3D modelling of highly conductive massive sulphides; a Voisey's Bay case study

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Summary

There has been a need in EM exploration for interpretation tools that can model a large earth volume with fine resolution and high conductivity contrasts. In response to this, a multigrid EM solution was developed for use in practical EM modelling of time domain EM data. This solution is an extension of multigrid methods to geophysical inductive EM problems. We illustrate the use of this tool by modelling UTEM data over the Voisey's Bay Ovoid deposit. Starting with a conductivity model derived from published drill sections the methodology was successful in rendering both the early-time large current channeling response generated by the host troctolite dyke and the very long late time decay of the highly conductive massive sulphide core.

Introduction

Large scale fixed loop EM methods are important tools in surface and borehole EM surveys that have contributed to the discovery of numerous mineral deposits. Practically all interpretation has been done using free air thin sheet approximations of 3D conductivity models which may be non-ideal in areas of complicated 3D geology.

The data of medium scale EM surveys have been successfully inverted using 3D inversion making use of finite volume methods (Haber et al., 2007) but attempts at inversion of large scale multi-fold data have been limited by available forward modelling tools (Yang, 2010). These tools cannot jointly render closely spaced data while inverting for surveys extending several kilometres without making compromises. This prompted us to develop a multigrid EM modelling tool for both electric and magnetic field step responses for fixed loop EM measurements,

Multigrid methods are now seen to be the way forward to overcome these modelling limitations (Newman, 2013) and have seen some use in 2D and 3D DC resistivity applications (Moucha and Bailey, 2004; Lu et al., 2012). Multigrid algorithms rely on using solutions on coarser meshes to speed up the solution on a fine mesh and have long been the textbook methods to solve problems involving Poisson's equation (Press et al. 1988). There is also a distinction between multigrid methods (MG), where the coarser meshes are only used to speed up the solution on the fine mesh, and full multigrid methods (FMG) where a solution is sought at every mesh level. For magneto-static and eddy current problems of convex shapes, MG methods, called algebraic multigrid (AMG), were first applied in finite element modelling (Hiptmair and Hoppe, 1995; Hiptmair, 1997). The shape limitations in AMG methods have been removed in later developments by Hiptmair and Xu (2006) and Bochev et al., (2007) resulting in two distinct solutions valid for high conductivity contrasts and general shapes.

Methodology

The FMG method we use is similar in general formulation to the AMG methods discussed above but is applied in a less general cartesian cubic mesh more amenable to geophysical modelling, inversion and imaging methods. The complete method is referred to as MGEM and it has been used for forward modelling of surface and down-hole data and for target detection studies. It has been validated against analytical and numerical models and electric field modelling results have been shown in Lamontagne and Langridge (2012). Below we present details on the mesh design which differs from standard AMG methods and on convergence issues pertaining to the modelling of high conductivity targets.

MGEM uses a staggered mesh with **H** field-like vector potential edge elements. At each coarser level of mesh the linear size of the solution volume increases by a factor of ~4/3 such that the number of mesh points decreases by $\sim(2/3)^3$ for each coarser level (Figure 1). The boundary condition H_t (tangential H) $=0$ is only applied on the coarsest mesh. On finer mesh levels, H_t is set to the value interpolated from the next coarser mesh. This mesh design allows for the modelling of regional structures surrounding the target area as required in this case study.

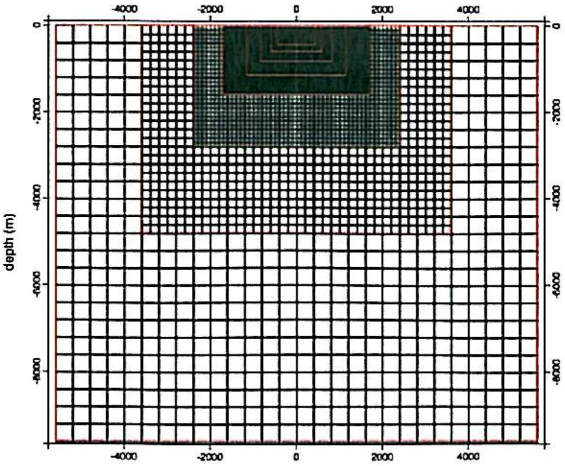

Figure 1: Cross-section of the multigrid expanding below the earth's surface. Mesh boundaries are shown in red.

One important aspect of the implementation for the modelling of highly conductive bodies is that it should render the late time response accurately. A simple measure applied to the whole solution volume is needed to unambiguously detect the end of decay evolution and convergence at each time step. This is usually done by using the "right hand side" of the problem equation. The time stepping equation is represented as:

$$\nabla\times\rho\nabla\times\alpha\mathbf{D} + \mu_0\mathbf{D}/h_t = -\,\partial\mathbf{B}^{\mathrm{P}}/\partial t - \nabla\times\rho\nabla\times\mathbf{H} \qquad (1)$$

where α is 0.75, ρ is the resistivity, μ_0 is the magnetic, permeability of free space, h_t is the time interval, $\partial\mathbf{B}^{\mathrm{P}}/\partial t$ is the rate of change of the primary **B** field (step-on in $\partial\mathbf{B}^{\mathrm{P}}/\partial t$), **H** is the secondary magnetic field after the last time step and **D** the unknown difference in **H** to solve for over the next time step. In the finite difference code the RHS of (1) is the emf around a mesh cell area driving the system.

In Figure 2 we show the progression in time of the model RHS for a 40 kS/m, 50 m cube embedded in a resistive structure. Three L2 measures were tested: A with unity, B $1/\rho$ and C $1/\rho^2$ weights. A, B and C have units of V^2, W and A^2 respectively. Using A there does not seem to be any clear fall-off to indicate the end of time variations but the weighted measures both show a clear late time fall-off. The measure A is poor because the sum over the solution volume hides the eddy current activity occurring in small highly conductive volumes. Any simple automatic scheme based on A alone would likely stop time stepping well before 1s. Contrary to A, C flatlines far into the resistive limit and is not sensitive to E field errors in high resistivity volumes. Thus, for accurate rendering of both **H** and **E** fields we have found the measure B to be valid for end of run detection and as a convergence threshold at each time step using a threshold factor such as 10^{-10} (relative to the measure at the start of the time step).

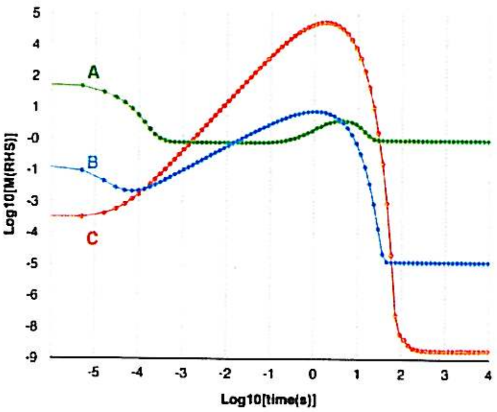

Figure 2: L2 RHS measures with weights of: unity (A), $1/\rho$ (B), and $1/\rho^2$ (C) for a 40kS/m 50m cube embedded in a high resistivity structure. B curve flatlines at (57s) the secondary **H** field response inside the target conductor has fallen to <0.01% of the primary field. C flatlines at <2PPB (289s) well into the resistive limit.

The Voisey's Bay Ovoid Deposit

The Voisey's Bay Ovoid Ni-Cu-Co deposit with its surrounding conductive dykes is an ideal test area for the modelling of highly conductive targets. It was the subject of a previous study in airborne EM modelling (Jahandari and Farquharson, 2014). The deposits in this area consist of multiple lenses of disseminated, semi-massive to massive sulphides hosted in an extensive troctolite dyke (Li and Naldrett, 1999; Balch, 1999). Locally, as in the case of the Ovoid deposit, the massive sulphides can be as thick as 110m. The major problem with modelling the Ovoid is that it is close to the surface (<20m depth-to-top) is highly conductive (>1000S), is relatively large (400x300x110m) and has a complex 3D bowl/wedge shape structure which does not easily lend itself to thin-sheet conductor modelling. The entire problem is compounded by the fact that the troctolite dykes attached to the ovoid are conductive. The dip of the dykes varies from moderate to steep with increasing depth. The dykes extend for over 3 km in strike length and 2 km along the dip. The entire dyke system can be viewed as one large conductor as disseminated sulphides within the dykes have been shown to be electrically connected (Bengert, 2006). In order the accurately render the full time varying response over the Ovoid deposit one must model both the Ovoid on a finely discretized grid but also be able to model the regional troctolite dykes over a significant strike and dip length. Therefore, 3D modelling on a relatively large and detailed mesh is required.

A plan view of the Voisey's Bay deposit can be seen in Figure 3; note the Ovoid at 1400E and the large extent of the troctolite dyke (the host of the sulphides). The Voisey's Bay Ovoid was the object of many geophysical surveys including a test 30Hz surface UTEM survey done in 1995. The UTEM vertical and north H field components over line 1400E are shown in Figure 4A.

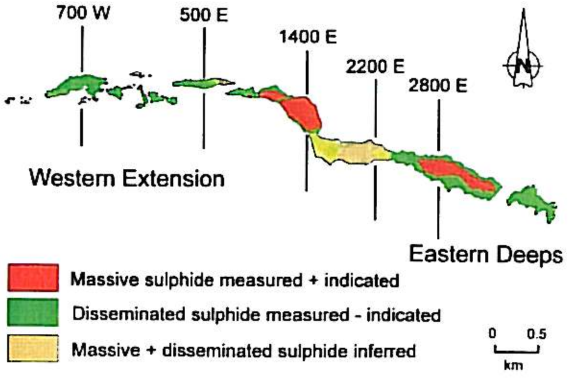

Figure 3: Plan view of the Voisey's Bay deposits. The ovoid centre is located at roughly 1400E. From King (2007) modified from Balch (1999).

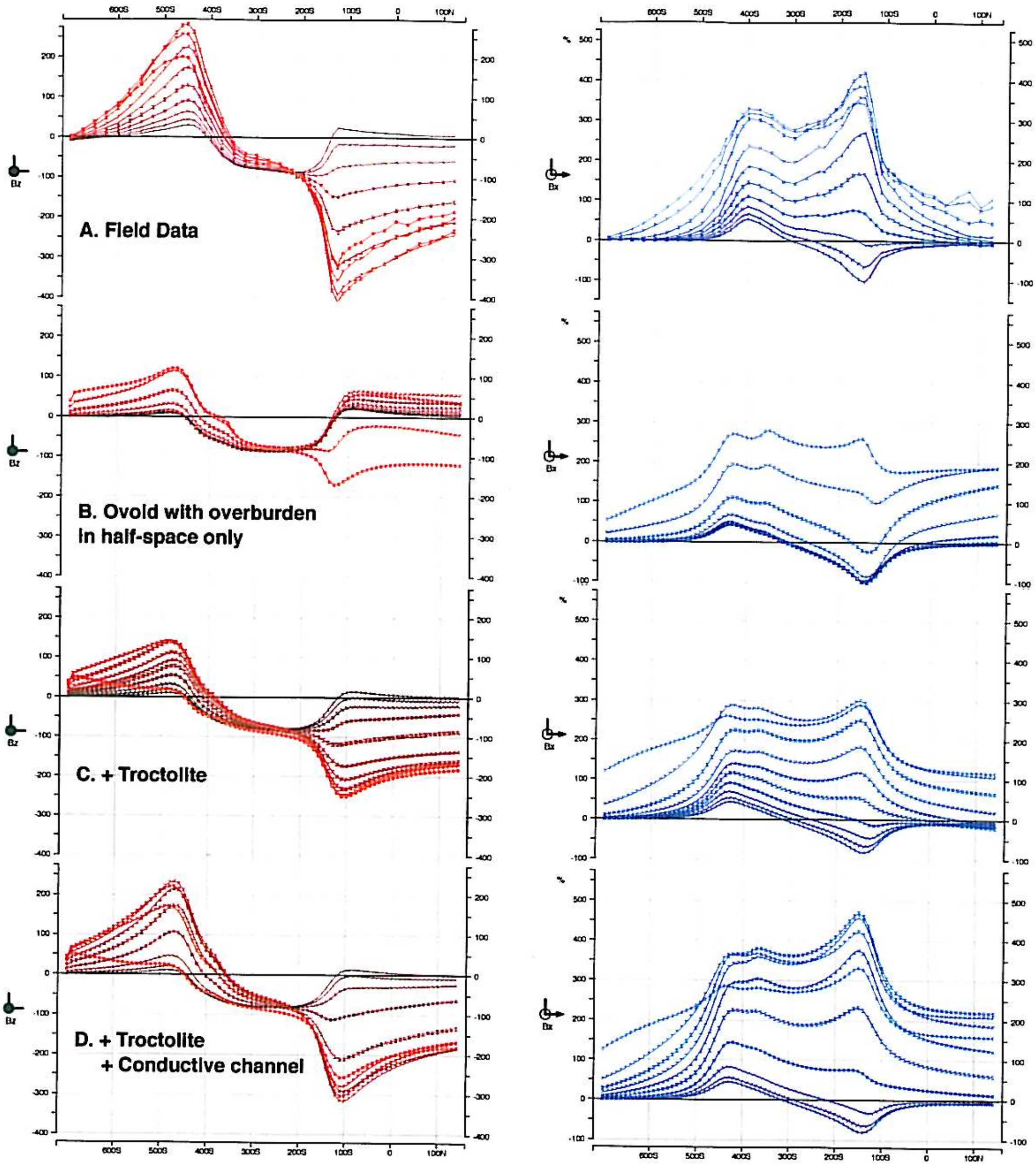

Figure 4: **A.** Field data over L1400E; **B.** Synthetic data over L1400E generated using an Ovoid model. **C.** Addition of troctolite dykes.; **D.** Addition of a conductive channel. The channels ranged from 25μs (light shading) to 12.8ms (dark shading). All data is secondary response normalized to the theoretical primary field (%). The vertical (left) and inline components are shown.

The 700m square transmitter loop was located 600m south of the Ovoid centre. The anomalies observed had more than 600% peak to peak amplitude. The first step in modelling the data was constructing the 3D shape of the Ovoid itself. The current software allows for the drawing and construction of arbitrary 3D shapes. The order of insertion of the objects in the list is analogous to the laws of superposition in a geological sense (i.e. adding Ovoid parts displace the prior dykes and the last entered overburden layer crosscuts all previous objects). Based on published sources such as Li and Naldrett (1999) and available NI 31-103 reports, the Ovoid was specified by drawing horizontal polygonal slices of 12m thickness. It was assigned a conductivity of 10 000 S/m with a sharp contact at the top and a thin disseminated halo of 1000 S/m along the sides. The host rock resistivity was set to 4000 Ωm.

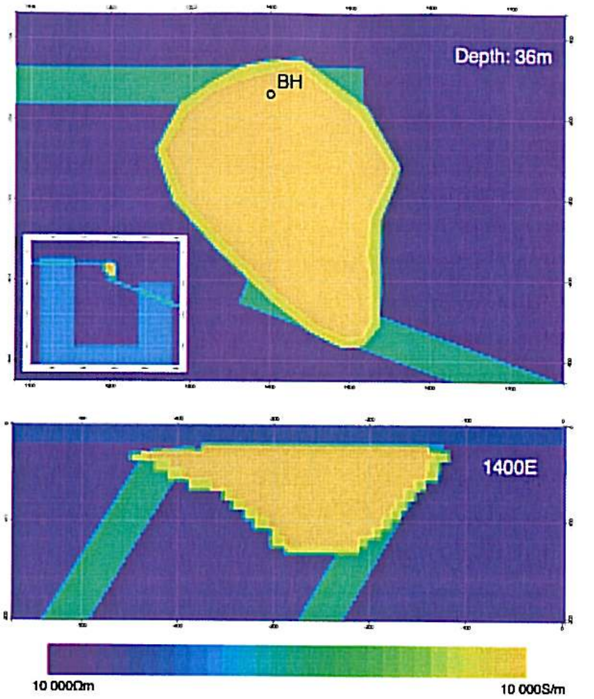

Figure 5: Plan view and cross-section of the final Voisey's Bay Ovoid model at the finest multigrid level (3.125 m resistivity cells). The section shows the 12 m depth slices used to assemble the Ovoid. The U-shape in mesh level 5 is shown in the insert.

A resistivity discretization of 3.125 m allowed for a solution mesh of 6.25 m spacing on the finest mesh. This model was run with 140^3 fine mesh cells using 8 multigrid mesh levels as shown in Figure 1.

In Figure 4B the late-time anomaly seems to be well rendered, suggesting the Ovoid model is accurately represented. However, the early channel response is poorly rendered, with amplitudes lower than expected. This early time response is thought to be due to current channelling concentrated by skin effect along the edge of the deposit. The modelling proceeded with the inclusion of the conductive dykes of shapes generalized from published information (Li and Naldrett, 1999) resulting still in an insufficient early-time current channelling response (Figure 4C). To approximately fit the observed early channel amplitudes and response times, a U-shaped overburden layer was added (inspired by the swampy environment surrounding the Ovoid site except to the northeast). Further adjustments in the resistivity of this feature and of the main overburden layer, as well as fine adjustments to the dip of the dykes at depth resulted in a more reasonable fit of the field data in both in early and late-time (Figure 4D). The final model is shown in Figure 5.

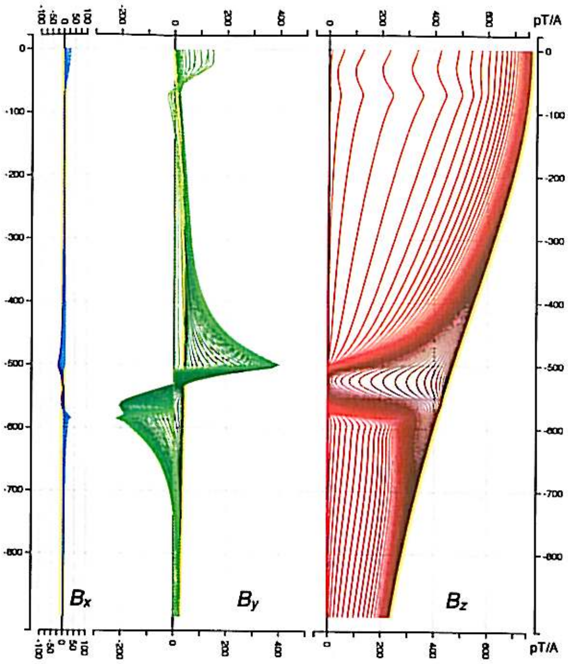

Figure 6: Calculated total-field in-hole step response (10 μs to 115 s) in a vertical borehole near the northern tip of a hypothetical deep ovoid (plan location in Figure 5). The primary field late time limit is shown in yellow. The fine grid contained 202x202x268 cells resulting in a volume of 1256x1256x1667 meters.

To illustrate the usefulness and versatility of this method in understanding EM induction, Figure 6 shows the **B** field from 10 μs to 115 s in a vertical borehole placed in the model (plan location can be seen in Figure 5). For this particular example, the Ovoid was lowered to a depth-to-top of 500 m, and an in-loop configuration was modelled. Even in this hole very close to the edge of the 10 kS/m Ovoid, the 1/e decay time is 5.6s and there is a complete skin effect shielding up to 0.5 s.

The computation times for the model data shown in this work depended mainly on the size of the fine mesh (140x140x140 or 202x202x268) and on the number of time steps (42-59). They ranged from 20 to 162 minutes running as single threaded code on a 2014 iMac computer.

Conclusion

We have shown the application of a full multigrid finite difference modelling method in the exploration for highly conductive massive sulphides. The results obtained suggest that MG methods have great potential for fast and accurate modelling of mineral deposits for geophysical applications.

Acknowledgement

We wish to thank Edward Chew for his system programming help during the development of the FMG code.