ACQUISITION, PROCESSING, AND INTERPRETATION OF GRAVITY DRILL HOLE DATA

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BACKGROUND

A high-precision borehole gravity (BHGM) survey was acquired in five drill holes intersecting the host-rock periphery of the Lalor VMS deposit. The benefits of using borehole gravity for exploration were recognized more than 64 years ago by Smith (1950). Considering that the decay of the gravity field is inversely proportional to the squared distance between an anomalous mass and the gravimeter, it is obvious that the potential for detecting a local anomalous mass at depth is significantly enhanced in comparison to surface or airborne gravity surveys. The first borehole gravity surveys were limited to petroleum applications where gravimeters were deployed in large-diameter and near vertical boreholes (see for example McCulloh *et al.*, 1967; McCulloh 1965; LaFehr 1983; Popta *et al.*, 1990). A new generation of borehole gravimeters (GRAVILOG) has recently been developed that is small enough to be deployed in boreholes with NQ (47.6 mm core) diameter (Nind *et al*., 2007) which is a commonly-used standard in mineral exploration. This innovation made it possible to conduct the gravity drill hole survey of the Lalor deposit.

In February 2014 borehole gravity data were acquired by Abitibi geophysics in 5 drill holes intersecting the host-rock envelope of the Lalor deposit. These drill holes were selected from a limited subset of surface exploration drill holes that were left open in the periphery of the massive sulphide ore zones (all the other drill holes were cemented to protect the excavation of mine workings at depth from infiltrating surface water). The objectives of the drill hole gravity survey were to interpret the density distributions associated with geological formations in the hanging wall and footwall of the VMS deposit and to identify additional anomalous masses potentially associated with massive sulphide mineralization lying outside the drill-intersected portion of the deposit. The geological significance of the gravity drill hole data was evaluated by comparing the derived apparent density logs with co-located lithofacies and immobile element ratios logs computed from drill hole lithogeochemistry. In addition, gamma-gamma density logs that were previously acquired in a multi-parameter geophysical log survey, provided a secondary information source for mapping the subsurface density distribution and aided the correlation of apparent density anomalies across larger distances.

Four of the surveyed drill holes (DUB202, DUB280, DUB282 and DUB287) intersect geological formations in the down-plunge extent of the Lalor sulphide ore lenses, while one drill hole (DUB279) intersects the host rocks up-plunge from the known sulphide ore lenses (Figure 1). The GRAVILOG sensor was lowered in each borehole using a cable-winch and left one hour to stabilize. Each borehole was logged twice in one direction for quality control. At least five readings were taken at each station. More readings were recorded when the difference between them exceeded 3 μGal.

Corrections and reductions applied to gravity drill hole data

Corrections of the borehole gravity measurements were conducted using routine processing procedures. After obtaining the observed gravity subsequent to the instrument corrections (for drift, tidal, temperature and sensor rotation) the Bouguer anomaly logs were computed from:

$$G_B = G_{obs} - F - BE \qquad [1]$$

Where F is the free-air gradient that compensates for the increase in gravity with depth (free-air correction):

$$F = -(0.308769 + 0.0004398 \sin^2 \varphi)h + 7.2125 * 10^{-8}h^2 \qquad [2]$$

Where φ is the latitude of the borehole and h is the depth of the stations in m and BE is the Bouguer effect for drill hole gravity data (twice the Bouguer effect of surface gravity data) and defined by:

$$BE = -4\pi G\rho h \qquad [3]$$

Where ρ is the slab Bouguer density and G the universal gravitational constant.

Computation of apparent density logs

The main application of borehole gravity measurement is to determine the mean bulk density of the geology formations where the borehole is traversed. Smith (1950); Hammer (1950) and LaFehr (1983) provide the theoretical basis for the method of governing bulk densities. Under the assumption of a horizontally-layered earth, the mean bulk density of the rock formations between two stations is proportional to the gravity gradient measured over these stations minus the free-air vertical gradient of the Earth's gravity within a radius of about five times their vertical spacing (Nind *et al*., 2007):

$$\rho_{n+1|n} = \frac{1}{4\pi G}\left\{F - \frac{(g_{n+1} - g_n)}{(z_{n+1} - z_n)}\right\} \qquad [4]$$

Where $\rho_{n+1|n}$ is the rock density between depths z_n and z_{n+1}, F is the free-air gradient, $g_{n+1} - g_n$ is the difference in gravity readings at depths z_{n+1} and z_n respectively and G is the universal gravitational constant. It should be noted that the

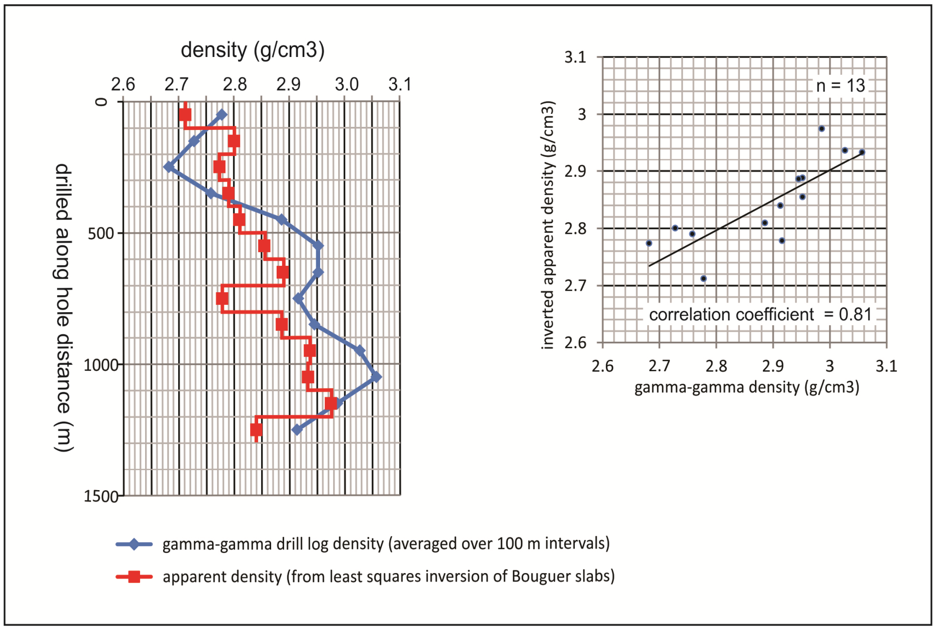

Figure 23. Apparent density and gamma-gamma density logs of borehole DUB202. Inset shows scatter plot between apparent and gamma-gamma densities.

density obtained in this calculation is an apparent density because it is based on the assumption of a horizontally-layered earth. As a result in settings with dipping geological formations, the apparent density anomaly can, dependent on the geological structure, be significantly offset from the causative mass intersected in the drill hole. MacQueen and LaCoste (2007) introduce a method to calculate densities using inversion techniques to accommodate for the influence of interval densities above and below the density interval considered. Application of this method can be useful to recover densities at station spacing as small as one meter.

INTERPRETATION OF GRAVITY DRILL HOLE DATA

In order to support geological interpretation of the apparent density logs, co-located lithofacies and Zr/TiO_2 immobile element ratio logs were compiled from the industry drill hole database. Detailed lithofacies descriptions of FROM-TO intervals of the industry drill hole database were encoded into 16 lithofacies classes. This classification categorized volcanic and volcaniclastic rocks into felsic, intermediate and mafic classes of volcanic rock composition. The volcaniclastic rocks were further subdivided into coarse tuff breccia and finer-grained lapilli tuff and tuff lithofacies. Intensely hydrothermally-altered and metamorphosed equivalents of these rocks were subdivided into schist and gneiss, while the remainder of rock units intersected in the drill holes were classified into argillite, gabbro, fault rocks, quartz veins and sulphide ore, yielding a total of 16 lithofacies classes. The Zr/TiO_2 immobile element ratio, routinely used as a proxy to differentiate volcanic protoliths of felsic, intermediate and mafic composition (Winchester and Floyd, 1977) was particularly useful to interpret the apparent density logs across drilled intervals of gneiss and schist in the hydrothermally-altered footwall of the deposit where it is virtually impossible to visually recognize the volcanic/volcaniclastic rock of origin (i.e. protolith).

DUB202

Borehole DUB202 is the only drill hole for which a gamma-gamma density log is available. Figure 23 shows the apparent density and gamma-gamma density log, the latter being averaged over 100 meter intervals to facilitate comparison with the apparent density intervals. Note that although the minimum and maximum amplitudes of the averaged gamma-gamma density logs exceed the extremes of the apparent density logs, the log patterns are broadly similar. Moreover, the apparent and averaged gamma-gamma density values appear to be highly-correlated (Figure 23). The difference in amplitude range is obviously due to the much larger rock volume sampled in the drill hole gravity measurements around the drill hole in comparison to the rock volume sampled in the gamma-gamma density log survey. The gamma-gamma density log, in turn, is highly correlated with the densities of 32 rock samples that were co-located within 10 cm from the stations of the geophysical wireline log (Figure 24). The rock density samples show distinctly higher density for sulphide ore samples and a linear increase from felsic to intermediate to mafic volcanic host rock compositions. The gneiss and schist samples span this full range, suggesting that the density variations of their volcanic protoliths from which they were derived were preserved (Figure 24).

A distinct approximately linear trend from 2.72 to 2.98 g/cm^3 can be observed in the apparent density log from surface to 1200 m (Figure 25), which is likely due to a regional background effect, in which density gradually

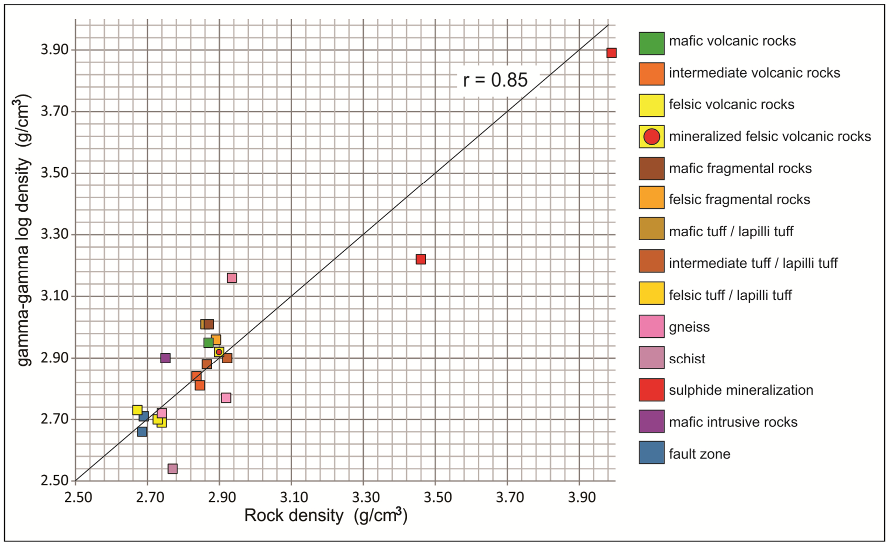

Figure 24. Scatterplot of gamma-gamma density logs averaged over 100 m intervals versus drill core sample densities co-located along borehole DUB202 within 0.1 m.

increases with depth. Higher spatial frequency apparent-density variations, superimposed on this trend, approximately correspond to alternating mafic and felsic volcanic and volcaniclastic rock units in the hanging wall of the Lalor VMS ore zones. Apparent density values ranging between 2.72 – 2.82 g/cm^3 correspond to felsic volcanic units (rhyolite and rhyodacite), whereas apparent-density values between 2.82 and 2.98 g/cm^3 correspond to mafic volcanic (basalt, andesite) and mafic volcaniclastic units (mafic tuff breccia). An acute decrease in apparent density at a drilled distance of 1200 m occurs 50 m below the contact between mafic volcaniclastic rocks in the hanging wall of the Lalor deposit and schist and gneiss in its footwall. The significant decrease in apparent-density of approximately 1.0 g/cm^3 across this contact is readily explained by the high Zr/TiO_2 ratio between 1220 and 1340 m (Figure 25), which suggest that the gneisses were derived from a felsic volcanic protolith with preservation of a relatively low density of 2.80 g/cm^3.

Another local apparent-density low occurs at a depth of 1420 m. This low corresponds to another more localized Zr/TiO_2 peak, suggesting that this relatively thin interval also corresponds to a gneiss with a felsic volcanic protolith. The spatial association between apparent density lows and felsic volcanic rocks are also evident on DUB280 and DUB282. The highest apparent density anomalies between 3.01 and 3.02 g/cm^3 occur at depths of 1450 and 1520 m and correspond to gneisses of mafic composition. Their anomalously high values compared to rock intervals of mafic composition elsewhere along the hole may suggest that they are also due to sulphide ore in the vicinity of the drill path of DUB 202.

DUB279

The apparent-density log of DUB279 (Figure 26) shows a significant increase from 2.83 to 2.89 g/cm^3 at 155 m corresponding to the contact between felsic volcanic and mafic volcaniclastic rocks and an abrupt decrease of the Zr/TiO_2 log. A highly variable interval from 600 to 800 m cannot be unequivocally correlated to the corresponding lithofacies interval of intermediate and felsic volcanic rocks. Also the Zr/TiO_2 log shows peaks that are only locally consistent with volcanic rocks of intermediate composition. The apparent density log shows a variable but a high average density of approximately 3.0 g/cm^3 between 820 and 940 m, corresponding to mafic volcaniclastic and volcanic rocks in the lithofacies log. At 840 m a local anomaly of 3.12 g/cm^3 (Figure 26) which is the highest apparent density value obtained for the gravity drill hole survey, appears to correspond to a 20 m thick weakly mineralized mafic tuff unit and a carbonate-altered pyrrhotite-bearing argillite. These thin lithofacies intervals, exhibiting disseminated mineralization only, however, unlikely explain this significant apparent-density anomaly. Considering the proximity of the ore horizon at this structural level, the alternative interpretation is that the anomaly is due to more massive sulphide ore in the vicinity of the drill hole. To corroborate this interpretation the excess mass was computed from the corresponding peak-to-peak Bouguer anomaly of 0.661 mGal, assuming a spherical causative body not intersected in the drill hole Blakely (1996):

$$M = 0.1A.D^2 \quad with \ \ R = 0.7D \qquad [5]$$

Where M is the excess mass in tonnes, A = the peak-peak amplitude (in μGal), D is the peak-peak distance in meter and R is the radial distance from the center of the anomaly to the center of mass in meters (Nind *et al.*, 2007). Using this formula yields an excess mass of 0.7 mT at a distance of approximately 100 m from the borehole, which would be consistent with the interpretation that the Bouguer anomaly is caused by a nearby mass not intersecting the borehole, potentially representing sulphide mineralization.

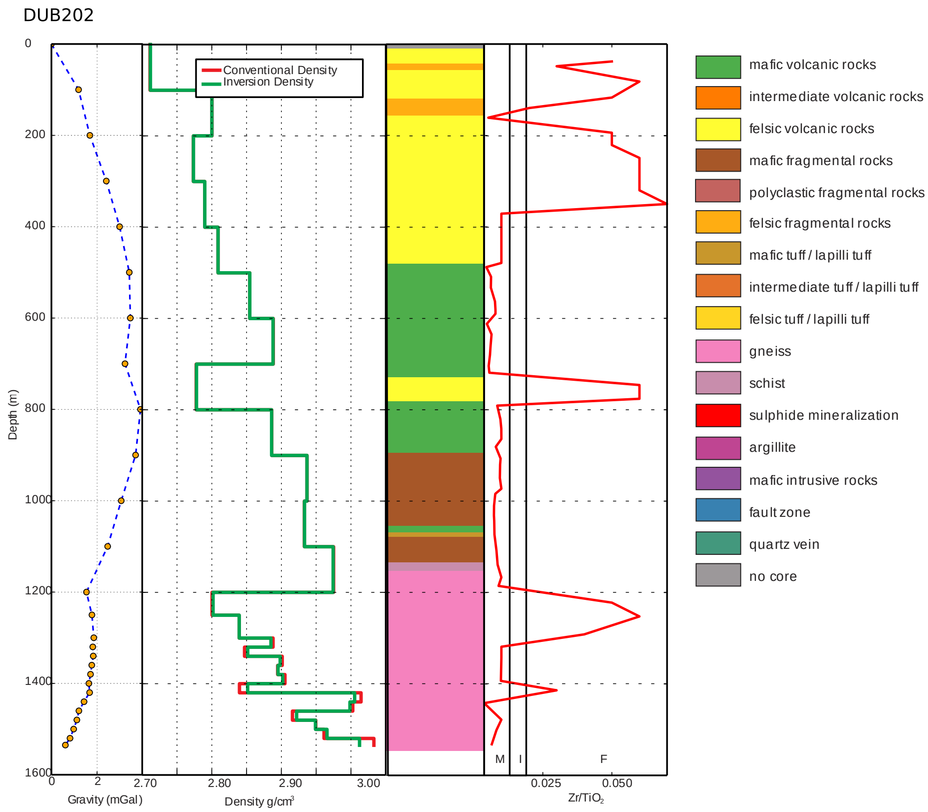

Figure 25. Bouguer, apparent density, lithofacies and Zr/TiO2 logs of borehole DUB202.

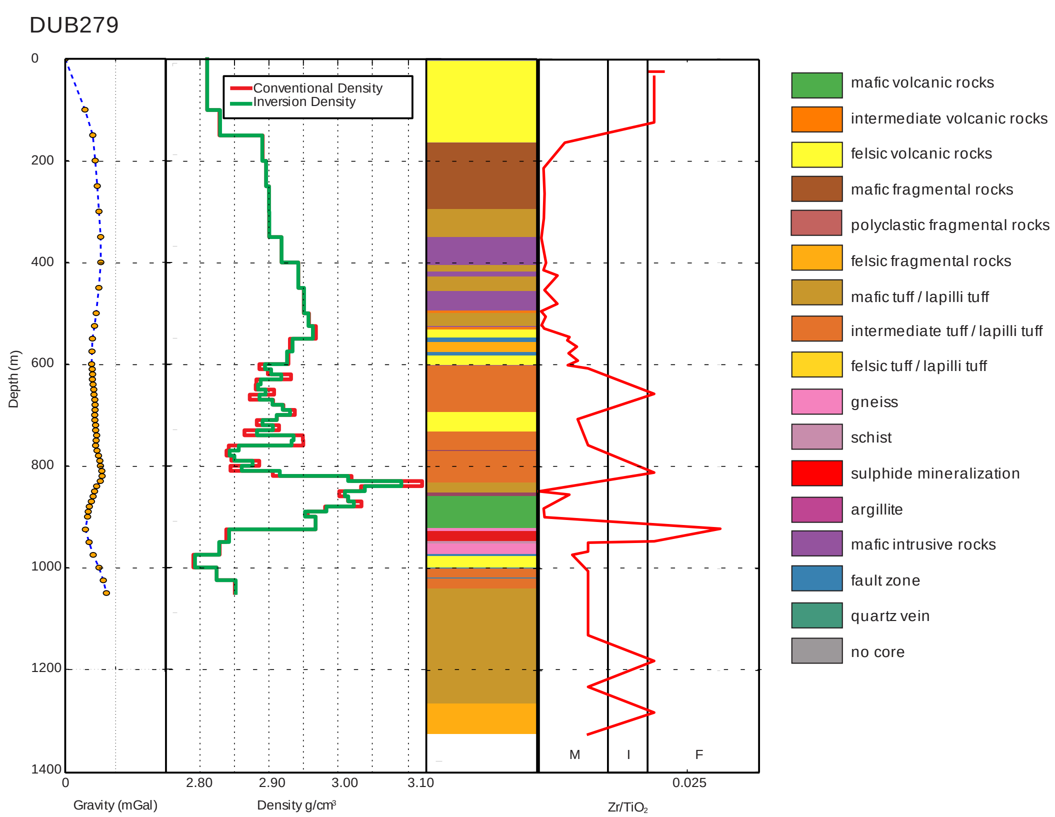

Figure 26. Bouguer, apparent density, lithofacies and Zr/TiO2 logs of borehole DUB279.

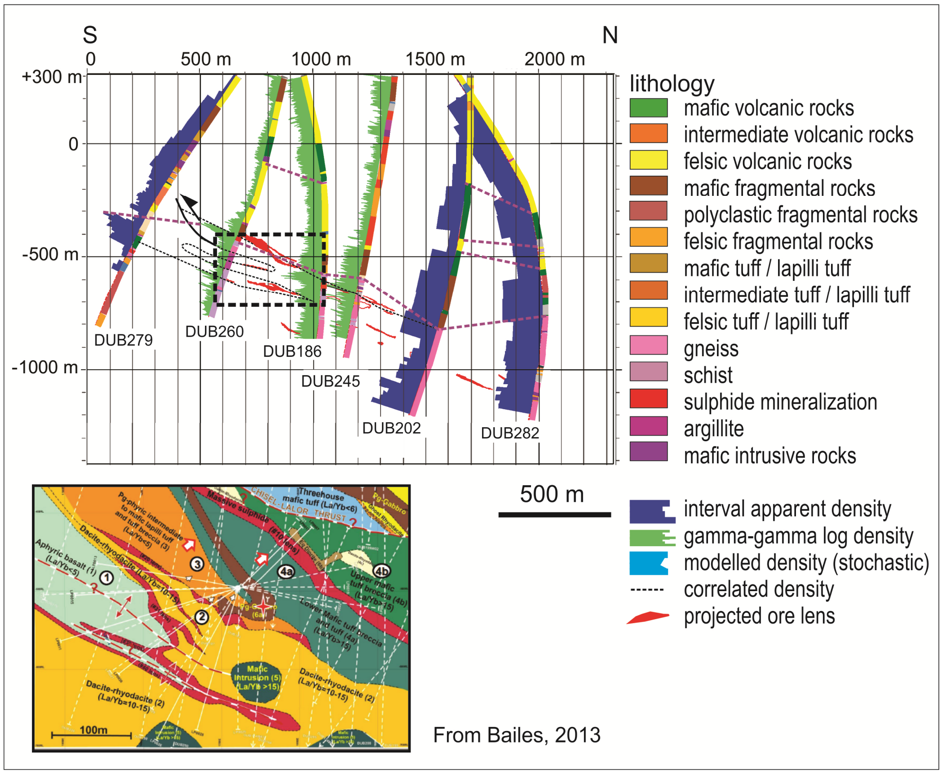

Figure 27. NS-oriented section to interpret hole-to-hole correlation of apparent and gamma-gamma density anomalies (purple lines) with projections of lithofacies logs and 3D sulphide ore shell models; Inset shows detailed section of geological interpretation of underground mapping and geological interpretation of drill logs from Bailes (1993). This section shows S-vergent isoclinal syncline of the ore horizon (red colour) enveloping basalt in its core. See text for more details on the interpretation.

Correlation of apparent density anomalies across the Lalor deposit

A number of distinct apparent density anomalies of similar geological origin, such as the sharp decrease in density across the hanging wall and footwall of the Lalor ore zone, can be recognized in the gravity boreholes. In an attempt to correlate these anomalous features from hole to hole, the apparent density logs were together with their associated lithofacies logs projected on a NS-oriented vertical section (Figure 27). The projected gamma-gamma density logs of three drill holes and 3D models of the sulphide ore lenses were included on this section to facilitate correlating density signatures over the relative large distance between borehole DUB279 and the other four boreholes. Correlated apparent density anomalies on the sections are marked by purple lines, while associated hole-to-hole correlated lithofacies are marked by yellow lines. The overall conformable pattern and close spacing between these lines on both the NS- and EW-oriented sections shows that, overall, there is a good correlation between apparent density contrasts and geological units.

A distinct decrease in apparent density low between 750 to 1000 m depth can be correlated from borehole DUB282 to DUB202 on the northern extent of the NS-oriented section. This abrupt decrease marks the contact between mafic volcanic and volcaniclastic rocks in the hanging wall and gneiss and schist in the footwall of the massive sulphide lenses of the Lalor deposit and can be traced along this contact to similar breaks in the gamma-gamma density logs of boreholes DUB186 and DUB245 (Figure 27). The highest peaks in the gamma-gamma density logs, just below the hanging wall - footwall contact, correspond to massive sulphide intersections in boreholes DUB260, DUB186. The spiked gamma-gamma density signature of these two boreholes is tentatively correlated with the highest amplitude in the apparent density log of borehole DUB279 (Figure 27). The apparent offset between this peak in DUB279 and the gamma-gamma density signature of DUB260 is readily explained by a geological structure which after restoration of its apparent displacement would align this peak with the projected massive sulphide ore zones on the section. This structure brings rocks intersected in the drill holes south of DUB279 over rocks intersected in DUB279 along a N-dipping structure with a displacement that is in agreement with the apparent offset between intervals of sulphide mineralization in holes DUB279 and DUB260 (Figure 27).

This structure has been previously recognized in underground geological mapping campaigns in which the ore zone is involved in S-vergent asymmetric isoclinal folds and possibly a N-dipping shear zone abruptly separating intensely hydrothermally-altered from unaltered volcanic rocks (Bailes *et al.*, 2013; Caté *et al.*, 2013). It is interesting to note that if the excess mass of 0.7 mT (spherical body) computed for the Bouguer anomaly at DUB279 is caused by sulphide mineralization, this could suggest an up-plunge continuation of the main sulphide ore zone towards the S beyond current drilling extent.

CONCLUSIONS

The gravity borehole data acquired in drill holes in the Lalor VMS mine camp display significant apparent density anomalies that can be correlated across the NS extent of the deposit. An apparent offset between the density anomaly patterns is consistent with fold and fault structures inferred in underground mapping campaigns juxtaposing contrasting intensities of alteration and different geological units. Most of the apparent density anomalies correspond to alternations of mafic and felsic volcanic rocks in the hanging wall and their hydrothermally-altered and metamorphosed equivalents in the footwall. There is a consistent spatial association between apparent density lows and Zr/TiO_2 peaks indicative of felsic volcanic rocks throughout the hanging- and footwall- successions, including rocks affected by intense hydrothermal alteration and metamorphism in the proximal footwall of the VMS ore zones. This is an important result, which suggests that the density contrasts between volcanic protoliths in metamorphosed hydrothermally-altered rocks (e.g. gneiss and schist) remain intact despite their intense hydrothermal alteration and subsequent metamorphic recrystallization. This finding also corroborates the analysis of compressional seismic velocity and density data from drill core samples that supported the interpretation of the 3D seismic cube (see section on physical rock properties) which shows that seismic impedance contrasts between rock units (i.e. gneiss /schist) with protoliths of felsic and mafic composition remain preserved.