ABSTRACTS ACCEPTED
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1:

Finding Targets in Complex Hosts using Airborne EM

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Two basic questions lay at the heart of AEM surveys, one concerning the basic physics of the process, the other the interpreter's capability. Is the equipment capable of exciting the target to the extent that it will produce a detectable signal above background response? Can the presence of a target be deduced from this signal?

Using the 2.5D finite-element program, ArjunaAir, this study examines the response of a 400 Siemen sulphide lens in an altered ultramafic lying at the boundary of a faulted host under a moderately conductive saprolite cover. In one case, the surface is flat and in the other, the whole lies under moderately steep topography. The study compares the response of fixed wing time-domain, helicopter time-domain and helicopter frequency-domain systems, assuming constant receiver ground clearance.

For this type of model, the impulse response Geotem-style fixed-wing system had considerably greater target differentiation capability than was the case for the step B Tempest style system. Aerotem gave reasonable target differentiation. The real surprise was the effectiveness of low frequency in-phase HEM, especially the co-axial component.

Although there was ample information to differentiate the target from barren hosts in time-domain data, it was very difficult to recognise the target from looking at profiles. Imaging methods built on one-dimensional earth models such as conductivity-depth transforms were not very useful. Frequency-domain HEM offered the advantage of localised target response in comparison to the more spread out signal of time-domain systems.

2:

Impulsive moments at work

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The moments of the impulse response have emerged as a new tool for interpretation of transient electromagnetic data. The n^{th} moment M^n is given by the expression

$$M^n = \int_0^\infty t^n \, I(t)\, dt$$

where t is the delay time and $I(t)$ is the impulse response with the delta function at time t=0 removed.

When the earth structure is infinite in lateral extent, analytic expressions have been derived for the low-order moments. These can be inverted to generate maps of the conductivity or conductance in an area. For the high-order moments, the integrand is unbounded because the t^n term increases faster than the $I(t)$ term decreases. However, an improvement of the method to account for a finite upper bound of integration and a repetitive waveform has resulting in a method for converting the high-order moments to conductance or conductivity. The high-order conductance images give a good reflection of deep conductive features.

In the case when the conductor is finite in lateral extent, the moments are also a powerful tool for interpretation. Numerical experiments have shown that the first-order moment response of a large body is very similar to the sum of the moment responses of a large number of smaller bodies (with similar time constants) that occupy the same volume. This means that it is possible to discretize the earth into small bodies and invert for the time constant of each small body. In this way it is possible to invert the measured EM data to obtain a time constant/depth section. Preliminary results show this to be a promising approach. It is believed that this will provide a fast imaging technique in cases when the current flow in the body is primarily inductive.

Another advantage of the moment formulation is that the moment responses are extremely fast and easy to calculate. Also, the additive nature of the moment response suggests that the background response could be simply subtracted to give an anomalous target response. This is very similar to potential field data, suggesting that tools like those used in potential field interpretation could be adapted for interpretation of moment data. Along these lines, we have developed an interpretation package that allows for the interactive selection of moment data from the Geosoft montaj environment. The background response can be subtracted and the residual response modelled. The forward modelling is fast and can be inverted in real time to interatively improve the fit. The types of bodies that can be inverted for are spheres and plate-like bodies (approximated with “dipping spheres”). In this manner it is possible to determine the depth, conductivity, and radius and in some cases the dip of the target structure. If possible, we would like to give an interactive demonstration of this modelling and inversion software.

3:

Approximate 2D Inversion of AEM Data using the adaptive Born approximation

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Approximate 1D inversion (imaging) and, still more often, nonlinear 1D inversion is the main approach to inversion of large EM data sets. For profile oriented data from airborne TEM measurements it is the standard processing tool. As long as the subsurface conductivity is laterally slowly varying, a 1D inversion is justified, but often airborne TEM measurement are carried out with the purpose of locating localized conductors in mining investigation, a situation which is clearly not 1D. For localized conductors in a conducting environment the interpreter has had no other choice than to live with the artifacts of 1D inversion and try and interpret model sections full of pant-leg effects.

We have developed an approximate inversion method that deals with laterally inhomogeneous sections. The method is based on the adaptive Born Approximation (Christensen 1997, 2001) previously applied in 1D imaging and to the interpretation of central-loop ground 2D EM profiles. The technique reproduces synthetic models of moderate conductivity contrasts without the artifacts typically seen in 1D sections. The computing speed is comparable to that of stitched-together 1D inversions.

An example of processing field data over a massive Nickel Sulfide deposit shows promising results for routine application on large AEM data sets.

4:

Modelling the 3D EM response of Nickel Sulphide orebodies

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We apply recently developed 3D and 2.5D EM modelling software to study the responses of two orebodies, taking into account both geological and EM system complexity.

The first target was the Harmony NiS deposit near Leinster, Western Australia, which consists of a thin dipping conductive zone between two thicker, but less conductive, shale horizons. Because the host is resistive, the AEM response of the complex can be modelled with a number of thin plates. Initially we applied our 3D and 2.5D programs to this simplified model to confirm their accuracy. We then modelled the actual geology by including the structure of the overburden.

The Maggie Hays complex in Western Australia consists of small deep (between 375 and 450 m) zones of massive NiS mineralisation with shallower disseminated zones in a generally resistive host. It is covered by a thick (~75 m) irregular conductive regolith and lies adjacent to conductive faulted BIFs, making it a difficult target for airborne and surface EM methods.

We modelled the 12.5 Hz Sirotem system response of the Maggie Hays ore body using two configuration types. The first was a three-component in-loop survey. For the second configuration, we modelled surface and two down-hole traverses using three large surface transmitter loops, positioned to illuminate different aspects of the model. One of the downhole surveys intersects only the disseminated zone while the other intersects part of the massive sulphide body.

Good matches with field data were obtained both for the AEM response of the Harmony deposit and the in-loop and downhole response of the Maggie Hays deposit. Moreover, we show we show that mapping the current flow in the model affords a valuable insight into the physics of EM induction allowing better survey planning and data analysis.

5:

Three-dimensional interpretation of the helicopter-borne electromagnetic (HEM) survey in the Voisey's Bay area, Canada

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Helicopter-borne electromagnetic (HEM) surveys are widely used in mineral exploration. The main difficulties in modeling and interpretation of the HEM data are related to the fact that for any new observation point one has to solve the forward problem anew for the corresponding position of the moving transmitter. In this situation, even forward modeling of HEM data over inhomogeneous structures requires an enormous amount of computations. That is why, until recently, the interpretation of HEM data was restricted to a simple 1-D inversion only. We have developed a new approach to modeling and inversion of multi-source array electromagnetic data based on so-called localized quasi-linear (LQL) approximation. In the framework of this approach, forward modeling and the inversion of multi-source data can be calculated at once for all different positions of the transmitters. We use the spectral Lanczos decomposition method to speed up the inversion with multiple regularization parameter values. We apply this method to HEM data collected by INCO Exploration in the Voisey's Bay area in Canada. This area is characterized by high-conductivity Ni-Cu sulphide deposits hosted by resistive troctolite dikes. We have chosen to invert the data from the central part of the area that correspond to the location of the "Ovoid" deposit. This is a flat-lying deposit of very high conductance, and comprises 70% massive sulphide. We have used both the coplanar and coaxial components of the magnetic field for inversion. The results seem reasonable and in good agreement with the existing information about the Ovoid deposit. In particular, a large elongated conductive body is located approximately at the center of the inverted area. The body is extended towards the SE and the W-NW. The reliability of these results is enhanced by the fact that, despite small differences, inversion results for different components, as well as joint inversion results, agree relatively well with each other. The successful application of the LQL inversion to real HEM data in a complex geological environment with large resistivity contrasts shows that the method can be an effective tool for fast 3-D inversion in mineral exploration.

6:

Two-dimensional inverse and three-dimensional forward modelling of MT data to evaluate the mineral potential of the Amphitheatre Mountains, Alaska, USA

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Magnetotelluric (MT) data were used as part of an integrated geological and geophysical study to evaluate the mineral potential in the Amphitheatre Mountains of south central Alaska, USA. Data acquired along two parallel MT profile lines during the summer of 2002, along with data from detailed gravity, and helicopter electromagnetic and magnetic surveys are being used to investigate a feeder system to a Late Triassic flood basalt, the Nikolai Greenstone. The Fish Lake and Tangle PGE-bearing layered mafic-ultramafic sills form the Amphitheatre synform. The geophysical data suggest the presence of a substantial root of ultramafic material below the synform, and several conductive, dense, possibly sulphide-bearing lenses within the Tangle Formation. If these features prove to represent Nikolai-related ultramafic complexes, they would widen the distribution of the magmatic roots to the flood basalt province over 100km west of its previously documented occurrence in the Amphitheatre Mountains, and may have significant economic importance.

Seventeen, remote-reference, broadband MT soundings were acquired with an EMI MT24 system using a station spacing of approximately 5 km and line spacing of 15 km. Both lines are centred over the Amphitheatre Synform. The data from the HEM survey was used to assess and correct MT static shifts. A prominent conductivity anomaly was clearly observable in the apparent resistivity data on each line. Two-dimensional (2D) inversion was used to model the geometry of the synform, electrical properties related to possible mineralization in the top few kilometres, and validate the presences of a feeder root to the magmatic system indicated by the potential fields and geological models. The synform plunges to the west where its most conductive feature (< 10 ohm-m), lies at a depth of roughly 1.5km on the eastern line.

Sensitivity analyses were performed to aid in evaluating the accuracy of the interpretation. Two-dimensional models were computed from several different algorithms including the rapid-relaxation inversion, the conjugate-gradient method, and Occam's inversion using different combinations of the apparent resistivity and impedance phase for the transverse electric (TE) and magnetic (TM) modes, with and without static shift corrections and topography. Fits were much better for the TM mode, but the significant features were present in most all the models. Three-dimensional forward models were constructed from the 2D, MT models, and other geophysical and geological information, to understand the non-2D responses, and further refine the final model.

7:

GILD EM Modeling In Nano-Geophysics and Nano-Materials Using Magnetic Field Integral Equation

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In this paper, we present a Global Integral and Local Differential Equation (GILD) method for the magnetic field propagation in the nanometer material. A new 3D boundary integral-differential equation for the magnetic field is presented. We proved the equivalence between the new magnetic integral equation and Galerkin equation for the magnetic field. Our magnetic integral equation can be used for the electromagnetic field in the super conductive media. .
Synthetic model simulations show that our GILD magnetic filed modeling method in the nanometer material is accurate and fast. Our GILD magnetic field modeling are very useful for, electromagnetic engineering, geophysics and material sciences, in particular, for investigating the physical and chemical properties and production in the micro and nanometer materials. When super high frequency electromagnetic field (Gamma ray) propagate and interactive with nanometer materials, we observe that there are GILD electromagnetic numerical quanta in the electromagnetic scattering radiation field.

Key Words: GILD EM modeling and inversion, nanometer materials, GL EM modeling and inversion, Electromagnetic Numerical Quanta, Nano-Geophysics

8:

Examples and Issues for AEM 3D Conductivity Mapping in Land Management Applications

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In a land management context, conductivity can be related to quantities such as salt store, ground water salinity, clay content, hydraulic permeability, degree of groundwater saturation, or more generally to definition of regolith and bedrock units. These relationships open the way for the use of electromagnetic methods to measure subsurface conductivity. Increasing concern over the potential for dryland salinisation together with technological improvement has seen the amount of AEM data acquired for this application increase over the past two decades in Australia. Sporadic small-scale trials were carried out in the 1980's. Surveys covering larger areas form part of coordinated land management investigation programs in the new millenium.

From the very early trials, efforts have always been made to transform the measurements to conductivity. One factor behind this is that the relative degree to which the 1D approximation is satisfied compared to the case of discrete conductors in base metal mineral exploration applications. Equally important has been the realisation that conductivity forms the bridge that links geophysicists with others working in this application.

The real-world presents a myriad of difficulties, that translate into errors and artifacts in 2D (para-)sections or 3D (para-)volumes produced from individual 1D conductivity transformation solutions. There are many different acquisition systems, each with different geometry, transmitter waveforms, receiver characteristics and noise levels. Spatial and spectral elements of the data processing sequence are rarely defined or incorporated in subsequent processing or interpretation. The range and diversity of acquisition systems is matched by the available conductivity routines. At this time, all of the practical methods for transformation to conductivity include a 1D assumption. The vertical portrayal of conductivity variations can be quite different for different methods, leading to doubts over the underlying certainty in any specific prediction.

Reconciliation of AEM conductivity predictions with other spatial information presents a deceptively difficult challenge. Whether the comparison is done for purposes of quality control, integration or as a prelude to the definition of inversion constraints, knowledge of the underlying spatial variability of conductivity is required. Core samples, conductivity logs and AEM measurements sample vastly different volumes (~10^{-4} m^3, ~1 m^3, and ~10^5 m^3, respectively). Geostatistical methods provide a means to quantify the spatial variability (through semi-variograms) and to combine or compare samples with different volumes (through scaling laws and co-kriging).

And what of the future? Better knowledge of acquisition system parameters, documentation of processing sequences and knowledge of noise levels will be utilised in conductivity transformations. Greater awareness of the need for explicit constraints will fuel increasing usage of constrained inversions. Conductivity predictions will be accompanied by a realistic estimate of the uncertainty in the predictions. 2D and 3D approximate transformations will surely arrive in some force. More accurate portrayal of conductivity in 3D will lead to a greater degree of integration with other spatial information and more effective use of AEM information in land management investigations and planning.

9:

3-D electromagnetic modeling and inversion incorporating topography

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The electromagnetic (EM) responses of 3-D earth topography are simulated using a staggered-grid finite-difference algorithm. The modelling examples include frequency-domain responses for magnetotelluric(MT), controlled-source MT, airborne EM, and ground EM methods. The linear system of equations resulting from the finite-differencing is solved using the imcomplete Cholesky biconjugate gradient (ICBCG) method. Despite the difficulty associated with the high resistivity contrast between the air and the earth, good convergence rates are achieved by alternating ICBCG iterations with the static divergence correction procedure. The accuracy of the solution for MT response is verified by comparison with 2-D finite-element solution. The solutions for airborne and ground EM responses are checked against the analytic response of an inclined surface. The extention of modeling to inversion is straightforward. As an example of 3-D inversion incorporating topography,3-D inversion of an airborne EM data set that simulates the land-slide investigation is presented.

10:

3D EM modeling of a new Magnetometric Resistivity System

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We are completing work at the University of Wisconsin - Madison via full three-dimensional electro-magnetic (EM) modeling to verify the applicability of a direct current (DC) forward modeling solution to an experimental ERT/MMR system. The EM responses are being compared to solutions from an existing steady state approximation. Comparison of the EM solution to the static solution defines the range of environments where the zero frequency solution is applicable.

In general, the character of the responses from both codes are similar, however the EM responses are nearly always larger in magnitude than the DC solutions. The results of the EM code confirmed some observations documented previously based on the DC algorithm for the same target. No notable induction effects have been observed even with the addition of a magnetic permeable target.

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11:

Airborne electromagnetic measurements of Antarctic sea ice thickness: a three-dimensional model study

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The Antarctic sea ice thickness distribution is an important parameter in models of global climate, and is at present poorly understood. A large proportion of the total volume of Antarctic sea ice is thought to be contained within three-dimensional structures such as pressure ridges. Pressure ridges formed in Antarctic sea ice are generally smaller than those in the Arctic, and electromagnetic (EM) systems suitable for Antarctic sea ice mapping must be sensitive to relatively small variations in thickness. Rapid estimation of sea ice thickness at pressure ridges remains a significant problem in EM data interpretation.

Three-dimensional EM modelling code (Marco_air and Loki_air) has been used to simulate the response of geophysical low-frequency EM systems to simplified Antarctic sea ice pressure ridges. The model data have been used to assess the potential utility of airborne electromagnetic (AEM) methods for mapping the small sea ice thicknesses typical of Antarctic conditions. Responses have been modelled for a single-frequency ship-borne system, a new two-frequency helicopter-borne system developed specifically for sea ice thickness measurements, and a five-frequency helicopter-borne system typical of those employed for mineral exploration.

The small width and depth extent of the sea ice pressure ridge models, and the relatively low flight height of EM systems employed for sea ice thickness measurements, have required that careful attention be paid to model discretisation. For a ship-borne electromagnetic system flown at an altitude of 3 m, model cells as small as 1 m × 1m × 0.5 m in size must be used in order that the computed responses converge and that reciprocity is satisfied.

A major focus of this study has been to compare the spatial resolution of the surface and airborne EM systems, by computing the responses of multiple, closely-spaced, pressure ridges. The model results clearly demonstrate the superior resolution of the airborne vertical coaxial coil geometry in comparison with the horizontal coplanar configuration. However, for AEM systems with small transmitter-receiver separations, the vertical coaxial electromagnetic anomalies due to typical Antarctic pressure ridges would be too small to detect in practical surveys. Sea ice thicknesses determined by one-dimensional

inversion of pressure ridge model data typically underestimate the actual maximum ridge thickness by around 50%. This highlights the need for rapid two- or three-dimensional interpretation tools for sea ice thickness mapping.

12:

Stable 3-D inversion of MT data and its application for geothermal exploration

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A stable three-dimensional (3-D) magnetotelluric (MT) inversion technique has been developed and applied to MT data obtained in geothermal fields in Japan. The inversion method is based on the Gauss-Newton (linearized least-squares) method with smoothness regularization (Sasaki, 2001). The forward modeling is by the staggered-grid finite difference method. Data fitting was performed for the off-diagonal components of the MT impedance. Static shifts can be treated as unknown parameters in the inversion. A Bayesian criterion ABIC was applied to search the optimum trade-off among the minimization of the data misfit, model roughness and static shifts, by assuming Gaussian distribution in these quantities. 3-D inversion was first performed to a synthetic dataset and then applied to a few datasets obtained in geothermal fields in Japan. The inversion was performed stably to achieve a good fitting between observed and computed apparent resistivity and phase. The 3-D models are compared with 2-D inversion results and with the existing geological models and logging data in the geothermal fields.

13:

Magnetometric Resistivity-Electrical Resistivity Tomography Field results and inversion ground truth

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Electrical Resistivity Tomography (ERT), which has seen increasingly wide use for environmental monitoring uses the measurement of electrical potentials induced by a low-frequency electric current source. Magnetometric resistivity, measures the magnetic fields produced by the same type of low-frequency electric current source used for ERT. Combining these two methods and thus the two types of data provides an opportunity for producing improved subsurface images in a wider range of environments.

This paper presents the results of field data and the comparison with developed forward and inversion results. The Idaho National Engineering and Environmental Laboratory (INEEL) developed and is testing a new system for environmental applications of Magnetometric Resistivity (MMR) combined with Electrical Resistance Tomography (ERT). The data collection system uses an ERT system to transmit current and lock-in amplifiers to measure the resulting B fields (Bernd Kulessa et al.). Field Data is being collected at The INEEL Mud Lake Test Site and will be used to verify the applicability of the MMR-ERT system to see targets and as well as fluid movement thought the subsurface. Field data of known layouts, targets, and target orientation are being used to test the responses produced by the steady state, direct current (DC) MMR approximation inversion routines (LaBrecque and Ward, 1987, LaBrecque, et. al., 2003).

INEEL scientists developed MMR instrumentation to spatially resolve the surface magnetic field associated with an induced subsurface alternating current low between borehole ERT electrode pairs. The instrumentation consists of a variable frequency alternating current source and a synchronously detected, spatially resolved vector B-field measurement system. Comparison of the results of numerical codes against a comprehensive set of field measurements at the Mud Lake, Idaho sediment beds allow for instrumentation and code enhancement as well as initial interpretations of MMR-ERT results in terms of subsurface structures

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14:

Status of the Rayleigh Scattering Approach in Three-Dimensional Electromagnetic Modeling

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The Rayleigh scattering method offers distinct advantages over differencing or integral formulations but an inherent error in the Rayleigh hypothesis has severely limited its wider application. The method can be numerically implemented to be very fast and subsurface and topographic geometries can be described simply by digitized surface and interface values. This contrasts with gridding throughout a volume as used in finite difference and finite element methods. However, the error in the Rayleigh method prevents the modeling of steep topography and very high subsurface slopes such as the vertical sides of prismatic bodies.

The inherent Rayleigh error, or famous Rayleigh ansatz (approximation), exists because the formulation assumes that scattering above a rough surface is described by a superposition of upward-scattered plane waves or plane wavelets only. This does not allow multiple scattering with downward components that should occur in topographic depressions. Manifestations of this error are non-convergence behavior, numerical instabilities, and incorrect results.

Valid results are obtained for plane wave EM sources normally incidence on *buried* 2-D and 3-D structures having interface slopes as high as 50-60^o. In the air, above the topography, the surface slope limit can be extended to over 74^o by adapted-regularization.

In the near-field, on 2-D topography, surface slopes of only 26^o are properly modeled for the TM (transverse magnetic) mode. Since the physics of 3-D scattering can be dominated by TM-like (galvanic) effects, 3-D topography is probably limited to slopes of about this value unless regularization schemes are used. Regularization and close attention paid to stable computation codes are considered the keys to extending the Rayleigh method to general 3-D EM modeling.

New ways of extending the validity of the Rayleigh scattering method justify more interest in the geophysical EM community especially for 3-D surface and airborne modeling.

15:

Two-dimensional Magnetotelluric Responses of Three-dimensional Bodies

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The magnetotelluric (MT) tensor has significantly different forms depending on whether the subsurface is one-dimensional, two-dimensional or three-dimensional. In subsurface geologies that are not one-dimensional, two-dimensionality is often assumed, as inversion routines for two-dimensional earths are much simpler and more readily available than those for three-dimensional earths. In two dimensions, the MT tensor splits into two independent modes, the transverse electric (TE) mode and the transverse magnetic (TM) mode, and often during commercial operations only one of these modes is collected. Field data were collected with the Mount Isa Mines Data Acquisition System (MIMDAS) in the Kalkaroo region of the Curnamona Province in South Australia. The target for the survey was an elongate magnetic anomaly of a type that would be approximated to be two-dimensional but has a finite strike length and is therefore a three-dimensional body. With this in mind, the applicability of interpreting data defined as TE and TM are assessed and the advantages and disadvantages of each mode are determined. These are then compared with the advantages gained by collecting both modes, which allows for joint inversion using an invariant, determination of the accuracy of the assumption of two-dimensionality using Mohr circles, detection of galvanic distortion also using Mohr circles, and determination of the direction of strike of the local and regional geology using Lilley angles. To further optimise the interpretation of MT data, the processing codes of Chave (Robust Remote Reference MT), Egbert and MIM were compared as were the non-linear conjugate gradients (NLCG) modelling routine of Mackie and the Occam modelling routine of de-Groot Hedlin and Constable.

Each of the processing codes gave very similar results, as did the modelling codes although Occam produced smoother models in less iterations than NLCG. We show that the TM mode accurately delineates boundaries and that since boundary charges are included in the inversion formulation, it also provides accurate values of resistivity. The TE mode provides poor boundary delineation and underestimates the resistivity of this

three-dimensional body since boundary charges are not included in the inversion formulation. The TM mode is also more accurate than joint inversions however the determination of dimensionality, strike and detection of galvanic distortion mean that collection of both data modes is still preferable.

16:

Three-dimensional magnetotelluric modeling of the Serra da cangalha impact crater, northeastern Brazil

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The result of a three-dimensional forward modeling of a magnetotelluric (MT) survey carried out in the region of the Serra da Cangalha impact crater located in northeastern region of Parnaiba basin Brazil is presented. The 13 km impact structure has been investigated because of its explicitly three-dimensional shape. Within the framework of an integrated geophysical study of the Serra da Cangalha impact crater in Brazil, we recorded MT data in a broad frequency range between 0.001s and 1095s at 25 sites. The sites are aligned across the crater structure along three radial profiles (NE – SW, NW –SE and ENE – WSW) with a site spacing of 1 km and 2 km, respectively. The spacing of the sites provides a good spatial coverage to study the regional resistivity structure across the crater in detail. The MT results at some sites are strongly affected by 3D effects (we observe high skews, phases and Groom-Bailey distortion parameters). Therefore, the 3D finite-difference forward modeling algorithm of Mackie and Booker (1999) has been applied to acquire information about subsurface structure of the impact crater and to explain the observed data. The central part of the model covers an area of approximately 13 x 13 Km and involves the main outcropping geological features. The model of the study area, constructed using a 3-D mesh of 22 x 19 x 25 (29325 cells) was based both on the a *priori* information of the geology of the region and results of the 2D magnetotelluric inversion. Nine frequencies were calculated for the 3-D model (0.001, 0.03, 0.01, 0.03, 0.1, 0.3, 1, 3, 10 Hz). The 3-D body, with a homogeneous resistivity of 300 Ωm, is a rough approximation of a truncated cone that cropped out at the model surface and reached a maximum depth of 1.2 Km. The resistivity structure obtained indicate an uplifted basement at the center of the crater. The observed 3D effects are explained as a shallow resistive ring structure embedded in a conductive medium. The modeling studies suggest that the base of the uplifted structure continue down to 1.2 km. The three-dimensional model results indicate that a valuable picture of the regional electrical resistivity can be obtained from 3-D interpretation of the determinant impedance tensors using polar diagrams. A local 3-D body embedded in a regional and large scaled layered earth represents the final model. The results emphasize the feasibility of 3D forward modeling in impact crater studies.

Key words: Impact crater, Resistivity structure, 3D forward modelling, 3D finite-difference algorithm, Uplifted basement.

17:

Magnetotelluric and Flow Modelling and Joint Inversion for Geophysical Exploration

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In this paper, we presented a magnetotelluric and flow modeling and joint inversion for geophysical exploration using the GILD modeling and inversion. We formulate two and half GILD electromagnetic modeling and inversion. Also, we formulate the Dacy flow modeling and inversion. Then we developed MT flow joint inversion . The synthetic data tests show that our modeling and joint inversion are high resolution. We use our method to interpret our real data from Taiwan Earth exploration.

18:

Electromagnetic Model for S. Miguel Island-Azores

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This work presents a 3D geoelectric model around the Sete Cidades Volcano in S. Miguel Island, the largest in the Azores. S. Miguel is a young (<4 My) volcanic island with three volcanoes running along its main axis. This is an active volcano, with a circular caldera displaying pumice cones, maars and domes. The Terceira Rift cuts the caldera NW-SE controlling the location of several scoria cones.

Eleven long period MT sites (T>1 s) were distributed inside and outside the caldera, a couple of kilometers apart from each other. Most of the data was collected single reference but some was remote referenced. The data display a strong influence from both the ocean and topography. The model indicates an increasing resistivity regime with depth throughout but for the indication of an enhanced conductivity layer towards the end of the period range.

19:

Mapping 3D salt with 2D marine MT - Case study from Gemini Prospect, Gulf of Mexico

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Scripps Institution of Oceanography has developed instrumentation and data processing techniques to routinely collect broadband magnetotelluric (MT) data on the continental shelves, allowing the subsurface electrical resistivity to be mapped to depths of tens of kilometers. Over the past 7 years, the Gemini sub-salt petroleum prospect in the Gulf of Mexico has served both as a test bed for developing our sea-floor magnetotelluric instrument system and also as a case study for the use of marine MT methods to map base of salt. The Gemini salt body lies 2-5 km below the sea-floor in 1 km deep water and has a high electrical resistivity compared with the surrounding sediments, making it a suitable target for electrical methods. We have collected 34 sites of MT data in the period band 1-3000 seconds in a two- dimensional (2D) grid over the Gemini salt body, making our data set an excellent test bed for 2D and three-dimensional (3D) modeling techniques.

We present 2D inversion models obtained from inverting the entire set of Gemini MT data, along with a comparison to the Gemini salt volume boundaries obtained from high resolution 3D seismic data. While 2D inversion models recover the salt boundaries remarkably well despite the complex 3D shape of the Gemini salt body, the results are heavily dependent on choosing the "correct" mode of data to invert. For instance, 2D inversion of TE mode data along a transect striking at 315 degrees across Gemini produces a model that agrees well with the seismic salt volume data, while inversion of the TM mode data produces a model with no structural similarity at all. 2D inversion of transects along 45 degree strikes exhibit similar behavior, but with the TM mode being the preferred mode to invert. Synthetic 2D inversions of the 3D MT forward response of the salt volume validate the observed mode sensitivities and illustrate how the response from 3D structures affect 2D inversions. A 3D movie of all the 2D models allows for comparison of the structural agreement between the independent inversion models. (http://mahi.ucsd.edu/SEMC/gemini2Dmovie.html)

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20:

DEVELOPMENT OF PRACTICAL 2-D INDUCTION LOG INVERSION

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Traditional log interpretation treats the "raw" induction and other logs at each depth level as independent of each other. However, a logging tool typically responds to a formation volume larger than the sampling interval. Therefore, the logs are often severely influenced by the shoulder beds and invasion zone and the log values may differ significantly from the true formation properties. Conventional chart-book type of correction methods assume that various effects are additive and the corrections can be done in a series of 1-D models, which may not be valid. Various inversion methods have also been investigated or developed by many authors. However, routine application of the methods is rare, mostly because of the significant computational time required and the non-uniqueness in solution.

This work intends to correct the environmental effects on induction logs through inversion before the logs are used in the water saturation calculation. To simultaneously correct for shoulder and invasion effects and to fully account for the non-linearity in the response function, a 2-D inversion code is developed. The software is based on the familiar Marquardt method. However, we also introduced a number of efficiency enhancements to improve the calculation speed and to stabilize the solution. In particular, we have a hybrid calculation of the Jacobian matrix. We also tried to separate the bed boundary determination from the inversion algorithm to minimize the number of unknown.

Several invasion profiles are considered in the numerical experiments, covering conductive invasion, resistive invasion, and low resistivity annulus invasion profiles. We found that inversion can provide the means to correct simultaneously the undesirable effects on resistivity logs, which enables more accurate hydrocarbon reserve evaluation. The prototype software demonstrates the feasibility and usefulness of 2-D inversion processing. With the refinement in algorithm and continuing improvement in computer speed, we foresee that inversion will be part of routine log processing.

21:

3-D Electromagnetic Modeling for Wireline and MWD Logging Development

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Numerous efforts have been devoted to development of three-dimensional (3-D) electromagnetic modeling algorithms during the past few decades. However, real application of 3-D simulation algorithms has been uncommon. This situation is being changed within Baker Hughes Corporation where 3-D modeling techniques are increasingly accepted as an integral part of the well logging business for both tool design and data interpretation. In this paper, we shall discuss our latest 3-D modeling development and demonstrate its applications with two examples.

Our first example is concerned with the design of a measurement-while-drilling (MWD) logging instrument. A fundamentally important part of an MWD resistivity logging tool is the antenna system that transmits and receives electromagnetic energy into and from the surrounding medium, respectively. To survive in a hostile drilling environment, the antenna system usually has quite a complex structure. The wire is buried beneath the metal surface and electromagnetic energy is transmitted and received through long and narrow slots cut axially on the tool surface. To model the radiation pattern of the antennas, the thick metallic tool body (drill collar) must be taken into account. Moreover, ferritic materials are often placed in the slots to enhance the performance of the antennas that have also to be modeled. Previously, the design of such antenna systems has been based heavily on empirical experiments.

We have developed a finite-difference algorithm to model the MWD antenna system. This newly developed algorithm differs from many other finite-difference algorithms for geophysics in that it uses a cylindrical coordinate system. The cylindrical coordinates allow the tool body and the slots to be accurately modeled. The Lanczos decomposition method is employed to solve the linear equation system so that multiple frequencies can be calculated simultaneously. To accurately model the ferritic materials that have a large magnetic permeability contrast with the surrounding medium, a material averaging method is carefully designed. Simulation examples will be given to show the use of the modeling technique in the design of a 9.5-in MWD tool.

In the second example, we discuss the interpretation of multicomponent induction measurements in a 3-D earth environment. The multicomponent induction tool was designed to resolve the anisotropy property of the earth formation. The anisotropy can derive from microscopic alignment of particles or macroscopic structures such as fractures. The 3-D finite-difference algorithm we developed is capable of simulating tri-axial induction responses for an arbitrarily inhomogeneous, anisotropic medium. In this paper, we shall focus on the interpretation of multicomponent induction logs for drilling-induced fractures. Two basic questions are to be addressed regarding a drilling-induced fracture: its strike and its depth of penetration. The depth of penetration greatly influences the borehole stability and drilling mud loss. Using a Gulf of Mexico data set, we illustrate how we jointly use acoustic and induction logging data to interpret for fracture parameters. The acoustic data are used to determine the fracture strike while the induction data are used to estimate the depth of penetration. For the latter purpose, we apply the 3-D modeling algorithm to simulate the tool response for various fracture depths. An inversion method is then applied to obtain the fracture depth.

22:

Modelling EM Dipole-Dipole Drill-Hole Data with the Loki Edge-Finite-Element Program

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Electromagnetic drill-hole measurements are an important tool for locating conductive orebodies in detailed exploration scale. Dipole-dipole systems have good spatial resolution, especially if all three magnetic components are measured over a wide frequency range. Interpretation of field data requires the use of sound 3D modeling tools capable of dealing with high conductivity contrasts and the close proximity of boundaries to the source or receiver.

We modelled the response of the SlimBoris dipole-dipole drill hole system going through a block target using Loki, a 3D, full-domain, edge finite-element approach based on vector shape functions and scalar unknowns. This method achieves considerable speed advantage over conventional finite-element methods since only the one tangential component rather than three orthogonal components need be solved at each “node”. Moreover, since no boundary conditions are violated in this approach, contrasts in excess of one million to one can be modelled accurately as verified through semi-analytical layered earth solutions. Computation time can be reduced by a further factor of five by solving initially for Schelkunoff potentials rather than electric or magnetic fields. This is due to the superior condition number of the resulting matrices. Accuracy is maintained using Green’s function projectors to obtain the fields at the receivers rather than differentiating the potentials. A 30,000 cell model takes 20 seconds on a 1.9GHz Intel chip per frequency per transmitter position. Control files for complex models can be set up rapidly using either the Encom EMGUI or Maxwell from EMIT.

The results were in close agreement with scale model results at all contrast ranges. Another check was made using a 3D integral equation program. As expected, close agreement was obtained at contrasts of less than 300 but the integral equation results deteriorated at high contrast.

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23:

Three-dimensional magnetotelluric modeling of the central portion of Parana Basin

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A geoelectric model is proposed for the central part of Parana Basin. A major part of that intracratonic basin has one of the most voluminous flood basalt inshore complex up to 2 km thick, covering an area of some 800,000 km^2. The basalt overlies a series of Paleozoic sediments including hydrocarbon source rocks. This paper presents a three-dimensional geolectric model for the central portion of the basin, based on a data set comprising 231 broadband MT sites with a frequency range spanning 0.001s to 600s, covering an area of 5x10^4 km^2. Sites were deployed along 9 profiles running SW-NE, and one NW-SE. Site spacing is compatible to a regional study. The obtained model reveals the sedimentary basin structure through its basement, reaching lower crustal depths at its SE end. In particular it has revealed a more complex structure for the Ponta Grossa Arch than previously thought. There is some indication of accretion of mantle material in the base of the crust. This is suggested by oscillations in crustal thickness and zoning of enhanced conductivity values. The results emphasize the feasibility of 3D forward modelling in practice.

24:

Three-Dimensional Inversion of Magnetotelluric Data in Complex Geological Structures

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Interpretation of magnetotelluric data over inhomogeneous geological structures is still a challenging problem in geophysical exploration. We have developed a rapid 3-D MT inversion method and a computer code based on full nonlinear conjugate gradient inversion and quasi-analytical (QA) approximation for forward modeling solution (Zhdanov and Hursan, 2000; Zhdanov, 2002). Application of the QA approximation in forward modeling and Frechet derivative computations speeds up the calculation dramatically. However, in order to control the accuracy of the inversion, our method allows application of the rigorous forward modeling in the intermediate steps of the inversion procedure and for the final inverse model. The main distinguishing feature of this algorithm is application of the special stabilizing functionals that allow construction of both smooth images of the underground geoelectrical structures and models with sharp geoelectrical boundaries. The 3-D magnetotelluric inversion code has been carefully tested on synthetic models and applied to the practical MT data collected in an area with complex geology. The rapid inversion of the array magnetotelluric data (observed with the hundreds of multi-frequencies observation stations) can be done within a few minutes on a PC to generate the full 3-D image of subsurface formations on a large grid with the tens of thousands cells. The new fast 3-D MT inversion technique has been applied to three-dimensional MT data collected by the INCO Exploration in Canada. The goal of this survey was to study the application of the MT method to typical Ni-Cu-Fe sulphide mineralization zone exploration in complex geological structures. The 3-D MT survey consists of several hundreds MT sites. The area of inversion was discretized in about fifty thousand cells. We demonstrate that for such complex geoelectrical models the 3-D inversion can provide a much more adequate interpretation of the array MT data than conventional 2-D inversion.

25:

Efficient 3-D Electromagnetic Modeling in the Presence of Anisotropic Conductive Media Using Integral Equations

Sheng Fang[#], *Guozhong Gao*[*], *Carlos Torres-Verdin*[*]

We present a novel technique to simulate numerically the measurements performed by a borehole induction-logging tool in 3D anisotropic rock formations. The simulations are based on an integral equation formulation. Previously, such a formulation was considered impractical for solving large-scale problems due to the resulting large full matrix. To overcome this difficulty, we assume a uniform background model and make use of a uniform grid whereupon there is no need to construct explicitly all of the entries of the full Green's function matrix.

Using a uniform background model, the entries of the corresponding electric and magnetic Green's tensors are relatively easy to calculate. In the presence of a uniform grid (not necessarily cubic), it is only necessary to calculate the first row of the resulting electric Green's function matrix. Further, because the matrix is block Toeplitz, it can be rewritten into a block circulant form, and therefore matrix-vector multiplication can be efficiently performed with two FFTs and one inverse FFT. This strategy reduces the computation cost from O(N*N) to O(N*$\log_2$N). In addition to the substantial computer savings, the FFT technique also substantially reduces memory storage requirements because only the first row and the first column in the block Toeplitz matrix are needed to perform the computations of the remaining entries of the matrix.

Numerical simulations of the measurements performed with an induction tool in dipping and anisotropic rock formations are benchmarked against accurate 3D finite-difference code and 1D code. These benchmark exercises show that the newly developed integral-equation algorithm produces accurate and efficient simulations for a variety of borehole and formation conditions.

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26:

Integral equation approach to modeling 3-D electromagnetic field. Examples of application to borehole problems

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We report development of a new code for modeling electromagnetic fields in complicated 3-D environments and provide examples of the code application to a number of typical borehole problems. The code is based on an integral equation for the scattered electromagnetic field presented in the form used by the Modified Iterative Dissipative Method (MIDM). Such integral equation possesses contraction properties that allow for the equation to be solved using an iterative-perturbation or conjugate gradient approach. The iterative sequence of approximations for the equation converges to the solution at any frequency and for an arbitrary earth model and sources of the electromagnetic field. The approach can also be applied to media with anisotropy of electrical properties with or without accounting for replacement currents.

The system of linear equations that represents a finite-dimensional counterpart of the continuous integral equation is derived using a projection definition of the system matrix. In this definition, the matrix is calculated by integrating the Green's function over the "source" and "receiver" cells of the numerical grid. The system of linear equations preserves contraction properties of the continuous equation and can be solved using the same technique. The condition number of the system matrix depends only on the physical properties of the model under consideration (e.g., lateral contrast of the conductivity distribution). It remains independent of the numerical grid used for numerical simulation. The approach provides estimates for the truncation and approximation errors caused by termination of the iterative process after a finite numberof iterations as well as by finite size of the numerical grid.

The 3-D codes based on the above principles have been applied to a number of problemsof subsurface and borehole geophysics. The applications include such problems asglobal electromagnetic induction, regional and local magnetotelluric and magneto-variational soundings with natural and controlled sources, through-casing resistivity measurements, etc. In this presentation, we compare our results with independent results obtained for models allowing for a quasi-analytical solution. The independent results were obtained using finite-difference and other integral equation approaches. The robustness of the algorithm is demonstrated by running the same model with different numerical grids.

Models used for the code demonstration include a vertical borehole in a stratified formation excited by co-axial induction and co-planar tools. We also consider tilted boreholes and decentralized tools.

27:

3D Inversion of magnetic induced polarization data

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Magnetic induced polarization (MIP) is an exploration technique used to derive information about the induced polarization characteristics of the subsurface through measurements of the magnetic field associated with steady-state current flow in the earth. The intimate relationship between MIP and magnetometric resistivity (MMR) is analogous to the relationship between electrical induced polarization (EIP) and DC measurements. That is, the MIP makes use of observations of the secondary magnetic field associated with the polarization current, whereas the MMR makes use of the magnetic field due to the ohmic current. Following the expression, derived by Seigel (1974), the polarization magnetic field can be obtained as follows

$$H_s = -\sum_i \eta_i \frac{\partial H}{\partial \log \sigma_i} \quad , \qquad (1)$$

where H is the magnetic field component due to the ohmic current flow, s_i and $?_i$ are the conductivity and chargeability of the i^{th} domain having non-zero IP characteristic. The magnetic field H and its derivative with respect to logarithmic conductivity (or sensitivity) can be computed by subsequently solving a Poisson's equation and a magnetostatic problem in terms of potential using a finite-volume algorithm (Chen et al., 2002). The apparent chargeability, obtained by normalizing Hs with the magnetic field, can be thus explicitly expressed as

$$\eta_a = \mathbf{H}^{-1}\mathbf{Q}\mathbf{A}^{-1}\mathbf{G}\eta \quad , \qquad (2)$$

where H^{-1} denotes a diagonal matrix with elements being the reciprocal of the magnetic field, Q is a projection matrix which extracts the magnetic field from the EM potentials, A^{-1} is the inverse of the discrete coefficient matrix for solving for the potentials, G is a matrix and ? is a vector of the chargeability at each cell. Similar expressions can be derived for percent frequency effect (PFE) and relative phase shift (RPS) for MIP survey in the frequency-domain. Equation 2 shows that the data $?_a$ are linearly related to the intrinsic chargeability ?. The intrinsic chargeability can be recovered by solving a linear inverse problem. We formulate this as an unconstrained optimization. We use a Gauss-Newton method to obtain the model perturbation at each iteration and the system of equations is solved using conjugate gradients.

Inverting MIP data for a single source is rather like involving with gravity data; there is no depth resolution. Geologically meaningful results therefore require that a depth weighting be included in the inversion to counteract the 1=r2 decay of the kernels.

The inversion algorithm was applied to a set of field MIP data collected at Binduli, Australia. There are 275 stations with one Tx array. After 15 iterations, the recovered 3D chargeability model clearly shows that there exists an elongated polarizable body at depth of 80 m, which is still waiting for confirmation from involved geologists.

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28:

The modelling of AEM anomalies with dipoles in a layered earth

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An automated algorithm is described that selects and models spatially discrete anomalies in airborne EM (AEM) data sets. For anomalies to be selected they have to be wide enough to have their origin in the subsurface and narrow enough to be caused by a discrete conductor. After determining background conductivity models with layered-earth inversions from the EM data, identified EM anomalies are modelled with magnetic and electric dipoles buried inside a layered earth. Magnetic dipoles are appropriate models for discrete, sheet-like conductors inside a resistive host, i.e. in scenarios where vortex currents dominate, whereas electric dipoles are expected to model well elongated structures excited by current channelling. The model parameters determined from each data segment include for magnetic dipole solutions: the target conductor position, depth, dip, size and conductance, and for electric dipoles: the position and depth.

Recent advances in modelling AEM data with magnetic and electric dipoles inside a layered earth include the formulation of the approximate EM response in the frequency-domain and the use of fast Hankel transform techniques. The former improved code flexibility allowing the modelling of any frequency-domain and transient EM data. The latter increased the program speed with AEM anomalies now being inverted within 30 seconds.

Results from modelling synthetic AEM data indicate the efficiency and reliability of the method. Modelled field data include Geotem data acquired across the Harmony nickel-sulphide deposit in W.A. and Tempest data acquired across the Bull Creek magnetite-pyrrhotite deposit in Queensland. These results show that the algorithm provides a sensible description of both mineralisations. Other modelled anomalies are interpreted as being caused by shallow structures channelling current, discrete conductors beneath the overburden and regolith structures.

29:

Mapping current flow in 3D Airborne EM Models

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Electromagnetic surveying proceeds by inducing currents to flow in subsurface conductors, hence interpreting EM data is equivalent to interpreting current flow within the earth. Most EM interpretation is concerned with interpreting the fields produced by these currents.

We compare data for DIGHEM-like and 25 Hz GEOTEM-like systems. In order to validate both the visualisation and the software, we examined current flow in two simple models. In a thick conductive (1 Ω-m) plate hosted in a resistive (1000 Ω-m) half space, we show vortex currents flowing in the target. In the second model, a quarter space (100: 1 1 Ω-m, West: East), we show smoke rings propagating in one quarter space before being slowed at the boundary between the two spaces.

Next, we examined current flow in two more realistic models. The first of these was the Harmony NiS deposit in WA. The synthetic second model incorporated moderate-relief topography and consisted of a shallow dipping target buried beneath a paleochannel and thick conductive cover and lying adjacent to a dipping fault. For both these models, we can directly attribute features in EM profiles to current flow in particular areas of the model.

Our results show that because of its valuable insights into the physics of EM induction, mapping current flow in 3D models is a particularly useful aid both in planning surveys and modelling data.

30:

3D Finite Difference Time Domain Modeling of Electromagnetic Fields

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The Finite Difference Time Domain modeling technique provides much needed insight about the response of transient electromagnetic fields in complicated conductivity structures. The FDTD method, introduced by Yee in 1966, has remained the subject of continuous development. There are several reasons for the expansion of interest in FDTD solution approaches for Maxwell's curl equations.
Being a fully explicit computation, FDTD avoids difficulties with linear algebra that limit the size of conductivity models to generally fewer than 106 electromagnetic field unknowns. Moreover, the sources of error in FDTD calculations are well understood. While the trend of rapidly increasing computer capacities positively influences all numerical techniques, it is of particular advantage to FDTD methods which are founded on discretizing space over a volume, and therefore inherently require large memory.

We have developed a solution for 3D problems, which is based on a time-stepping of the system of Maxwell equations using a staggered-grid approach. By introducing a transformation of the spatial and temporal variables, a regular grid is obtained which reduces the need for many enlarged conductivity blocks near the boundaries of the modeling domain. This is of particular interest, since the inhomogeneous boundary condition at the air-earth interface requires an upward continuation of the magnetic field which is performed by a two-dimensional Fourier transform. The regular grid avoids numerical inaccuracies which would occur by interpolating the fields at the non-transformed model surface. In contrast, interpolation is computed in the wavenumber domain by zero-padding and proper windowing the spectra, thus preserving the spatial frequency content of electromagnetic fields.

31:

Layered 2-D Inversion of Profile Oriented Data

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We present a layered 2D inversion scheme for profile oriented data based on an algorithm developed for 1D data (Christiansen et al., 2002). The inversion procedure is unchanged but the 1D forward routine is replaced by a 2D routine. In principle, any data set with an available 2D forward code can be inverted using this principle, but so far DCresistivity is the only 2D code implemented and tested in the program. In the near future, we plan to include both a 2D MT response as well as an approximative 2D TEM response.

Most 2D inversion programs operate with an ill-conditioned problem, and a substantial regularisation is needed to constrain the inversion scheme, which results in smooth earth models (minimum structure models). Theese are often hard to interpret in a geological or hydrogeological sense, as formation boundaries are not easily recognised. Furthermore, a full sensitivity analysis of the model parameters is normally not obtained. The analysis on the parameters is especially important in a groundwater investigation and comes as an integrated part of this layered 2D inversion scheme.

The model parameters are layer resistivities and thicknesses discretised at a number of nodes along the profile. The parameters are tied together laterally by introducing a mutual covariance between them, forcing the algorithm to use variations in the geology to minimize the model variance. This means that information from models with a small variance migrates through the lateral bands to models with higher variance. Each model or sounding in the 1D inverse case is equivalent to one node in the full 2D model and may include any a priori information on the model parameters. The a priori information also migrates through the lateral bands to the adjacent nodes. The output is a laterally smooth 2D layered earth model including a full analysis on the model parameters.

The regularised inversion is an iterative, damped, least-square routine as described by e.g. Johansen (1979). The data misfit is minimized in combination with the length of the parameter vector and the lateral constraints. This approach is in principal similar to the sharp boundary approach presented by Smith et al. (1999) for MT data. Preliminary results for the resistivity case on both synthetic data and field data show that a layered 2D approach enables a detailed description of layered 2D structures not possible with a 1D or a 2D minimum structure formulation. The model complexity is controlled and balanced by the lateral constraints on depths and resistivities.

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32:

A New Approximation for 3D Electromagnetic Scattering in the Presence of Anisotropic Conductive Media

Guozhong Gao, Sheng Fang#, Carlos Torres-Verdin**

Accurate and efficient modeling of three-dimensional (3D) electromagnetic (EM) scattering remains an open challenge in the presence of anisotropic conductive media. Numerical algorithms used to simulate the response of dipping and anisotropic rock formations can easily exceed standard computer resources as EM fields become fully coupled in general.

In the past, several scattering approximations have been developed to efficiently simulate complex EM problems arising in the probing of subsurface rock formations. These approximations include Born, Rytov, Extended Born (ExBorn), and Quasi-Linear (QL), among others. However, so far none of these approximations has been adapted to simulate scattering in the presence of anisotropic conductive media. In this paper, we describe and benchmark a novel EM scattering approximation that remains accurate and efficient in the presence of 3D anisotropic conductive media. The approximation is based on the integral formulation of EM scattering and takes advantage of the spatial smoothness and general vectorial properties of EM fields internal to scatterers. A general vectorial formulation is used to properly account for complex EM coupling due to anisotropy.

Several numerical examples borrowed from borehole induction logging are used to describe and assess the accuracy and efficiency of the new EM scattering approximation. The approximation allows one to accurately simulate the EM response of more than 1 million cells within a few minutes of CPU time on a serial computer with standard memory and speed resources.

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33:

Improvements on 3D DC Resistivity Inversion

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In multi-dimensional inversion problems the number of free model parameters is usually higher than the number of data points. Furthermore, when data errors are considered, a lot of possible models exist, which agree with the data within a given error limit. Thus, such problems are generally ill-posed and have to be regularized in an appropriate way to obtain a confident and plausible result. The difficulties can be significantly reduced by the following ways:

Effective data sets Especially in 3d problems it is useful to think about effectively combining various measurements which give a maximum of information at a given cost. One has to find a trade-off between resolution and data quality.
Model parameterization The arrangement of model cells has to consider the resolving capabilities of the data set. This can be obtained by SVD analysis of the Jacobian matrix. The result is a reduction of cells without loss of information. Hence one has to distinct model discretization for inverse procedure and forward calculation.
Optimized Regularization The optimal choice of regularization method and strength is very important. The latter can be determined by regarding the L-curve of the varying regularization parameter ?. The solutions for many $?_i$ can be obtained simultaneously using fast CG-based algorithms.
Sensitivity calculation In nonlinear inversion the Jacobian (or sensitivity) matrix has to be computed in every iteration step. This can be accomplished by updating schemes like Broyden's method or by Finite Difference (FD) approximations of the sensitivity theorem. The decomposition into normal and anomalous potential in the forward operator can be exploited to derive an update formula, which is more accurate than FD approximations, since the anomalous potential is generally smaller and smoother than the normal potential.

The new approaches are applied to three-dimensional inversion of synthetic and field data sets. It can be seen, how the solution of the inverse problem is improved in a fast way.

34:

3DElectromagnetic Modeling in Frequency Domain - Studies of Underground Measurements in a Salt Mine

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Five geophysical methods (electromagnetics, ground penetrating radar, dc-geoelectrics, seismics and sonar) for locating areas like brine filled fissures or brine zones in a salt mine were applied (Kurz et al. 2001). The test field is in a salt mine gallery, in a depth of ca. 400 m. Dry rock salt with resistivity higher than 10^4 ? m is undetectable with electromagnetic methods and can be considered as an insulator. On the contrary the resistivity of brine (0.035 ? m) is very low and acts as a good conductor. This high resistivity contrast, which might be easily detected by electromagnetic methods, is in the focus of the measurements.

The EM-measurements were done in the frequency domain with an Apex MaxMin I+10 equipment in horizontal coplanar configuration (Max I Mode) with frequencies from 110 up to 14080 Hz. The Coil separations were 20 m and 40 m and the spacing between the measuring points were every 5 m or 10 m. The profile has an extension of 300 m (point -50 til 250 m). The gallery was 10 m wide and the height reaches from 2 m up to 5 m. At profil point 0 m there was a gallery crossing. At this place brine seeps into the tunnel.

Detail considerations are necessary, because commercial software for interpreting underground data is very sparse. Analytical solutions can be found for simple geometries, like layered earth models. But these are not able to interpret the data sufficiently; on the other hand basic approaches for approximations are possible. A concept to calculate apparent resistivity values from in-phase and out-of-phase components has been taken over from half space considerations (Kruk et al. 2000). But this approach is not regarding 3D structures. For a more accurate data interpretation a 3D finite difference modelling code was applied (Newman & Alumbaugh 1995). First studies are dealing with a full space model to examine the effects of salt rock above and beneath the coil system. The 3D code was validated and the results were compared with analytical solutions. In further considerations the whole gallery was considered. Gallery crossings were implemented and will be successively completed with brine scenarios to get a more realistic model.
This project is supported by the German Federal Ministry of Education and Research under Contract No. 02 C 0871.

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35:

Kernel Methods for approximating the solutions to EM inverse problems: how to find the thickness of a buried spherical shell.

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This paper introduces a method for approximating the solutions of EM inverse problems using a kernel algorithm. Kernel algorithms, the most well known of which is the Support Vector Machine, have come to prominence in the computer learning community in the last seven years. In this paper, I "teach" an algorithm to find the thickness of a metallic shell buried in a half-space. The algorithm is shown *n* examples of such shells, generated using a physically realistic forward modeling program, and uses the principal of Structural Risk Minimization to interpolate between them. If the thickness, *t*, of a shell were linearly related (it is not!) to a vector, *d*, of data representing the response of the shell to magnetic fields applied at different frequencies, then a vector of coefficients, *c*, could be found such that $t = c \cdot d$. To find *c*, we usually construct a matrix, *D*, where the data from each example occupies a row of the matrix. The solution depends on the product *D'D*. (For example, the least squares solution is $c = inv(D'D)D't$). The entries in the matrix *D'D* are averages of the values in each position in the data vectors, i.e. $D'D_{1,1} = \sum_n d_{1,n} d_{1,n}$. In order to use a kernel method, we need to solve a dual problem. We find a set of coefficients ω and α such that $t = w \cdot d$, $w = \sum_n a d_n$, and α depends on the product *DD'*. The entries in *DD'* are the dot products of the data vectors with each other, i.e., $(DD')_{n,m} = d_n \cdot d_m$. In order to introduce non-linearity into the relationship between *t* and *d*, we now employ a "kernel trick." We replace all of the dot products in the solution with a function called a kernel, which corresponds to a dot product in a higher dimensional Hilbert space. To see how this works, consider the dot products between two-dimensional vectors $X = [x_1, x_2]$ and $Y = [y_1, y_2]$. Replace the dot product $X \cdot Y = x_1 y_1 + x_2 y_2$ with the kernel $X \circ Y = (X \cdot Y)^2 = x_1^2 y_1^2 + 2 x_1 y_1 x_2 y_2 + x_2^2 y_2^2$. We notice that $X \circ Y = X^* \cdot Y^*$ where $X^* = [x_1^2, \sqrt{2} x_1 x_2, x_2^2]$ and $Y^* = [y_1^2, \sqrt{2} y_1 y_2, y_2^2]$. We have now allowed the various components of X and Y to interact with each other in a non-linear way. I will show how this idea can be adapted to approximate more complicated geophysical solutions.

36:

Three-dimensional DC resistivity forward modeling using finite elements in comparison with finite difference solutions

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A 3D finite element scheme for direct current resistivity modeling is presented. The singularity is removed by formulating the problem in terms of the secondary potential which improves accuracy considerably. The resulting system of linear equations is solved using the conjugate gradient method. The incomplete Cholesky preconditioner with a scaled matrix has been proved to be faster than the symmetric successive over-relaxation preconditioner. A compact storage scheme fully utilizes the sparsity and symmetry of the system matrix.

The finite element (FE) and a previously developed finite difference (FD) scheme are compared in detail. Generally, both schemes show good agreement, the relative error in apparent resistivity for a vertical dike model presented in this paper is overall less than 0:5 percent. The FD scheme produces larger errors near the conductivity contrast, whereas the FE scheme requires about 3:4 times as much storage as the FD scheme and is less robust with respect to coarse grids.

As an improvement to the forward modeling scheme, a modified singularity removal technique is presented. A horizontally layered earth or a vertical contact is regarded as the normal structure, whose solution is the primary potential. The effect of this technique is demonstrated by two examples: a cube in a two layered earth and a cube near a vertical contact.

37:

Finite element modeling of electromagnetic fields in three-dimensional anisotropic structures using scalar and vector potentials

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We have developed a finite element (FE) algorithm for electromagnetic induction modeling in three-dimensional (3D) anisotropic structures. The problem is formulated in terms of scalar and vector potentials. The Coulomb gauge condition is applied to ensure the uniqueness of the vector potentials. The resulting sparse system of linear equations is solved using a preconditioned conjugate gradient method.

The 3D FE algorithm is validated by comparison with finite difference solutions for 3D isotropic structures and a previously developed FE solution for 2D anisotropic structures. The algorithm is applied to model the conductivity distribution in the Southern Chilean Andes.

38:

Finite element resistivity modeling for three-dimensional structures with arbitrary anisotropy using secondary potentials

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A 3-D finite element algorithm for direct current resistivity modeling is presented, which can model inhomogeneous media with arbitrary anisotropy. The problem is formulated in terms of secondary potentials. Mixed boundary conditions are explicitly derived. Our method consumes about the same computation time as it would take to model isotropic structures. We have verified the finite element method using an anisotropic two-layered earth, its analytical solutions are available. Within the environment of the German Continental Deep Drilling Project (KTB) steeply dipping structures were encountered. These structures were covered by thin layers of graphite that are nearly impossible to model macroscopicly. Therefore, intrinsic anisotropy is the only feasible way to approach such problems. We show model studies that are related to such structures.

39:

The General Theory of Geoelectromagnetic Sounding Accounting the Electrodynamics of Spherical Sources

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The incompleteness and limitation of physical treatment of formation of the electromagnetic response inherent to the classical MT-theory, is almost obvious and is fixed even terminologically if to take into account the spherical of sources of MT-fields. As is known, that electrodynamics of the spherical sources differs from the usual electrodynamics, because, along side with an induction there are two such excitations as — dynamo, when the magnetic field is created by magnetic field, and by the generation of toroidal fields by spherical components of a current. The result of the general concept, theoretical bases (including the global and local approaches), functional ratio between spherical and flat models, methodical orientation of field experiment and data processing, modeling and inversion-requires reconsideration. Most significant theoretical result related with the affinor of input impedance and scalar conditions of impedance type or an arbitrary closed discontinuity are presented. We propose a new approach to the problem of processing data MT-methods that is based on the conception of the scalar conditions of impedance type that enables to simplify and unify an experiment. It is important that in that case the experiment is fully and uniformly conducted in terms of scalar input impedances and their horizontal gradient independently from the concept of impedance tensor, telluric and magnetic transient functions and vectors induction. The idea of unification of methods of magnetotelluric sounding (MTS), horizontal spatial gradient analysis (HSG) and deep geomagnetic sounding (GDS) is realized. The approach envisages an alternative strategy for practical implementation.

40:

Three-Dimensional Magnetotelluric Inversion: Data Space Method

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We have developed a 3-D inversion algorithm for the full magnetotelluric (MT) impedance tensor. Our approach is a data-space variant on the 2D MT OCCAM scheme, which minimizes a data misfit/model roughness objective function with a model-space search, using a full computation of the data sensitivities. The major problem with extending the model space approach to 3D is the CPU time and memory required to construct and invert model-space matrices. This problem can be overcome with a data-space approach, where matrix dimensions depend on the size of the data set, rather than the number of model parameters. Calculation of data sensitivities is still required for the data-space OCCAM approach, but these computations can be speed up significantly by using reciprocity, and by solving the required linear systems approximately using only a small number of iterations of QMR. In addition, with a data space approach, the model covariance is not explicitly formed, leading to further efficiencies. Instead, the product of the model covariance and columns of the sensitivity matrix are computed by solving a diffusion equation with an operator splitting method. For a modest number of sites (9 x 12 sites) our implementation of 3D data-space OCCAM is practical to run on a PC. Experiments with synthetic data show that the method converges to a reasonable model in an idealized case. Results from initial experiments with real data will be presented.

41:

High frequency 3-D EM modeling using vector finite elements.

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We have developed a 3-D electromagnetic (EM) modeling algorithm using finite element method (FEM) to interpret EM data more efficiently. When conventional nodal based FEM is applied to EM modeling, spurious solutions due to discontinuity of normal electric field, so called 'vector parasite', are occurred and may lead the modeling result to be completely erroneous one. Various methods are introduced to remove this problem. We adopted vector element method among these methods of which basis function has the amplitude and direction.

To reduce computational cost of FEM, we use complex bi-conjugate gradient (CBCG) method as iterative solver and point Jacobi method as its pre-conditioner. To verify the developed 3-D EM modeling algorithm, electric and magnetic fields calculated for layered-earth model were compared with those of layered-earth solution. Results from developed code showed good agreement with the layered-earth solution. Testing the applicability to high frequency modeling, 100 MHz was used as the operating frequency for the layer structure.

Results from the developed code also matched fairly well with those of layered-earth solution for dielectric anomaly as well as for conductive anomaly. Since 3-D EM modeling code developed in this study can reflect the response of dielectric anomaly as well as conductive anomaly, it may be a ground-work not only to apply high frequency EM method to the field survey but also to analyze the field data obtained by high frequency EM method.

42:

Three-Dimensional Electromagnetic Inversion Combining a Finite Difference Forward Solver with Fast Approximate Jacobians Based on Integral Equations

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Conjugate gradient (CG) iterative solvers for estimating the parameter ensemble step in 3-D EM data inversion have an advantage in computer storage over direct Gauss Newton

(GN) step solutions by avoiding formation of the full pseudo-Hessian matrix. A second advantage of CG is lack of requirement to compute parameter sensitivities (Jacobians) at each measurement site individually. However, experience with CG indicates that convergence to a solution can be slow, sometimes necessitating hundreds of iterations, while good convergence of the GN solution is well known. Emerging computer capabilities, especially clusters, are starting to allow solution of GN step matrices appropriate to practical 3-D field data sets. In this paper, we address the need to reduce Jacobian computation time by combining integral equations (IE) and finite difference (FD) algorithms.

Our approach starts with the general IE expression for the Jacobian of the secondary field $\mathbf{F}_{rs}$ ($\mathbf{E}_{sr}$ or $\mathbf{H}_{sr}$) at receiver r due to parameter m of the N parameters (denoted 'cells' here) defined in the FD mesh of the 3-D model (e.g., Eaton, 1989, Geophys. Prosp.):

$$\partial\mathbf{F}_{rs}/\partial\sigma_{bm} = G_{rm}\bullet\mathbf{E}_{bm} + \Sigma(\sigma_{bn}-\sigma_{l})\, G_{rn}\bullet\partial\mathbf{E}_{bn}/\partial\sigma_{bm} \;, \qquad (1)$$

where G_{rn} is the 3x3 finite-cell volume Green's function for an arbitrarily defined layered host to all structure, σ_{bn} is the conductivity of mesh cell n, σ_l is the local value of the layered host conductivity, and $\mathbf{E}_{bn}$ is the total average electric field within cell n, and the summation is n = 1,N (Wannamaker et al., 1984, Geophys.). The first term on the right is independent of cell conductivity and may be called the Born approximation term. It has been used just by itself as the Jacobian by other workers often with good result. It is perfectly accurate at zero conductivity contrast between the body and layered host.

The second term on the right above denotes how the internal E-fields of the cells change as conductivity of cell m changes and may be called the depolarization term. Our efforts here center on a good approximation to this term. Considering the expression for the IE forward problem (equation 11 of Wannamaker et al.) and differentiating w.r.t. the σ_{bm} (Eaton, 1989), one gets:

$$[G(s_b-s_l) - \mathbf{I}] \bullet\partial\mathbf{E}_b/\partial\sigma_{bm} = -G_m\bullet\mathbf{E}_{bm} \;, \qquad (2)$$

where G is the 3Nx3N Green's function matrix coupling all cells, including m=n, (s_b-s_l) is the diagonal matrix of anomalous conductivities, $\mathbf{E}_b$ is the vector column of E-fields in all N cells of the body, G_m is the vector column m of G, and $\mathbf{E}_{bm}$ is the vector electric field in cell m. Comparison of this expression with cell field Jacobians derived from differencing two nearly equal forward problems shows excellent agreement, almost always within 1%. The Born term alone, however, disagrees with differenced values by factors of 2-5 for cells having 10:1 contrast with the host. For inversion in our case, values of $\mathbf{E}_{bn}$ are obtained efficiently using the FD forward problem of Sasaki (2001, J. Appl. Geophys.).

Although equations 1 and 2 are far more efficient computationally than forward problem differencing, they are too slow for achieving the Jacobians in typical field data inversion problems where there may be 10,000 cells or more in the model. Our approach is to lump FD cells into groups whose numbers increase with distance from parameter m in accord with the concept of EM scaling. This recognizes that the amplitudes of the individual cell terms $\partial\mathbf{E}_{bn}/\partial\sigma_{bm}$ fall off rapidly with distance from cell m. The lumped cell approach requires definition and solution of an ~100x100 cell matrix for each parameter, but this is quite rapid on today's desktop computers. The lumped cell anomalous conductivity is the volume-weighted linear average of the anomalous conductivities of the FD cells within it, while the total electric field in the lumped cell is that which equates the total anomalous current moment in the lumped cell to that of the sum of the FD cells.

43:

The Relationship between the Magnetotelluric Tensor Invariants and the Phase Tensor of Caldwell, Bibby and Brown

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We examine the relationship between the seven invariants of the complex MT tensor, which we previously proposed as a vehicle for testing the dimensionality of the regional conductivity structure prior to an analysis of MT data, and the three invariants of the real 'phase tensor', recently introduced as an innovative aid in the treatment of MT data. It is found that the relevant invariants, and the necessary conditions on them for galvanically distorted data to be consistent with 1D, 2D or 3D regional structures, agree in almost every detail for the two approaches. The new method does lead, however, to an improved normalisation of the eighth (dependent) invariant previously introduced. It is shown that the phase tensor can be expressed as a sum of three simple matrices, clearly associated with 1D, 2D and 3D regional conductivity structures respectively. It is further shown that it can be depicted graphically as a single Mohr circle that retains the principal properties of the separate real and imaginary Mohr circles associated with the MT tensor. The simplicity and elegance of the phase tensor method is achieved by dispensing with the capability of distinguishing between galvanically distorted and undistorted data in 1D and 2D regions, a distinction that is ultimately unimportant and unnecessary with real data. The paper concludes with a simple illustrative example of the theory applied to a real MT dataset from NE Australia. A shallow 1D regional conductivity structure associated with a sedimentary basin is revealed, and a 2D anomaly with calculated strike angle is also identified.

44:

Secondary Potential Finite-Element Algorithm for 3-D DC Resistivity Modeling Using Shifted Incomplete Cholesky Conjugate Gradient Method

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An accurate and efficient 3-D finite-element (FE) forward algorithm for dc resistivity modeling is developed. Firstly, the total potential is decomposed into the primary potential caused by the source current and the secondary potential caused by changes in the electrical conductivity. Then, boundary value problem for the secondary field and its equivalent variational problem are presented, where the finite-element method is used. This removes the singularity caused by the primary potential, resulting in an accurate 3-D resistivity modeling. Secondly, a large amount of numerical work is required in the 3-D FE resistivity modeling, however, FE method yields symmetric, positive definite but not diagonally dominant linear system for irregular grids, so its incomplete cholesky splitting becomes unstable and the traditional incomplete cholesky conjugate gradient (ICCG) iterative method which has been successfully used in 3-D finite-difference modeling fails to achieve convergence for 3-D FE applications. In this study, I introduce the row-indexed sparse storage mode to store coefficient matrix and shifted incomplete cholesky conjugate gradient (SICCG) iterative method to solve the large linear system derived from 3-D FE calculation. The effects of the complexity of the model and irregularity of the grid on the algorithm are illustrated. The SICCG method converges very quickly and stably on a set of test problems, and requires much less storage of computer. It takes approximately 20s on 1000 MHz Pentium computer for an irregular grid with 39×39×20 = 30420 nodes, shows more efficient than direct method, i.e. elimination solver with the banded cholesky factorization. It also has an advantage over SSOR-preconditioning conjugate gradient method (SSOR: symmetric successive over- relaxation). Numerical examples of a three-layered model with high conductivity contrast and a vertical contact show that the results from secondary potential FE method agree well with analytic solutions (0.28% and 0.54% average errors, respectively), and achieve much higher accuracy than those solving the total potential with the same grid nodes. Also a 3-D cubic body is simulated, and the dipole-dipole apparent resistivities agree well to the results from other methods.

By defining the analytical solution of a vertical contact as the primary potential, a more complicated model with several 3-D inhomogeneities near a vertical contact is presented. The secondary potential FE method also obtains good results for this model. It confirms that the algorithm is effective while considering more complicated model for the primary potential.

45:

The 3D GILD EM And Acoustic Modeling And Joint Inversion

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The electromagnetic (EM) and acoustic modeling and inversion play an important role in the geophysical, earthquake exploration and materials sciences. In this paper, we present a 3D GILD EM and acoustic modeling and joint inversion method. We prove that the acoustic integral differential equation is equivalent to the Galerkin equation. We describe the relationship between the EM and acoustic modeling and inversion. The new advanced GILD – GL modeling is used to solve EM and acoustic modeling without any artificial boundary and no any absorption condition. The integral geometry Born inversion is presented.

We discussion the joint condition and joint frequency band. The synthetic model data and some field data from Taiwan earthquake are used to test our 3D GILD EM and acoustic modeling and joint inversion.

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46:

Application of 3-D resistivity tomography to delineate subsurface structures

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We have developed a three-dimensional (3-D) resistivity tomography code, where resistivity data are measured using electrodes installed in several boreholes as well as at earth surface. The algorithm is based on the finite element approximations for the forward modeling and ACB (Active Constraint Balancing) algorithm is adopted to enhance the resolving power of the smoothness constraint least-squares inversion. Sensitivity analysis with numerical verifications shows that 3-D resistivity tomography is a promising tool to get high-resolution 3-D image of subsurface structures. We have also shown that topography effect should be incorporated in the inversion to get accurate 3-D image without artifacts. In the application of the method to the field data set acquired at the granite quarry mine, we could successfully delineate the 3-D attitude of the fault or fracture in the site. Moreover, we have shown that 3-D attribute of substructure structures can be accurately defined by combining the 3-D resistivity tomography and borehole radar reflection method.

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47:

Electrical Anisotropy and Seafloor EM Exploration – A Forward Modeling Problem

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In regions where cross-beddings, faults or conductive rods in the earth are well developed, an isotropic earth might be an inadequate geophysical model. The parallel alignment of these structures results in the change of conductivity of the earth with the direction of the current flow (i.e. electrical anisotropy). Due to the huge memory and time requirements, general 3D modeling for these fine structures is practically impossible, so that some global parameters, e.g., the electrical anisotropy, can be very helpful in the interpretation of EM measurements over these structures.

The electromagnetic modeling introduced in this paper for a layered anisotropic medium is essentially a 3D problem. However, via a 2D Fourier transform, the 3D problem in the space domain is changed into 1D problem and solved in the wave number domain. This is to develop an algorithm to calculate the primary EM field in an electrically anisotropic medium for more complicated anisotropic modeling with 2D or 3D inhomogeneous structures. In this research, the EM field is represented by two scalar potentials, describing the poloidal and toroidal part of the magnetic field. We obtain two coupled ordinary differential equations in the vertical coordinate. To stabilize the numerical calculation, the wave number domain is divided into two parts. For small wave numbers, the EM field is continued in the anisotropic earth from layer to layer using the continuity conditions, where a transverse isotropic layer requires an extra treatment because the two scalar potentials are uncoupled and the requirement for the field continuation is not satisfied. For large wave numbers, the EM field is calculated by a Green's function. Furthermore, the EM field is solved in the air half-space and in conductive salt water. At the bottom of the sea, they are connected to the field in the anisotropic earth. For EM exploration on the seafloor, where the transmitter and receiver (T-R) are usually positioned at the seafloor, the apparent resistivity defined from the electromagnetic impedance is introduced to present the calculation results. Numerical experiments show that when the medium above the T-R is very conductive, as is the case of salt water, the earth anisotropy under the sea can only be explored at the high frequency range. At low frequency, the EM field concentrates in the conductive sea, so that the apparent resistivity reflects the true resistivity of the salt water. Polar plots of apparent resistivities at different frequencies can be used to identify the anisotropic character of the earth, e.g., principal anisotropic orientations.