**Geological interpretation of the northern flank of the
Matagami Camp, Quebec, using gravity and magnetic
inversions**

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Abstract

The northern flank of the Galine anticline of the Matagami camp has been well known for decades for hosting polymetallic VMS deposits (mostly copper and zinc). In such an explored area, sophisticated exploration tools must be used in the hope of generating new information. By integrating geophysical, petrophysical and geological data into a 3D Common Earth Model to constrain gravity and magnetic inversions, our objective is to validate and improve the geological interpretations of the area and to highlight geophysical anomalies unexplained in the current geological model.

Both three-dimensional magnetic and gravity data inversions confirm the surface geometry and the steep dip of the geological units. The inverted gravity models indicate that units observable at the surface of the northern flank extend subvertically to several kilometers depth. The pyroxenitic phase of the Bell River Complex is most certainly steeply dipping to the south, contrary to some surface measurements. The Olga pluton shows no significant decrease in width at depth, with the exception of the west end, which appears to be an apophysis. A major unknown mass, which may correspond to a synvolcanic mafic intrusion that is not outcropping, is revealed in the Allard

37 River volcanic rocks. The improved geophysical model featuring geometrical constraints
38 obtained by careful processing and inversion of the potential-fields data could contribute to new
39 exploration targets.

40

41 Keywords: gravity; magnetic; inversion; geology; Matagami.

Draft

Introduction

In a context where most of the surface deposits have been discovered, it is crucial to better understand the three-dimensional geometry of mining districts in order to identify deeper potential areas, especially in the case of mature camps such as the Matagami mining camp (Abitibi Greenstone Belt, Quebec, Canada). The volcanogenic massive sulfide polymetallic deposits in this region are zinc and copper-rich with additional gold and silver (Galley et al. 2007) and have been known and exploited since the late 1950s. Since the first discovery, the camp has produced 45.9 Mt of metals, with more than half extracted from the Mattagami Lake mine. The camp features higher zinc grades compared to VMS-type deposits in other camps (such as Noranda) which contain relatively more copper. Currently only one mine is in operation, the Bracemac-McLeod mine, managed by Glencore. Mined for over 50 years, this camp has probably not yet revealed all its resources as evidenced by the recent discoveries of several deposits (Bracemac and MacLeod). However, in a well-known camp, new discoveries require sophisticated analysis and interpretation for which the surface or near-surface information is not enough. If drilling provides extremely accurate information locally, geophysics provides a broader view and has the ability to detect potential targets at considerable depths.

In the Matagami Camp (Fig. 1), the Bell River Complex, a major layered gabbroic intrusion, forms the core of the Galine anticline (MacGeehan et al. 1981; Piché et al. 1993; Pilote 2010; Pilote et al. 2011). One of our major objective is to better define its extension and dip on the northern flank of the anticline using geophysical data; it would help in discriminating between several structural interpretations of the camp. The presence of unsuspected geological bodies and the geometrical relationship between the Olga pluton and the surrounding Wabasse Group will also be tested (Fig. 1).

Gravity and magnetic data of the Matagami mining camp are available from compilations done by the Geological Survey of Canada (Jobin et al. 2009; Keating and D'Amours 2010; Keating et al. 2010). Geological mapping has been improved thanks to detailed fieldwork carried out by the provincial geological survey (Ministère des Ressources Naturelles et de la Faune) (Pilote 2010). Data integration and comparison are necessary to make use of the wealth of new data. Here we use both the known geology along with the geophysical data to test hypotheses and build geological models that fit all the observations. Recent advances in interpretation with sophisticated computer tools allow the generation of 3D models of physical properties of the geological units from potential-fields data (Li and Oldenburg 1996, 1998; Oldenburg and Li 2003) taking into account a variety of information such as geological maps or structural trends (Boulanger and Chouteau 2001; Lelièvre et al. 2009). This is done using geophysical data inversion. Potential-field inversion is an underdetermined non-unique problem, but if it is properly performed and realistically constrained to include various types of information, it allows finding a distribution of the subsurface physical properties that is close to reality (Oldenburg and Li 2005). Thus, appropriate and sufficient data used as *a priori* information is often able to efficiently constrain the solution and to produce an interpretable result. Inversion can also be used as an efficient tool to test the validity of a geological model, to define the extensions of some major geological structures or to limit the depth range of targets, particularly in mature, well-studied camps as Matagami (Beaudry and Gaucher 1986; Hammouche et al. 2010; MacGeehan 1979; Piché et al. 1993; Pilote et al. 2011; Rabeau 2013; Williamson 2013). Improving the knowledge of the geometry of the geological units is important to identify exploration areas that may contain volcanogenic massive sulphide (VMS) deposits. Some work along those lines was already done on the south and west flank of the Matagami camp to test a structural link between the rhyolitic horizons of each flank (Boszczuk et al. 2011). The present work completes the

previous studies by performing the same methodological approach for the northern flank of the Galine anticline. However, constraints will be selected differently in order to comply with the local geology.

We invert the gravity and magnetic data, constrained by the mapped geology and the rock properties available from existing database and additional measurements we have made. We use the programs GRAV3D and MAG3D of the University of British Columbia - Geophysical Inversion Facility (UBC- GIF) (Li and Oldenburg 1996, 1998).

Geological Context

Piché et al. (1993) provided a very detailed description of the camp that forms the basis of recent knowledge about the Matagami mining camp. This work has been augmented by several major contributions from PhD students' theses and field work performed by the provincial geological survey (Ministère des Ressources Naturelles et de la Faune du Québec) (Debreil et al 2018; Genna et al. 2013; Pilote et al. 2011; Ross et al. 2014).

The Matagami camp is located in the Abitibi subprovince, Québec, Canada. It consists mainly of Archean mafic to felsic rocks metamorphosed to the greenschist facies. It is bounded to the north by the contact with the Opatika subprovince and to the south by the Cameron deformation zone. The different parts of the camp have a common stratigraphy. At the base, the volcanic sequence is predominantly felsic rocks of the Watson Lake Group (2726 +/- 1 Ma) (Ross et al. 2014). The mafic volcanic rocks of the Wabasse Group overlies these rocks. The Wabasse Group can be split into several units: the Bell River volcanic rocks of tholeiitic affinity and the Allard River volcanic rocks with calco-alkaline affinity. Various dykes, generally made of synvolcanic gabbro, are present in this sequence. The Cu-Zn-Ag-Au deposits are Volcanogenic Massive Sulphides

111 (VMS) and are mostly located at the interface between the Watson Lake Group and the Wabassee
112 Group. The Key Tuffite, a cherty sulphide horizon, is a benchmark level for mineralization. Its
113 origin is still a topic for discussion (Genna et al. 2013; Liaghat and MacLean 1992).
114 Several major mafic intrusions are also present on the northern flank (Fig. 1) of the Galine
115 anticline. The 2725 $\pm$ 3 Ma Bell River Complex (Mortensen 1993) is located at the base of the
116 Watson Lake Group. It consists of gabbro that may be anorthositic, pyroxenitic or granophyric.
117 The Radiore complex, also located at the base of the Watson Lake Group, consists of gabbro,
118 locally pegmatitic, and diorites. Various felsic to mafic enclaves are present in this complex. An
119 economic deposit was mined from 1979 to 1980 in one of these enclaves, the Radiore-2 mine.
120 Subvertical Proterozoic diabase dykes with an azimuth N065° crosscut the entire camp. Their
121 magnetite content makes them particularly clear on the aeromagnetic maps.
122 Two plutons intrude the Wabassee Group to the East. The Olga pluton is considered syn- to post-
123 tectonic (2693.2 $\pm$ 1.6 Ma) (Goutier et al. 2004) and has a predominantly tonalitic composition
124 while the Dunlop pluton is "an early phase with a composition from quartz diorite to
125 monzodiorite and a late tonalitic phase " and is interpreted as synvolcanic (Pilote 2010).
126 The structure of the mining camp is largely the result of the regional north-south shortening due
127 to the collision with the Opatika, the subprovince immediately to the north (Calvert et al. 1995).
128 The area is extremely deformed and has an important network of syntectonic faults. Several
129 deformation corridors like the Lake Olga or Lake Matagami corridors, oriented east-west and
130 east-northeast respectively, define several kilometer-scale thrust slices tectonically transposed
131 (Piché et al. 1993; Pilote et al. 2011). The volcanic sequence exhibits an average dip of 80° to the
132 north and is traditionally interpreted as the northern flank of the Galine anticline (Piché et al.
133 1993; Pilote et al. 2011).

The mines of the northern flank, none of which is active today, are concentrated along a felsic horizon at the interface between the Watson Lake Group and the Wabassee Group. There is just one exception, the Radiore 2 mine.

Inversion tools

The geophysical signal integrates the responses due to all the geological bodies of different physical properties in the subsurface. To be able to create models and to calculate their response, we mesh the subsurface into cells. Each cell has a size and an assigned property. For potential-field methods, the response of the model is the sum of the response due to each cell. Inversion process adjusts the values of the property distribution until the response of the model reproduces the observed geophysical data. However, this is an underdetermined problem because there are generally more parameters to solve for than data. Therefore, to find a realistic model among the infinite possibilities, it is a common practice to use known information about the geology as constraints (Lelièvre et al. 2009; Williams 2008).

The inversion algorithm used within GRAV3D and MAG3D is based on the minimization of an objective-function Φ (eq. (1)) composed of two additive terms (Li and Oldenburg 1996, 1998):

$$(1) \quad \Phi(\mathbf{m}) = \Phi_d(\mathbf{m}) + \mu\Phi_m(\mathbf{m}).$$

The first term Φ_d expresses the data misfit according to a L2 norm (eq. (2)):

$$(2) \quad \Phi_d(\mathbf{m}) = \|W_d(F(\mathbf{m}) - \mathbf{d}_{obs})\|_2^2,$$

where $F(\mathbf{m})$ is the forward modeling operator that computes the predicted data from the current physical property model $\mathbf{m}$ while $\mathbf{d}_{obs}$ is the observed data. The diagonal matrix W_d contains the inverse of the estimated data variance as a measure of the data precision. By construction, the

value of Φ_d after the inversion process for the final model must be less than or equal to the number of input data to consider that we have fit the data correctly.

The second term Φ_m is referred to as the regularizer and controls the smoothness and the smallness of the resulting model through the evaluation of several weighted L2 norms of the model $\mathbf{m}$ (eq. (3)) (Williams 2008):

$$(3) \quad \Phi_m(\mathbf{m}) = \alpha_s \|W_s W_{DW}(\mathbf{m} - \mathbf{m}_0)\|_2^2 + \sum_{i \in \{x,y,z\}} \alpha_i \|W_i G_i W_{DW}(\mathbf{m} - \mathbf{m}_0)\|_2^2.$$

The first term estimates the model smallness by evaluating the deviation of the recovered model $\mathbf{m}$ compared to a reference model $\mathbf{m}_0$. The next terms estimate the directional smoothness of the model by evaluating its gradients in the x , y and z directions, defined by the matrices G_i . The global weighting parameter α_s emphasizes the smallness while the parameters α_i help emphasize the smoothing in a particular direction. We then have the local weights. The matrix W_s determines the confidence in the reference model for each cell. The matrices W_i control the smoothness of each cell of the model in the i -direction, allowing the creation of interfaces by decreasing the importance of the gradient terms.

The scalar μ is a trade-off parameter between the data misfit and the model roughness. Its initial value is automatically determined by the inversion program and decreased through the inversion process to give more and more importance to the data misfit over the *a priori* information stored in the regularizer (Farquharson and Oldenburg 2004).

Finally, the matrix W_{DW} is our depth-weighting. It increases the sensitivity of cells at depth to counteract the natural decrease of the signal and thus forces the sources of anomalies to be located deeper in the model instead of being only concentrated at the very surface (Oldenburg and Li 2003). It is a diagonal matrix whose elements w are defined in function of the depth of the cell z :

$$(4) \quad w(z) = \frac{1}{(z+z_0)^{\beta/2}}.$$

The parameter β controls the amplifying rate of the depth weighting strength with increasing depth while z_0 is mainly here to avoid singularities at ground surface; it should be small compared to the depth increment of the mesh.

Physical Properties

Physical property contrasts between different rocks is the link between the geophysical and geological data. Density and magnetic susceptibility are the physical properties that control gravity and magnetic responses respectively. To relate the anomalies in the geophysical signal with the geology, we need to characterize the physical properties contrasts between the different types of rock that are present in the area.

To do this, we measured the densities of 497 samples from several outcrops and drill cores and the apparent magnetic susceptibility of 114 outcrops and of 410 core and outcrops samples (samples location is shown in Fig. 3 and 4). We divided the rock samples into six classes depending on their composition (mafic, intermediate or felsic) and their nature (volcanic or intrusive).

The density ρ is measured using Archimedes' principle (Enkin et al. 2012):

$$(5) \quad \rho = \frac{M_a}{M_a - M_w} \times (f_T \times \rho_{water}(T = 4^\circ C)) \times f_e,$$

where the saturated sample mass in air is denoted by M_a and its mass in water by M_w . The water density normalized at 4°C is denoted by $\rho_{water}(T=4^\circ C)$ and its value is 1 g/cm³. We then have several correction factor. The factor f_T corrects the density of the water according to the water temperature and the factor f_e corrects any residual instrument drift in time using a standard sample measured every 30 minutes. We used a Classic Light PL-8001-S (Mettler Toledo,

Mississauga, ON, Canada) balance that allows determination of sample weights up to 8100 g in air with a precision of 0.1 g and in water with a precision of 0.3 g. The results of the density measurements are summarized in Table 1 and Fig. 2.

The magnetic susceptibility was measured using a KT-9 kappameter, a hand-held magnetic susceptibility meter manufactured by Exploranium GS Ltd (Mississauga, ON, Canada). For each measured sample or outcropping unit, we took ten measurements to obtain a mean value. The estimates are apparent susceptibilities for samples because of their small size. Unfortunately, we have not been able to precisely characterize magnetic susceptibility for each unit, as the measurements were too erratic and did not show a systematic variation between rock units.

However, the magnetic data (Fig. 4) shows some specific continuous horizons that can be correlated with the geological map, such as the pyroxenitic phase of the Bell River Complex or the synvolcanic gabbroic dykes, whose samples gave values between 0.001 and 0.1 SI (Fig. 4).

The density distribution of each lithological unit, represented as box plots, shows that different rock units can be easily separated based on their density (Fig. 2). Felsic rocks can be distinguished from intermediate to mafic rocks due to their lower density. Distinction between the volcanic and plutonic rocks of the same composition is more tenuous. Intermediate volcanic rocks have almost the same density as the mafic volcanic rocks and thus cannot be distinguished from them.

Geophysical data

We use the available gravity and magnetic data from the Geological Survey of Canada (Jobin et al. 2009; Keating and D'Amours 2010; Keating et al. 2010) for the various inversions. The gravity data set consists of 357 stations, extracted from a larger survey of 2168 stations, with a

maximum spacing of 500m. The original Bouguer anomaly was calculated using a free-air correction of 0.3086 mGal/m and a crustal density of 2.67 g/cm³.

The magnetic data are part of a high-resolution aeromagnetic survey compilation of the Abitibi region. The line spacing of the surveys was 200 m or less and their terrain clearance was 120 m or less. The data were upward continued to 120 m when the terrain clearance of the survey was less than this value (Keating and D'Amours 2010; Keating et al. 2010).

To adapt the data to our objectives, a regional component calculated using an upward continuation of 15 km is removed from these data. We expect to remove the very-low frequencies anomalies due to the deepest bodies (Jacobsen, 1987).

The Bouguer anomaly was recalculated by using a density of 2.90 g/cm³ instead of the usual crustal density of 2.67 g/cm³ for the Bouguer correction in order to better reflect the regional average density. This density value was estimated from the samples measurements, weighted by the expected proportion of each rock unit based on the geological map and assuming their vertical continuation.

The residual Bouguer anomaly (Fig. 3) shows a good correlation with the geological map and the density samples. The Bell River Complex appears as a positive anomaly. The high-density (~3.07 g/cm³) pyroxenitic phase of the Bell River Complex is particularly visible with values up to 11 mGal above the surrounding areas (Fig. 3, BRC). In the eastern part of the studied area (Fig. 3), the Olga pluton also appears as a strong negative anomaly, with values up to 14 mGal below the surrounding areas. The amplitude of this negative anomaly displays a slow attenuation toward its west end. An important positive anomaly is located in the Allard River volcanic rocks (Fig. 3, A-ARV). The surface geological map cannot explain its source. Indeed, there are even some outcrops in this area showing densities around 3.0 g/cm³, very close to the expected density for the surrounding mafic rocks. This positive anomaly is interpreted to be the response of an

intrusion that does not reach the surface. In the following interpretation, we will investigate the source of that anomaly in order to generate the subsurface geological model of the region.

The magnetic data (Fig. 4) was used as a mapping tool to draw the geological map (Pilote 2010), thus the high correlation between the two. The magnetite-rich pyroxenitic phase of the Bell River Complex appears as a very clear positive anomaly in the magnetic data (Fig 5, BRC). The others anomalies are mostly attributed to mafic synvolcanic dykes (Fig 5, ARVd).

Data Integration and definition of constraints

The objective here is to add new elements to the geological map and to the 3D subsurface model by linking the data collected in the field and the magnetic and gravity datasets. As shown above, one anomaly displayed in the gravity survey (Fig 5, A-ARV) cannot be related to known surface geology and it is a new element to consider.

The area is 17.4 km (east-west) by 7.6 km (north-south). Considering the regional components removed on both data sets, the maximum depth extent (lower limit) of the 3D model is set at - 7000 m for a total vertical extent of 7500 m. A padding zone 1500 m thick around the model is added to reduce edge effects. The influence of the edge cells is less than 0.7% (Boulanger and Chouteau 2001). The cell size is 100 m x 100 m x 100 m for a total of 1 024 100 cells in the 3D model.

The geophysical surveys, the geometry of the main lithologies at surface and their contacts are integrated within a common earth model. The main interest of this data integration is to create a palette of tools allowing the geophysical inversions to be properly constrained for a better understanding of the northern flank of the Matagami Camp.

In addition, *a priori* information about the geology can be used to guide the inversion (Lelièvre et al 2009; Williams 2008). We have explored the possible parameters space by trial and error using the gravity data inversions. For each parameter, several values, generally within the recommended ranges (Oldenburg and Li 2005), have been tested, only varying one parameter at a time. As the mathematical construction of this *a priori* information about the geology is the same in the magnetic and gravity inversions, the same sets of parameters (except for the depth weighting factors, which parameters are dependent on the physics of the method and the discretization) were applied to magnetic inversions.

The parameters to include this *a priori* information can be separated into two categories: global and local. The global parameters will be the same for the whole model; these are the depth weighting factors and the directional smoothing parameters.

The choice of the depth weighting factors β is related to both the geophysical method and the desired recovered features in the model. The outcropping geological bodies are constrained at relatively shallow depth by using depth-weighting factors that balance the natural attenuation rate of each method (see Table 2).

The directional smoothing parameters α_i , are often presented in term of length scales L_i (eq. (6)) in the various Cartesian i -directions x , y and z , which give them a geological meaning (Williams 2008):

$$(6) \quad L_i = \sqrt{\frac{\alpha_i}{\alpha_s}}.$$

These parameters define *prior* preferential scales and orientations for the recovered anomalies in the inversion result. We base our choice of these length scales on the geological knowledge.

Existing geological maps indicate an east-west trend with steeply dipping units (over 80°).

Consequently, we fix the parameters α_i to favour this orientation (Table 2).

In addition to the global parameters, local parameters can be set to favor certain features in predefined locations. We favour the creation of interfaces in the inverted models by decreasing the importance of the smoothness parameters in the objective function for the cells located close to an interface between two geological units. To perform this, geological interfaces were defined up to a depth of 1 km, the maximum depth reached by drilling, by extending the surface lithological contacts of the geological map in accordance with the structural measurements done at the surface (Fig. 5). We have also limited the range of physical properties values in the inverted model in accordance with our measurements. The density contrasts from the background are limited between -0.3 and 0.5 g/cm^3 for the entire model and the susceptibility contrasts between 0 and 0.2 SI. Moreover, the density of the first layer of cells for each geological group is fixed with a tolerance of 0.1 g/cm^3 around its average density (Table 3). This approach was not used for magnetic inversions due to the high variation observed for the magnetic susceptibilities inside a same geological group.

The geological map already relies heavily on the magnetic data (Pilote 2010) and thus both present very similar features that are reproduced in our *a priori* model. However, we also need to check, prior to inversion, the consistency of our *a priori* model with the gravity data. For this purpose, we generate synthetic gravity data from our estimated geological model. The predicted gravity data (Fig. 6) reproduce the same pattern as the observed data, except for the anomaly inside the Allard River volcanic rocks (Fig. 3, A-ARV), which tends to confirm the idea of an unidentified geological body in this area.

Results

Gravity

A gravity inversion was performed using the constraints and parameters mentioned above (Fig. 5 and Table 3). The inversion converged to the target misfit, using a flat uncertainty of 0.2 mGal for the observed data determined by trial and error while running the inversions to choose the inversion parameters.

The main geological structures are well recovered. The Olga pluton extends at large depth without narrowing, except its western extension that appears to be an apophysis with a recovered thickness of about 1000 m (Fig. 7, Olga). The Bell River Complex is also well delineated. In the inversion model, the pyroxenitic phase dips steeply to the south at a recovered angle of about 75°, in contrast with the regional north dip of the northern flank units. However, some south dipping units have been observed and measured on outcrops in the area.

The other anomaly mentioned above is located in the Allard River volcanic rocks (Fig. 7, A-ARV). The gravity anomaly of the Allard River volcanic rocks remains unexplained by the current geological map. Three rocks samples located above the positive anomaly have densities of 2.95 g/cm³, 3.03 g/cm³ and 3.06 g/cm³. These values are very close to the average density value of the enclosing basalts (3.03 g/cm³). In addition, the gravity anomaly is approximately spherical while the volcanic and intrusive rocks in this area are rather elongated in the east-west direction. The anomaly is thus interpreted as related to a geological body that does not reach the surface.

We have run a specific inversion for this anomaly (Fig. 8). Due to the lack of available geological data, we did not set any interface constraint. We have just restricted the density contrast to be between -0.1 g/cm³ and 0.3 g/cm³ to correspond to the locally known and estimated geology. The depth to the body is found to be between 400 and 500 m, assuming a density contrast of 0.1 g/cm³; this would explain why some drilling done in the 1950's, about 100 m deep, did not intersect the body.

This anomaly may correspond to a gabbroic dome-like intrusion, as synvolcanic gabbro dykes occur at the surface throughout the andesitic to basaltic Allard River volcanic rocks. The existence of this intrusion does not appear to be a potential target for the mineral exploration considering the usual location of mineralization in this mining camp at the interface between the Watson Lake Group and the Watabassee Group.

Magnetic

A magnetic inversion was performed with the same constraints and parameters as the gravity inversion mentioned above (Fig. 9). The inversion converged to the target misfit, using an uncertainty of 2% for the observed data determined by trial and error while running the initial unconstrained inversions.

The model shows magnetic structures until a depth of 2000 m (see discussion for the depth of investigation). The main magnetic feature is the pyroxenitic phase of the Bell River Complex. It displays a steep south dip at a recovered angle of 75°, which agrees with the gravity inversion results. Some of the synvolcanic gabbro dykes are also recovered but not enough to determine a dip. Neither the Olga Pluton nor the unknown body displayed by the gravity data show enough magnetic susceptibility contrast with the enclosing volcanic rocks to be imaged.

Both inversions are coherent with each other and show a good correlation for the pyroxenitic phase of the Bell River Complex, which is a body with both high density and magnetic susceptibility.

Discussion

The geometry inferred from inversion is coherent with surface and drillholes observations. They confirm the vertical dip and the depth extent of the displayed geological structures.

However, in these models, some effects have to be considered to ensure the validity of the results. Due to the discretization, the topography is not always well recovered, as we do not model variations less than 50m (half the cell size). The choice of the discretization is always a compromise between computational feasibility and precision. Although the topography varies from 244 m and 454 m in this area (Reuter et al. 2007), 90% of the area is characterized by elevations less than 292 m with smooth spatial variations. Moreover, the majority of the topography height is around 250 m, meaning that the model is almost flat. All the higher elevations are associated with Mont Laurier, a basaltic hill in the south-east corner of the map. We chose the vertical offset of our mesh so that one layer of our mesh is at a 250 m elevation to reduce as much as possible the discretization error of the topography in most of the area. The top of the mesh is set to englobe the highest point in the area, the top of the Mont Laurier. We estimated that for a contrast of 0.2 g/cm^3 , the maximum error due a 50 m offset of the mesh compared to the topography resulted in a calculated gravimetric data error that is less than 0.4 mGal. The effect of the topography on the magnetic data is generally considered as negligible. In our study, we interpret low-frequencies anomalies of around 10 mGal as being due to deep and large bodies. The impact of relatively small topography variations, compared to the targets and size of the model, is not expected to affect the final interpretation of the gravity inversion. Another possible source of error is the overburden that is not taken into account in our model. However, the overburden exists and variations in thickness combined with a density less than the underlying bedrock can cause gravity anomalies. The Matagami overburden consists mostly in sediments such as clay or organic-rich deposits (Veillette and Pomares 2003). These sediments have generally a density between 2 and 2.3 g/cm^3 (Telford et al. 1990). Considering the presence of many rock fragments in these sediments, we expect a density of 2.3 g/cm^3 for the overburden. Drillhole data show a maximum thickness of 50 m for an average of 24 m. However, the spatial

distribution of drillholes tends to be concentrated in a single area along the key Tuffite horizon and this does not allow us to come with a reliable map of the overburden thickness. Many outcrops occur in different sectors of the studied area, encouraging us to consider a relatively thin overburden over most of the region. Thus in the worst case scenario of a sudden change in overburden thickness of 50 m, the effect on the gravity data would be about 1.26 mGal, which is much lower than the interpreted anomalies of 10 mGal.

The gravity and magnetic models show different depths of investigation. For the gravity model, perturbations of the initial density distribution are visible until the deepest part of the model. The sensitivity of the different layers in the model was tested using a density contrast value of 0.3 g/cm³. It appeared that the global effect on the data of the deepest layer of the model (at -7250m depth) was only 0.2 mGal. Therefore, the depth of investigation of the gravity inversion seems sufficiently large to consider the entire model, although it is clear that at great depth the image resolution reduces drastically. For the magnetic susceptibility, we have created a synthetic model that is 3000 m in depth extent. We have calculated the magnetic response of this model and then inverted the synthetic dataset with the same constraints as for the actual inversion. The synthetic inversion result shows a similar depth of investigation of about 2000 m as previously observed.

Conclusion

This study confirms the geometry of the outcropping geological units and their subvertical extensions. The main geological bodies are well imaged by magnetic or gravity data, or both. The shape of the Olga pluton displayed by the interpretation of the gravity inversion is consistent with the geological map, in particular the western apophysis, which was confirmed by several outcrops of the Olga pluton in the area. This protuberance appears to be thin compared to the core of the

pluton that extends to the bottom of our model at a depth of 7500 m. The pyroxenitic phase of the Bell River Complex has a subvertical south dip that does not seem to change with depth as suggested by both the gravity and magnetic inversion models. This suggests that economic targets deeper than the previous mines (approximately 500 m) may occur at depth. Geophysics would be particularly efficient for exploration in an environment with few exploration vectors (such as the Radiore Complex area to the east) to look for mineralized enclaves such as the Radiore 2 mine.

Finally, if the vertical extensions of the units appear in our models to be continuing further down at large depths, these inversion models do not provide new information to interpret different tectonically transposed thrust slices such as inferred by Piché et al. (1993) or Pilote et al. (2011). This is mainly due to the strong similarities in the studied physical properties of the different tectonic panels. To distinguish such features, other geophysical methods for the detection of fault zones, such as electromagnetic or seismic methods, should be used.

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References

- Beaudry, C., and Gaucher, E. 1986. Cartographie géologique dans la région de Matagami. Manuscrits Bruts (MB) 86-32, Ministère de l'Énergie et des Ressources du Québec, Val d'Or, QC. Available from <http://gq.mines.gouv.qc.ca/documents/examine/MB8632/MB8632.pdf> [accessed 14 June 2018].
- Boszczuk, P., Cheng, L.Z., Hammouche, H., Roy, P., Lacroix, S., and Cheillett, A. 2011. A 3D gravity data interpretation of the Matagami mining camp, Abitibi Subprovince, Superior Province, Quebec, Canada: Application to VMS deposit exploration. *Journal of Applied Geophysics*, **75**(1): 77–86. doi:10.1016/j.jappgeo.2011.06.031.
- Boulanger, O., and Chouteau, M. 2001. Constraints in 3D gravity inversion. *Geophysical Prospecting*, **49**(2): 265–280. doi:10.1046/j.1365-2478.2001.00254.x.
- Calvert, A.J., Sawyer, E.W., Davis, W.J., and Ludden, J.N. 1995. Archaean subduction inferred from seismic images of a mantle suture in the Superior Province. *Nature*, **375**: 670-674. doi:10.1038/375670a0.
- Debreil, J.-A., Ross, P.-S., and Mercier-Langevin P. 2018. The Matagami District, Abitibi Greenstone Belt, Canada: Volcanic Controls on Archean Volcanogenic Massive Sulfide Deposits Associated with Voluminous Felsic Volcanism. *Economic Geology*, **113**(4): 891–910. doi:10.5382/econgeo.2018.4575.
- Enkin, R.J., Cowan, D., Tigner, J., Severide, A., Gilmour, D., Tkachyk, A., Kilduff, M., and Baker, J. 2012. Physical property measurements at the GSC paleomagnetism and petrophysics laboratory, including Electric Impedance Spectrum methodology and analysis. Open File (OF) 7227, Geological Survey of Canada. doi:10.4095/291564.

- 444 Farquharson, C.G., and Oldenburg D.W. 2004. A comparison of automatic techniques for
445 estimating the regularization parameter in non-linear inverse problems, *Geophysical Journal*
446 *International*, **156**(3): 411–425. doi:10.1111/j.1365-246X.2004.02190.x.
- 447 Galley, A.G., Hannington, M.D., and Jonasson, I.R., 2007. Volcanogenic massive sulphide
448 deposits. *In* Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District
449 Metallogeny, the Evolution of Geological Provinces, and Exploration Methods. *Edited by* W.D.
450 Goodfellow. Geological Association of Canada, Mineral Deposits Division, Special Publication
451 No. 5, pp. 141-161. doi:10.2113/gsecongeo.102.7.1355.
- 452 Genna, D., Gaboury, D., and Roy, G. 2013. The Key Tuffite, Matagami Camp, Abitibi
453 Greenstone Belt, Canada: petrogenesis and implications for VMS formation and exploration.
454 *Mineralium Deposita*, **49**(4): 489–512. doi:10.1007/s00126-013-0499-7.
- 455 Goutier, J., Rhéaume, P., and Davis, D. W. 2004. Géologie de la région du lac Olga (32F/14).
456 Rapport Géologique (RG) 2003-09, Ministère des Ressources naturelles de la Faune et des Parcs
457 du Québec, Val d'Or, QC. Available from
458 <http://gq.mines.gouv.qc.ca/documents/examine/RG200309/RG200309.pdf> [accessed 14 June
459 2018].
- 460 Hammouche, H., Boszczuk, P., and Roy, P. 2010. Géologie des feuilletés Île Lac MacIvor (32F13-
461 200-0101), région de Matagami. Rapport Préliminaire (RP) 2010-01, Ministère des Ressources
462 naturelles de la Faune du Québec, Val d'Or, QC. Available from
463 ftp://ftp.mern.gouv.qc.ca/Public/Bibliointer/Mono/2010/02/1023411/1_Doc_principal.pdf
464 [accessed 15 May 2018].
- 465 Jacobsen, B.H. 1987. A case for upward continuation as a standard separation filter for potential-
466 field maps. *Geophysics*, **52**(8): 1138–1148. doi:10.1190/1.1442378.

- 467 Jobin, D., Keating, P., and Lefebvre, D. 2009. Geophysical series, parts of NTS 32 E/9, 32 E/16,
468 32 F/11, 32 F/12, 32 F/13, and 32 F/14, Matagami gravity survey, Quebec. Open File (OF) 2009-
469 06, Geological Survey of Canada, Ottawa, ON. doi:10.4095/261332.
- 470 Keating, P., and D'Amours, I. 2010. Réédition des données numériques au format geosoft
471 (profils) des levés aéroportés de l'Abitibi, au Québec. Dossier Public (DP) 2010-09, Ministère
472 des Ressources Naturelles et de la Faune du Québec, Val d'Or, QC. Available from
473 <http://gq.mines.gouv.qc.ca/documents/examine/DP201009/DP201009.pdf> [accessed 14 June
474 2018].
- 475 Keating, P., Lefebvre, D., Rainsford, D., Oneschuk, D. 2010. Geophysical Series, parts of NTS
476 31, 32, 41 and 42, Abitibi Greenstone Belt, Quebec and Ontario. Open File (OF) 2010-05,
477 Geological Survey of Canada, Ottawa, ON. doi:10.4095/263389.
- 478 Lelièvre, P.G., Oldenburg, D.W., and Williams, N.C. 2009. Integrating geological and
479 geophysical data through advanced constrained inversions. *Exploration Geophysics*, **40**(4): 334–
480 341. doi:10.1071/EG09012.
- 481 Li, Y., and Oldenburg, D.W. 1996. 3-D inversion of magnetic data. *Geophysics*, **61**(2): 394–408.
482 doi:10.1190/1.1443968.
- 483 Li, Y., and Oldenburg, D.W. 1998. 3-D inversion of gravity data. *Geophysics*, **63**(1): 109–119.
484 doi:10.1190/1.1444302.
- 485 Liaghat, S., and MacLean, W.H. 1992. The Key Tuffite, Matagami mining district; origin of the
486 tuff components and mass changes. *Exploration and Mining Geology*, **1**(2): 197–207.
- 487 MacGeehan, P.J. 1979. The petrology and geochemistry of volcanic rocks at Matagami, Québec,
488 and their relationship to massive sulphide mineralization. Ph.D. thesis, Department of Geological
489 Sciences, McGill University, Montréal, QC. Available from

- 490 http://digitool.library.mcgill.ca/webclient/DeliveryManager?pid=76676&custom_att_2=direct
491 [accessed 15 May 2018].
- 492 MacGeehan, P.J., MacLean, W.H., and Bonenfant, A. 1981. Exploration significance of the
493 emplacement and genesis of massive sulphides in the Main Zone at the Norita Mine, Matagami,
494 Quebec. *Canadian Institute of Mining and Metallurgy Bulletin*, **74**: 59–75.
- 495 Mortensen, J.K. 1993. U–Pb geochronology of the eastern Abitibi Subprovince. Part 1:
496 Chibougamau–Matagami–Joutel region. *Canadian Journal of Earth Sciences*, **30**: 11–28.
497 doi:10.1139/e93-002.
- 498 Oldenburg, D.W., and Li, Y. 2003. On “3-D inversion of gravity and magnetic data with depth
499 resolution” (Maurizio Fedi and Antonio Rapolla, *Geophysics*, 64: 452–461). - Discussion.
500 *Geophysics*, **68**(1): 400–405. doi:10.1190/1.1552007.
- 501 Oldenburg, D.W., and Li, Y. 2005, 5. Inversion for applied geophysics: A tutorial. In *Near-*
502 *Surface Geophysics. Edited by D. K. Butler, Society of Exploration Geophysicists, Tulsa, OK,*
503 pp. 89–150. doi:10.1190/1.9781560801719.ch5.
- 504 Piché, M., Guha, J., and Daigneault, R. 1993. Stratigraphic and Structural Aspects of the
505 Volcanic-Rocks of the Matagami Mining Camp, Quebec - Implications for the Norita Ore
506 Deposit. *Economic Geology*, **88**(6): 1542–1558. doi:10.2113/gsecongeo.88.6.1542.
- 507 Pilote, P. 2010 - Géologie du flanc Nord de la région de Matagami. *In Résumé des conférences et*
508 *des photoprésentations, Documents divers (DV) 2010-06, Québec Exploration 2010, Québec,*
509 *QC, Canada, pp. 35. Available from <http://collections.banq.qc.ca/ark:/52327/bs2009382>*
510 [accessed 13 June 2018].
- 511 Pilote, P., Debreil, J.-A., Williamson, K., Rabeau, O., and Lacoste, P. 2011 - Révision géologique
512 de la région de Matagami. *In Résumé des conférences et des photoprésentations, Documents*

- 513 divers (DV) 2011- 03, Québec Exploration 2011, Québec, QC, Canada, pp. 13. Available from
514 <http://collections.banq.qc.ca/ark:/52327/bs2094048> [accessed 13 June 2018].
- 515 Rabeau, O. 2013. Modélisation géologique 3D du flanc ouest du camp minier de Matagami,
516 Géologie et Minière (GM) 67021, Ministère des Ressources Naturelles du Québec, Val d'Or,
517 Québec. Available from <http://gq.mines.gouv.qc.ca/documents/examine/GM67021/GM67021.pdf>
518 [accessed 14 June 2018].
- 519 Reuter, H.I., Nelson, A., and Jarvis, A. 2007. An evaluation of void filling interpolation methods
520 for SRTM data. *International Journal of Geographical Information Science*, **21**(9): 983–1008.
521 doi:10.1080/13658810601169899.
- 522 Ross, P.-S., McNicoll, V.J., Debreil, J.-A., and Carr, P. 2014. Precise U-Pb geochronology of the
523 Matagami mining camp, Abitibi greenstone belt, Quebec: Stratigraphic constraints and
524 implications for volcanogenic massive sulfide exploration. *Economic Geology*, **109**(1): 89–101.
525 doi:10.2113/econgeo.109.1.89.
- 526 Telford, W.M., Geldart, L.P., and Sheriff, R.E. 1990. *Applied Geophysics* (Second Edition).
527 Cambridge University Press. doi:10.1017/CBO9781139167932.014.
- 528 Thériault, R., and Beauséjour, S. 2012. Geological map of Québec. Various Documents (DV)
529 2012-07, Ministère des Ressources Naturelles du Québec, Val d'Or, QC. Available from
530 ftp://ftp.mrnf.gouv.qc.ca/Public/Bibliointer/Mono/2012/12/1123918/Doc_principal.pdf [accessed
531 14 July 2018].
- 532 Veillette, J.J., and Pomares, J.-S. 2003. Géologie des formations de surface et histoire glaciaire,
533 Lac Matagami, Québec. Carte Série “A”, Natural Resources Canada / Ressources naturelles
534 Canada, Ottawa, ON. doi:10.4095/214508.
- 535 Williams, N.C. 2008. Geologically-Constrained UBC–GIF Gravity and Magnetic Inversions with
536 Examples from the Agnew-Wiluna Greenstone Belt, Western Australia. Ph.D. thesis, Earth,

537 Ocean and Atmospheric Sciences Department, The University of British Columbia, Vancouver,
538 B.C. doi:10.14288/1.0052390.

539 Williamson, K., Pilote, P, and Rabeau, O. 2013. Modélisation régional du camp minier de
540 Matagami. Manuscript brut (MB) 2013-05, Ministères des Ressources Naturelles du Québec, Val
541 d'Or, QC. Available from
542 <http://gq.mines.gouv.qc.ca/documents/examine/MB201305/MB201305.pdf> [accessed on 15 May
543 2018].

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545 **Tables**

546 Table 1: Statistical analysis of the measured densities

Density		Samples	Average (g/cm ³)	Median	Minimum	Maximum	Standard deviation
Intrusive rocks	Felsic	37	2.78	2.73	2.64	3.11	0.12
	Intermediate	33	2.83	2.82	2.69	3.1	0.09
	Mafic	147	3.00	3.02	2.71	3.47	0.13
	Ultramafic	4	3.04	3.04	2.98	3.09	0.05
Volcanic rocks	Felsic	52	2.78	2.77	2.67	3.1	0.08
	Intermediate	103	2.90	2.91	2.66	3.09	0.11
	Mafic	123	2.95	2.99	2.69	3.36	0.13
	Mafic Group 1	80	3.03	3.03	2.9	3.36	0.07
	Mafic Group 2	43	2.80	2.82	2.69	2.89	0.06

547

548 Table 2: Summary of the inversion parameters

Chosen parameters			
Domain	Parameter	Symbol	Value
Depth Weighting		β	1.5 for gravity 3 for magnetic
		Z_0	1
Function-objective	Length Scale	α_s	4×10^{-6}
		Lx	500
		Ly	200
		Lz	500
Convergence	Mode		1
	chifact		1
	Tolerance		0.02 mGal for gravity 2% for magnetic

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551 Table 3: Selected density contrasts for each main geological unit (Fig. 5)

Color code	Description (from Pilote 2010)	Modelled density contrast (g/cm ³)
	Bell River Volcanic rocks	0
	Bell River Complex	0.2
	Granophyric gabbro	0
	Gabbro and pyroxenite with magnetite	0.26
	Pegmatitic gabbro and diorite (Radiore area)	0.2
	Diorite with quartz and magnetite (Radiore area)	0
	Granodiorite (Olga)	-0.3
	Allard River Volcanic rocks and synvolcanic intrusions	0
	Watson’s rhyolite	-0.1
	Mineralized area	0
	Diabase	0.3
	Felsic intrusion (Isle Dieu area, Southern Flank)	-0.3
	Felsic volcanic rocks (Isle Dieu area, Southern Flank)	-0.2
	Gabbro with granophyric portion	0.1
	Tonalite (Olga)	-0.2

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Figure captions

Figure 1: Geological map of the study area (based on data from Pilote (2010) and Thériault and Beauséjour (2012)): a) localization; b) simplified geology of the Matagami camp; c) detailed geological map: the northern flank of the Galine anticline (Mine sites: GL: Garon Lake Mine; NO: Norita Mine; NE: Norita-East Mine; R2: Radiore 2 Mine).

Figure 2: Density distribution sorted by lithology (arrow: expected trend).

Figure 3: Residual Bouguer anomaly to be inverted and field samples measured for density (thin grey lines: contour lines, thick black line: main road and city; black triangle: gravity stations; colored circle: density samples). The original gravity data are from Jobin et al (2009). The geological contours are based on data from Pilote (2010).

Figure 4: Residual Magnetic field amplitude to be inverted and field samples measured for magnetic susceptibility (thin grey lines: contour lines, thick black line: main road and city; black triangle: gravity stations; colored circle: magnetic susceptibility samples). The original magnetic data are from Keating and D'Amours (2010) and Keating et al. (2010). The geological contours are based on data from Pilote (2010).

Figure 5: Geological model showing the different units in order to define local constraints and magnetic susceptibility measurements (Color legend in Table 3; from Fig. 1: geological contours as black lines and faults as red lines (based on data from Pilote (2010))).

Figure 6: Comparison between the predicted data from the geological model proposed in Figure 6 and the observed gravity Bouguer anomaly (from Fig. 1: geological contours as black lines and faults as red lines (based on data from Pilote (2010))).

Figure 7: Density model from constrained gravity data inversion: a) depth slice at -500 m depth (from Fig. 1: geological contours as black lines and faults as red lines (based on data from Pilote

576 (2010)); b) vertical section BB' through the Olga pluton; c) vertical section CC' over the Bell
577 River Complex (BRC); d) vertical section DD' through the anomaly of the Allard River volcanic
578 rocks (A-ARV).

579 Figure 8: East-west cross-section (viewed from the south at $Y = 5519850$ m) of the constrained
580 inversion for the gravity anomaly of the Allard River volcanic rocks.

581 Figure 9: Magnetic susceptibility model from the constrained magnetic inversion: a) Horizontal
582 slice at -500 m depth (from Fig. 1: geological contours as black lines and faults as red lines
583 (based on data from Pilote (2010)); b) Vertical section BB' through the Bell River Complex
584 (BRC) and the gabbroic dykes.

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182 × 236 mm

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588 86 × 49 mm

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598 182 × 165 mm

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600 83× 70 mm

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