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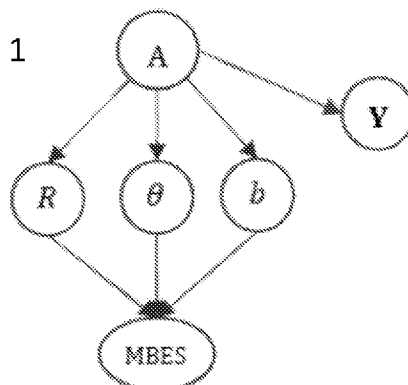
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(54) Title: METHOD OF ESTIMATING POLYMETALLIC NODULE ABUNDANCE

Fig. 1



(57) Abstract: A method of estimating a polymetallic nodule abundance of a seabed is provided. At least one acoustic parameter of the seabed is provided and the method comprises inverting the at least one acoustic parameter to estimate the polymetallic nodule abundance of the seabed. The at least one acoustic parameter may be determined at least partially from multi-beam echo sounder data.



Method of estimating polymetallic nodule abundance

5 The present invention relates to the field of seabed mineral exploration. In particular, in relates to a method of estimating a polymetallic nodule abundance, for example for seabed mineral exploration.

 Metals, such as manganese, nickel, cobalt and copper, that are found in polymetallic nodules can be valuable. As such, it can be desirable to explore for
10 and then harvest polymetallic nodules from the seabed. However, harvesting nodules, particularly in subsea locations, can be difficult and expensive.

 Current methods for estimating polymetallic nodule abundance for a particular target involve qualitative interpretation of multi-beam echo sounder (MBES) data and kriging (interpolation) of box core samples taken from the seabed.
15 However, such methods do not provide high resolution quantitative estimates of polymetallic nodule abundance.

 As such, there is a need for an improved method of estimating polymetallic nodule abundance, e.g. such that a more informed decision can be taken about whether to harvest them.

20 A first aspect of the invention provides a method of estimating polymetallic nodule abundance at a seabed, wherein there is provided at least one acoustic parameter of the seabed, the method comprising inverting the at least one acoustic parameter to estimate the polymetallic nodule abundance of the seabed.

 As such, the polymetallic nodule abundance of the seabed can be estimated
25 by inverting at least one acoustic parameter.

 The at least one acoustic parameter may be determined, at least partially, from MBES data. As such, MBES data may be processed (e.g. with signal processing) to determine the at least one acoustic parameter.

 Compared to the prior art methods described above, for example, such a
30 method, which involves acoustic (e.g. MBES) data and the inversion of one or more acoustic parameters, can provide a high resolution quantitative estimate of the polymetallic nodule abundance of the seabed. For example, in some cases a resolution of between 30 x 30 m² to 50 x 50 m² may be provided (i.e. polymetallic nodule abundance estimates may be determined for positions on a seabed with a
35 (two-dimensional/grid) spacing of around 30 to 50 m).

Another advantage is that using acoustic parameters (e.g. from MBES data) can allow the seabed slope to be estimated (e.g. from MBES travel times). This in turn can be used in an evaluation of the producibility of a possible resource (location of polymetallic nodules). This is because production equipment, for harvesting polymetallic nodules, typically can only operate over sea beds with a slope of around 8° or less. As such, the method may comprise estimating the slope of sea bed from the MBES data and, optionally, using the estimate of the slope of the sea bed in an evaluation of the producibility of the sea bed.

The polymetallic nodule abundance may be estimated as a mass per unit area, for example in kg/m^2 . The mass may be the wet weight of the nodules.

The polymetallic nodule abundance estimated as a mass per unit area (e.g. for a plurality of points) may be integrated or summed (where a plurality of discrete estimates are provided) over an area of interest to obtain an estimated total mass (or tonnage) of polymetallic nodules for that area of interest. The estimated total mass or tonnage may be measured in mega tonnes, for example. In some cases, the estimated total mass of polymetallic nodules for an area of interest may be a sum of the individual estimates (resources) which are above a particular threshold. The threshold may be around $4\text{--}8 \text{ km/m}^2$, for example.

The term seabed may mean an entire seabed. However, in most cases, it may mean a region or part of a seabed, and not necessarily the entire seabed of an ocean or sea.

Inverting or inversion is a well-known term in the art. It describes the process of calculating (or estimating), from at least one observed/measured parameter, the cause of the parameter (or at least one of the causes of the parameter). Thus, in the present case, physically speaking, the polymetallic nodule abundance affects the acoustic parameter(s) of the seabed. However, it is acoustic (MBES) data that is(are) measured and not the polymetallic nodule abundance. Estimating the polymetallic nodule abundance from acoustic parameter(s) may therefore be described as inverting.

The inversion may be considered to be a calculation that uses a (forwards) model (such as phenomenological model), such as discussed below. The model may relate the acoustic (and optionally other) parameter(s) to the polymetallic nodule abundance such that the polymetallic nodule abundance may be estimated from the acoustic (and optionally other) parameter(s). For example, the polymetallic nodule abundance may be estimated from the acoustic parameter(s)

by an optimisation inversion (solving an optimisation problem) and/or by a statistical inversion. A statistical inversion may involve computation of a posterior probability distribution of the acoustic parameter(s), given particular acoustic (MBES) data, for example, and an associated posterior mean abundance and, optionally, variance may be determined.

MBES data is a type of sonar data, which may be used to map the seabed. MBES data may be collected using known techniques, such as using a sonar device on a vessel's hull or on an AUV (autonomous underwater vessel). For example, MBES data may be acquired using an acoustic source array and a receiver array mounted on the hull of a ship or on an AUV.

MBES data may comprise: kinematic data (e.g. travel time(s)) and/or dynamic data (e.g. backscatter magnitude(s)). Parameters such as water depth and/or seabed slope may be computed from the kinematic data. The dynamic data (e.g. backscatter magnitude(s)) may depend on the acoustic properties of the seabed (including reflection coefficient(s), for example).

It can be advantageous to use MBES data in this method as MBES data may be used to map the bathymetry, and record backscatter amplitudes, which depend on the seabed sedimentation and nodule density. A seabed covered with polymetallic nodules, for example, has a higher backscatter amplitude than a seabed covered with pelagic sediments. Seamounts and basaltic extrusions may also have a high MBES backscatter, similar to polymetallic nodules. Further methods (e.g. based on an estimate of the seabed slope) may be used to identify such features.

An acoustic parameter may be any parameter that may be determined from acoustic data. For example, the at least one acoustic parameter may comprise one or more of:

- bathymetry data (e.g. water depth, which may be measured from a mean sea level, for example);
- bathymetry slope (e.g. seabed slope, which may be estimated or determined by differentiation of the bathymetry data with respect to horizontal coordinates (x and y)); and
- MBES backscatter amplitudes (e.g. the scattering strength of the seabed, part of which may comprise the acoustic reflection coefficient, and optionally also comprising diffraction effects).

Preferably, the at least one acoustic parameter comprises (at least) MBES backscatter amplitudes. In some embodiments, bathymetry data and bathymetry slope may also be provided, e.g. as additional constraints in the inversion.

5 The bathymetry data, bathymetry slope, and/or MBES backscatter amplitudes may be determined using standard MBES signal processing methods, such as performed by MBES service providers.

Bathymetry data may be determined or estimated from measured acoustic (MBES) travel times and, for example, a velocity profile model of the water layer.

10 Bathymetry slope may be determined or estimated from bathymetry data by determining the gradient (e.g. the derivative with respect to two horizontal axes (x and y)).

In some embodiments, at least one further (e.g. non-acoustic) parameter may be provided. The at least one further parameter is preferably a non-acoustic parameter (e.g. a parameter that is not determined from acoustic data, or that is
15 determined from data other than acoustic data). The method may comprise inverting the at least one non-acoustic parameter (or using the at least one non-acoustic parameter in the inversion) to estimate the polymetallic nodule abundance of the seabed. The at least one non-acoustic parameter preferably comprises one or more parameters that is/are not determined from multi-beam echo sounder data.

20 The at least one further (non-acoustic) parameter may comprise one or more geochemical parameters or measurements, such as one or more molecular concentrations (e.g. oxygen and/or CaCO_3 and/or O_2 concentrations) and/or one or more biological parameters or measurements (observations), such as an abundance of benthic macro fauna, and/or one or more oceanographic parameters.

25 The method may further comprise obtaining (e.g. from a memory or database) or measuring the MBES data, and/or obtaining (e.g. from a memory or database, such as an oceanographic database) or measuring non-acoustic parameter(s) (or data from which non-acoustic parameter(s) may be determined or estimated). The MBES data and/or non-acoustic parameters may be obtained or
30 measured using known techniques.

The processing of measured MBES data to determine the at least one acoustic parameter may be performed using any standard processing method.

The processing of measured MBES data may determine the at least one acoustic parameter as a function of horizontal position

Preferably, inverting the at least one acoustic (and optional at least one non-acoustic) parameter to estimate the polymetallic nodule abundance of the seabed comprises using a Bayesian inversion method and/or a phenomenological or forwards model.

5 The phenomenological or forwards model may use or be based on box core data and/or one or more equations describing underwater acoustics, for example.

The box core data may be obtained using known techniques, for example by gathering samples of the seabed at selected locations, e.g. 3-10 km apart.

10 The phenomenological or forwards model may be based, for example, on the Jackson model of underwater acoustics. As such, the equations describing underwater acoustics may comprise or be based on the Jackson model of underwater acoustics. For example, the equations describing underwater acoustics may comprise one or more of the Kirchhoff equation and equations determining composite roughness and large roughness contributions to the MBES backscatter
15 amplitudes.

The phenomenological or forwards model preferably models the MBES backscatter amplitudes, e.g. as a function of polymetallic nodule abundance. The (modelled) MBES backscatter amplitudes may be calibrated using the box core data.

20 The phenomenological or forwards model may be selected based upon expected trends relating the acoustic parameter(s) to the polymetallic nodule abundance of the seabed. For instance, an acoustic parameter may generally increase or decrease (depending on the acoustic parameter) with increasing polymetallic nodule abundance of the seabed. For example, in the case of MBES
25 backscatter amplitudes being the acoustic parameter, MBES backscatter amplitudes may increase with increasing polymetallic nodule abundance. The way in which the MBES backscatter amplitudes changes, or increases, with increasing polymetallic nodule abundance may vary depending on the type of sediment present on the seabed in question.

30 Thus, as can be understood from the above, the precise phenomenological or forwards model may be selected by a skilled person based upon knowledge of physics (e.g. acoustic) and other relations.

It should be understood that the phenomenological or forwards model may not show the full complexity of the system, i.e. the model may be intentionally
35 simplified such that the acoustic parameter(s) (e.g. that/those selected for use in

the method) is dependent only on the polymetallic nodule abundance. In reality, acoustic parameters generally depend on many variables. However, in the model(s) used in the present method, the acoustic parameter(s) (e.g. that/those selected for use in the method) may only depend on the variable of interest, which in this case is polymetallic nodule abundance. Thus, in the phenomenological or forwards model(s) used, preferably only the (acoustic) parameter(s) of interest for the statistical inversion are treated as stochastic parameters. Other (e.g. geophysical or other) parameters may be incorporated in the model as deterministic parameters with a fixed value.

There may be provided calibration data e.g. comprising at least one measurement of the acoustic (and/or optional non-acoustic) parameter and the polymetallic nodule abundance of the seabed. This data may comprise box core data, for example. Thus, the method may further comprise obtaining calibration data. The calibration data may preferably contain a plurality of measurements of the acoustic (and/or optional non-acoustic) parameter and the polymetallic nodule abundance of the seabed.

The method may comprise optimising the phenomenological or forwards model based on the calibration data. This optimisation may comprise using the calibration data to find the optimal values of the/any constant factors in the phenomenological or forwards model. Typically, the greater the amount of calibration data, the better the optimisation will be.

In order to optimise the phenomenological or forwards model, it may be assumed that the phenomenological or forwards model has a certain error distribution (i.e. the difference between the at least one acoustic (and/or optional non-acoustic) parameter and the polymetallic nodule abundance gives an error distribution). Preferably, the error distribution is assumed to be a Gaussian error distribution, preferably with zero mean. The phenomenological or forwards model may be optimised by reducing the error distribution so that it is as small as possible, such as by having a mean of the error distribution to be as close as possible to zero and by having a small a variance of the error distribution as possible. The optimisation may be achieved by finding the value(s) of the constant factor(s) in the phenomenological or forwards model that optimise(s) the phenomenological or forwards model.

The optimised phenomenological or forwards model may then be used in the inversion to produce a more accurate inversion.

The phenomenological or forwards model may be used in the inversion to calculate the probability distribution (and/or the mean and/or variance values (directly)) of the at least one acoustic (and/or optional non-acoustic) parameter, given a particular value of the polymetallic nodule abundance. This probability distribution function may be used to calculate the probability distribution of polymetallic nodule abundance (and/or the mean and/or variance values (directly)), given particular values of the acoustic (and/or optional non-acoustic) parameter.

By “phenomenological or forwards model” here, it may simply mean the mathematical relationships used in the inversion, such as the phenomenological or forwards model relating the acoustic (and/or optional non-acoustic) parameter to the polymetallic nodule abundance.

Performing the inversion in the Bayesian setting, as discussed above, can allow for an (accurate) estimate of the uncertainty in the calculated polymetallic nodule abundance to be found. Thus, the method may comprise finding the uncertainty in the estimated polymetallic nodule abundance.

The output of the method may include an estimate of, or information regarding, patchiness. Patchiness means that the polymetallic nodule abundance can exhibit both large and small patches of high abundance. This can be of great importance for planning a harvesting project, i.e. where large patches of high abundance are desired.

The output of the method may alternatively or additionally comprise an identification of areas with (possible) obstacles, which could potentially impact the producibility of nodules by means of harvesters at the seabed. Obstacles may include cliffs, escarpments, sharp ridges and/or sea mounts, for example. Obstacles may be detected or identified from bathymetry (slope) data. A slope constraint may be applied to a seabed. For example, seabeds with slopes greater than a certain value (e.g. around 8°) may be identified as not being suitable (or economically viable) for a harvesting operation, as seabeds with larger slopes will/may reduce the probability of there being producible nodules there.

The method may comprise inverting the at least one acoustic (and/or optional non-acoustic) parameter point-wise to estimate the polymetallic nodule abundance of the seabed for multiple different points or locations on the seabed. The multiple points of locations may have a spacing or around 30 – 50 m, for example.

The polymetallic nodule abundance of the seabed may be determined as a function of (preferably horizontal) position, e.g. on the seabed. For example, the polymetallic nodule abundance may be determined at a series or (two dimensional) array of points over a particular area or region of the seabed. The polymetallic
5 nodule abundance of the seabed may be determined as an average over a particular horizontal area or distance.

The above methods may calculate the polymetallic nodule abundance for a specific point or location of the seabed, said point or location corresponding to the point or location of the (at least one) acoustic (and/or optional non-acoustic)
10 parameter used in the inversion step (the acoustic and/or optional non-acoustic parameter(s) used in these methods may be the value of that parameter at a given point or location on the seabed). Therefore, in order to obtain a spatially dependent polymetallic nodule abundance function, the above inversion method may be performed point-wise for multiple different points or locations on the seabed. As
15 can be appreciated, the acoustic (and/or optional non-acoustic) parameter(s) may vary over the seabed, and this may correspond to a spatially varying polymetallic nodule abundance.

Thus, the method may comprise constructing a spatially dependent polymetallic nodule abundance function. This function may be constructed by
20 calculating the polymetallic nodule abundance for different points or locations on the seabed (preferably all points or locations on the seabed or over an area of the seabed). The polymetallic nodule abundance may be calculated over substantially the entirety of the seabed, or an area of the seabed, or over a particular (smaller) area thereof.

25 The polymetallic nodule abundance may be found in one or two dimensions.

The polymetallic nodule abundance may be found as function of horizontal location. This may provide the user with an estimate of the horizontal location of possible targets for polymetallic nodule harvesting.

In a further aspect, the invention provides a method of producing a
30 polymetallic nodule abundance map of a seabed, the method comprising performing any of the methods described above.

As can be appreciated, the above methods may be used when prospecting for polymetallic nodules, e.g. when planning and performing polymetallic nodule harvesting operations.

According to a further aspect, there is provided a method of prospecting for polymetallic nodules comprising performing the method described herein, with any of its optional or preferred features, and using the estimated polymetallic nodule abundance of the seabed in the decision-making process for deciding whether to
5 harvest nodules from the seabed.

For example, the method may further comprise making a decision to harvest polymetallic nodules from the seabed, e.g. if the polymetallic nodule abundance of the seabed is estimated to be above a particular cut-off (threshold). For example, a decision may be taken to harvest polymetallic nodules from the seabed if the
10 polymetallic nodule abundance of the seabed is estimated to be above around 4 – 8 kg/m². However, other factors, such as the slope of the seabed, may (also) be taken into account when deciding whether to harvest nodules from a seabed.

The method may then further comprise harvesting nodules from the seabed, e.g. if a decision is taken to do so. In some cases, a test harvesting may be
15 performed, e.g. before a larger (production-scale) harvesting is performed.

The above method is preferably, at least partially, performed on or implemented by a computer or computer system.

A further aspect of the invention relates to a computer program product comprising computer readable instructions that, when run on a computer, is
20 configured to cause one or more processors to perform the method described above, with any of its optional or preferred features.

A further aspect of the invention relates to a system for performing the above method, with any of its preferred or optional features. The system may comprise one or more software elements arranged to perform the method, or one or
25 more parts of the method, described above, with any of its optional or preferred features.

A system may comprise one or more memories and one or more processors configured to perform the method(s), or one or more parts of the method(s), as described above. The one or more memories may store data used as an input to
30 the method (e.g. seismic data) and/or data output from the method. The one or more processors may be programmed with software (e.g. computer program(s)) which causes them to perform the method, or one or more parts of the method, of the present invention. The system may comprise one or more screens and/or data input means, e.g. for a user to control the performing of the method, or one or more
35 parts of the method, and/or view an output of the method on a screen.

The methods in accordance with the present invention may be implemented at least partially using software e.g. computer programs. It will thus be seen that when viewed from further aspects, the present invention provides computer software specifically adapted to carry out the methods, or one or more parts of the methods, herein described when installed on data processing means (e.g. one or more processors), a computer program element comprising computer software code portions for performing the methods, or one or more parts of the methods, herein described when the program element is run on data processing means, and a computer program comprising code means adapted to perform one or more steps of a method or of the methods herein described when the program is run on a data processing system. The data processor may be a microprocessor system, a programmable FPGA (field programmable gate array), etc.

The invention also extends to a computer software carrier comprising such software which when used to operate a processor or microprocessor system comprising data processing means causes in conjunction with said data processing means said processor or system to carry out the steps (or one or more of the steps) of the methods of the present invention. Such a computer software carrier could be a physical storage medium such as a ROM chip, RAM, flash memory, CD ROM or disk, or could be a signal such as an electronic signal over wires, an optical signal or a radio signal such as to a satellite or the like.

It will be appreciated that in some embodiments, not all steps of the methods of the invention need be carried out by computer software and thus from a further broad aspect the present invention provides computer software and such software installed on a computer software carrier for carrying out at least one of the steps of the methods set out herein.

The present invention may accordingly suitably be embodied as a computer program product for use with (or within) a computer system. Such an implementation may comprise a series of computer readable instructions fixed on a tangible medium, such as a non-transitory computer readable medium, for example, diskette, CD ROM, ROM, RAM, flash memory or hard disk. It could also comprise a series of computer readable instructions transmittable to a computer system, via a modem or other interface device, either over a tangible medium, including but not limited to optical or analogue communications lines, or intangibly using wireless techniques, including but not limited to microwave, infrared or other transmission

techniques. The series of computer readable instructions embodies all or part of the functionality previously described herein.

Those skilled in the art will appreciate that such computer readable instructions can be written in a number of programming languages for use with many computer architectures or operating systems. Further, such instructions may be stored using any memory technology, present or future, including but not limited to, semiconductor, magnetic, or optical, or transmitted using any communications technology, present or future, including but not limited to optical, infrared, or microwave. It is contemplated that such a computer program product may be distributed as a removable medium with accompanying printed or electronic documentation, for example, shrink wrapped software, pre-loaded with a computer system, for example, on a system ROM or fixed disk, or distributed from a server or electronic bulletin board over a network, for example, the Internet or World Wide Web.

Throughout the specification, terms such as “calculating”, “determining” and “estimating” may be used. These are not intended to be limiting; rather they are merely meant to mean determining or obtaining a value for an actual physical value (or at least a (close) approximation or estimate of the physical value), such as polymetallic nodule abundance.

Preferred embodiments on the invention will now be described by way of example only and with reference to the accompanying drawings, in which:

Fig. 1 is an illustration of a Bayesian network for estimation of polymetallic nodule abundance; and

Fig. 2 is a flow chart illustrating a method of estimating a polymetallic nodule abundance of a seabed and harvesting polymetallic nodules.

As illustrated in Fig. 2, an embodiment of a method of estimating a polymetallic nodule abundance of a seabed (or an area of a seabed) and harvesting polymetallic nodules involves three main steps.

At step 1, oceanographic, geophysical, and acoustic data, including MBES data, are obtained over or for a seabed, or an area of a seabed. The seabed (or area of the seabed) may have previously been identified as an area which may contain relatively high polymetallic nodule abundance, e.g. based on other (larger scale) data from the area.

As step 2, the data is processed to obtain an estimate of the polymetallic nodule abundance of the seabed. The polymetallic nodule abundance is estimated as a function of horizontal position.

At step 3, if the estimate of the polymetallic nodule abundance (or an estimated total tonnage of polymetallic nodules for an area) is sufficiently high, then a decision may taken to harvest polymetallic nodules from that seabed. The harvesting operation may then be performed. The decision to harvest polymetallic nodules may also be based on other factors (such as seabed slop) as well as the estimate of the polymetallic nodule abundance.

Each of the above steps 1-3 will now be described in more detail.

At step 1, acoustic data, including MBES data, related to a seabed is obtained over a subsea area. Further (non-acoustic) data relating to the seabed may also be obtained, such as oceanographic, geochemical and/or biological data.

The subsea area is an area which has previously been indicated (e.g. based on other, larger scale data, of the area) as possibly containing relatively high polymetallic nodule abundance, and about which it is desired to obtain a better (e.g. more accurate and/or higher resolution) estimate of the polymetallic nodule abundance for that area. Selecting an area for this method from larger scale (regional) data is typically based on analysis and interpretation of bathymetry data (e.g. from the GEBCO database), measurements of chlorophyll content of surface water, carbonate compensation depth, distance to metal sources (on shore and oceanic ridges), and gravity data.

The subsea area to which the method is applied may have an area of around 10,000 – 50,000 km², for example.

In some embodiments, the data collected at this step consists of only MBES (acoustic) data. Such data can be collected using apparatus on board a survey vessel and there is not necessarily any need, for example, to send an autonomous underwater vehicle (AUV) down to the seabed to collect other kinds of geophysical data. Such data may be collected specifically for use in this method or it may have been collected for a different (initial) purpose.

However, in other embodiments, one or more other kinds of (non-acoustic) data (Y) may also be used.

In some embodiments, one or more geochemical parameters or measurements, such as one or more molecular concentrations (e.g. oxygen and/or CaCO₃ and/or O₂ concentrations) are used.

In some embodiments, one or more biological parameters or measurements (observations), such as an abundance of benthic macro fauna are used.

The geochemical and/or biological parameters or data can be acquired during research or exploration cruises, for example.

5 In some embodiments, one or more oceanographic parameters are used, such as parameters or data from (public) oceanographic databases such as GLODAP.

10 In some embodiments, obtaining the acoustic and/or non-acoustic data comprises measuring the data. In some embodiments, obtaining the acoustic and/or non-acoustic data comprises obtaining the data from a memory or database. In some embodiments, some data is measured and some is obtained from a memory or database.

As step 2, the acoustic (MBES) and non-acoustic data is processed to obtain an estimate of the polymetallic nodule abundance of the seabed.

15 Step 2 actually contains two stages: at stage (i), the MBES data collected at step 1 is processed to determine acoustic parameters such as bathymetry data (R), bathymetry slope (θ), and MBES backscatter amplitudes (b); and at stage (ii), the determined acoustic parameters together with any other kinds of (non-acoustic) data (if used) are inverted to estimate the polymetallic nodule abundance of the seabed.

20 In some embodiments, at stage (i) the MBES data collected at step 1 is processed to determine only MBES backscatter amplitudes (b). However, in other embodiments, all of bathymetry data (R), bathymetry slope (θ), and MBES backscatter amplitudes (b) are determined.

25 This processing step is now explained in more detail with reference to Fig. 1.

Dependencies between physical quantities can conveniently be represented by Bayesian networks. Fig. 1 shows a general multi Bayesian network for estimation of polymetallic nodule abundance A from parameters $\{R, \theta, b, Y\}$. As shown in Fig. 1, the acoustic parameters $\{R, \theta, b\}$ in turn depend on MBES data (MBES). In this figure, R is bathymetry data (range), θ is bathymetry slope, b is MBES backscatter amplitudes. Y is other (non-acoustic) data that may be available such as the oceanographic, geochemical and/or biological data described above.

30

The Bayesian network can be applied to obtain the joint distribution for a set of parameters, incorporating the principle of conditional independence. The joint probability of a set of stochastic nodes $\{x_1, \dots, x_n\}$ can be written as

$$p(x_1, \dots, x_n) = \prod_i p(x_i | x_i^{\text{pa}}), \quad (1)$$

5 where x_i^{pa} denotes the parents of x_i , i.e. nodes on the level above in the network.

From the network in Fig. 1 and using equation (1), and marginalizing hidden variables, the posterior distribution of polymetallic nodule abundance A given MBES data $\mathbf{d}$ can be written as

$$p(A|\mathbf{d}) = C \int p(A|\mathbf{m})p(\mathbf{m}|\mathbf{d})d\mathbf{m} \quad (2)$$

10 where C is the normalization factor, $\mathbf{m} = (m_1, m_2, \dots, m_n)$ is a vector of model parameters and $\mathbf{d} = (d_1, d_2, \dots, d_k)$ is a vector of data.

The integral marginalizes the model parameters.

The model parameters m_i may be backscatter amplitude (b), bathymetry (range) (R), or bathymetry slope (θ).

15 The data d_i are echo-level MBES recordings.

When the posterior distribution $p(A|\mathbf{d})$ is known, the posterior mean $\mu_{A|\mathbf{d}}$ and variance $\sigma_{A|\mathbf{d}}$ can be computed from the definitions.

As explained above, in practice, the method is performed in two steps:

- 20 (i) the echo level MBES data are processed to calculate the acoustic parameter(s) on which they depend (e.g. bathymetry data R , bathymetry slope θ , and MBES backscatter amplitudes b); then
- (ii) the acoustic parameters $\{R, \theta, b\}$, and optionally further (non-acoustic) parameter(s) Y , are inverted to determine the polymetallic nodule abundance A .

25 At step (i), typically, the processing of the MBES data is done using standard processing methods, correcting for spherical divergence, absorption in the water column, and source strength. This processing step is often performed by an MBES service provider. In addition, the uncertainty (error variance and covariance) of the acoustic parameters can be estimated.

30 At step (ii), the main challenge in the Bayesian inversion is to compute the posterior distribution $p(A|\mathbf{m})$, which can be written as

- 15 -

$$p(A|\mathbf{m}) = \prod_i p(m_i|A) p(A)$$

where $p(A)$ is the prior distribution for A . Assuming Gaussian error variances σ_{ei} , the likelihood distributions $p(m_i|A)$ are given by

$$p(m_i|A) = N_i e^{-\frac{(m_i - f_i(A))^2}{2\sigma_{ei}}}$$

- 5 where N_i are normalization factors, and $f_i(A)$ is the forward model of m_i . If the results of the MBES processing described in (i) are assumed to approximate the mean $\mu_{m|d}$ and covariance matrix $\Sigma_{m|d}$ of a Gaussian distribution, the posterior distribution $p(A|\mathbf{d})$ can be written as a convolution,

$$p(A|\mathbf{d}) = C \int p(A|\mathbf{m}) e^{-(\mathbf{m} - \mu_{m|d})^T \Sigma_{m|d}^{-1} (\mathbf{m} - \mu_{m|d})} d\mathbf{m}$$

- 10 As mentioned above, the inversion performed at step (ii) uses a forwards model. The forwards model is calibrated using box core samples acquired on the seabed in the area of interest. Typically, 30-50 box core samples are used.

- The model also uses equations describing underwater acoustics to model the MBES backscatter amplitudes (b). These equations include the Kirchhoff equation and equations determining composite roughness and large roughness contributions to the MBES backscatter signal b .
- 15

- In the inversion, bathymetry acts as a constraint from known depth intervals for occurrence of polymetallic nodules (typically 4000 – 5000 m), and the slope θ acts as a constraint on the maximum slope that can be handled by a harvester.
- 20 Hence, the output of the inversion, the posterior polymetallic nodule abundance A , is in practice an estimate of producible resources for a given harvester technology.

- An output of a previous, larger-scale estimation of polymetallic nodule abundance, e.g. based on larger-scale data, may be used as a prior into the inversion performed at step (ii).

- 25 Next, at step 3, if the estimate of the polymetallic nodule abundance is sufficiently high, then a decision may be taken to perform a harvesting operation for that/those polymetallic nodule(s), and the harvesting operation may then be performed. “Sufficiently high” may mean an estimated polymetallic nodule abundance of above around 4 to 8 kg/m² (e.g. 6 kg/m²), and/or a total tonnage of at least around 100 Mt.
- 30

- 16 -

A decision to perform a harvesting operation may also be based on other factors (as well as the estimate of the polymetallic nodule abundance or total tonnage) such as seabed slope.

5 The above method can be used when prospecting for polymetallic nodules,
e.g. when planning and performing polymetallic nodule harvesting operations.

Claims

1. A method of estimating polymetallic nodule abundance at a seabed, wherein there is provided at least one acoustic parameter of the seabed, the method comprising inverting the at least one acoustic parameter to estimate the polymetallic nodule abundance of the seabed.
2. As method as claimed in claim 1, wherein the at least one acoustic parameter comprises one or more of: bathymetry data, bathymetry slope, and multi-beam echo sounder backscatter amplitudes.
3. A method as claimed in claim 1 or 2, wherein at least one non-acoustic parameter is provided, and the method comprises inverting the at least one non-acoustic parameter to estimate the polymetallic nodule abundance of the seabed.
4. A method as claimed in claim 3, wherein the at least one non-acoustic parameter comprises at least one geochemical, biological and/or oceanographic parameter.
5. A method as claimed in any preceding claim, wherein the at least one acoustic parameter is determined at least partially from multi-beam echo sounder data.
6. A method as claimed in claim 5, further comprising obtaining or measuring the multi-beam echo sounder data.
7. A method as claimed in any preceding claim, wherein inverting the at least one acoustic and/or at least one non-acoustic parameter to estimate the polymetallic nodule abundance of the seabed comprises using a Bayesian inversion method and/or a phenomenological model.
8. A method as claimed in claim 7, wherein the phenomenological model uses box core data and/or equations describing underwater acoustics.
9. A method as claimed in claim 8, wherein the equations describing underwater acoustics include one or more of the Kirchhoff equation and

- 18 -

equations determining composite roughness and large roughness contributions to multi-beam echo sounder backscatter amplitudes.

- 5 10. A method as claimed in claim 7, 8 or 9, wherein the phenomenological model models the multi-beam echo sounder backscatter amplitudes.
- 10 11. A method as claimed in any preceding claim, the method comprising inverting the at least one acoustic and/or at least one non-acoustic parameter point-wise to estimate the polymetallic nodule abundance of the seabed for multiple different points or locations on the seabed.
- 15 12. A method of prospecting for polymetallic nodules comprising performing the method of any of the preceding claims and using the estimated polymetallic nodule abundance of the seabed in the decision-making process for harvesting polymetallic nodules from the seabed.
- 20 13. A method as claimed in claim 12, further comprising making a decision to harvest nodules from the seabed if the polymetallic nodule abundance of the seabed is estimated to be above a particular threshold.
- 25 14. A method as claimed in claim 12 or 13, further comprising harvesting nodules from the seabed.
15. A computer program product comprising computer readable instructions that, when run on a computer, is configured to cause one or more processers to perform the method of any of claims 1 to 13.

1/1

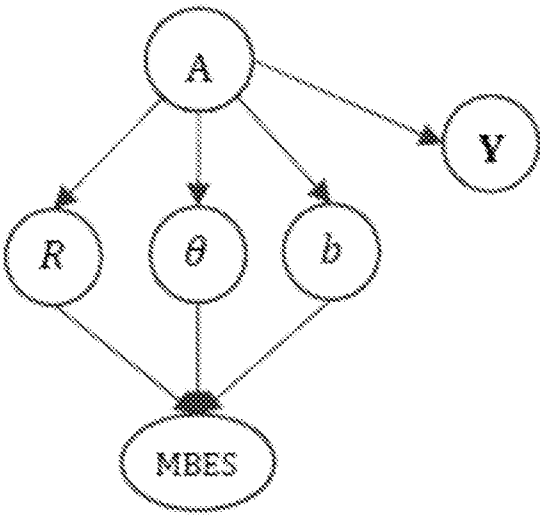


Fig. 1

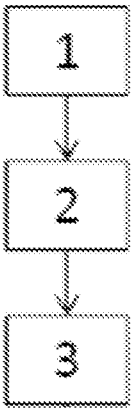


Fig. 2

INTERNATIONAL SEARCH REPORT

International application No.

PCT/NO2021/050223

A. CLASSIFICATION OF SUBJECT MATTER G01V 1/38 (2006.01)i; G01N 33/20 (2019.01)i; G01N 33/24 (2006.01)i; G01V 1/30 (2006.01)i; E21C 50/00 (2006.01)i 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; G01N; E21C Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched DK, NO, SE, FI: Classes as above Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPODOC, WPI, FULL TEXT: ENGLISH		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	WONG, L. J. et al., "Acoustic Assessment of Polymetallic Nodule Abundance Using Sidescan Sonar and Altimeter" published 2020.02.14 on https://ieeexplore.ieee.org , Electronic ISSN: 1558-1691. See abstract; page 133 left column; page 135 right column	1-6, 11-15 7-10
X A	US 4075599 A (KOSALOS, J. G.; COOKE, R. W.) 21 February 1978 (1978-02-21) col. 2 line 12-16; col. 3 line 1-7	1 2-15
X A	WO 2020180187 A1 (EQUINOR ENERGY AS) 10 September 2020 (2020-09-10) page 4 last paragraph, page 9, fourth paragraph	1 2-15
X A	GB 2044455 A (SUMITOMO METAL MINING CO) 15 October 1980 (1980-10-15) page 1 line 5-7, 25-31; page 5 line 32-37	1 2-15
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "D" document cited by the applicant in the international application "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "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 December 2021		Date of mailing of the international search report 22 December 2021
Name and mailing address of the ISA/XN Nordic Patent Institute Helgeshoj Allé 81, 2630 Taastrup Denmark Telephone No. +45 43 50 85 00 Facsimile No. +4543508008		Authorized officer OVERAA, Margrethe Telephone No. +45 43 50 80 08

INTERNATIONAL SEARCH REPORT

International application No.

PCT/NO2021/050223

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P A,P	WO 2020222652 A1 (EQUINOR ENERGY AS) 05 November 2020 (2020-11-05) page 1 line 5-7, 22-31; page 2 line 13-15; page 3 line 14-25; page 5 line 11-13; claims 20-23	7-10 1-6, 11-15
A	NEETTIYATH, U. et al., "An AUV Based Method for Estimating Hectare-scale Distributions of Deep Sea Cobalt-rich Manganese Crust Deposits," OCEANS 2019, 17-20 June 2019, Marseille, 6 pages, Electronic ISBN: 978-1-7281-1450-7. See abstract; page 2 "System overview"; page 4 "Conclusion"	1-15
A	WONG, L. J. et al., "Polymetallic nodules abundance estimation using sidescan sonar: A quantitative approach using artificial neural network" OCEANS 2017, 19-22 June 2017, Aberdeen, 6 pages, Electronic ISBN:978-1-5090-5278-3. See abstract	1-15
A	CN 111794753 A (SHENZHEN YOUHUA DEV CO LTD) 20 October 2020 (2020-10-20) fig. 1	14

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. Claims 1-11, 15

Claims 1-11 and 15 describes a method of estimating polymetallic nodule abundance at a seabed.

2. Claims 12-14

Claims 12-14 relates to harvesting of nodules from the seabed.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/NO2021/050223

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
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				FR	2451042	A	07 November 1980
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CN	111794753	A	20 October 2020	CN	212406719U	U	26 January 2021