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The Borehole Gravity Meter: Development and Results

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Summary

Borehole gravity (BHGM) measurements respond passively to the bulk density of a large rock volume surrounding the borehole, orders of magnitude larger than the volume sampled by nuclear logs or cores.

The first generation borehole gravity instrument was introduced in the 1960s and was suitable for large diameter petroleum wells. A second generation BHGM probe for mining and geotechnical applications was introduced in 2011. This paper includes a brief summary of the corrections applied to BHGM measurements as well as some interpretation guidelines. Several recent examples of BHGM data acquired in Canada and USA for mining exploration and CO_2 sequestration are presented.

Keywords: *Borehole gravity meter, BHGM, gravity, Bouguer*

Introduction

Borehole gravity log results have been reported in many papers between 1965 and 2000 (for example, McCulloh et al. 1968, Rasmussen 1975 and Popta et al 1990). First-generation BHGMs were limited to large-diameter, near-vertical boreholes and were deployed almost exclusively in hydrocarbon wells.

A second-generation BHGM has now been developed for mining and geotechnical applications (Nind et al 2007). The gravity sensor is based on fused quartz technology that has proved to be rugged and accurate in surface gravimeters. This BHGM probe can be operated on standard 4 or 7 conductor wireline in NQ (58 mm ID) mining drill rods with inclination from -30° to vertical and with ambient conditions limited to borehole temperatures and pressures typical in mining exploration. Sensitivity is better than 5 µGal.

Borehole gravity (BHGM) measurements respond passivley to the bulk density of rock volumes surrounding the borehole, orders of magnitude larger than the volumes sampled by nuclear logs or cores. Gravity measurements are unaffected by casing or formation damage caused by drilling (Smith, 1950; Jageler 1976; Beyer 1987, Table 1). A series of precise gravity measurements are collected at discreet intervals by stopping and reading the gravimeter at preselected borehole depths. These data require a series of processing steps to allow analysis of the local anomalous gravity responses.

Corrections Applied to Borehole Gravity Measurements

Gravimeter Drift

Drift in the measured values is modeled by revisiting measurement points to acquire enough statistical data for least-square analysis with sufficient degrees of freedom. The recommended method is to acquire gravity measurements from the bottom to the topof the borehole with no reversals of direction. The process should be repeated at least three times.

Earth Tides and Ocean Loading

Tidal and ocean loading gravity effects are removed using standard software algorithms based on time and location coordinates (for example, the ETGTAB tidal model from Wenzel 1996).

Free Air and Bouguer Slab

A BHGM log is dominated by the gravity of the entire Earth. For small depths, z, relative to the radius of the Earth, gravity varies approximately linearly with z. The first-order gradient in gravity, called the Free Air Gradient and denoted by FA, is approximately equal to -0.3086 mGal/m. The Free Air Anomaly (FAA) is calculated precisely and removed from the measured gravity by:

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$FAA = - (0.3087691 - 0.0004398 \sin 2\varphi)z + 7.2125x10-8z2$, in milliGal, (1)

where φ is the latitude at the well and z is the depth in meters. The large effect of the Free Air Anomaly on gravity measurements must be removed using Eq. 1 to reveal the much smaller anomalies of target density zones.

The Free Air Anomaly does not take into account the densities of the formations intersected by the borehole. A second-order correction, called the Bouguer Slab (BGA), is applied to account for the mass surrounding the gravity sensor.

$BGA = 4\pi G \rho z = (0.0838\rho) z$, in milliGal, (2)

where z and ρ are the measurement depth and mean density from the surface to the measurement depth, in metres and g/cm3 respectively.

The change of gravity caused by the combined Free Air Anomaly and Bouguer Slab, Δg, in milliGal, between two stations vertically separated by Δz, in metres is thus

$\Delta g/\Delta z = (0.3086 – 0.0838\rho)$, in milliGal per metre (3)

Extreme care must be taken to ensure that depth measurements are accurate. Depth induced error in Δ**g** is typically comparable to the sensitivity of the gravity measurement itself.

Latitude
Borehole gravity measurements are subject to variations in latitude, θ, given by

$\boldsymbol{\Delta g/\Delta y = 0.813\sin 2\theta - 1.78\times10^{-3}\sin 4\theta}$, in microGal per metre north **(Δy)** (4)

This correction is required when a borehole is inclined or when multiple boreholes are being logged.

Surface Topography and Underground Workings
Borehole gravity measurements are effected by topographic variations and underground workings in the vicinity of the borehole. Corrections may be calculated using forward modeling routines or “terrain correction” algorithms.

Regional Gradient
In some circumstances, there may be substantial regional gravity gradients due to large scale geologic features. Their effects may be removed by reference to regional gravity maps or by acquiring surface gravity measurements.

Simple Interpretation Rules-of-Thumb for BHGM Data

After applying these corrections, the residual “Bouguer gravity” data provides information about the distribution of densities in the geologic formations both in the vicinity of the hole and remote from it. Gravity data collected in a borehole that passes by a massive body located in an otherwise uniformly dense half space may be analyzed using simple interpretation rules-of-thumb **(Fig. 1)**.

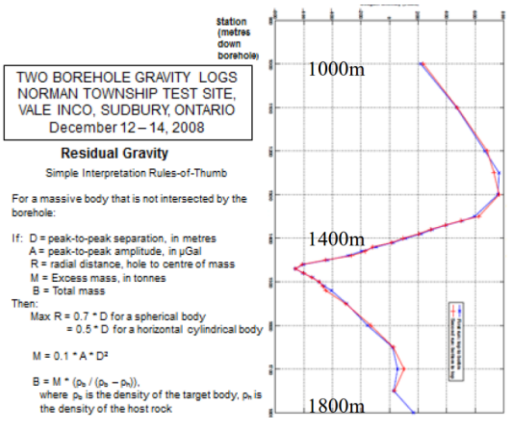


Fig. 1— Analysing Residual Bouguer Gravity from Borehole Gravity Measurements.

The residual anomaly “crossover” in **Fig. 1** is caused by the gravity sensor passing by the edge of a massive formation at a wireline depth of about 1400 metres. The host rock in this example from the Sudbury Basin in Ontario, Canada, has a fairly constant density of 2.77 g/cm^3. Some simple rules-of-thumb for estimating the off-hole distance and excess mass of a body that would cause this gravity response may be applied here:

If, D = peak-to-peak separation, in metres
A = peak-to-peak amplitude, in µGal
R = radial distance, hole to centre-of-mass
M = Excess mass, in tonnes
B = Total mass, in tonnes

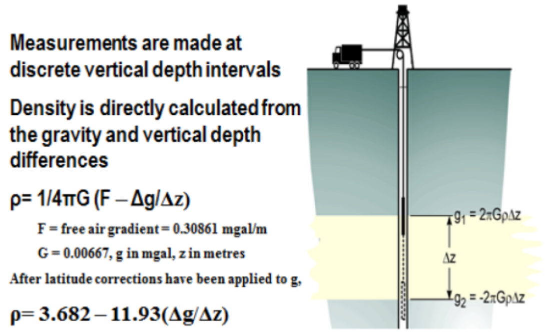
Then, $R_{max} = 0.7$ D, for a spherical body
= 0.5 D, for a horizontal cylindrical body
$M = 0.1 A D^2$
$B = M (\rho_b/(\rho_b-\rho_h))$, where ρ_b is the density of the target body, ρ_h is the density of the host rock

When a borehole intersects a massive body, the gravity anomaly is more complex and obeys Poisson's equation.

When gravity measurements are acquired in three or more boreholes bracketing a massive body, forward modeling and inversion routines (for example, Shamsipour et al 2010) can be used to construct a three-dimensional representation of the subsurface geology. An example of inversion using co-kriging is included in **Fig. 11**.

Bulk Density from BHGM Measurements

An application unique to borehole gravity is bulk density determination. In a strata dipping less than about 5º with locally uniform lateral density, $\Delta g/\Delta z$ is proportional to the bulk density of the bracketed layer **(Fig. 2)**.



Measurements are made at discrete vertical depth intervals

Density is directly calculated from the gravity and vertical depth differences

$\rho = 1/4\pi G\,(F - \Delta g/\Delta z)$

F = free air gradient = 0.30861 mgal/m

$G = 0.00667$, g in mgal, z in metres

After latitude corrections have been applied to g,

$\rho = 3.682 - 11.93(\Delta g/\Delta z)$

Fig. 2 – Shows the Concept of Obtaining Bulk Density from Borehole Gravity Measurements. $\Delta g = g_1 - g_2$ and $\Delta z = z_1 - z_2$.

In some cases, these apparent interval densities can be compared to core density and porosity or to nuclear density logs to separate the anomalous gravity component (Rasmussen 1975; Beyer 1971).

Bulk densities calculated from borehole gravity measurements are affected by complex geological structures and by strata that dip more than 5º. Densities simply calculated from $\Delta g/\Delta z$ by ignoring anomalous effects are *apparent* interval densities (LaFehr 1983).

Inversion Bulk Densities

The inversion BHGM density method described by MacQueen 2007, allows stable calculation of interval densities over much closer station spacings than are feasible using the conventional method. The damped least-squares techniques used in the inversion stabilize the density calculations.

The inversion bulk-density method has been employed in the examples below. Since the inversion method is a smoothing operator, sudden large, real changes in density between formations may be attenuated. In practice, bulk densities should be computed using both the conventional and the inversion routines.

Bouguer Gravity in Boreholes where Host Rock Density is Not Constant

When the borehole intersects formations with varying densities, the assumption behind the calculation of the simple Bouguer Slab correction is no longer valid. Brady et al 2013 describes processing methods that may be adopted to aid in visual recognition of the anomalous density zones.

The simple Bouguer Slab correction assumes that the gravity gradient in the borehole, after correcting for the free-air gradient, may be related to a constant density ρ_{BG}.

$$\frac{dg}{dz} = -4\pi G \cdot \rho_{\mathrm{BG}} \tag{6}$$

The gravity effect of a constant density is, thus, a linear gravity/depth trend.

$$g(z) = g_0 - 4\pi G \cdot \rho_{\mathrm{BG}} z \tag{7}$$

g_0 is an arbitrary integration constant, which can be ignored since BHGM logs are relative logs. A constant density is used to compute the Bouguer gravity for the entire log. **Fig. 1** above is an example where the assumption of constant density is reasonable.

A constant density with depth is often an invalid assumption, in which case computing Bouguer gravity using **Eq. 7** will yield misleading results. Brady et al 2013 describes the bulk density log measured in an injection well (**Fig. 3**). The injected mass has increased the density at the bottom of the well. **Fig. 4** is the result of processing these gravity data using a constant density with depth.

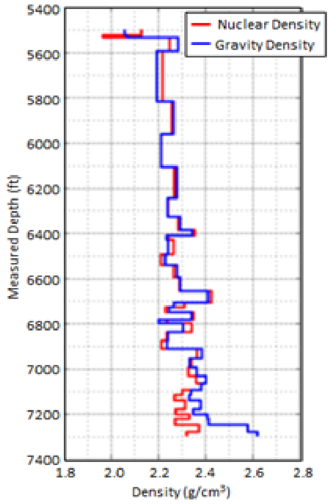


Fig. 3—The Bulk Densities calculated from Borehole Gravity Measurements in an Injection Well are shown and compared with Nuclear Density Measurements in the same Well.

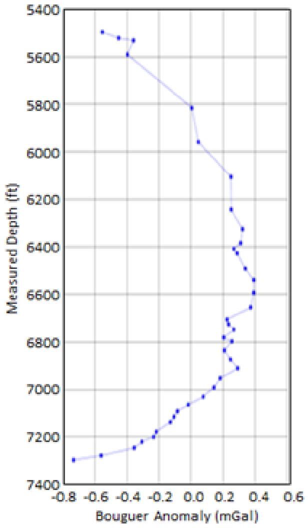


Fig. 4—The Bouguer anomaly of the well shown in Fig. 3, calculated using a constant density.

Eq. 7 may be extended to the case of linear density increase with depth, which is commonly encountered in sediments.

$$g(z)=g_0-4\pi G\left(\rho_0\left(z-z_0\right)+L\left(z-z_0\right)^2\right) \tag{8}$$

where ρ_0 is the density at depth z_0 and L is a constant.

Applying **Eq. 8** to the gravity measurements acquired in the well in **Fig. 3**, with a suitable choice of z_0 and ρ_0, yields the Bouguer gravity for the linear density/depth case plotted in **Fig. 5.**

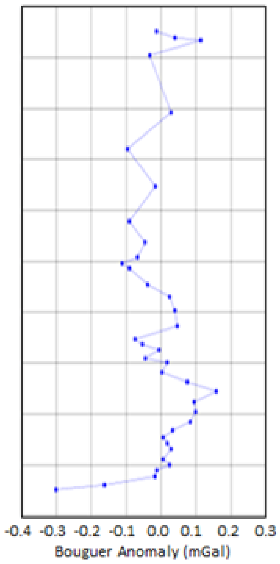


Fig. 5—The Bouguer anomaly of the well shown in Fig. 3, from 5400 ft to 7400 ft measured depth, calculated using a linear density/depth relationship.

When pre-existing density information is available from a nuclear density log of the well, the ability of BHGM gravity data to indicate anomalous density zones can be enhanced. Gamma-residual Gravity (GRG) extends the Bouguer Slab concept to further refine the gravity derived densities. GRG at a given depth z is defined as the residual gravity after forward modelling the densities from an existing nuclear density log of the well.

$$\mathrm{GRG}\left(z\right)=\mathrm{FAA}\left(z\right)-g_\gamma\left(z\right) \tag{9}$$

where FAA(z) is the BHGM free-air corrected gravity and $g_\gamma(z)$ is the calculated gravity from forward modelling the nuclear log densities. If the nuclear densities $\rho_\gamma(z)$ are provided over a depth range from z_t (shallowest) to z_b (deepest), $z_t \le d \le z_b$, then $g_\gamma(d)$ can be calculated by integration, adding the gravity from the mass below d and subtracting the gravity from the mass above d.

$$\begin{aligned} g_\gamma\left(d\right) &= \int_d^{z_b} 2\pi G\rho_\gamma\left(z\right)dz-\int_{z_b}^{d} 2\pi G\rho_\gamma\left(z\right)dz \\ &= 2\pi G\left(\int_d^{z_b}\rho_\gamma\left(z\right)dz-\int_{z_b}^{d}\rho_\gamma\left(z\right)dz\right) \end{aligned} \tag{10}$$

The GRG result for the gravity measurements acquired in the well in **Fig. 3** is plotted in **Fig. 6**.

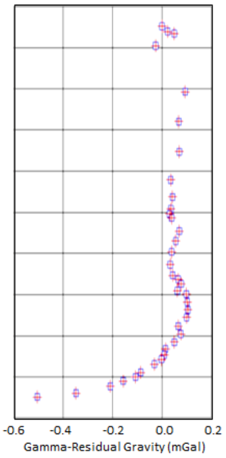


Fig. 6—The gamma-residual gravity of the well shown in Fig. 3, from 5400 ft to 7400 ft measured depth

Results from Four Borehole Gravity Surveys

Matagami, Quebec, Canada

The borehole gravity data recorded in March 2012, in a borehole drilled into Donner Metals / Xstrata Zinc's Bracemac KT Zone deposit in the Matagami region of Quebec (**Fig. 7**) shows responses to both the intersected high-density gabbro layer and an off-hole mass (**Fig. 8**). The borehole gravity crossover response at 340 m vertical depth is coincident with a BHEM crossover, directly correlating excess mass with a conductor. The longer wavelength gravity anomalies can be explained by density changes of the formations intersected by the borehole, with lower density rhyolites bracketing a thick wedge of higher density gabbro.

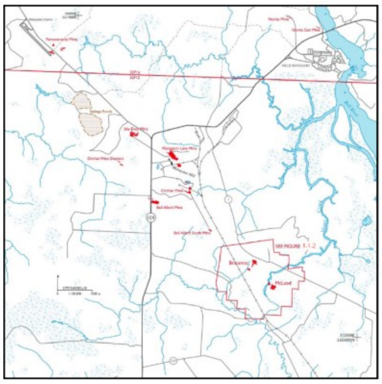
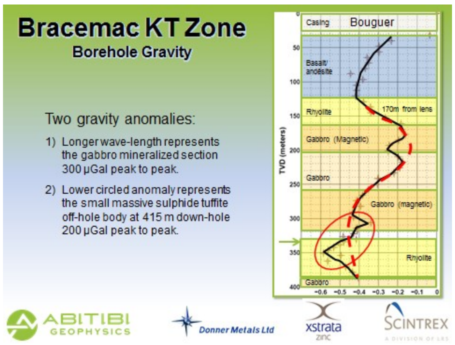


Fig. 7 _ The Location of the Bracemac Deposit in the Matagami Region of Quebec.



Bracemac KT Zone

Borehole Gravity

Two gravity anomalies:

1) Longer wave-length represents the gabbro mineralized section 300 µGal peak to peak.
2) Lower circled anomaly represents the small massive sulphide tuffite off-hole body at 415 m down-hole 200 µGal peak to peak.

Fig. 8 _ The Bouguer Gravity recorded in Bracemac KT Borehole BRC-07-49. The location of the BHEM crossover is marked by an arrow.

Middle-North Territory, Quebec, Canada

In March, 2012, gravity data were acquired in four boreholes on Virginia Mines' Coulon Project, Lens 44, a Zn-Cu-Ag deposit in the Middle-North Territory of Quebec (Fig. 9). Forward modeling (Giroux et al, 2006) and stochastic 3D inversion (Shamsipour et al, 2010) of the multi-hole borehole gravity data (Fig. 10) match and potentially extend the Coulon Lens 44 deposit published on Virginia Mines' website, http://minesvirginia.com.

Coulon Project, Virginia Mines, Quebec

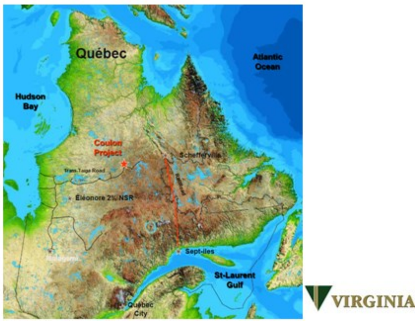


Fig. 9 _ The location of Virginia Mines' Coulon Project, Quebec.

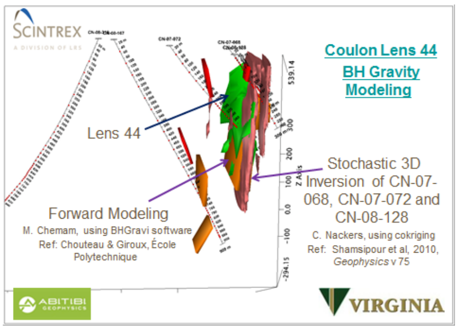


Fig. 10 _ Forward Modeling and Stochastic 3D Inversion of Borehole Gravity Data acquired in Multiple Holes at Virginia Mines' Coulon Project, Lens 44, compared to the extent of the deposit published on Virginia Mines' website.

Schefferville, Quebec, Canada

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 (**Fig. 11**). Strong alteration has removed most of the cementing silica and left a sandy friable texture resulting in poor core recovery.

In December, 2012, gravity data were acquired in several boreholes at Labrador Iron Mines' James South Extension deposit. The location of four of these boreholes is shown in **Fig. 11**. The borehole gravity data from one of these boreholes is shown in **Fig. 12**. 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.

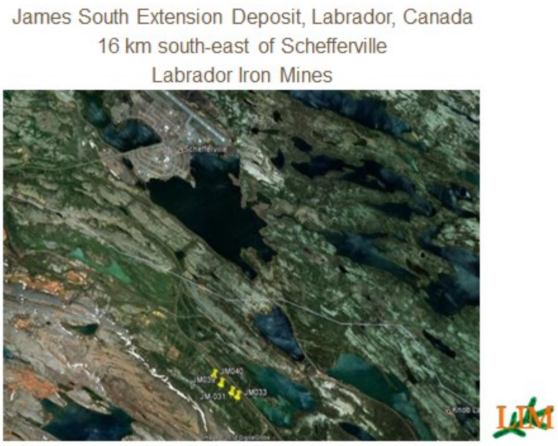


Fig. 11 _ The Location of Labrador Iron Mines' James South Extension Deposit. Gravity Data was acquired in the boreholes marked with yellow pins.

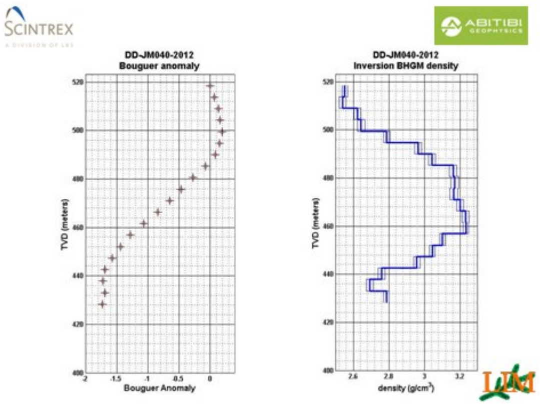


Fig. 12 _ Gravity Data and BHGM Densities recorded in Labrador Iron Mines's James Southern Extension Borehole DD-JM040-2012, located at north-west yellow pin on Fig 14.

Conclusions

Borehole gravity systems suitable for mining and geotechnical applications are now commercially available. Modern, innovative equipment and methods are critical elements in 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. The borehole gravity method can 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.

Baseline surveys have been conducted in the USA to assess the value of BHGM to monitor underground storage of CO_2 and other substances.

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