) surveys employ electromagnetic sensing technology to obtain an indication of the presence and extent of hydrocarbon bearing formations. In subsea applications, a typical survey involves towing a dipole source above the seafloor to transmit an electromagnetic field into the geological formations below the sea bed. The dipole source may use a horizontal and/or vertical dipole.
- 15 Different geological formations have different effects on the electromagnetic field, and modify it in some way. The modified field is monitored by one or more (typically an array) of receivers. Hydrocarbon-bearing formations typically show a higher degree of resistivity compared to surrounding geological formations, and this information can be used to detect the presence of hydrocarbon-bearing formations.

20

- The data obtained from a CSEM survey is fed into models to estimate the nature and properties of the geological formations in the area surveyed. A particular problem arises from subsurface formations that have anisotropic resistivities, such as sands and shale. This is described in, for example, Ellis et al, "Importance of anisotropic rock physics modelling in integrated seismic and CSEM interpretation", 2011, First Break,
- 25 29, 87-95.

- Failure to take into account the anisotropy of a geological subsurface, when using the obtained data in an EM inversion model to predict the properties of the geological subsurface, can lead to large errors and misinterpretation of the resistivity. In order to attempt to estimate the anisotropy, the dipole must induce both vertical and horizontal currents in an attempt to distinguish horizontal and vertical resistivity. EM inversion is used on the obtained data to model the geological subsurface, and the presence of anisotropy complicates the EM inversion. It is therefore important that the model used
- 30 takes account of the degree of anisotropy of the geological subsurface being modelled.
- 35

However, most models used require input parameters that are hard to measure in frontier areas, such as porosity, amount of bound water and salinity.

SUMMARY

5

It is an object of the invention to provide methods for estimating anisotropic resistivity of a geological subsurface for use in an EM inversion using data that is readily available or easily obtained.

10 According to a first aspect, there is provided a method of estimating anisotropic resistivity of a geological subsurface in a region of interest. Elastic wave velocity data is obtained for the region of interest. The obtained elastic wave velocity is related to vertical and horizontal components of resistivity for the region of interest using empirically derived coefficients. Elastic wave velocity data is easily obtained, so the
15 method gives a very quick and reliable way of estimating anisotropic resistivity for a subsurface.

The obtained vertical and horizontal resistivity components are typically used as a starting point for electromagnetic inversion to model the geological subsurface.

20

Any type of elastic wave velocity data may be used. Elastic wave velocity data may be obtained by any of, for example, P-wave measurements, S-wave measurements, rock physics modelling and sonic well logging measurements.

25 As an option, the elastic wave velocity is related to a vertical and horizontal component of resistivity using the equation:

$$R_{h,v} = \alpha e^{\beta V_p} + \psi e^{\xi V_p}$$

where R is resistivity, α , β , ψ , ξ are empirically derived coefficients and V_p is elastic wave velocity. The empirically derived coefficients may, according to an
30 embodiment of the invention, be obtained using well log data. Furthermore, they may be derived using the assumption that the geological subsurface comprises brine-saturated rocks.

As a further option the method includes, prior to obtaining elastic wave velocity data for the region of interest, obtaining elastic wave velocity data and horizontal and vertical resistivity data for a known region having a similar lithology to the region of interest. The elastic wave velocity data and horizontal and vertical resistivity data for the known
 5 region are then used to empirically derive the coefficients. The elastic wave velocity data and horizontal and vertical resistivity data may be obtained for a known region from a well log.

According to a second aspect, there is provided an apparatus for estimating anisotropic
 10 resistivity of a geological subsurface in a region of interest. The apparatus has access to a database of coefficients relating elastic wave velocity to horizontal and vertical resistivities for a given lithology. The apparatus comprises a processor for comparing elastic wave velocities obtained from a region of interest with elastic wave velocities stored in the database and, as a result, estimating the horizontal and vertical
 15 resistivities of the geological subsurface.

As an option, the processor is further arranged to use the estimated vertical and horizontal resistivity components in brine filled rocks as a starting point in an electromagnetic inversion model to model the resistivity of the geological subsurface.
 20

The elastic wave velocity for the region of interest may be obtained from any of P-wave measurements, S-wave measurements, rock physics modelling and sonic well logging measurements.

25 As an option, the processor is arranged to relate the elastic wave velocity from the region of interest to a vertical and horizontal component of resistivity using the equation:

$$R_{h,v} = \alpha e^{\beta V_p} + \psi e^{\xi V_p}$$

where R is resistivity, α , β , ψ , ξ are empirically derived coefficients and V_p is
 30 elastic wave velocity. In an embodiment, the empirically derived coefficients are obtained using well log data. The processor may be further arranged to, prior to obtaining elastic wave velocity data for the region of interest, obtain elastic wave velocity data and horizontal and vertical resistivity data for a known region having a similar lithology to the region of interest. The processor can then use the elastic wave

velocity data and horizontal and vertical resistivity data for the known region to empirically derive the coefficients for storage in the database.

As an option, the apparatus further comprises a receiver for receiving elastic wave
5 velocity information from a remote computer device.

As a further option, the apparatus further comprises a transmitter for sending the estimated horizontal and vertical resistivities of the geological subsurface to a further computer device.

10

According to a third aspect, there is provided a computer program comprising computer readable code means which, when run on a computer apparatus, causes the computer apparatus to perform the method as described above in the first aspect.

15 According to a fourth aspect, there is provided a computer program product comprising a computer readable medium and a computer program as described above in the third aspect, wherein the computer program is stored on the computer readable medium.

BRIEF DESCRIPTION OF THE DRAWINGS

20

Figure 1 is a flow diagram showing the steps according to an embodiment of the invention;

Figure 2 is a graph showing burial depth vs vertical and horizontal resistivity for a
25 sandstone lithology;

Figure 3 is a graph showing burial depth vs vertical and horizontal resistivity for a mixed sand and shale lithology;

30 Figure 4 is a graph showing burial depth vs vertical and horizontal resistivity for a shale lithology;

Figure 5 is a graph showing burial depth vs predicted and recorded anisotropic resistivity for a well for different volume fractions of shale;

35

Figure 6 is a graph showing predicted and recorded horizontal resistivity vs vertical resistivity for the well of Figure 4;

Figure 7 is a graph showing true vertical depth subsea (TVDSS) vs vertical resistivity
5 estimated using different input parameters;

Figure 8 is a graph showing TVDSS vs horizontal resistivity estimated using different input parameters; and

10 Figure 9 illustrates schematically in a block diagram in apparatus according to an embodiment of the invention.

DETAILED DESCRIPTION

15 Elastic wave velocities and lithology are used to estimate the horizontal and vertical resistivity of anisotropy in the geological subsurface. Values for horizontal and vertical resistivities are estimated for brine saturated rocks, and are used in a background model for EM inversion. P-waves (also referred to as seismic waves) are an example
20 of elastic waves that can travel through fluids and solids. In an isotropic solid, P-waves propagate longitudinally through the solid, meaning that the solid vibrates along or parallel to the direction of the wave energy. The measurement of P-waves can be used to probe the structure of the subsurface. Changes in the P-wave velocity through the earth indicate a change in the phase or composition of a subsurface.

25 The EM inversion model using anisotropic resistivity is determined using an exponential function and four empirically derived coefficients. The coefficients are found by calibrating to a well with known properties. As a first step, vertical and horizontal resistivities from formations around the well were logged from close to the surface to a depth of more than 2 km.

30

P-wave velocities were obtained from a sonic log of the well. For P-wave velocities lower than observed, constant resistivity values corresponding to the resistivities for the lowest observed velocity can be used.

The logged horizontal and vertical resistivities are empirically mapped to the obtained P-wave velocity for a given lithology. Subsequently, for regions of interest where the horizontal and vertical resistivities are not known, measured (or otherwise obtained) P-wave velocities can be used to estimate the horizontal and vertical resistivities.

5

In frontier areas, anisotropic resistivity can be estimated either from seismic velocities if available. Alternatively, elastic wave velocities can be estimated using rock physics modelling.

10 The basic concept is illustrated in Figure 1, with the following numbering corresponding to that of Figure 1:

S1. For a region with a known lithology, such as a well, horizontal and vertical resistivity measurements are obtained along with elastic wave velocity measurements.

15

S2. Empirical constants are derived to relate the horizontal and vertical resistivity measurements to the elastic wave velocity measurements.

20 S3. P-wave (or other elastic wave) velocity is obtained for a region of interest where the horizontal and vertical resistivities are not known or cannot be easily obtained.

S4. The empirically derived coefficients are used to relate the P-wave velocity to vertical and horizontal resistivity for the given lithology

25 S5. The vertical and horizontal resistivity can then be used in an EM inversion model to predict the properties of the geological subsurface in the region of interest.

30 The vertical and horizontal resistivities for a given brine saturated lithology are estimated as a function of P-wave (or other elastic wave) velocity only. This enables anisotropic resistivity predictions to be made for regions in which very limited knowledge about subsurface conditions is available.

35 By way of example, a relationship between anisotropic resistivity and P-wave velocities has been established using data obtained from a well. Models were calibrated to data for three lithologies:

- Sands, volume fraction shale (V_{sh}) ≤ 0.2 ;
- Mixed lithology, $0.4 \leq V_{sh} \leq 0.6$; and
- Shale, $V_{sh} \geq 0.8$.

- 5 The model calibration is performed by constrained multivariate nonlinear regression between modelled and observed data. The calibration is best done in a computing environment such as Matlab. A V_{sh} dependent weight function is used to interpolate between these three. This includes medium to very fine silt plus clay and shale bound water. Resistivity estimations are made using Equation 1 as follows:

10

$$R_{h,v} = \alpha e^{\beta V_p} + \psi e^{\xi V_p} \quad (\text{Equation 1})$$

where V_p is P-wave velocity, R_v is vertical resistivity, R_h is horizontal resistivity and α , β , ψ and ξ are empirically derived coefficients.

15

The empirically derived coefficients are iterated to find a combination of coefficients that makes the modelled resistivity deviate as little as possible from the calibration data. In order to speed up the iteration process and avoid unrealistic values for the coefficients, limits may be placed on the possible coefficient values.

20

The empirically derived coefficients are determined for a given lithology and for vertical (R_v) and horizontal (R_h) resistivities separately. Exemplary coefficient values for horizontal and vertical resistivity modelling are given in Tables 1 and 2, respectively.

- 25 Table 1: Coefficients used to estimate horizontal resistivities (R_h).

Lithology	α	β	ψ	ξ
Sand	10000	-4.2	0.013	1.0
Mixed	4	-0.3	0.004	1.5
Shale	100	-1.9	0.128	0.9

Table 2: Coefficients used to estimate vertical resistivities (R_v).

Lithology	α	β	ψ	ξ
Sand	10000	-3.9	0.009	1.2
Mixed	6	-0.2	0.002	1.7
Shale	100000	-4.0	0.191	1.1

The coefficients are subsequently used to estimate horizontal and vertical resistivities where only elastic wave data is available. Note that P-wave velocity data may not always be available. In this case, other types of elastic wave data may be used. In exploration cases, seismic velocities can be used as input to calculate resistivity depth trends for given lithologies. Alternatively, where some information about the lithology is known, a rock physics model can be used to estimate P-wave velocities, which can be used subsequently as input to obtain estimated horizontal and vertical resistivities. Lithology can either be obtained from geological interpretation, extrapolation from nearby wells or seismic data analysis such as amplitude versus offset (AVO) or inversion. If no lithology information is available, the model can only come up with trends for various given lithologies.

Note that the model can be used to estimate R_v and R_h from well log V_p (P-wave velocity). If a gamma ray or Vsh log is available, the lithology can be classified based on a Vsh log, as described above, and used directly as input to the model.

The model has been tested against well log data to obtain an indication of its accuracy. By way of example, Figure 2 is a graph showing a comparison of measured and predicted horizontal and vertical resistivities with respect to burial depth for a sandstone lithology. It can be seen that the resistivities predicted using the empirically derived coefficients for both vertical and horizontal resistivity closely correspond to the logged vertical and horizontal resistivities.

Figure 3 shows similar data to that illustrated in Figure 2, but for a mixed sand and shale lithology rather than a sandstone lithology. Again, it can be seen that the resistivities predicted using the empirically derived coefficients for both vertical and horizontal resistivity closely correspond to the logged vertical and horizontal resistivities.

Figure 4 is a graph showing a comparison of measured and predicted horizontal and vertical resistivities with respect to burial depth for a shale lithology. It can be seen that the resistivities predicted using the empirically derived coefficients for both vertical and horizontal resistivity closely correspond to the logged vertical and horizontal resistivities.

In Figures 2, 3 and 4, except for some low horizontal resistivity values in the mixed lithology example of Figure 3, the resistivity model replicates the large scale trends observed with depth.

10

Turning now to Figure 5, modelled anisotropic resistivity is shown for different volume fractions of shale at different burial depths. Again, it can be seen that the modelled results closely correspond to the measured results.

Figure 6 shows horizontal resistivity against vertical resistivity for different volume fractions of shale. Again, the modelled results closely correspond to the measured results.

Figure 7 and 8 demonstrate anisotropic resistivity prediction when the elastic wave velocity source is not obtained from well logs. Figure 7 shows data for vertical resistivity, and Figure 8 shows data for horizontal resistivity. In the key, "sst" refers to sandstone, "sh" refers to shale, "well" refers to data obtained from well logs and "seismic" refers to velocities derived from seismic data. It can be seen that velocities originating from seismic data can result in realistic predictions of vertical and horizontal resistivities when compared to data obtained from well logs.

It is preferred to implement the techniques using a computer, as shown in Figure 9. A computer device 1 is shown that is provided with a processor 2. A computer readable medium in the form of a memory 3 is also provided that is operably connected to the processor 2. A database 4 of empirically derived coefficients for different lithologies is also provided, along with a program 5 which, when executed by the processor 2, causes the processor 2 to estimate horizontal and vertical resistivities as described above. The processor 2 may also be used to feed the estimated horizontal and vertical resistivities into an EM inversion model to model a geological subsurface.

35

The computer device 1, in some embodiments, may also be provided with any of a user input 6, a display 7 and an in/out device 8. The user input 6 is used for receiving user instructions and allowing a user to enter data. The display 7 is used for displaying results to a user. Note that the user input 6 and the display 7 may be provided at a remote computer device, particularly in the case where the processor 2 is intended to implement the technique remotely from the user. The in/out device 8 is used to receive data from other sources, such as well logs, and to send data to other sources. For example, the computer device 1 may be used only to estimate the horizontal and vertical resistivity, and subsequently send this data via the in/out device to a further computer device that uses the estimated horizontal and vertical resistivities in an EM inversion model.

Directly correlating P-wave velocities to horizontal and vertical resistivities using empirically derived coefficients greatly improves the accuracy of EM inversion modelling where values for anisotropic resistivity are not known. The technique can be easily implemented in existing software where such possibilities exist, and relies only on a few, easily accessible input parameters. The technique has been shown to reproduce observed trends of anisotropic resistivity in brine saturated sands and shale from close to the surface to a burial depth of greater than two km depth.

20

It will be appreciated by the person of skill in the art that various modifications may be made to the above-described embodiments without departing from the scope of the present invention. For example, the above description only refers to shale and sandstone, but it will be appreciated that the techniques may be used for any lithology. Furthermore, while the technique is described in detail using P-wave velocities, it will be appreciated that the horizontal and vertical resistivities may be related to any elastic wave velocity, and the elastic wave velocity may be measured, estimated or modelled. Note also that the above description refers to determining the coefficients by calibrating to resistivity measurements obtained from well log data, but it is possible to determine the coefficients by calibrating to resistivity measurement obtained in other ways, such as laboratory measurements on core plugs.

The following abbreviations have been used in the above description:

35 AVO amplitude versus offset

	CSEM	Controlled Source Electromagnetic
	EM	Electromagnetic
	R_h	horizontal resistivity,
	R_v	vertical resistivity,
5	TVDSS	true vertical depth subsea
	V_p	P-wave velocity
	Vsh	volume fraction shale

CLAIMS:

1. A method of estimating anisotropic resistivity of a geological subsurface in a region of interest, the method comprising:
 - 5 obtaining elastic wave velocity data for the region of interest; and
using empirically derived coefficients, relating the elastic wave velocity to a vertical and a horizontal component of resistivity.
2. The method according to claim 1, further comprising:
 - 10 using the obtained vertical and horizontal resistivity components as a starting point for electromagnetic inversion to model the geological subsurface.
3. The method according to claim 1 or 2, wherein the elastic wave velocity is obtained from any of P-wave measurements, S-wave measurements, rock physics
 - 15 modelling and sonic well logging measurements.
4. The method according to any of claims 1 to 3, wherein the elastic wave velocity is related to a vertical and horizontal component of resistivity using the equation:

$$R_{h,v} = \alpha e^{\beta V_p} + \psi e^{\xi V_p}$$
 - 20 where R is resistivity, α , β , ψ , ξ are empirically derived coefficients and V_p is elastic wave velocity.
5. The method according to claim 4, wherein the empirically derived coefficients are obtained using well log data.
6. The method according to claim 5, wherein the empirically derived coefficients are derived assuming that the geological subsurface comprises brine-saturated rocks.
7. The method according to any of claims 4, 5 and 6, comprising:
 - 30 prior to obtaining elastic wave velocity data for the region of interest, obtaining elastic wave velocity data and horizontal and vertical resistivity data for a known region having a similar lithology to the region of interest;
using the elastic wave velocity data and horizontal and vertical resistivity data for the known region to empirically derive the coefficients.

8. The method according to claim 7, comprising obtaining elastic wave velocity data and horizontal and vertical resistivity data for a known region from a well log.

5 9. An apparatus for estimating anisotropic resistivity of a geological subsurface in a region of interest, the apparatus comprising:

a database containing coefficients relating elastic wave velocity to horizontal and vertical resistivities for a given lithology;

10 a processor for comparing elastic wave velocities obtained from a region of interest with elastic wave velocities stored in the database and, as a result, estimating the horizontal and vertical resistivities of the geological subsurface.

10. The apparatus according to claim 8, wherein the processor is further arranged to use the estimated vertical and horizontal resistivity components in brine filled rocks as a starting point in an electromagnetic inversion model to model the resistivity of the geological subsurface.

11. The apparatus according to claim 9 or 10, wherein the elastic wave velocity for the region of interest is obtained from any of P-wave measurements, S-wave measurements, rock physics modelling and sonic well logging measurements.

12. The apparatus according to any of claims 9, 10 or 11, wherein the processor is arranged to relate the elastic wave velocity from the region of interest to a vertical and horizontal component of resistivity using the equation:

$$25 \quad R_{h,v} = \alpha e^{\beta V_p} + \psi e^{\xi V_p}$$

where R is resistivity, α , β , ψ , ξ are empirically derived coefficients and V_p is elastic wave velocity.

13. The apparatus according to claim 12, wherein the empirically derived coefficients are obtained using well log data.

14. The apparatus according to any of claims 12 and 13, wherein the processor is further arranged to, prior to obtaining elastic wave velocity data for the region of interest, obtain elastic wave velocity data and horizontal and vertical resistivity data for

a known region having a similar lithology to the region of interest and, using the elastic wave velocity data and horizontal and vertical resistivity data for the known region, empirically derive the coefficients for storage in the database.

- 5 15. The apparatus according to any of claims 9 to 14, further comprising a receiver for receiving elastic wave velocity information from a remote computer device.

16. The apparatus according to any of claims 9 to 15, further comprising a transmitter for sending the estimated horizontal and vertical resistivities of the
10 geological subsurface to a further computer device.

17. A computer program comprising computer readable code means which, when run on a computer apparatus, causes the computer apparatus to perform the method as claimed in any of claims 1 to 8.
15

18. A computer program product comprising a computer readable medium and a computer program according to claim 17, wherein the computer program is stored on the computer readable medium.

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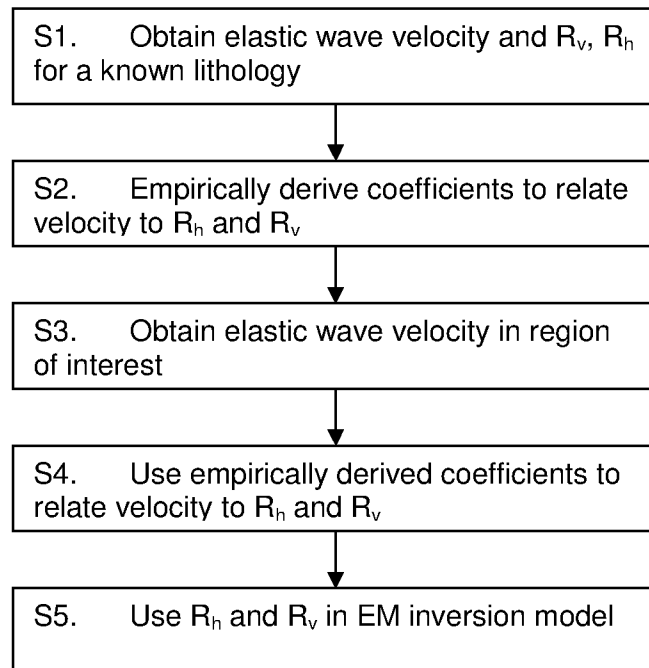


Figure 1

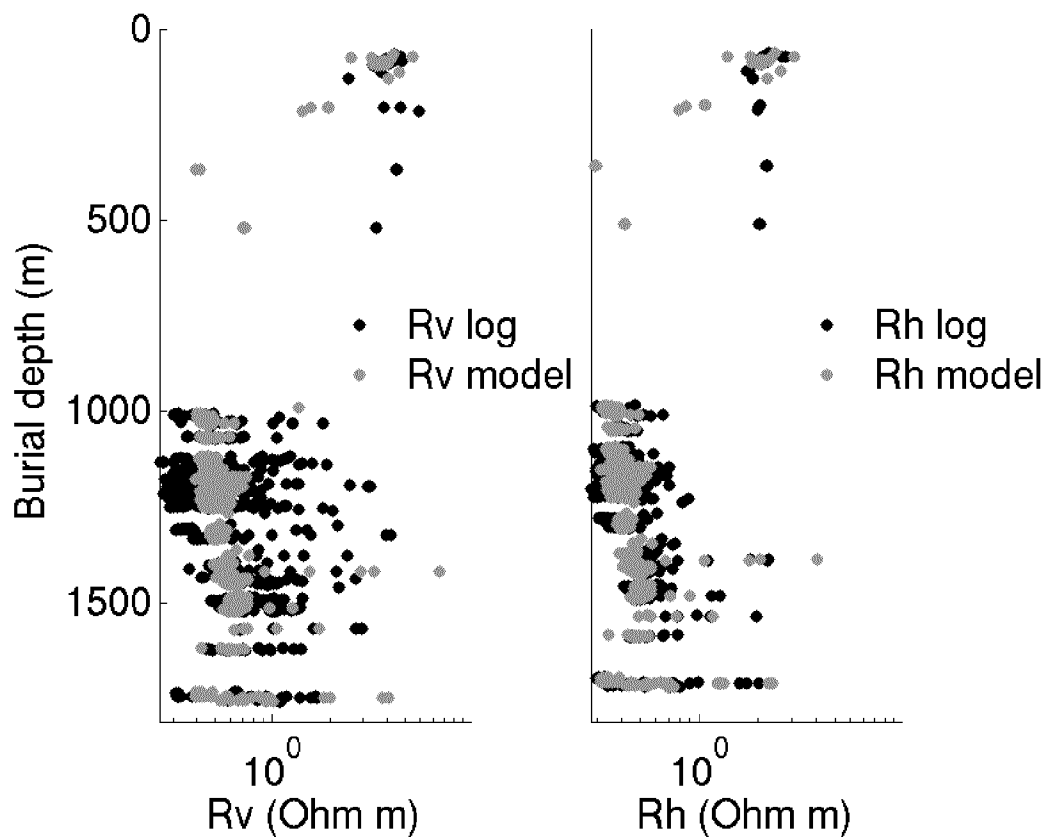


Figure 2

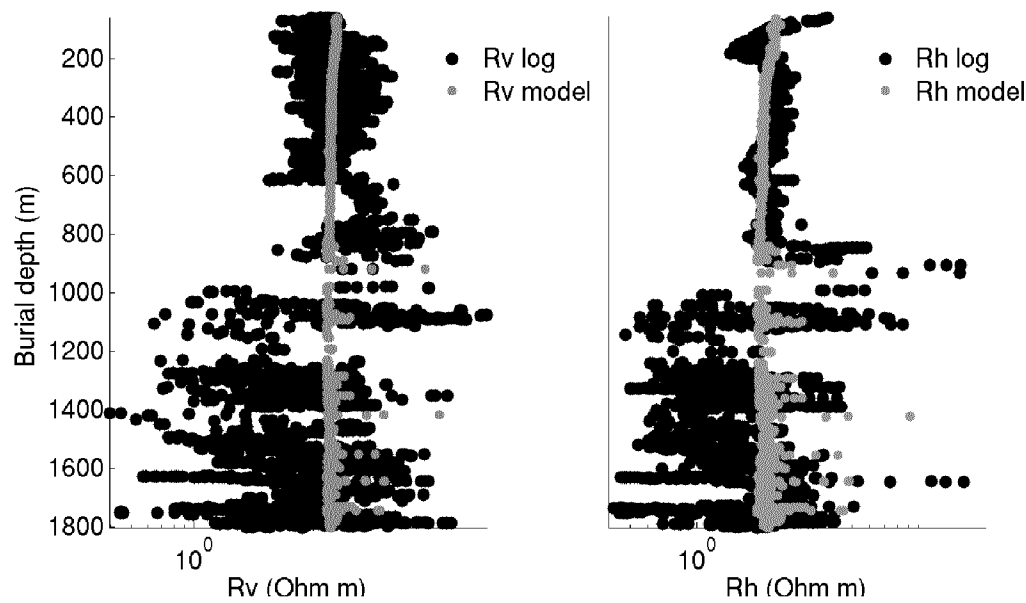


Figure 3

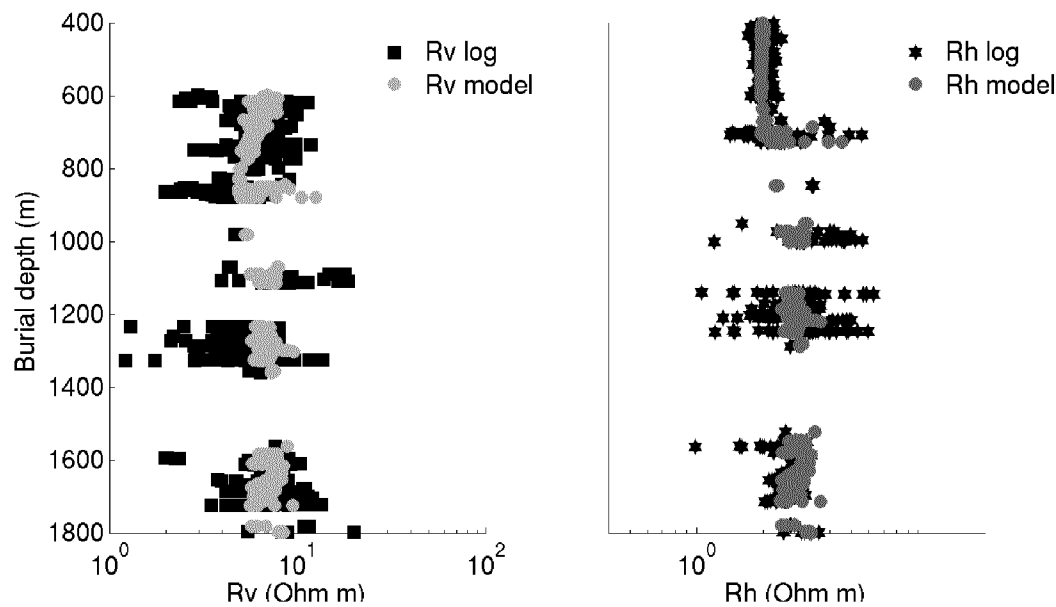


Figure 4

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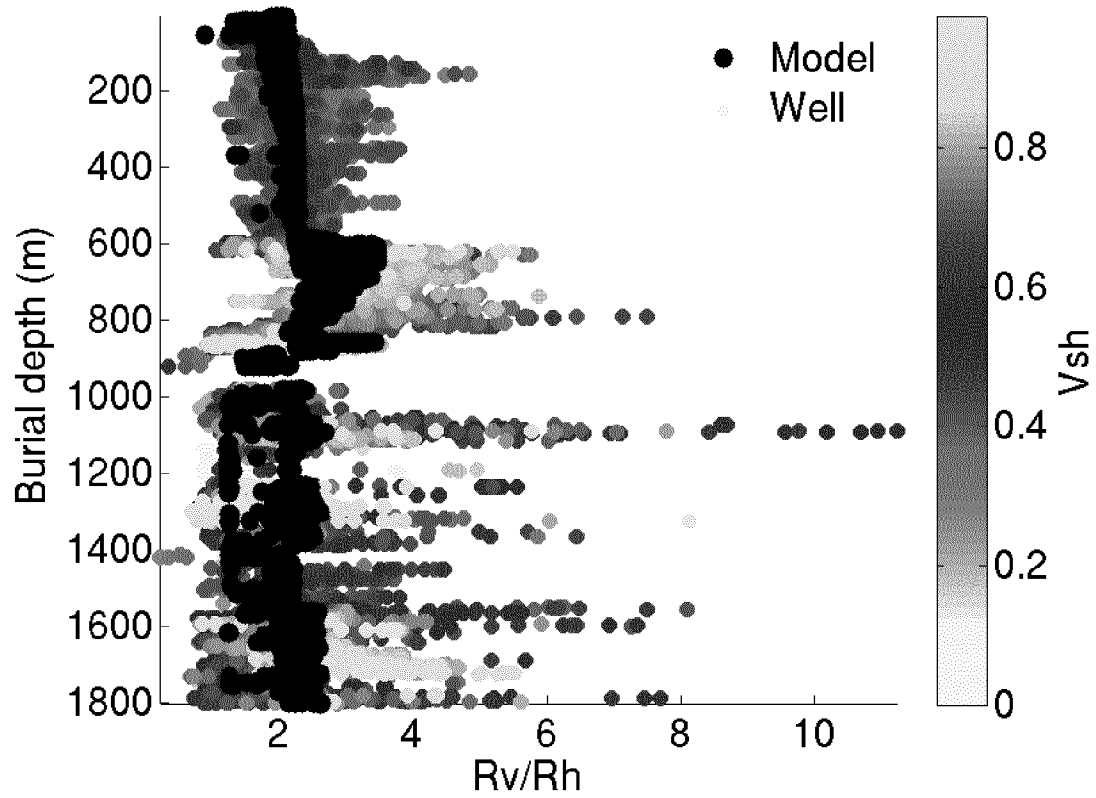


Figure 5

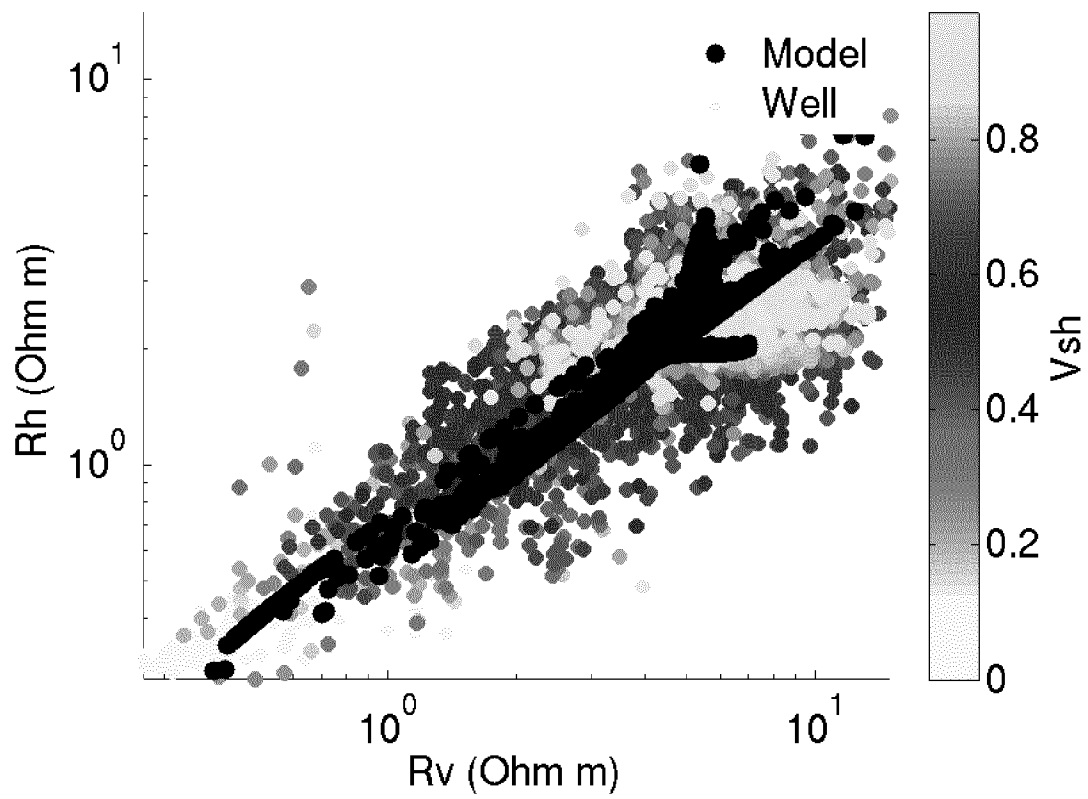


Figure 6

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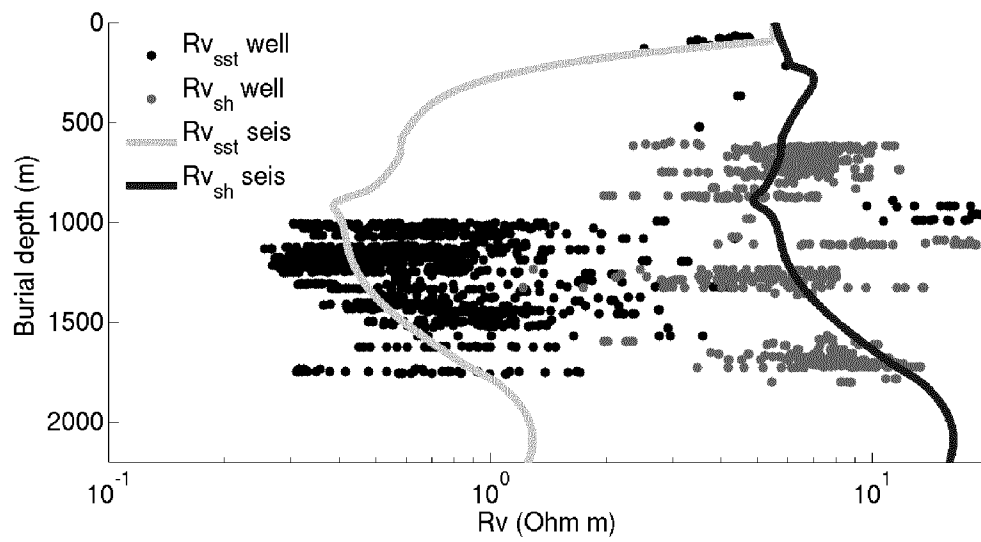


Figure 7

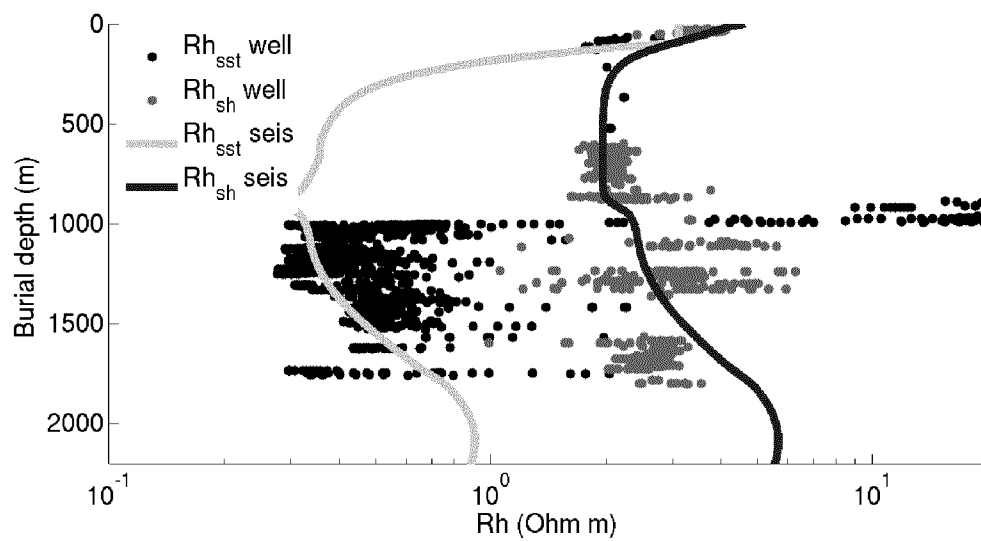


Figure 8

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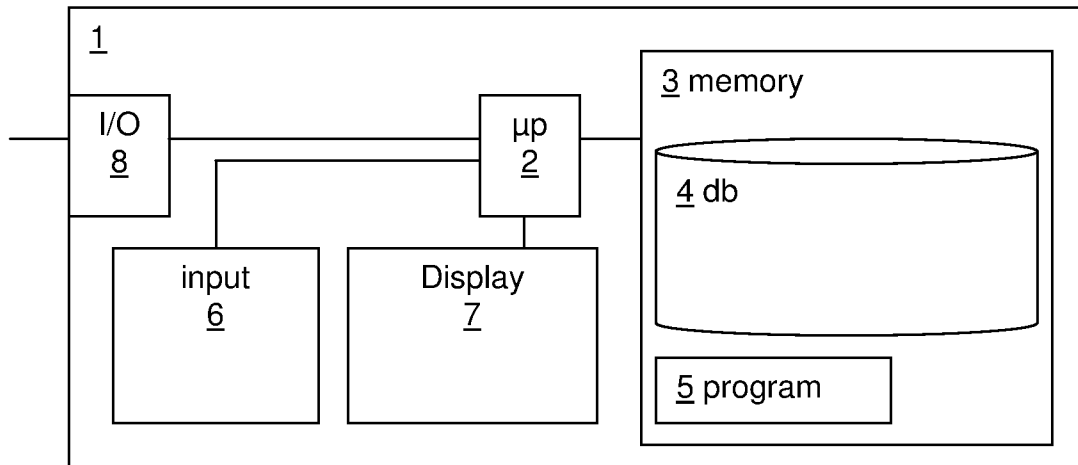


Figure 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/056221

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01V11/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010/326669 A1 (ZHU YAPING [US] ET AL) 30 December 2010 (2010-12-30) page 3, paragraphs 0030, 0032, 0034 page 8, paragraph 0072 -----	1-3, 9-11, 15-18
A	US 2011/292766 A1 (BACHRACH RAN [US]) 1 December 2011 (2011-12-01) page 2, paragraph 0027 page 4, paragraph 0040 - paragraph 0045 -----	15-18
A	US 2011/166840 A1 (GREEN KENNETH E [US] ET AL) 7 July 2011 (2011-07-07) ----- -/-	1-18



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"P" document published prior to the international filing date but later than the priority date claimed

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

22 January 2013

Date of mailing of the international search report

28/01/2013

Name and mailing address of the ISA/

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Swartjes, Harrie

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2012/056221

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SAUNDERS J H ET AL: "Constrained Resistivity Inversion Using Seismic Data", GEOPHYSICAL JOURNAL INTERNATIONAL, BLACKWELL SCIENTIFIC PUBLICATIONS, OXFORD, GB, vol. 160, 1 January 2005 (2005-01-01), pages 785-796, XP008146221, ISSN: 0956-540X, DOI: 10.1111/J.1365-246X.2005.02566.X -----	1-18

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2012/056221

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