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Production of a residual gravity anomaly map for Gaspésie (northern Appalachian Mountains), Quebec, by a graphical method

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Abstract: The authors present a residual gravity map for Gaspésie based on a separation of the regional and residual fields by a graphical method. This map results from the smoothing of 24 gravity profiles with lengths that far exceed the dimension of the zone of interest. The base value of the regional field has been estimated by taking into account surface data and by calculating the maximum gravity lows associated with relatively low-density Silurian-Devonian rocks. The residual gravity map includes all the gravity features that are clearly associated with shallow sources and shows a minimum distortion of the shape of the anomalies.

Résumé : Nous présentons une carte de l'anomalie de Bouguer résiduelle de la péninsule de la Gaspésie basée sur une méthode graphique de séparation des composantes régionale et résiduelle du champ de gravité. Cette carte résulte du lissage de 24 profils de gravité dont la longueur excède grandement les dimensions de la zone d'intérêt. La valeur de base de la composante régionale a été estimée en prenant en compte les données de surface et en calculant les bas gravimétriques maximums associés aux roches siluriennes et dévoniennes de densité relativement faible. La carte de l'anomalie de Bouguer résiduelle comprend l'ensemble des anomalies clairement associées à des sources peu profondes et montre une distorsion minimale de la forme des anomalies gravimétriques.

INTRODUCTION

The gravity method is one of the oldest geophysical methods. Its theory is well established and the acquisition of data can be relatively simple and low cost; however, many earth scientists do not feel confident with this method because of the nonuniqueness of possible interpretations.

From a practical point of view, gravity interpretations have two inherent problems: 1) the separation of the signal associated with the geological structure under examination from the long-wavelength signal referred to as the regional field, and 2) the attribution of an anomaly (once it has been separated from others) to a 'geological' source.

In this paper, the authors deal only with the first point; however, it must be recognized that the separation of the 'residual' and 'regional' fields has important consequences on the second point (e.g. Leaman, 1994). For example, depending on the residual and regional separation, a long-wavelength anomaly may be either attributed to the regional field (deep source) or to the residual field (subhorizontal, broad, shallow source).

PROBLEM

The gravity field is a superposition of anomalies resulting from density changes at various depths. Some anomalous bodies lie at depth in the zone of interest, but some bodies are much deeper. With such a perspective, the regional gravity field may be broadly defined as associated with sources deeper than the level of interest. For Gaspésie (northern Quebec Appalachian Mountains), the depth range the authors wish to emphasize includes the Early and Middle Paleozoic sedimentary basins. In this case, the purpose of the production of a residual gravity map is to remove the effects of the gravity component due to density variations within the 'crystalline' basement or to undulations of the crust-mantle interface. Once produced, the residual gravity map may be used for quantitative modelling.

The procedures that separate the regional and the residual fields have been a subject of gravity studies for decades (Nettleton, 1954; Skeels, 1967; Gupta and Ramani, 1980; Jacobsen, 1987; Cowan and Cowan, 1993; Blakely, 1995; among others) and may be divided in two groups: those which favour a mathematical approach (polynomial fitting, spectral- and space-domain filtering, upward continuation), and those which involve a more or less visual smoothing on profiles or maps. None of these procedures is devoid of assumptions; however, information external to the gravity data are integrated more implicitly in the second type of procedures.

GEOLOGICAL FRAMEWORK

Gaspésie can be schematically described as the imbrication of two tectonic wedges: the Late Proterozoic–Early Paleozoic wedge deformed mainly during the Ordovician Taconian Orogeny and the Middle Paleozoic wedge resulting mainly from the Devonian Acadian Orogeny.

Late Proterozoic–Early Paleozoic rocks form the Humber Zone which constitutes the frontal tectonostratigraphic zone of the Canadian Appalachian Mountains and structurally overlies the autochthonous rocks of the St. Lawrence Platform (Williams, 1979). Deep seismic-reflection data collected in the Gulf of St. Lawrence suggest that the Grenville metamorphic province forms the 'crystalline' basement of the offshore extension of the Humber Zone (Marillier et al., 1989). In Gaspésie, the Humber Zone is divided into external and internal subzones (Fig. 1; St-Julien and Hubert (1975)). The external Humber Zone has been interpreted to represent a typical north-directed foreland fold-and-thrust belt (St-Julien and Hubert, 1975). It includes Cambrian to Middle Ordovician rift and passive margin slope and rise sedimentary rocks

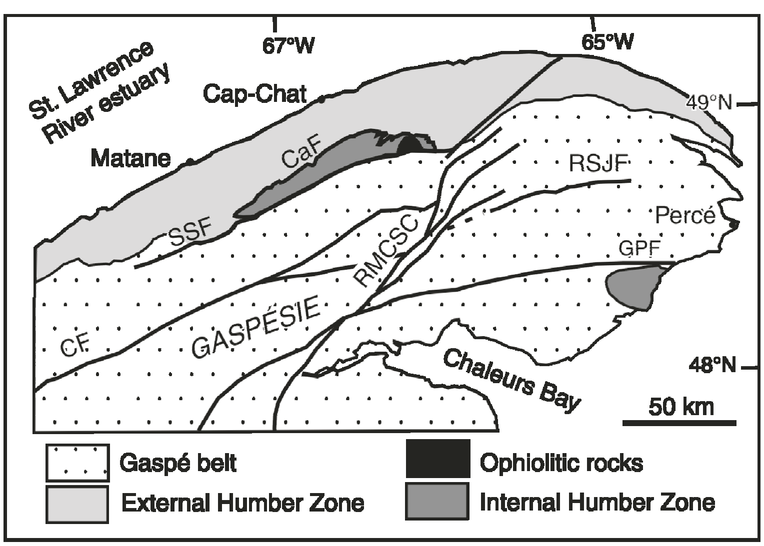

Figure 1. Geological framework of Gaspésie. CF = Causapscal Fault; CaF = Cascapédia Fault; GPF = Grand Pabos Fault; Rivière Madeleine–Campbellton structural corridor, RSJF = Rivière St-Jean Fault, SSF = Shickshock-Sud Fault.

(Lavoie et al., 2003) and Middle to Late Ordovician synorogenic flysch deposits (Hiscott, 1995). The internal Humber Zone is predominantly composed of Late Proterozoic to Cambrian tholeiitic metabasalt (Shickshock Group, Camiré et al. (1995)). The Shickshock Group is structurally overlain by the Mont-Albert ophiolitic complex, which is attributed to the Dunnage Zone of Williams (1979).

Middle Paleozoic shallow to deep marine sedimentary and volcanic rocks form the Gaspé belt (Fig. 1) and rest unconformably on, or are in fault contact with, older rocks belonging either to the Humber or the Dunnage zones (Bourque et al., 2001). The thickness of the preserved Middle Paleozoic sedimentary rocks varies along strike and reaches 7 km or more in some regional synclines.

GEOPHYSICAL FRAMEWORK

In Gaspésie, the Bouguer anomaly map is derived from 3850 gravity stations with an average spacing of 3 km (Pinet et al., 2005; Brouillette et al., 2006). On Figure 2, these data have been integrated in a larger area. Outside the recently surveyed area, gravity data from the Canadian Geodetic Information System were used, after rejecting some suspicious values. It should be noted that the geographic distribution of gravity stations varies considerably outside Gaspésie. Some areas, such as the Sept-Îles intrusion, benefit from a detailed gravity coverage (Loncarevic et al., 1990), whereas in other areas, such as in Chaleurs Bay, neighbouring stations may be more than 20 km apart.

The general level of the Bouguer anomaly over the Gaspésie area of the Appalachian Mountains is significantly higher than over the Grenville Province, where it ranges between –20 mGal and –60 mGal (Miller, 1995). The Bouguer anomaly over Gaspésie is also significantly higher than over Témiscouata and Bas-Saint-Laurent in the Appalachian Mountains (west of Mont-Joli), which demonstrates that the regional gravity variations are significant both across and along the strike of Appalachian tectonostratigraphic subdivisions.

On Figure 2, some high-amplitude, relatively long wavelength (>15 km) positive anomalies are clearly associated with exposed or shallow depth sources. In particular, a west-southwest-trending anomaly (A on Fig. 2) closely matches the map distribution of the high-density (2.95 g/cm^3, *see* 'Graphical method of separation of the regional and residual fields' section) Shickshock Group (internal Humber Zone), and an ovoid anomaly (B on Fig. 2) correlates with the greenschist facies Maquereau Group, that forms an inlier of the Humber Zone within the Gaspé belt. These anomalies provide one of the criteria by which the separation of the regional and residual fields can be tested: they should be absent from the regional field.

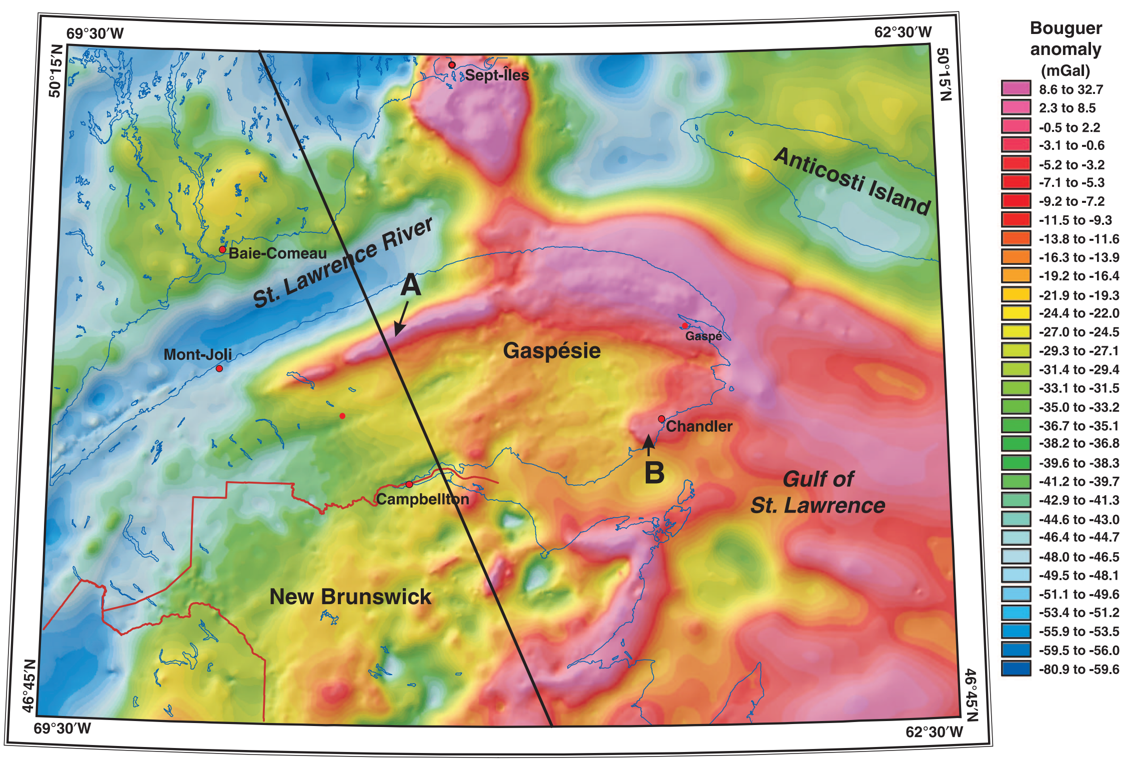

Figure 2. Bouguer anomaly map of Gaspésie and surrounding areas. Anomalies A and B are discussed in the text. The location of the gravity profile is shown.

GRAPHICAL METHOD OF SEPARATION OF THE REGIONAL AND RESIDUAL FIELDS

Geological data may be integrated in graphical methods of separation of the regional and residual fields. Among these data, specific gravity measurements provide the necessary link between geological units and gravity anomalies. In Gaspésie, over 1000 density measurements are now available (Pinet et al., 2005; N. Pinet and D. Lavoie, unpub. data, 2006). In the external Humber Zone, densities of rocks do not vary significantly with their position within the stratigraphic column, and average 2.66 g/cm^3. This value is in marked contrast with the average density (2.95 g/cm^3) of the Shickshock Group rocks (internal Humber Zone). Within the Gaspé belt, the density of sedimentary rocks varies from 2.53 g/cm^3 for the youngest rock assemblage (Middle Devonian) to 2.69 g/cm^3 in the oldest exposed assemblage (Late Ordovician).

Twenty-four gravity profiles (Fig. 3), showing a variable obliquity with the structural grain, have been extracted from the Bouguer anomaly map shown on Figure 2. The lengths of these gravity profiles (250 km to 600 km) far exceed the dimension of the zone of interest (Gaspésie) in order to provide a clearer picture of the regional trend of the gravity field.

Extraction of a residual Bouguer anomaly has been achieved by the removal of a smooth regional component by a graphical method. In most gravity profiles a trend (attributed to the regional field) is obvious and the main issue was to determine the base value of the regional field. This issue has been achieved with the assumption that lithotectonic zones formed by outcropping units with a density higher than the reduction density (2.67 g/cm^3) must be characterized by a positive residual anomaly. This assumption is based on a common increase of density with depth in sedimentary basins, a characteristic that has been validated by specific gravity measurements in Gaspésie. This assumption has, however, not been considered in zones characterized by magnetic anomalies, suggesting intrusive bodies and areas near the St. Lawrence River shore where the gravity component due to the autochthonous rocks belonging to the St. Lawrence Platform are difficult to estimate in absence of density measurements. The issue has also been achieved by computing the maximum gravity lows associated with relatively low-density Silurian-Devonian sedimentary rocks. For that, the geometry and thickness of these rocks were derived from geological maps and/or seismic profiles and the computation of the maximum negative anomaly has been achieved with a 2.5-D gravity modelling approach based on the method of Talwani et al. (1959).

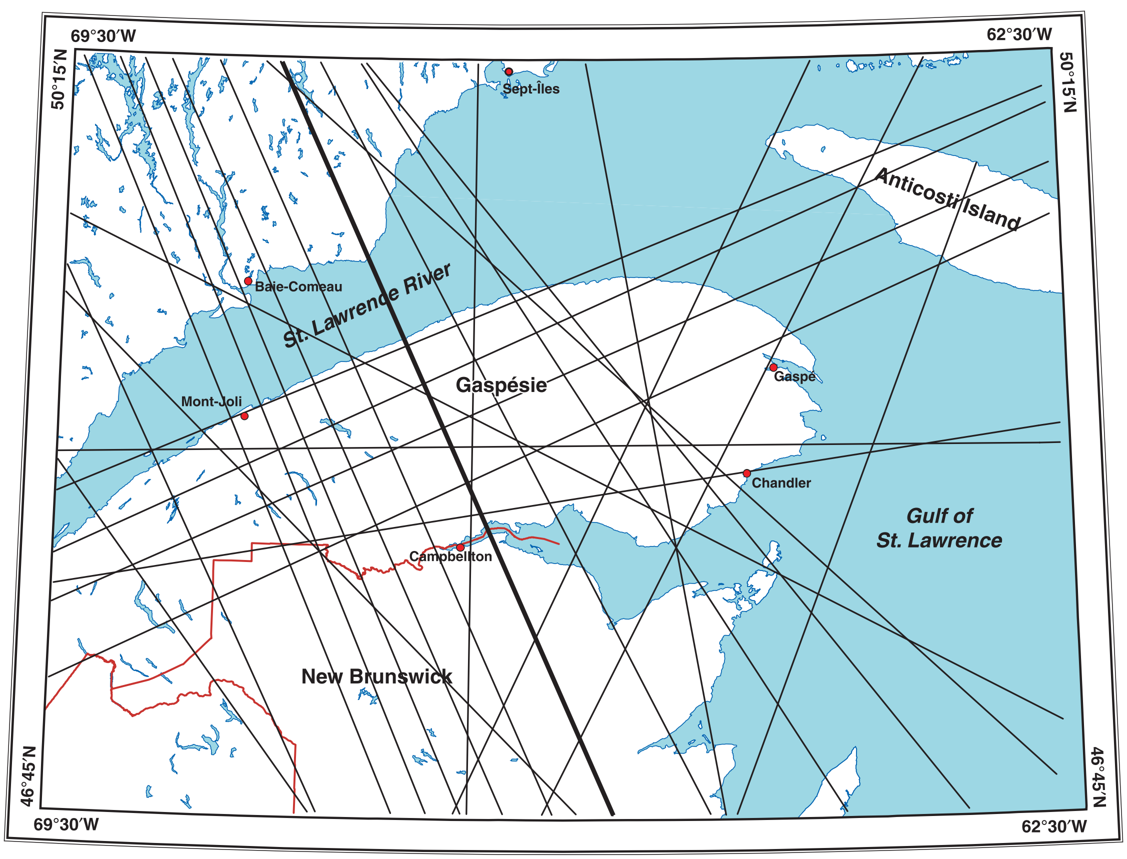

Figure 3. Location of gravity profiles used for the separation of the regional and residual fields.

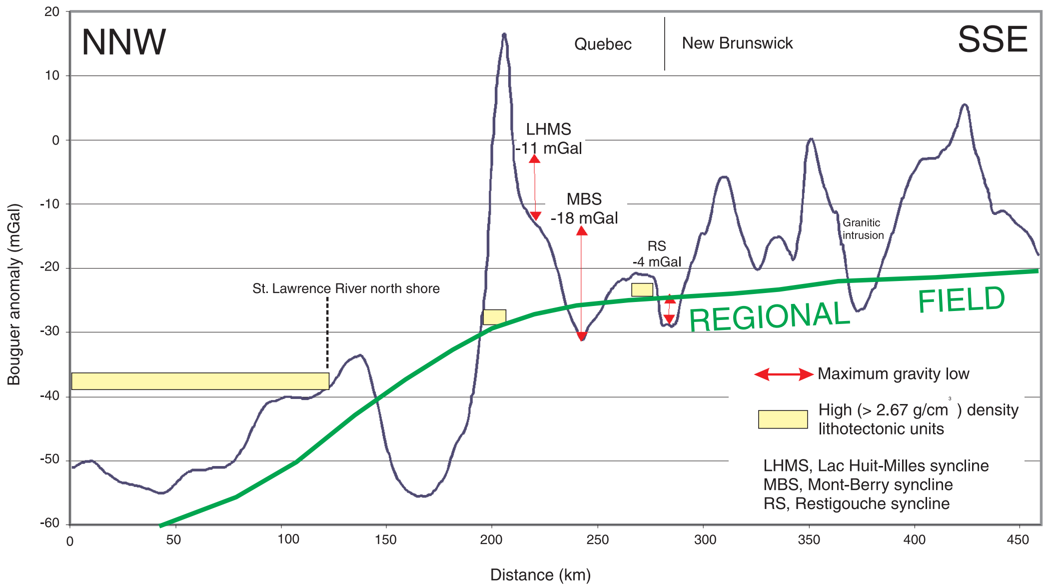

Figure 4. Smoothing of a gravity profile using geological parameters. Comments in the text.

Figure 4 illustrates such an approach for the determination of the regional component along a profile trending north-northwest (location on Fig. 2). The maximum gravity lows associated with relatively low-density sedimentary rocks have been calculated for three geological structures (Fig. 4): the Lac Huit-Milles syncline (11 mGal), the Mont-Berry syncline (18 mGal), and the Restigouche syncline (~4 mGal). On Figure 4, the extent of lithotectonic zones formed by outcropping units with a density higher than the reduction density has also been shown.

Drawing a smooth regional component, the emphasis has been on 'smooth'. For this reason, on Figure 4, the value of the regional field decreases slightly from the Restigouche syncline to the Lac Huit-Milles syncline, in agreement with the general trend of the gravity field; and consequently, the residual anomaly over the Lac Huit-Milles syncline is positive, despite the fact that outcropping rock units are characterized by a density lower than the reduction density. On Figure 4, higher value of the regional component of the gravity field would be difficult to reconcile with the maximum gravity low in the Restigouche syncline. It should be recognized, however, that a lower value of the regional component is also acceptable.

Once such an analysis has been done for the profiles corresponding to key geological cross-sections, each subsequent profile examined has forced reconsideration. The coherency of the regional component of the gravity field has been then validated by the comparison at points of intersections between transverse and longitudinal profiles. A grid that matches the interpreted value of the regional component has then been computed to create a map of the regional field over Gaspésie. The regional component of the gravity field (Fig. 5) decreases in a west-northwest direction from –22 mGal near Chandler to –48 mGal near Mont-Joli. If interpreted solely in terms of crust-mantle interface depth variation, and using a density contrast of 0.5 g/cm^3, this 26 mGal difference in the regional field corresponds to an approximately 1.3 km deepening of the Moho toward the west-northwest.

A residual gravity map (Fig. 6) has been then computed by subtracting the regional component of the gravity field from the Bouguer anomaly.

CRITERIA FOR EVALUATION OF THE RESIDUAL GRAVITY MAP

No unique determination of the regional component of the gravity field is possible without the precise knowledge of the mass distribution from the surface to the Earth's centre. Thus, extraction of the residual component of the gravity field includes inevitably some assumptions of the interpreter, especially with the graphical method (smoothing of profiles).

In Gaspésie, the residual map obtained by the graphical method described above agrees with three criteria by which the regional and residual separation can be tested :

The regional field does not include gravity features that are clearly associated with shallow depth sources. In particular, the positive anomalies associated with the exposed internal Humber Zone (Shickshock and Maquereau groups) have been totally removed.

Anomalies in the residual field follow the Appalachian Mountains' tectonic grain and some major geological features limit gravity domains characterized by different gravity

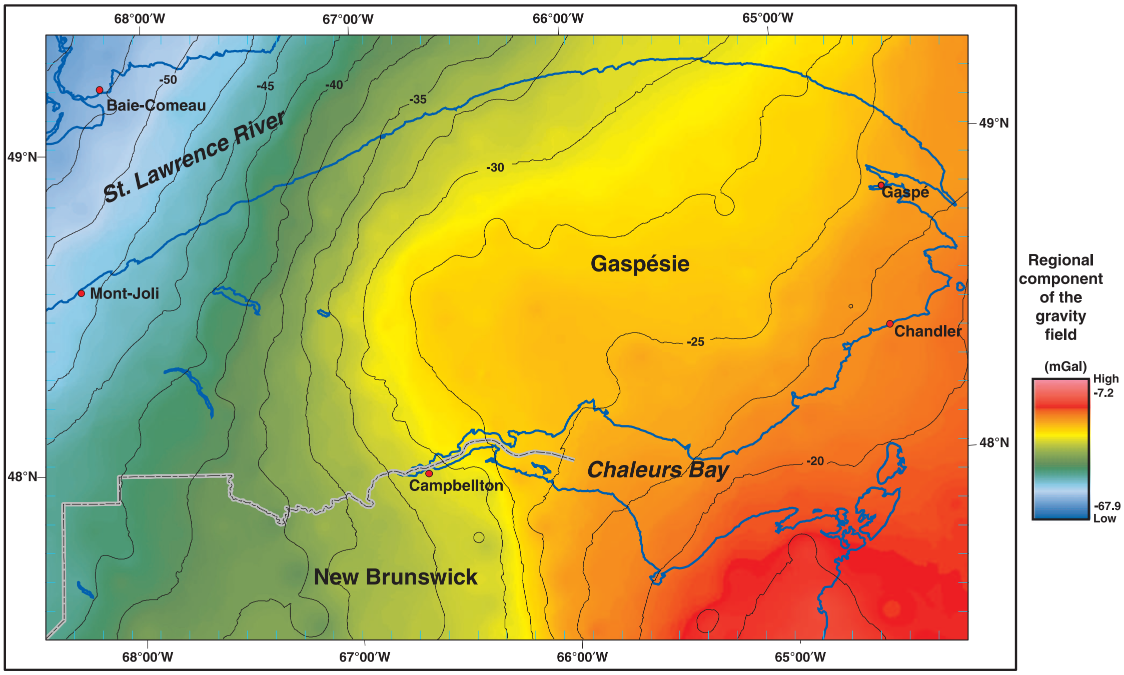

Figure 5. Regional component of the gravity field over Gaspésie.

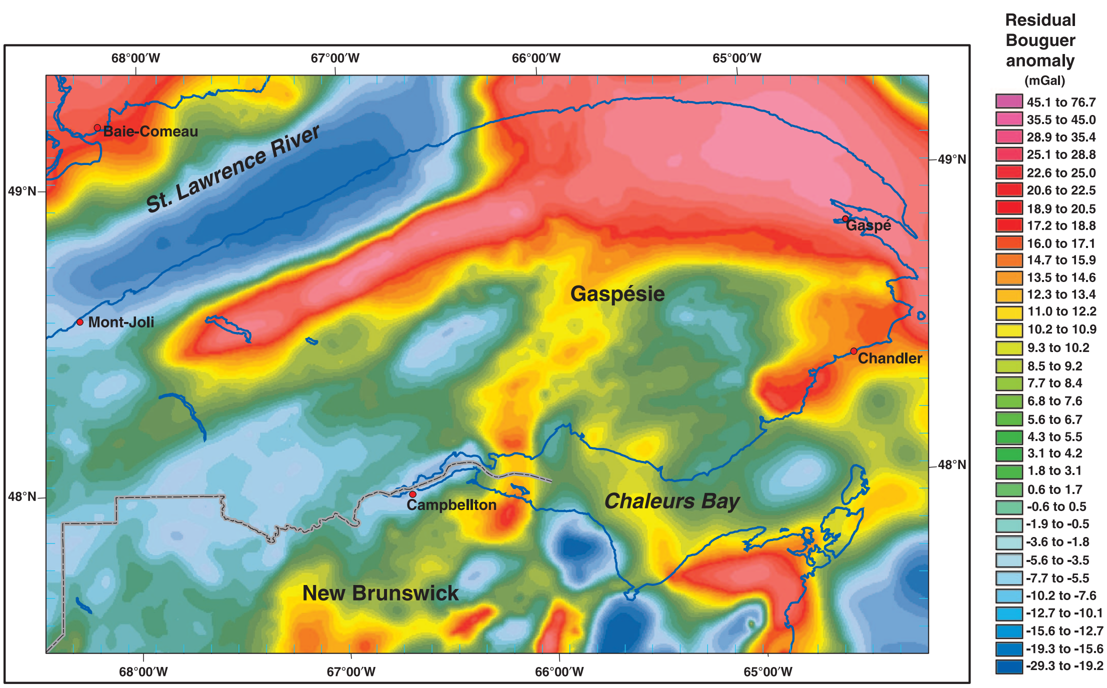

Figure 6. Residual component of the gravity field over Gaspésie.

signatures. In other words, the regional and residual separation results in a minimum (if any) distortion of the shape of gravity anomalies.

The value of the residual Bouguer anomaly is compatible with the authors' geological understanding of Gaspésie as shown by 2.5-D gravity modelling (N. Pinet, P. Keating, and D. Lavoie, work in progress).

FUTURE RESEARCH

Future work will include a comparison of the residual Bouguer anomaly map resulting from the graphical method described above with those obtained with other geophysical methods for the separation of the regional and residual fields. These methods include: the estimation of the regional field by a polynomial fit (Nettleton, 1954); frequency-domain filters built to separate long-wavelength anomalies from the gravity field (Petersen, 1979); upward continuation transformation that tends to accentuate long-wavelength anomalies that are generally caused by deep sources (Jacobsen, 1987); and space-domain filters that replace 'short-wavelength' anomalies by interpolated values (Naudi and Dreyer, 1968). These methods will be discussed qualitatively using the three criteria listed above and their usefulness for gravity modelling will be evaluated.

The degree of smoothness of the regional component maps derived from mathematical filtering operations depends of parameters chosen by the interpreter: the degree of the polynomial fit, the cut-off wavelength for frequency-domain filter, and the continuation height for upward continuation transform. Preliminary investigation indicates that a relatively low degree of smoothness results in regional maps that clearly include anomalies associated with near-surface bodies, then a high degree a smoothness results in negative residual Bouguer anomalies that are incompatible with the geological evidence. A shift in the datum may be applied to change the mean of the residual Bouguer anomalies; however, as mentioned by Gupta and Ramani (1980), the choice of a constant datum shift would create distortions (in shape and amplitude) in some part of the map. These preliminary results suggest that the separation of the regional and residual fields is best achieved by applying geological thought to the problem (Gupta and Ramani, 1980; Leaman and Richardson, 1989; Leaman, 1994).

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