

A Program to Model and Interpret Borehole Gravity Data

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Introduction

Borehole gravity measurements reflect the distribution of rock densities at depth with greater target sensitivity and spatial resolution than surface measurements. In conjunction with geological information and other geophysical parameters, continuously logged borehole gravity data provide input for 3D quantitative modelling of subsurface environments. In addition to the usual exploration quantitative, bulk-density information about the formations being traversed by the hole. In several stages of mining activity, including deposit evaluation, mine planning and grade control, it is important to have an accurate measure of the bulk

technology which is small enough in diameter to enter the exploratory boreholes commonly drilled in mining programs, while retaining the same sensitivity as current surface gravimeters. As part of the project, the applied geophysics group of École Polytechnique de Montréal is working with Scintrex to develop a software package to interpret logging results and to predict the subsurface gravity from modelled geology. In this contribution, this software package is presented along with a case

Theoretical background

There are two general approaches to three-dimensional discretization of solid volumes: regular grids composed of cells of cuboidal shapes, and irregular grids built with polyhedrons of arbitrary shapes. The former is also a particular case of the latter. Sharp topographic relief and geological bodies of complex shapes are usually more accurately described by polyhedrons with arbitrary number of faces than with regular grids. The topology of arbitrary polyhedrons is however more challenging to handle. Nevertheless, the ability to compute the gravity response of arbitrary polyhedron is favoured because specialized computer libraries facilitate their creation and processing. Numerous authors proposed algorithms allowing this (Barnett 1976; Götze and Lahmeyer 1988; Coggon 1976). We retained the approach of Singh and Guptasarma (2001) for its simplicity and efficiency.

In the approach of Singh and Guptasarma (2001), a fictitious distribution of surface mass-density on the envelop of a solid body is defined to compute efficiently the gravity field due to the body. This surface mass-density is derived from the surface integral expression of the gravity field vector **F**:

$$\mathbf{F} = Gr \iint (1/r) (\mathbf{r}/r) \cdot \mathbf{u}_{n} ds = Gr \iint (\rho r \cdot \mathbf{u}_{n})/r^{2} ds,$$

where G is the universal gravitational constant, ρ is the uniform volume density of the body, \mathbf{u}_n is the unit outward normal vector at the surface element ds and r is the vector pointing from the observation point to the element of surface ds. The term $(\rho r \cdot \mathbf{u}_n)$ has units of mass per squared length, and is coined surface mass density. For one of the plane facets bounding the body, each component of vector **F** can be obtained (Guptasarma and Singh 1999)

$$F_{x} = Gr \iint r \cdot \mathbf{u}_{n} (x/r^{3}) ds,$$

$$F_{y} = Gr \iint r \cdot \mathbf{u}_{n} (y/r^{3}) ds,$$

$$F_{z} = Gr \iint r \cdot \mathbf{u}_{n} (z/r^{3}) ds.$$

The originality of the approach is in the evaluation of the surface integrals. Guptasarma and Singh (1999) developed expressions to transform this surface integral into a function of the solid angle Ω subtended by ds at the origin and three line integrals over the edges of the facets, denoted P, Q and R respectively. The components of vector **F** become

> $F_x = -G\rho d (I\Omega + nQ - mR),$ $F_{v} = -G\rho d (m\Omega + IR - nP),$ $F_z = -G\rho d (n\Omega + mP - IQ),$

where $d=r \cdot \mathbf{u}_n$ and (l,m,n) are the components of \mathbf{u}_n . The computation of the coefficients Ω , P, Q and R is fairly straightforward, as shown in Guptasarma and Singh (1999).

Software Description

developed to generate or import the density model, to with GoCAD that has been imported in BHGravi. visualize in 3D the model, borehole trajectories and surface stations, to perform the calculations, and to **Survey data** view and compare modeled and measured gravity data.

Geological model management

The geological models can be built entirely by the user mode for imported models.

to build model components: cone, cuboid, cylinder and response of the model of Figure 1. ellipsoid. Topography is not considered in this mode, and to optimize the calculations the background is set Core computing routines to null. As a consequence, a density contrast value is models, with an example of a cylinder and ellipsoid.

complex shape, heterogeneous background or severe programmed in C++, within the VTK framework. topographic relief can be considered. In the program,

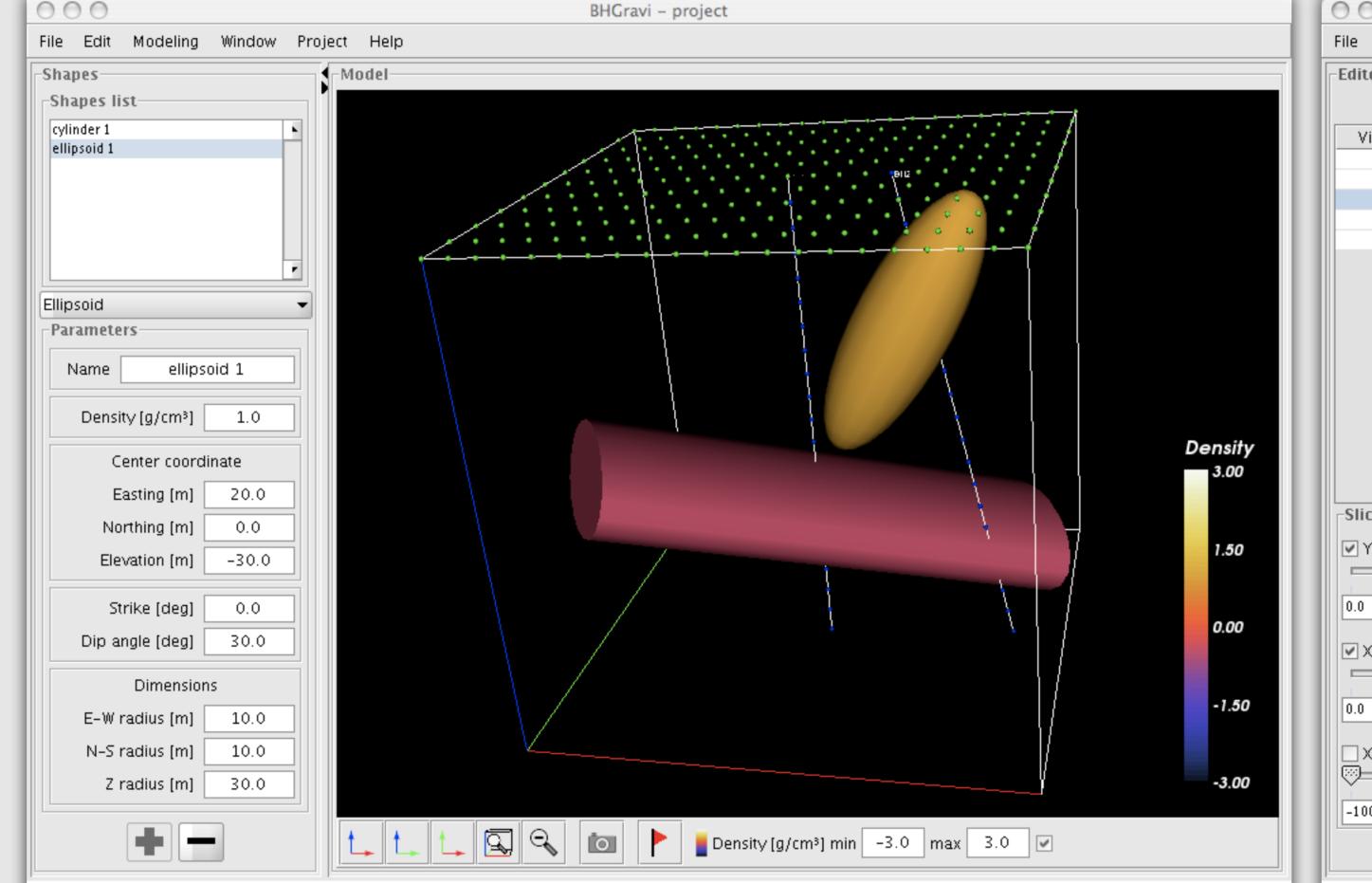
BHGravi is programmed in Java (http://java.sun.com) the user has the possibility to change the density of any graphical user interface (GUI) was position. Figure 2 shows an example of a model built

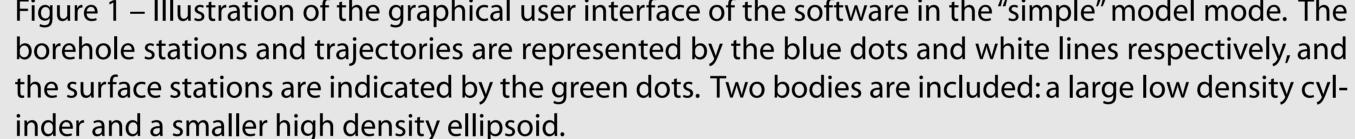
The 3D visualization components of the software are Borehole and surface survey data can be incorporated open source VTK library into a modelling project. The survey gravity data need (Visualization toolkit, http://www.vtk.org). The software to be corrected at least for regional, latitude, and drift relies extensively on the capabilities of the VTK library before input to the program. If field data are not polyhedrons used in the calculation of the gravity surface profiles in order to compute the anticipated response over the selected geological model. See Figure 3 for survey management windows.

Visualization of the results

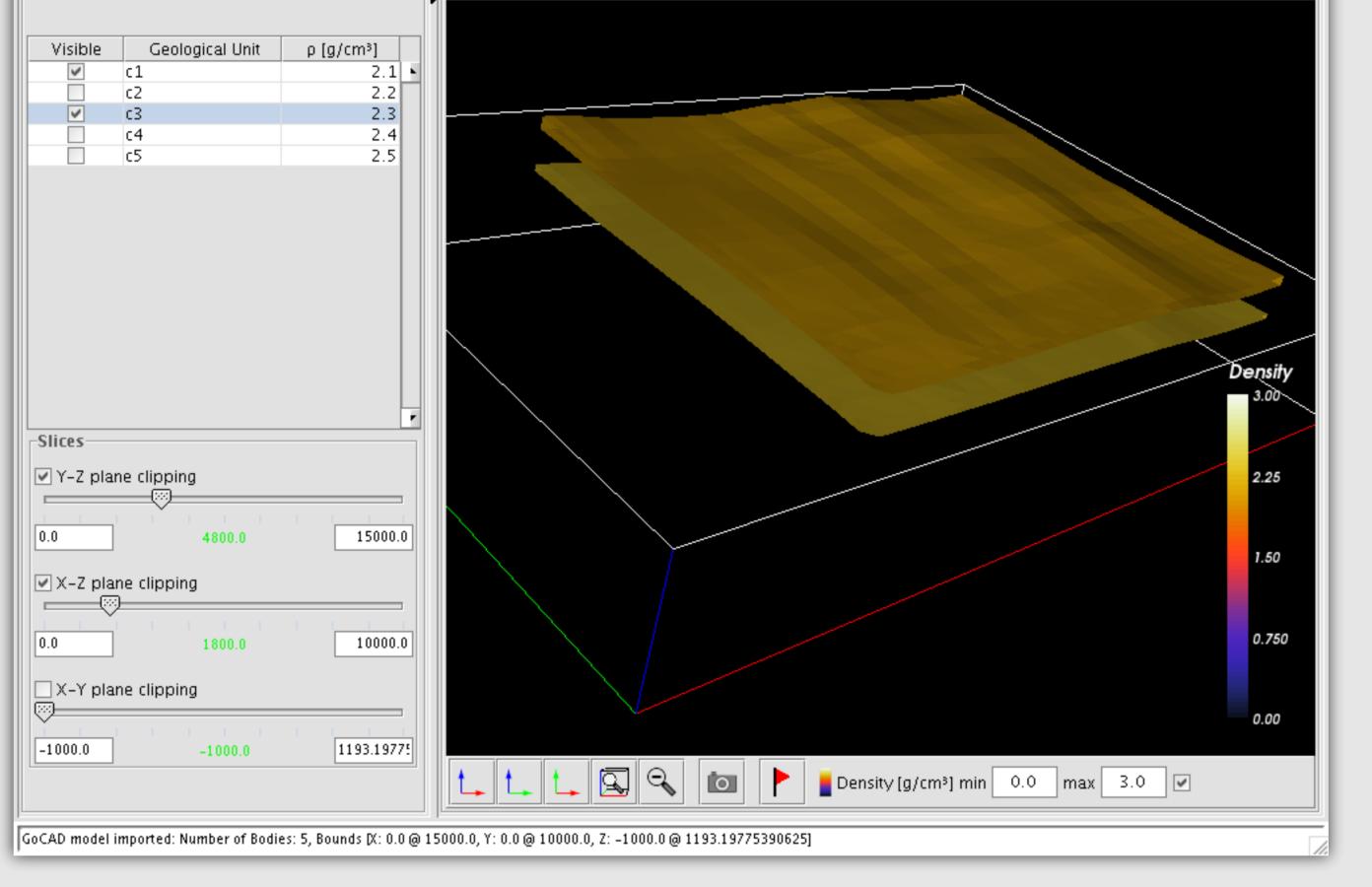
inside the software, or created outside in a third party. Computed borehole g_z and $\Delta g_z/\Delta z$ profiles and surface application such as GoCAD and subsequently imported. q_z values can be plotted along with field data for direct Both types of model are managed differently; with a comparison. Surface maps can also be drawn (along "simple" mode for user defined models and a "complex" the topo) and visualized in 3D. The maps and plots can be saved as images, and the computed responses can be exported in ASCII format for further processing in In the simple mode, four primitive shapes are available—third party applications. Figures 4 and 5 show the

assigned to each earth body constituting the model. As mentioned above, the polyhedral objects are created Figure 1 shows the GUI for the construction of simple and managed using facilities of the VTK library, which is written in C++ and which functions can be called from Java. For efficiency reasons (memory management and In the complex mode, models with geological bodies of raw number crunching), the computational routines are





Simple Shape edited: Ellipsoid, ellipsoid 1, Density: 1.0 g/cm³, Coordinates: [20.0,0.0,-30.0], Strike [deg]: 0.0, Dip angle [deg]: 30.0, Dimensions: [10.0,10.0,30.0]

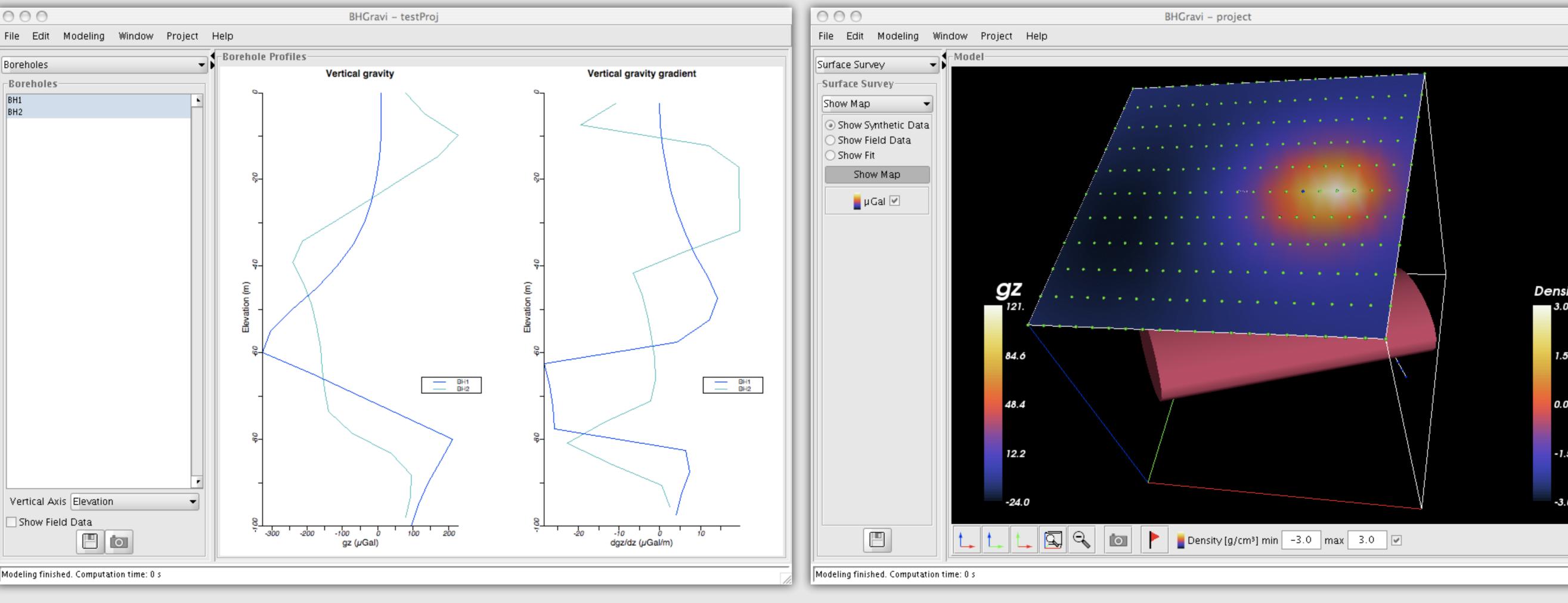


BHGravi - project 2

Figure 1 – Illustration of the graphical user interface of the software in the "simple" model mode. The Figure 2 – Illustration of the graphical user interface devised to manage GoCAD models. The density borehole stations and trajectories are represented by the blue dots and white lines respectively, and of the geological objects can be edited in the upper left table.



Figure 3 - Panels used to define the survey parameters and station location, and to import field data. It is possible to tie the modeling results with field data at a common reference station. It is also possible to include the Free-Air effect in the modeling, and add a Bouguer correction to the modelled data.



over the cylinder and ellipsoid of Figure 1. When available, field data can also be plotted, in order to survey stations, when present. appraise the model fit.

Figure 4 - Example of borehole gravity response, g_z on the left and $\Delta g_z/\Delta z$ on the right, as modeled Figure 6 - Surface survey results on a map. The surface of the map follows the topography of the

Case Example

The borehole gravity response of Inco's well documented Kelly Lake Ni/Cu sulphide ore body, located in the Sudbury mining camp has been modelled to illustrate some of the possibilities offered by the software. ones are between 100 and 600 m depth. The main zone is 700 deep. Depths are measured from the surface, which is between 200 to 300 m ASL.The bodies have been delineated by intensive drilling and densities within the zones have been estimated for blocks of host rock density is about 2.8 g/cm³, and the density contrast of the ore body zones with the host rock varies from zero to about 1.3 g/cm³.

The structural complexity of the Kelly Lake ore body is evident in the figures below. The borehole gravity response will be complex, with anomalies indicating pockets of excess mass (high density) within the zones. We have used this real-world ore body to model four distinct scenarios that could occur in borehole gravity surveys. The vertical component of the gravity response g_z and the vertical gradient $\Delta g_z/\Delta z$ are modelled for the effect of the excess mass.

Figure 6 shows the case of a vertical hole that would have missed the Kelly Lake bodies. The vertical gravity anomaly, q_z , and the vertical gravity gradient anomaly, $\Delta q_z/\Delta z$, are represented on the right side of Figure 6 by solid and dashed lines respectively. The vertical gravity anomaly, q_z , will be positive when the gravity meter is above a high density pocket and negative below, with a cross-over opposite the pocket, due to excess mass at this location in the ore body. There are two recognizable of anomalies on this profile. The shallower anomaly shows a peak to peak response of about 200 µGal with a cross-over at about 300m depth (surface at 250m ASL) and a separation between peaks of about 250m. The vertical gravity gradient anomaly, $\Delta g_z/\Delta z$, has a positive peak at about 310m depth, coincident with the gz cross-over. These results indicate the presence of excess mass at a distance of about 250m from the borehole at a depth of about 300m. The borehole passes between the two shallower zones of the ore body at this location, as indicated in Figure 6. A second q_z anomaly is evident in Figure 6, with a cross-over at about 900m depth, a peak-to-peak response of about 150 µGal and a peak-to-peak separation of about 400m. There is a $\Delta q_z/\Delta z$ peak at about 850m depth. These results indicate the presence of excess mass at a distance of about 400m from the borehole at a depth of 850-900m. Referring to Figure 6, the borehole gravity response is indicating a pocket of high density near the top of the deeper zone of the Kelly Lake ore body. This is consistent with the density model of the ore body. The borehole gravity data in Figure 6 clearly indicate the presence of shallow and deep zones of excess mass remote from the borehole.

Figure 7 shows the case of a dipping hole that intersects one of the shallow zones of the ore body. The q_z cross-over in the vicinity of the intersection at a depth of 375 m shows a peak-to-peak response of about 150 µGal. The $\Delta q_z/\Delta z$ peak coincides with the q_z cross-over. The responses from 375 m to 500 m depth are complex, indicating that the intersection is not a simple one and may actually be a number of individual lenses of varying densities within this depth range. There is a clear indication of another massive body at depth at the bottom of both g_z and $\Delta g_z/\Delta z$ logs, suggesting that the hole should be extended.

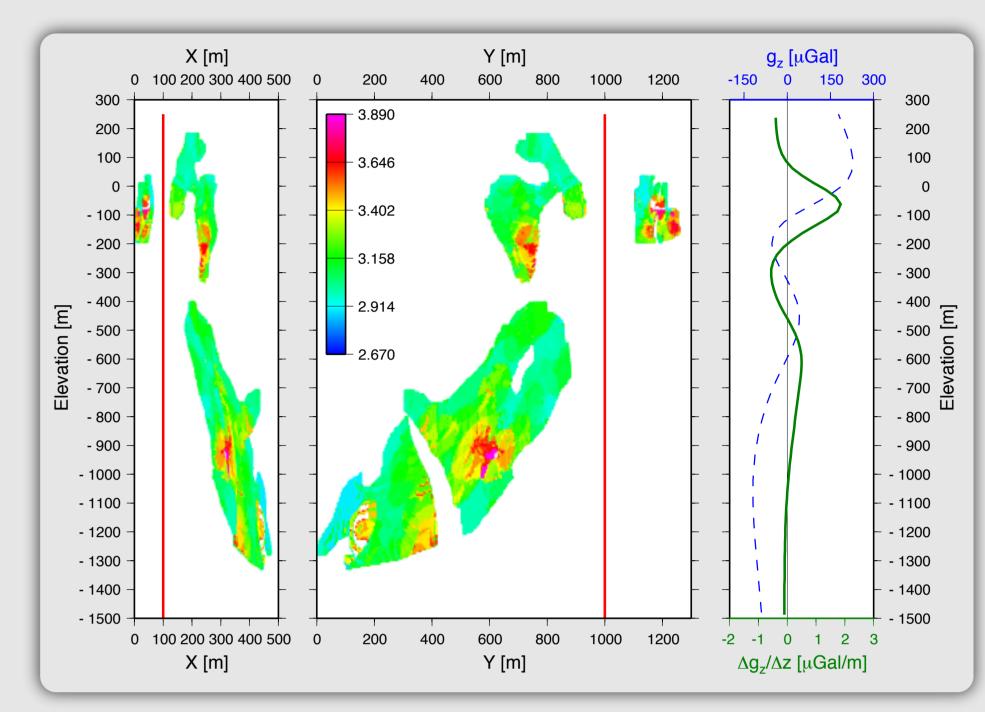


Figure 6 - The borehole has missed the Kelly Lake ore body. The density model of the three zones in the ore body is shown projected into the xz (left) and yz (middle) planes along with the trace of the borehole. The panel on the right displays computed profiles of the vertical component of gravity, g_7 , (solid line) and the vertical gradient of gravity, $\Delta g_z/\Delta z$, (dashed line). The colour bar shows the density distribution in g/cm³. The host rock density is 2.8 g/cm³. The borehole gravity profiles show g_z cross-overs and $\Delta g_z/\Delta z$ peaks corresponding to off-hole excess masses, indicating both shallow and deep zones remote from the borehole.

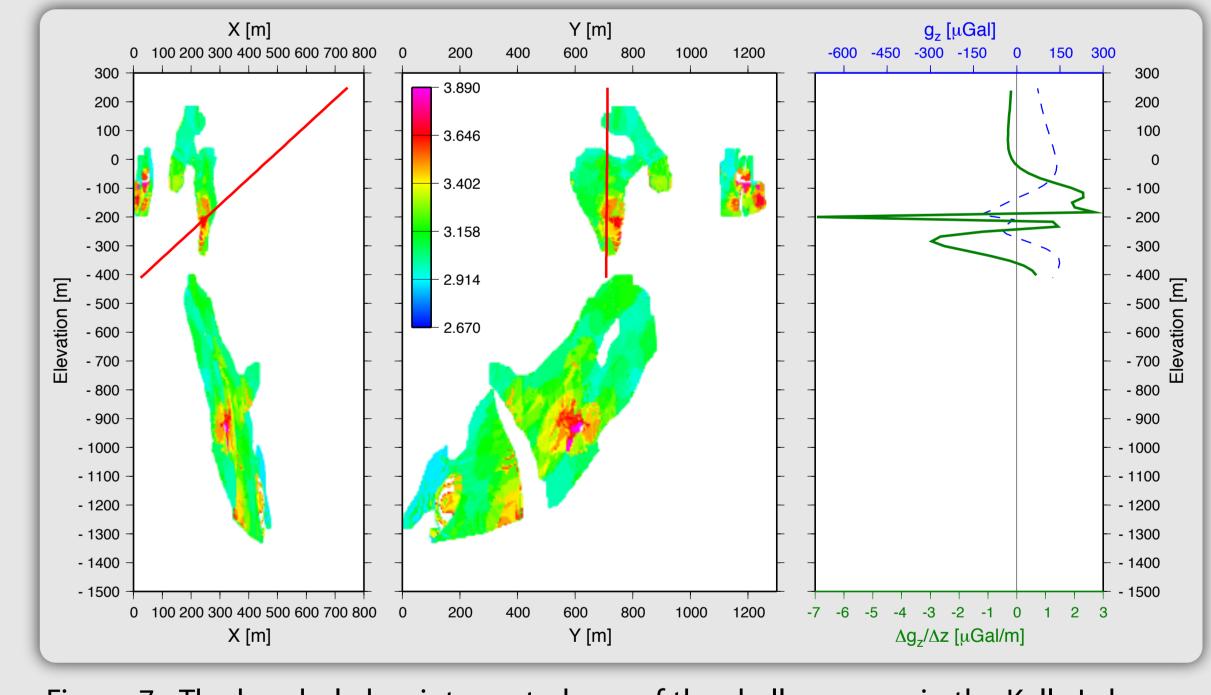


Figure 7 - The borehole has intersected one of the shallow zones in the Kelly Lake ore body. The gravity responses display abrupt and complex changes in the vicinity of the intersection. There is evidence of a deeper zone below the bottom of the borehole.

Conclusion

An interactive 3D modelling software was developed to interpret borehole gravity data and to predict the subsurface gravity from modelled geology. The core computing routines are based on an efficient surface integral approach, and the software relies on an optimized visualization library to generate and manage the polyhedrons that build the geological model. Near-future developments include 3D stochastic gravity inversion using cokriging and cosimulation. The inversion method will allow inclusion of density constraints and geological boundaries.

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