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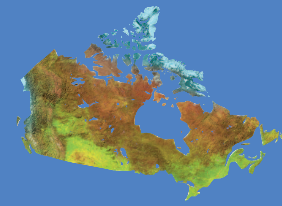

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P. Shamsipour, M. Chouteau, P. Keating, and D. Marcotte

Geological Survey of Canada

Current Research 2010-12

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Canada

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ISSN 1701-4387
Catalogue No. M44-2010/12E-PDF
ISBN 978-1-100-16763-3
doi: 10.4095/286079

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Recommended citation

Shamsipour, P., Chouteau, M., Keating, P., and Marcotte, D., 2010. Three-dimensional stochastic inversion of gravity data: application to gravity data from the Matagami region, Quebec; Geological Survey of Canada, Current Research 2010-12, 10 p.

Critical review
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Correction date:

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Abstract: An innovative geostatistical approach has been used to produce a 3-D model of the density distribution in the Matagami area. Gravity data are from a detailed survey where the station spacing averages 500 m. The validity of the 3-D model is evaluated by a conditional cosimulation. The gravity, density, and gravity-density covariance matrices are estimated using the observed gravity data. Then, the densities are co-kriged using the gravity data as the secondary variable. The model allows us to include noise in the oservations. The proposed method was first tested on synthetic data. The results show the ability of the method to integrate complex *a priori* information. The technique was then applied to actual gravity data from the Matagami mining camp. The results of the inversion and the simulation methods are in good agreement with the observed surface geology in the survey region.

Résumé : Une approche géostatistique innovatrice a été utilisée pour obtenir un modèle 3D de la distribution de la densité dans la région de Matagami. Les données gravimétriques proviennent d'un levé détaillé pour lequel l'espacement moyen des stations était de 500 m. La validité du modèle 3D est estimée par une cosimulation conditionnelle. Les matrices de covariance de la gravité, de la densité et de la gravité-densité sont estimées à partir des valeurs de la gravité observée. Les densités sont ensuite obtenues par cokrigeage en utilisant les valeurs de gravité comme variable secondaire. Le modèle nous permet d'inclure le bruit dans les observations. La technique proposée a d'abord été testée sur des données synthétiques. Les résultats montrent la capacité de cette méthode à utiliser a priori des informations complexes. La technique a été appliquée sur des données gravimétriques en situation réelle provenant du camp minier de Matagami. Les résultats des méthodes d'inversion et de simulation concordent avec la géologie de surface dans la région du levé.

INTRODUCTION

In inverse problems, one wants to use the measured data *d* to find the model parameters *m* characterizing some physical process which reduces to solving the system:

$$G(m) + e = d$$

where *G* is a forward mapping operator (linear or nonlinear) that maps the model parameters *m* into observations *d*, and *e* are the errors in the measured data. In the case of gravity, *G* is linear. In 3-D gravity inversion, the model *m* can be defined in different ways. One flexible way is to describe the model by a grid of prismatic cells. The subsurface is divided into prisms of known sizes and positions. The density contrasts are supposed constant within each cell and the parameters to be estimated are the cell densities. There are, therefore, no assumptions about the shape of the sources or distribution of density; hence theoretically the approach involves a high level of ambiguity. Besides, when the number of parameters is larger than the number of observations, the system does not provide enough information to determine uniquely all model parameters. In this situation, the problem is said to be underdetermined. As a result, even if a solution that satisfies the observed data can be found, the problem of nonuniqueness remains due to the physics and underdetermined nature of the problem. Many strategies can be used to deal with the nonuniqueness problem in gravity inversion. They all involve some kind of constraints to limit the resulting solution. Green (1975) proposed using a weighting matrix to fix some of the parameters when geological or density information is available. Last and Kubik (1983) sought a compact solution with a minimum volume constraint. Smoothness or roughness of the density distribution which control gradients of parameters in spatial directions were used in magnetic inversion by Pilkington (1997). Li and Oldenburg (1998) counteracted the decreasing sensitivities of cells with depth by weighting them with an inverse function of depth. Another 3-D inversion technique allowing definition of depth resolution was proposed by Fedi and Rapolla (1999). Prior information in the form of parameter covariances can be included (Tarantola and Valette, 1982) to orient the search for a solution. Montagner and Jobert (1988) used exponential covariance functions in which the rate of exponential decay determines the correlation length of the parameters.

Geostatistical methods in geophysical inversion were applied by Asli et al. (2000), Gloaguen et al. (2005, 2007), and Giroux et al. (2007). Linear stochastic inversion was first described by Franklin (1970). Asli et al. (2000) co-kriged gravity anomalies to obtain cell densities. Chasseriau and Chouteau (2003) used the Tarantola and Valette (1982) approach for 3-D inversion of gravity data using an *a priori* model of covariance. Geostatistical simulations allow stochastic imaging of inverted fields. There exist many efficient simulation algorithms (Chilès and Delfiner, 1999) to simulate structured models. The Fast Fourier Transform Moving Average simulation (FFT-MA) is a fast simulation algorithm for generating regular grid nonconditional Gaussian stationary processes (Le Ravalec et al., 2000). The realizations obtained are then postconditioned to gravity data by using co-kriging (Journel and Huijbregts, 1978). Here, the authors use a stochastic approach to the inversion of gravity data using co-kriging and cosimulation. Full description of the method is given by Shamsipour (2009) and Shamsipour et al. (2010). The stochastic approach is applied to data collected over the Matagami mining camp in Quebec.

GEOLOGY OF THE MATAGAMI AREA

The Matagami mining camp is located in the northern part of the Abitibi greenstone belt. Rhyolitic to basaltic sequences are present as well as some mafic and felsic intrusions. The Watson Lake volcanic rocks, mostly felsic units, are overlain by the Wabassee Group, which consists of mafic to intermediate volcanic rocks. Many volcanogenic massive-sulfide deposits have been identified at the contacts of bimodal volcanic sequences in the Archean Abitibi greenstone belt. The Matagami volcanic complex of northern Abitibi belt is formed by two major phases of volcanism (Piché et al., 1993). The end of the initial volcanic phase produced rhyolite of the Watson Lake Group and the beginning of the late volcanic phase formed the basaltic Wabassee Group. A simplified geology map of the study area (M. Allard, pers. comm., 2009) is presented in Figure 1. The intrusive rocks can be summarized as follows (Boszczuk, 2009):

- The Bell River Complex is composed of 80% of gabbro, overlapping with the basis of the Watson Lake Group.
- Mafic-ultramafic intrusions outcrop locally as dykes which crosscut volcanic sequences. Most of these dykes are easy to identify as they have a strong magnetic response.
- The McIvor pluton has a heterogeneous granodiorite composition. Its complex shape and the spatial variability of its chemical composition could indicate a synvolcanic, syntectonic, or post-tectonic origin; however, recent dating (V. McNicoll, pers. comm., 2010) indicated a synvolcanic origin.
- The Cavelier pluton has a felsic composition, is interpreted from geophysical data, and does not outcrop.

Geophysics has played an important role in the discovery of the various orebodies in this area. The first mine of the mining camp was discovered by geophysics. The original Matagami Lake mine discovery was the result of the follow-up of an airborne electromagnetic anomaly by ground geophysics. The orebody also has a magnetic signature and its gravity anomaly is 1.5 mGal (Paterson, 1966). The main reason for using geophysics in this region is the lack of outcrop as most of the area is covered with thick overburden.

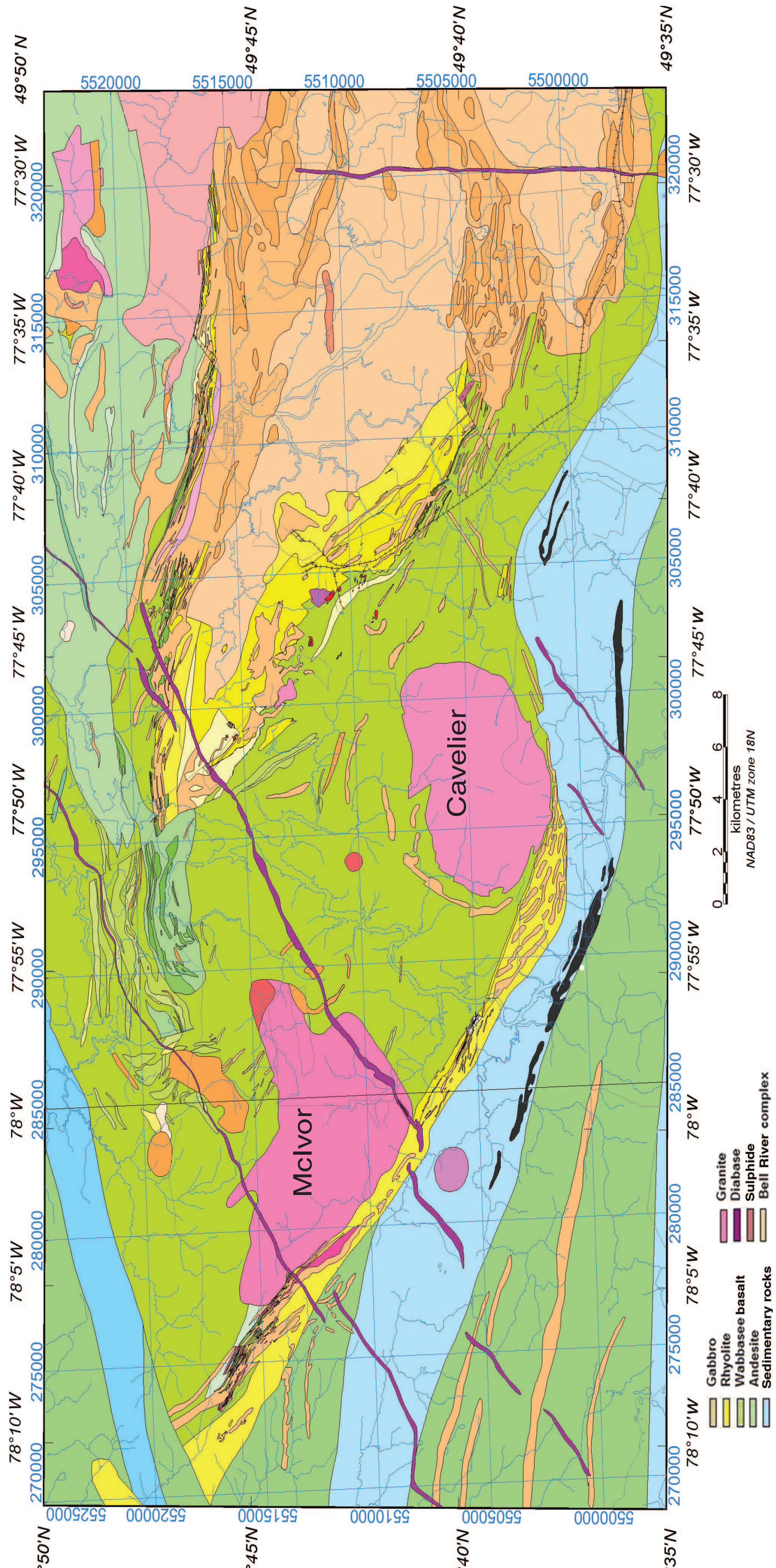

Figure 1. Geology of the study area.

APPLICATION TO SURVEY DATA

Gravity data were acquired at an average spacing of 500 m, access permitting. Measurement points were located by differential global positioning system and there are 1570 within the study area. A density of 2670 kg/m^3 was used for the Bouguer correction. The accuracy of the data is estimated to be 0.17 mGal (Jobin et al., 2009). Because of access problems there are some gaps in the coverage. The Bouguer anomaly is shown in Figure 2a and its values range from –65.2 mGal to –37.1 mGal. A residual Bouguer anomaly (Fig. 2b) was obtained by subtracting the Bouguer anomaly upward continued to 10 km from the original Bouguer anomaly. In this study, the authors assume that the residual Bouguer anomaly is due to density in homogeneities located within the first 5 km of the crust.

INVERSION BY CO-KRIGING

An inversion by co-kriging is used to estimate the density model (Shamsipour, 2009; Shamsipour et al., 2010). The experimental gravity covariance matrix is calculated from the residual Bouguer anomaly. The inversion domain is divided into 99 by 38 by 10 cubes of dimension 500 m × 500 m × 500 m. So, the whole domain is 49.5 km × 19 km × 5 km, the total number of prisms is m = 37 620, and the total number of gravity data are 2061. The adjusted density variogram model using the V-V plot method is anisotropic and spherical with covariances C_0=105 (kg/m^3)^2, C=5500 (kg/m^3)^2, and $a_{h,45}$=6.5 km, $a_{h,135}$=7.5 km, and a_{vert}=5 km are the variogram ranges along horizontal directions 45° and 135° and the vertical direction, respectively. The covariance vectors *vexp* (experimental) and *vth* are shown in Figure 3. The densities estimated by co-kriging are actually density contrasts. Therefore, a density of 2670 kg/m^3 is added to the contrasts estimated by co-kriging. This value may change if new data from boreholes or geological information were available. For example, recent density data from the Matagami region indicate a somewhat higher estimate for the mean.

The estimated density distributions are shown in Figures 4 and 5. Comparing these figures with the geological setting of the study area reveals an agreement with the geology on the surface. Two sections of the estimated densities at y = 5 515 000 m and z = 1000 m are presented in Figure 5. The figure shows that the structure of the studied area matches well with the geology.

The 3-D inversion can delineate geological units displaying density contrasts with surrounding rock types. Areas corresponding to the McIvor and Cavelier plutons and to the Group Watson Lake rhyolite on the southern flank of the Galinée anticline show low density contrasts. On the contrary, basalt, andesite, and gabbro are associated with high densities. The low density in the northern part of the study area could be due to the presence of the Watson Lake rhyolite at depth. In this unconstrained inversion, areas corresponding to the Watson Lake Group on the southern flank of the Galinée anticline do not show a 45° dip as indicated by Piché et al. (1993); however, the gravity signature of the McIvor pluton does not perfectly match the mapped geology.

Inversion using co-kriging gives a smooth estimate of the density model; however, it is desirable and useful to obtain various reasonable solutions to see the variability that can be expected from the density covariance model that is adopted. This can be achieved using geostatistical simulation algorithms instead of co-kriging (Le Ravalec et al., 2000). Using this approach, many statistically equivalent density models are calculated. Figure 6 shows three random realizations of cosimulated densities at section y = 5 515 000 m along with the probability map of 2700 $<\rho<$ 3000 kg/m^3 in this section. The histogram of maximum density gradient norm is also shown in this figure. Based on the study of synthetic cases (Shamsipour et al., 2010), the authors expect the maximum gradient in the real model to be closer to the cosimulation than co-kriging. The contact of between rock types can be determined from the location of maxima magnitude of the horizontal gravity gradient. It is shown by Shamsipour et al., (2010) that this property can be obtained more precisely by cosimulation rather than co-kriging.

DISCUSSION

Co-kriging provides one smooth solution to the underdetermined problem, whereas cosimulation provides a set of equally possible solutions, aimed at reproducing the spatial variability of the true density field. Simulation results are helpful to better estimate nonlinear functions of the inverted densities, such as the maximum density gradient found in a given area. Simulations enable, because they reproduce the variability of the field, to better estimate the gradient norm than co-kriging. Obtaining a good fit between the theoretical and experimental covariances is sometimes challenging. Nevertheless, it is possible to obtain at least crude estimates of the sill and the ranges along principal geological directions. It is also possible to validate prior estimates deduced from geological knowledge. For large systems one idea is to discretize the field initially with much larger blocks to find the covariance at this scale. Often, it is relatively easy to deduce the approximate covariance model for smaller blocks.

In the case study, the number of prisms is large. Therefore, the required storage and computational costs needed to compute a cross-covariance and observed covariance can be prohibitive. The authors solved this problem by using the method proposed by Nowak et al. (2003). The authors found the method useful and it has lower computational complexity. This approach works best when gravity data are located on a regular grid (not necessarily full), and the density covariance is isotropic.

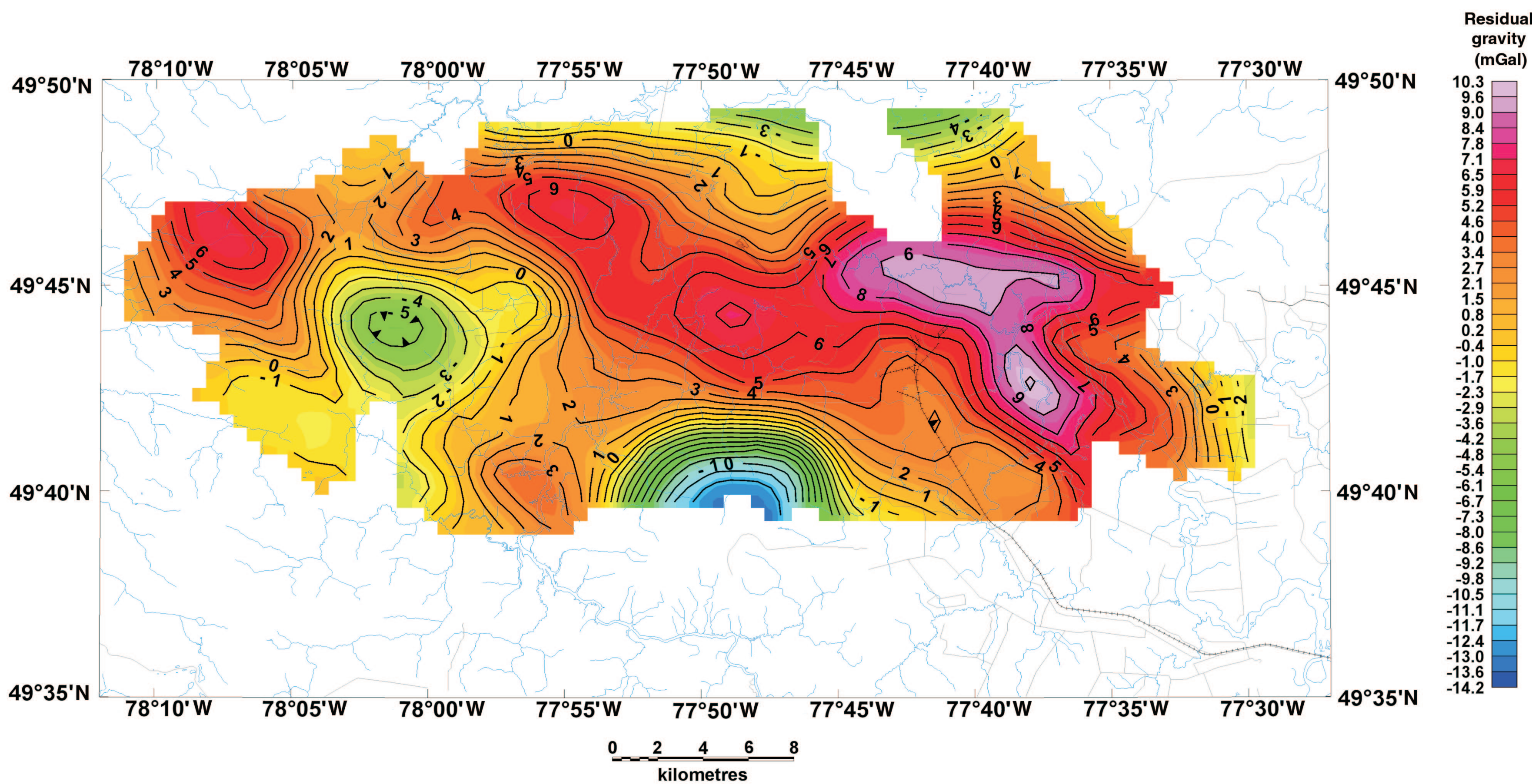

Figure 2. Residual gravity anomaly obtained by subtracting the Bouguer anomaly upward continued to a height of 10 km from the observed Bouguer anomaly.

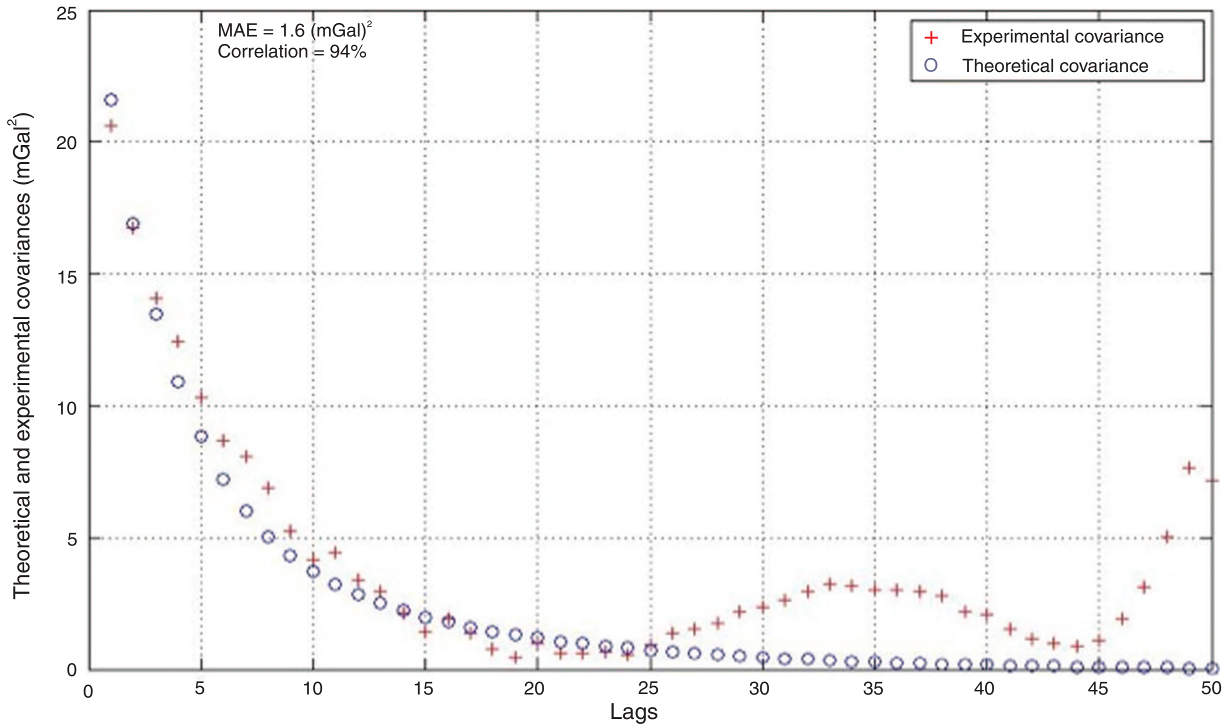

Figure 3. Fit of the experimental and theoretical gravity covariance matrices. The x axes are the index of the bins. Density variogram model: anisotropic and spherical with C_0 = 105 (kg/m³)², C = 5500 (kg/m³)², and a_{45} = 6500 m, a_{135} = 7500 m, and a_{vert} = 5 000 m.

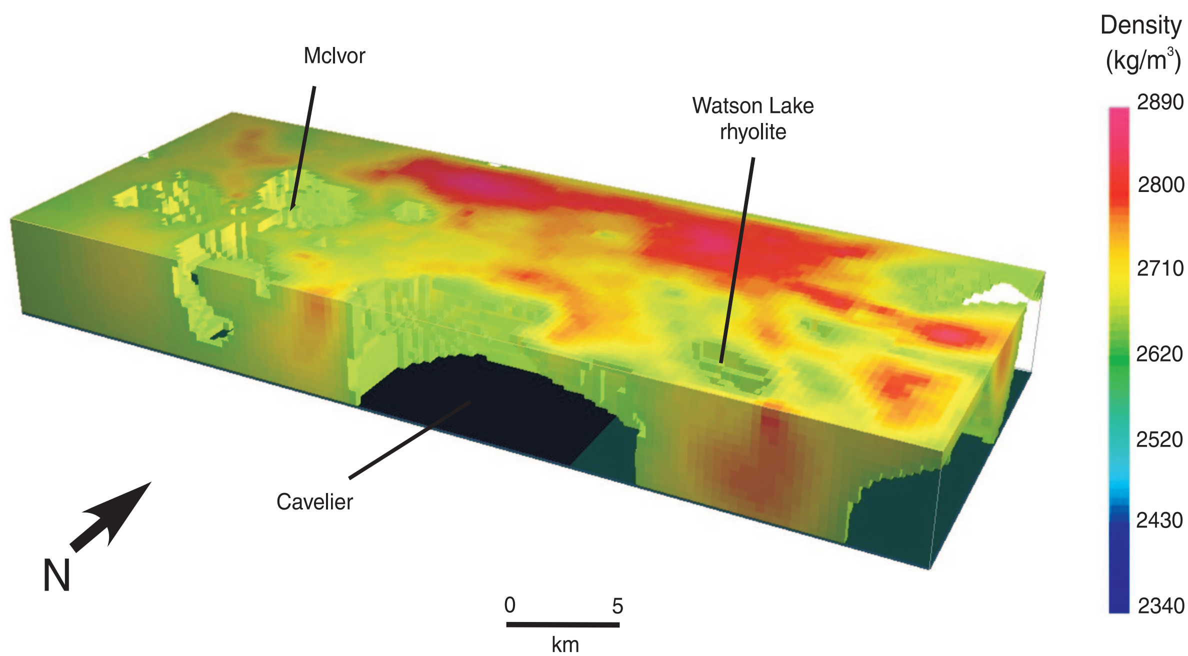

Figure 4. Three-dimensional model obtained from the inversion. Only prisms with a density higher than 2620 km/m³ are illustrated.

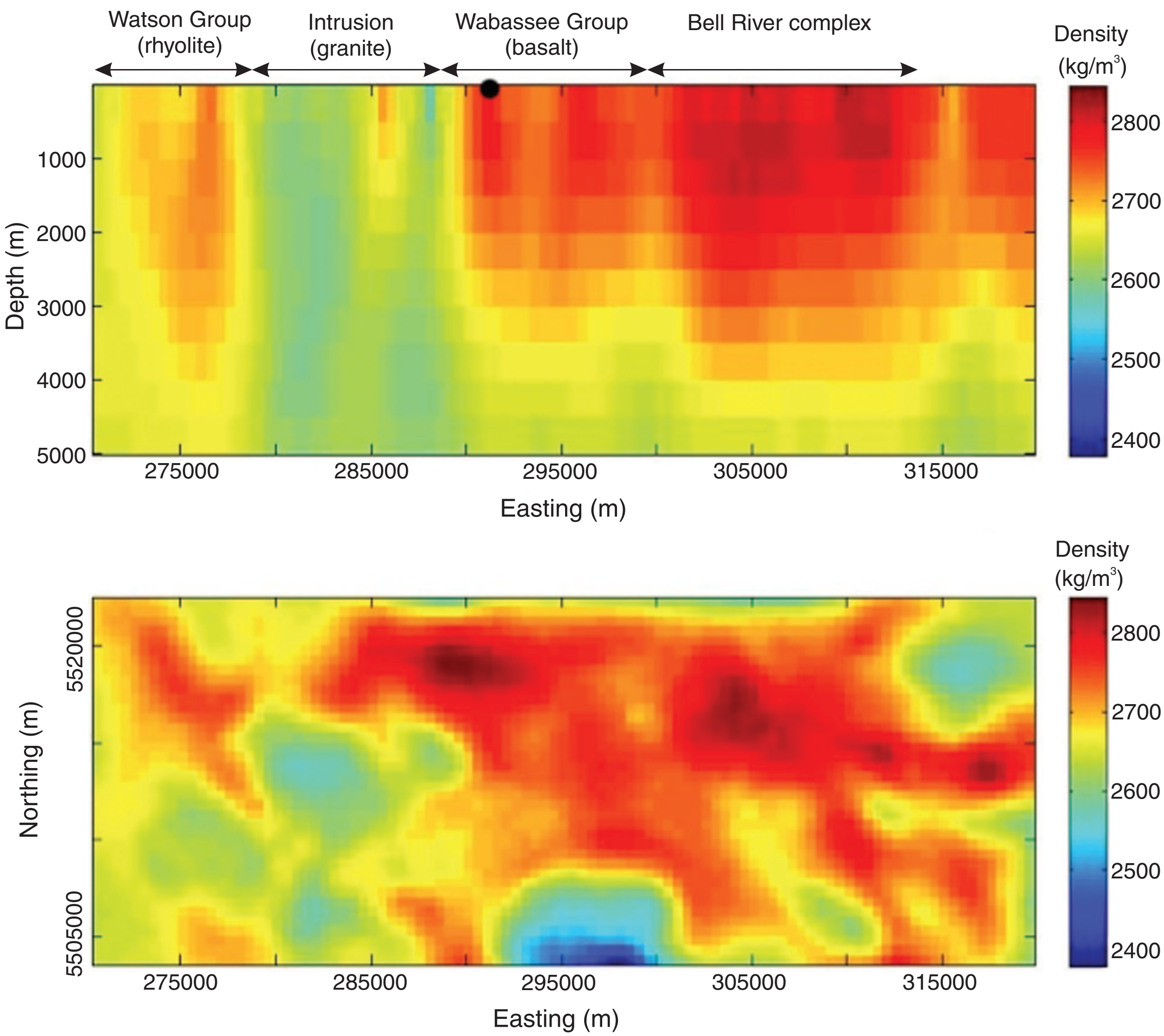

Figure 5. The estimated densities along northing 5 515 000 m and at depth of 1000 m using inversion by co-kriging.

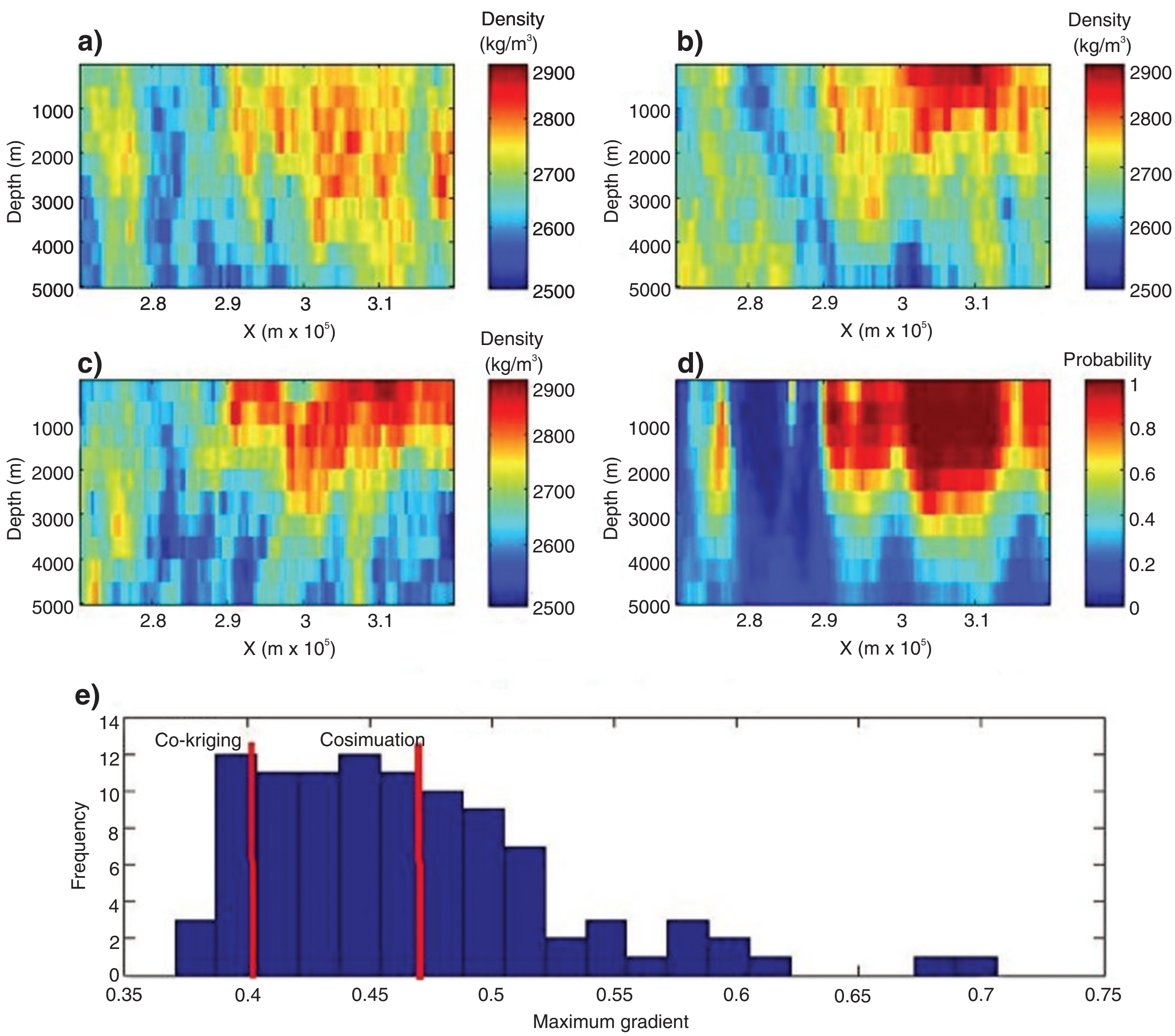

Figure 6. The estimated densities at section y = 5 515 000 m using inversion by co-kriging. **a)**, **b)**, **c)** Cosimulated densities (three realizations selected at random), **d)** Probability map of 2700 <ρ <3000 kg/m³. All the figures are from section y = 5 515 000 m. **e)** Histogram of maximum gradients. The maximum gradient of co-kriging and also the mean of maximum gradient density norm of the cosimulation are indicated.

SUMMARY AND CONCLUSION

In this paper, the authors presented an inversion method based on a geostatistical approach (co-kriging) for three-dimensional inversion of gravity data including geological constraints. and extended the approach to cosimulation of densities. The proposed inversion method based on co-kriging and cosimulation is computationally efficient as it is noniterative and practical solutions exist for large problems. The algorithm is flexible as it can be used for both regularly and nonregularly spaced data. Moreover, it is stable and robust in the presence of noise. It enables one to incorporate easily any known density values. The authors applied the proposed method on real data from the Matagami area. Based on the results of the inversion, the densities that exist in this region were interpreted in terms of rock units.

The three-dimensional inversion can show geological units as displayed by density contrasts. The McIvor and Cavelier plutons show a low-density contrast and prove the felsic composition of these zones. The gravity method was useful for determine the presence of the Cavelier pluton because this part of the studied area is covered with overburden. The Watson Lake Group rhyolite on the southern flank of the Galinée anticline show low-density contrasts as the authors expected and basalt, andesite, and gabbro, all mafic rocks, show high densities.

The current geological model assumes continuity between the Watson Llake rhyolite and the rhyolite mapped to the west of the McIvor pluton. These assumptions lead geologists to imply the existence of a syncline associated to the Galinée anticline. Unfortunately, the result of the unconstrained inversion can not confirm this model and future inversion will need to be constrained.

ACKNOWLEDGMENTS

The authors wish to thank Research Affiliate Program (RAP) of Natural Resources Canada and the Geological Survey of Canada contribution 20080670 for their financial support. The authors wish to express sincere thanks to M. Allard from Xstrata Zinc for his guidance and support.

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