An update on the development and use of Borehole Gravity

C. Nind*, Scintrex Ltd, J. MacQueen, Micro-g LaCoste Inc, R. Wasylechko and M. Chemam, Abitibi Geophysics, C. Nackers, École Polytechnique de Montreal

Abstract

A new generation of borehole gravity meters is now successfully deployed in boreholes for mining exploration in Canada and USA, and in wells used for CO_2 injection, sequestration and leaching in Canada, USA and Europe. Scintrex has developed and will be testing a dual sensor borehole gravity probe in early 2013.

A brief review of the borehole gravity development and specifications is presented, followed by several recent case histories. The result from Donner Metals / Xstrata Zinc's Bracemac KT Zone in the Matagami region of Quebec is the first documented use in mining exploration of borehole gravity to measure excess mass coincident with a borehole EM conductor. Forward modeling and inversion of borehole gravity data from multiple holes has proven effective in outlining the mineralization and estimating the tonnage of the Virginia Mines' Lens 44 on the Coulon property in Quebec. Apparent bulk density measurements from multiple holes at the Labrador Iron Mines' James South Extension iron ore deposit near Schefferville, Quebec reduce drilling costs and time needed to obtain this information.

A major source of error in bulk density measurements of thin beds is minimized by the dual sensor borehole gravity system. In addition to eliminating the error in the depth interval between the sensors, common mode noise rejection improves the gravity difference data.

Introduction

The potential of borehole gravimetry as an exploration tool was the topic of a paper in Geophysics in 1950 by N.J. Smith (Smith, 1950). A tool for acquiring borehole gravity measurements was built by LaCoste & Romberg in the early 1960s, and survey results have been reported in several papers between 1966 and 1990 (see, for example, McCulloh, 1966, and Popta *et al*, 1990). The deployment of these first generation borehole gravimeters was limited to large-diameter, near vertical boreholes, and their use was almost exclusively for hydrocarbons.

Scintrex has developed the GRAVILOG borehole gravimeter for mining and geotechnical applications (Nind *et al*, 2007). The gravity sensor is based on the fused quartz technology proven to be rugged and accurate in land gravimeters. The basic sensor technology has been miniaturized and equipped with self-leveling capabilities. The associated electronics modules have been packaged to fit into a narrow diameter borehole sonde. The tool has been designed to log inside NQ (57 mm I.D.) drill rods to 2,500 m depth, using standard 4 or 7 conductor wireline cable, with a sensitivity of better than 5 μGals. It can be deployed in boreholes inclined from -30° to vertical. This new borehole gravity meter has undergone extensive laboratory testing, followed by several successful mining industry sponsored downhole tests.

Abitibi Geophysics has leased a system to provide borehole gravity surveys for mining exploration in Canada and USA using in-house crews. Example results from three recent borehole gravity surveys in Canada are presented below.

In 2013, Scintrex introduced a dual sensor borehole gravity system, which incorporates two gravity sensors spaced 1.5 metres apart in a single probe. This tool eliminates the error in the relative depths of these two sensors, which improves measurements of the bulk density of thin formations intersected by the borehole.

Borehole Gravity

Modern gravity meters measure acceleration with microGal precision, 1 part per billion of g. This is the equivalent of detecting a flea (0.1 gram) landing on a whale (100,000 kg). The force of gravity attenuates as the square of distance, so the utility of gravity measurements is dependent on being able to measure with exquisite accuracy, close to a source. A borehole gravity meter brings the sensor closer to the target, and away from surficial "noise".

In a uniform host rock, excess mass and off-hole radial distance can be estimated from the crossover response measured by the gravity sensor as it passes by a massive body (Figure 1). Knowledge of the density contrast between the target body and the host rock then provides an estimate of tonnage.

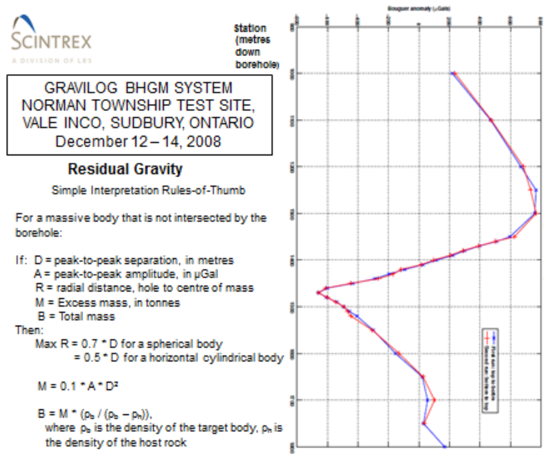

Figure 1. The borehole gravity crossover response from an off-hole massive body in a uniform host rock, with simple rules-of-thumb for estimating off-hole distance and excess mass. The hole was logged twice.

In a simple, layer cake geology, the vertical gravity gradient is directly proportional to the bulk density of the horizontal layer between the measurement points (Figure 2). Figure 3, copied from an old LaCoste & Romberg slide modified from McCulloh *et al*, 1968, illustrates a simple "rule-of-thumb" about the radial penetration of borehole gravity density logging. Borehole gravity does not require active sources, and extends the density information beyond the borehole. This unique feature of borehole gravity data has been successfully used by the petroleum industry for reservoir characterization and fluid saturation monitoring (Popta *et al*, 1990) and for locating off-hole reef formations (Rasmussen, 1975). When the geology is more complex and dipping, these calculations yield apparent densities and require gravity modeling and inversion techniques to interpret.

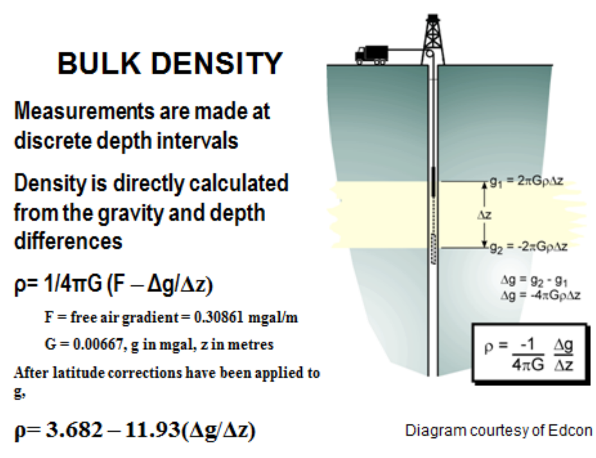

Figure 2. Bulk Density from Borehole Gravity

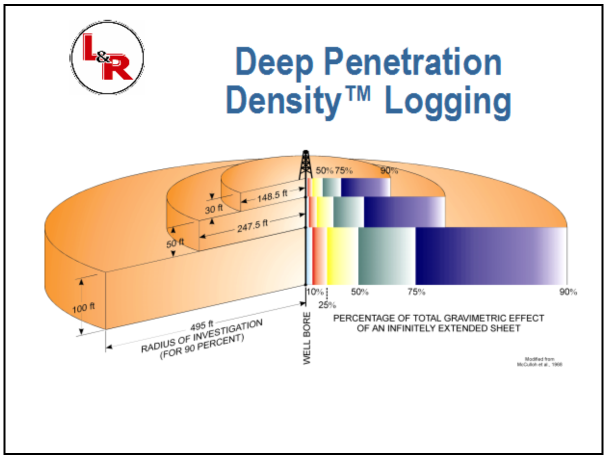

Figure 3. The radial penetration of borehole gravity density measurements. As a simple rule-of-thumb, when the borehole intersects a density layer, the radial penetration is about 5 times the downhole station spacing.

The GRAVILOG Borehole Gravity Meter

Scintrex developed the GRAVILOG borehole gravimeter with specifications suitable for mining and geotechnical applications (Nind *et al*, 2007). The miniature fused quartz spring gravity sensor is mounted inside a sphere that is smaller than a golf ball (Figure 4). This ball is mounted in a yoke which auto-levels the gravity sensor in inclined holes.

Figure 4. The GRAVILOG sensor ball and first stage oven

Results from Three Borehole Gravity Surveys

The borehole gravity data recorded by a combined Scintrex / Abitibi Geophysics crew in March 2012 in a borehole drilled into Donner Metals / Xstrata Zinc's Bracemac KT Zone deposit in the Matagami region of Quebec show responses to both the intersected high density gabbro layer and an off-hole massive sulphide tuffite (Figure 5). The tuffite had previously been identified as a conductor on a Crone BHEM log. The borehole gravity crossover response at 340 m vertical depth confirmed a direct correlation of excess mass to this conductor.

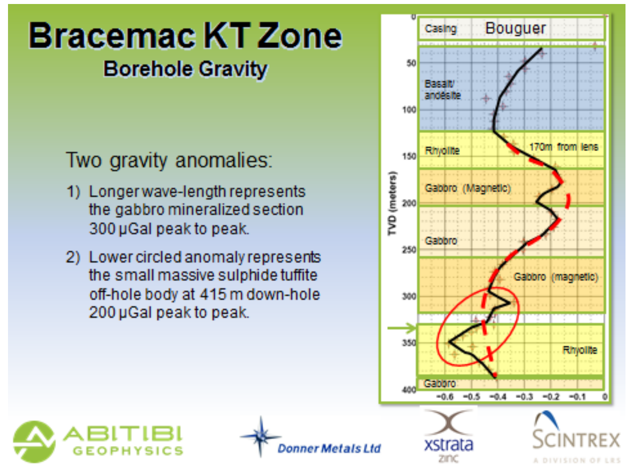

Figure 5. Bracemac KT borehole BRC-07-49. The gravity data are plotted against Total Vertical Depth, and the location of the BHEM crossover is marked by an arrow. Note that the gravity and EM crossovers are coincident. Also note the gravity anomaly caused by the changes in host rock density, as the gravity sensor passes from low density rhyolite into higher density gabbro.

In March, 2012, gravity data were acquired by an Abitibi Geophysics crew in four boreholes on Virginia Mines' Coulon Project Lens 44, a Zn-Cu-Ag deposit in Northern Quebec (Figure 6). Forward modeling (Giroux *et al*, 2006) and stochastic 3D inversion (Shamsipour *et al*, 2010) of the multi-hole borehole gravity data (Figure 7) match and potentially extend the Coulon Lens 44 deposit published on Virginia Mines' website, http://minesvirginia.com. This example shows a situation commonly encountered where a borehole has not been extended far enough past the deposit to completely resolve the gravity anomaly (Figure 8).

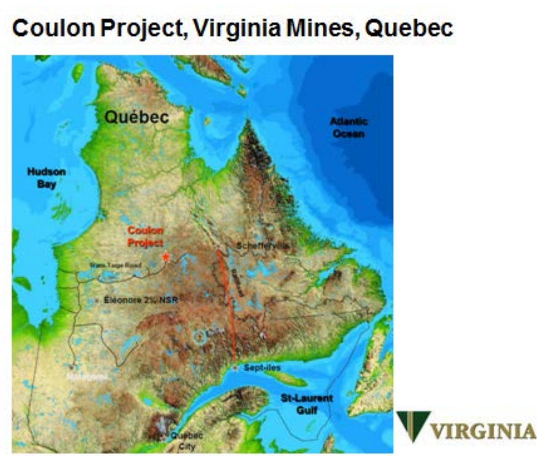

Figure 6. The location of Virginia Mines' Coulon project, Quebec, Canada

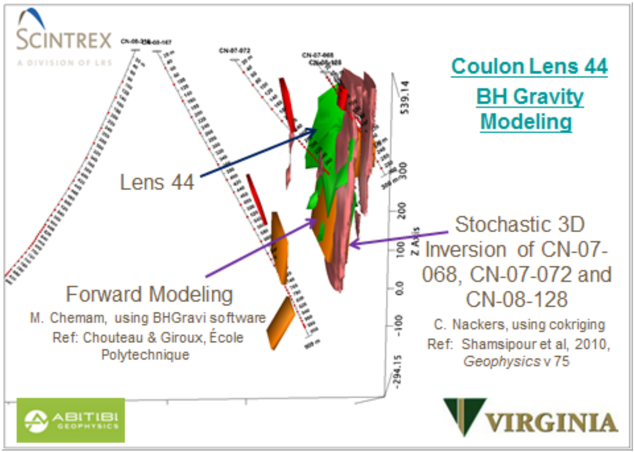

Figure 7. Forward Modeling and Stochastic 3D Inversion of borehole gravity data acquired in multiple holes at Virginia Mines' Coulon Project, Lens 44, compared to the extent of the deposit published on Virginia Mines' website.

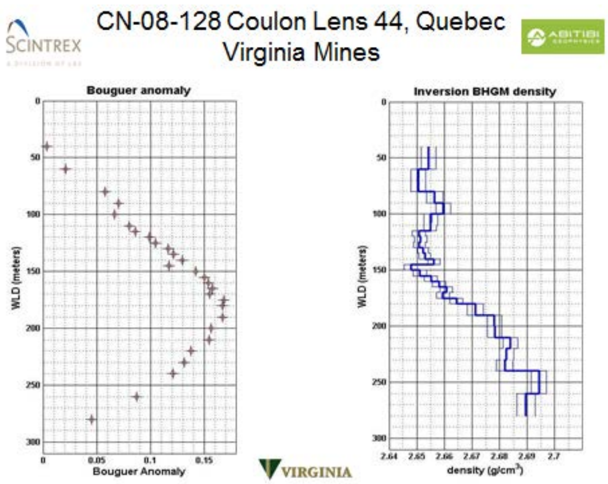

Figure 8. Borehole Gravity and Apparent Density measurements recorded in borehole CN-08-128 at Virginia Mines' Coulon Project Lens 44 deposit. The borehole does not extend far enough below the deposit to measure the complete gravity anomaly.

The determination of the bulk density of a formation has direct economic value in situations where ore grade is proportional to density. Labrador Iron Mines encountered difficulty obtaining density analysis on portions of the James Mine iron ore deposit, near Schefferville, Quebec. Strong alteration has removed most of the cementing silica and left a sandy friable texture resulting in poor core recovery.

In December, 2012, an Abitibi Geophysics crew acquired gravity data in several boreholes at Labrador Iron Mines' James South Extension deposit (Figure 9). The borehole gravity data from one of these boreholes is shown in Figure 10. The density profile of this resource was completed using a combination of the borehole gravity data and hundreds of core samples collected in multiple holes drilled between 2006 and 2010. Density data can now be determined onsite as samples are collected during the drilling season and combined with the borehole gravity data.

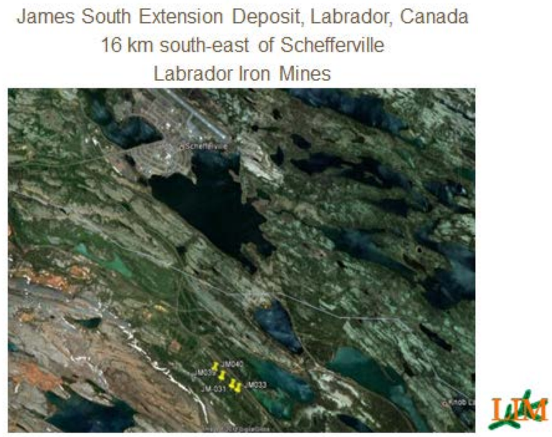

Figure 9. The location of Labrador Iron Mines' James South Extension deposit. Gravity data were acquired in the boreholes marked with yellow pins.

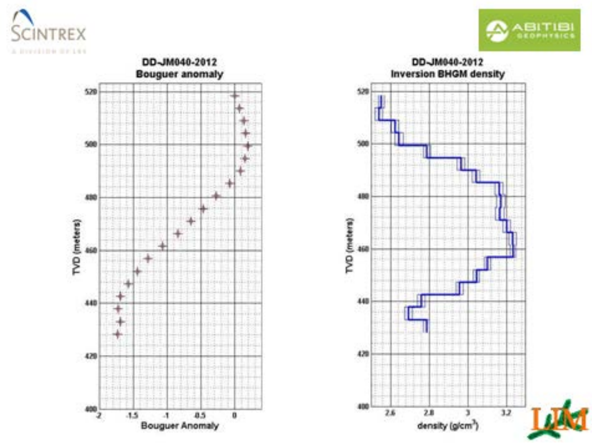

Figure 10. Gravity data recorded in Labrador Iron Mines's James Southern Extension borehole DD-JM040-2012, located at north-west yellow pin on Fig 9.

The Dual Sensor Borehole Gravity Probe

Referring back to Figure 2, depth control is essential for accurate density measurements. For example, an error of 2 cm between measurements spaced by 2 metres will result in an error in density of about 0.02 g/cm^3. Scintrex has developed a borehole gravity probe with two gravity sensors separated by 1.5 metres in the sonde (Figure 11). In addition to eliminating the spacing error between these sensors, data are recorded in parallel. Common mode noise is eliminated by differencing the two gravity channels.

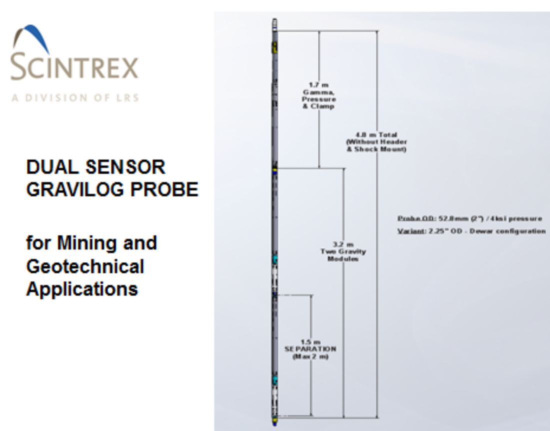

Figure 11. Scintrex dual sensor borehole gravity probe

Conclusions

Borehole gravity systems suitable for mining and geotechnical applications are now commercially available. Modern, innovative equipment and methods are critical elements for exploration success. The results presented in this paper, from recent borehole gravity surveys, show the potential of borehole gravity surveys to detect off-hole excess mass. Potentially the borehole gravity method will reduce exploration cost and time by delivering quantifiable information on the mass of the mineralization from a few boreholes early in the exploration cycle. Similarly, by extending in situ density measurements beyond the borehole, a real-time continuous density profile will help improve grade control.

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The dual sensor borehole gravity probe improves the accuracy of density measurements by removing a major source of error related to sensor separation.

Acknowledgments

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