

Application of gravity and pseudogravity geophysical treatments to structural targeting in the Eeyou Istchee Baie-James region, Québec Superior Province: Preliminary interpretations

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MB 2017-14

Énergie et Ressources naturelles
Québec

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Ministère de l'Énergie et des Ressources naturelles, Québec

by

Nathan R. Cleven[1]

June 16, 2017

Supervision by Lyal Harris[2], Carl Guilmette[1], and Jean Goutier[3]

[1]Université Laval, Department of Geology and Geological Engineering
[2]Institut National de la Recherche Scientifique (INRS)
[3]Ministère de l'Énergie et des Ressources naturelles

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Abstract/Résumé

In this report, we describe the basic treatment methodology and the structural interpretation of gravity and aeromagnetic geophysical surveys of the Eeyou Istchee Baie-James region of the Québec Superior Province. The Archean geology of the region exhibits complex structural patterns that are difficult to determine from analysis of field geology alone. The purpose of this study is to use structural interpretation of gravity and aeromagnetic geophysical maps to provide a preliminary, large-scale understanding of the regional tectonic history. Treatments of the geophysical datasets were applied to aid structural and tectonic interpretation, and the most useful examples are provided. The examples illustrate how analysis of geophysical maps provides extensive benefit for both cartography and mineral exploration in this region. The geophysical data sets treated include selected portions of the Natural Resources Canada gravity survey data, and the high-resolution aeromagnetic survey of the Eeyou Istchee Baie-James region provided by the Ministère de l'énergie et des Ressources Naturelles du Québec. Maps and interpretation of the theta angle treatment, and the theta angle of the residuals, of the gravity survey data are included. Treatment and interpretation of the aeromagnetic survey data are focused on a pseudogravity transformation of the survey data, and the maps provided include the tilt angle treatment of the short wavelength residuals, and the tilt angle treatment combined with the long wavelength. Our analyses of the maps focus on lineament patterns, structures that compose regional Superior Province subprovince tectonic boundaries, and the structures that exist in mineralized regions. Apparent correlations between mineralization occurrences and structural patterns are examined, and a preliminary analysis of potential exploration targets based on the structural interpretation is provided.

Dans ce rapport, la méthodologie de base du traitement et l'interprétation structurale des données gravimétriques et des ensembles de données géophysiques aéromagnétiques à haute résolution sont décrites pour la région Eeyou Istchee Baie-James de la province du Supérieur, au Québec. La géologie archéenne de la région contient de nombreux patrons structuraux qui sont difficiles à déterminer à partir de l'analyse de la géologie de terrain. L'objectif est d'utiliser l'interprétation structurale des cartes des levés géophysique, gravimétrique et aéromagnétiques afin d'obtenir une compréhension préliminaire de l'histoire tectonique de la région. Des traitements spécifiques des données géophysiques ont été appliqués pour faciliter l'interprétation structurale et tectonique, et des exemples sont fournis. Les exemples fournis illustrent comment l'analyse des cartes géophysiques offre un avantage significatif tant pour la cartographie que pour l'exploration minérale dans cette région. Les données géophysiques traitées comprennent des portions sélectionnées des données de levés gravimétrique de Ressources naturelles Canada et des levés aéromagnétiques haute résolution de la région Eeyou Istchee Baie-James fournies par le ministère de l'énergie et des Ressources Naturelles du Québec. Les cartes et l'interprétation du traitement «angle theta», et l'angle theta du signal résiduel du levé gravimétrique sont incluses. Le traitement et l'interprétation des données du levé aéromagnétique sont axés sur les traitements de type «pseudo-gravité», y compris le traitement de l'angle d'inclinaison du signal résiduel de longueur d'onde courte et le traitement de l'angle d'inclinaison combiné à la longue longueur d'onde. L'analyse se concentre sur l'interprétation de linéaments à grande échelle, sur les structures qui composent les frontières tectoniques des sous-provinces du Supérieur et sur les structures observées dans les régions minéralisées. Les corrélations apparentes entre les minéralisations et les modèles structuraux sont examinées et une analyse préliminaire des cibles potentielles d'exploration en fonction de l'interprétation structurale est fournie.

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1 Introduction

1.1 Geophysics in the Superior Province

Subprovince boundaries in the Canadian Superior Province have traditionally been interpreted where regional-scale faults or strong metamorphic transitions separate regions with contrasting ages and lithological sets (Card and Ciesielski, 1986; Card, 1990; Poulsen et al., 1992; Card and Poulsen, 1998). The delineated regions typically conform to one of the four standard types of Archean litho-tectonic domains: volcano-plutonic subprovinces, meta-sedimentary subprovinces, plutonic subprovinces, and high-grade gneissic subprovinces. Three significant problems with boundary interpretation are present in the Québec superior: 1) lithological and characteristic similarities exist between some of the standard types of domains, such as volcano-plutonic subprovinces that contain extensive meta-sedimentary rocks which border similar meta-sedimentary domains, or in situations of gradational transitions from lower to higher grade metamorphism between meta-sedimentary provinces and high grade gneiss domains; 2) major bounding structures such as faults and shear zones do not have compilations of kinematic indicators, and the senses of motions across most faults is not well defined; 3) access is difficult, and therefore certain contacts or lengths of contacts have received little effort for research.

Geophysical maps have been used for more than three decades to aid in the delineation of boundaries and the understanding of sub-surface geology in the Canadian Superior. Seismic surveys have aided in developing the subsurface structure across the country (Calvert et al., 1995; Percival et al., 2006; Frederiksen et al., 2007; Percival et al., 2012), though the surveys do not include the northeast Superior Province. Airborne magnetic surveys and gravimetric profiles (Telmat et al., 2000; Eaton and Darbyshire, 2010; Dufréchou and Harris, 2013; Dufréchou et al., 2014) aided some of the early boundary interpretations, as they alleviate some of the above mentioned significant problems by depicting significant transitions from paramagnetic mineral bearing units to non-bearing units (in the case of magnetic surveys), or severe density contrasts (in the case of gravity profiles). This report applies more advanced treatments methods of existing magnetic and gravity data that isolate aspects of the respective signals from deeper and shallower contributing sources. This allows a comparison between the organization and structure of deeper, possibly basement units, versus the effects attributable to supracrustal coverings or shallow structures. Their interaction over a protracted geologic history may be discernible. This adds a dimension to the analysis that is directly applicable to the problems mentioned above. Lithological similarities across prospective boundaries observed at surface can be confirmed or discounted by the correlation between the geophysical signatures representing the unit at depth and shallow levels. It may provide evidence for the reasons behind the differential exposition of various metamorphic levels at surface. Our methods may be of great use for mineral exploration, as in this region mineralization is largely controlled by the interaction between deep structures that mobilized fluids and minerals, and the shallow structures that focused the fluid flow and now host the minerals (Dufréchou et al., 2011; Leclerc et al., 2012).

1.2 The Eeyou Istchee Baie-James region

The goal of this report is to generate targets for future mapping, sampling, fault analysis and potential for mineralization in the Eeyou Istchee Baie-James region (Fig. 1). The

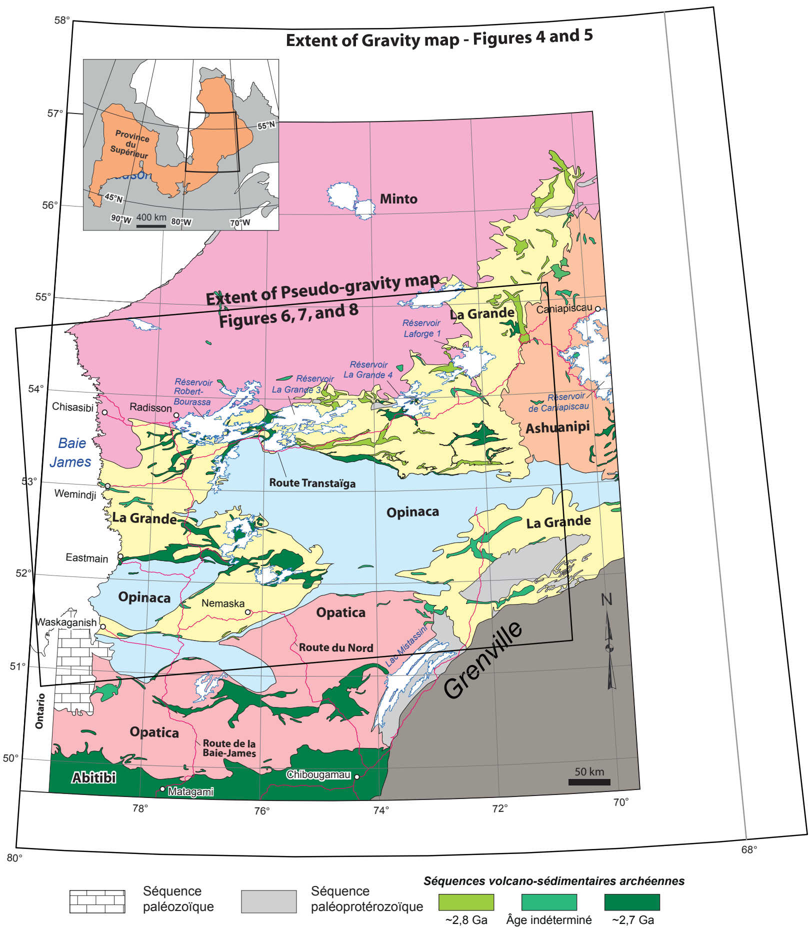

Figure 1: Subprovinces of the Superior in the Eeyou Istchee Baie-James region. Modified from Houlé et al. (2015).

geologic and tectonic setting of the Opinaca and La Grande subprovinces in the Eeyou Istchee Baie-James region are the large-scale scientific goals of our research group, but they are situated in the wider context of the surrounding province. Therefore, geophysical maps of a larger scale than the target subprovinces were generated to provide this context, and to offer general understanding of contacts and boundaries between domains. These maps will help develop an understanding of the region's tectonic framework, including major lithotectonic contacts, a common site for mineral occurrences (Mercier-Langevin et al., 2012; Aucoin et al., 2012; Fontaine et al., 2015; SIGÉOM, 2016). The natures of the contacts between the La Grande and Opinaca subprovinces, a specific goal of our work, are under-studied and inherently difficult to define. The contacts between them (Figure 1) in the southwest (Bandyayera et al., 2010), southeast, northwest (Goutier et al., 2000, 2001) and north (Goutier et al., 2002; Bandyayera et al., 2011) are structurally unique from each other, and comprise three types of contact relationships: metasediment in contact with metasediment; metavolcanic in contact with metasediment; cut by late intrusions. The high-grade metamorphism in both (especially the Opinaca) has destroyed many primary sedimentary relationships, more so in the east, leaving the nature of their original depositional contact unclear, and overprinted by subsequent tectonic episodes. The following geophysical gravity and pseudogravity maps will provide a detailed view at the internal structure of the contacts and units, as well as a relative idea of the deep crustal constituents of the subprovinces.

1.3 Structure of this report

This report provides an initial basic review of the geophysical data treatments used to produce two gravity and three pseudo-gravity maps. Each map provides a slightly different aspect of utility, although the treatments generally have the intended goal to delineate boundaries. The key aspects of the maps will each be described, as well as the methods and reasons for interpreting the line work. The regional interpretations that stem from each map will be included, and targets generated during the analysis concerning geological mapping and mineral exploration will be presented. Future work directions will be discussed to conclude.

2 Methodology

All digital maps produced for this report have been generated from publicly available data sets using the computer data analysis and visualization software Oasis Montaj by Geosoft. Treatments of the data were performed by Lyal Harris of the Institut National de la Recherche Scientifique (INRS), in Québec City, with the participation of the author. Full size high resolution versions of each data treatment presented are available as georeferenced raster images. The following section will not explain in detail the geophysical concepts used in the data treatments, rather the purpose, effects, shortcomings and uses of the data treatments. However, brief, simplified explanations of the geophysical concepts will be provided.

2.1 Gravity

2.1.1 Gravity data

The gravity data set used for this study is the publicly available 2 km grid spacing Natural Resources Canada data set. The density of points is actually variable, generally between less than 1 km to possibly more than 20 km (throughout Canada). The study region is indicated on Figure 1. In the study region no sub-regions appeared to have low density of points (not less than 2 km), and many regions had high density of measurements. Bouguer anomalies were calculated using a standard vertical gradient and average crustal density, then interpolations were calculated to grid over a region larger than the study area.

The initial Bouguer anomalies are depicted in Figure 2A, in a small format map, to provide an example of the initial data. It generally shows the variations in density of the combined crust and mantle, smoothed over the region. The relative homogeneity of the mantle, compared to the crust, provides a long wavelength signal in the Bouguer anomaly map that has a short wavelength signal superimposed by the highly heterogeneous crust. High density lithologies such as those in greenstone belts may be thin veneers at the scale of the crust, and contributed to the variation seen in the Bouguer anomaly map. Separating the long wavelength from the short wavelength signals allows maps that can represent the distribution of densities in mantle rocks or basement (long wavelength) or can depict contrasts of densities in the crust (short wavelength).

2.1.2 Gravity treatments

Bouguer anomaly data from a region larger than the study area is used initially (Fig. 2A) to prevent edge effects from occurring during treatment. Isolating long/short wavelength signals requires calculations to be made for each datum that consider the surrounding points, therefore edges may not not have been calculated correctly. The long and short wavelength data sets are calculated using a Butterworth filter based on the slope of the radially averaged power spectrum, from the method of Spector and Grant (1970). This

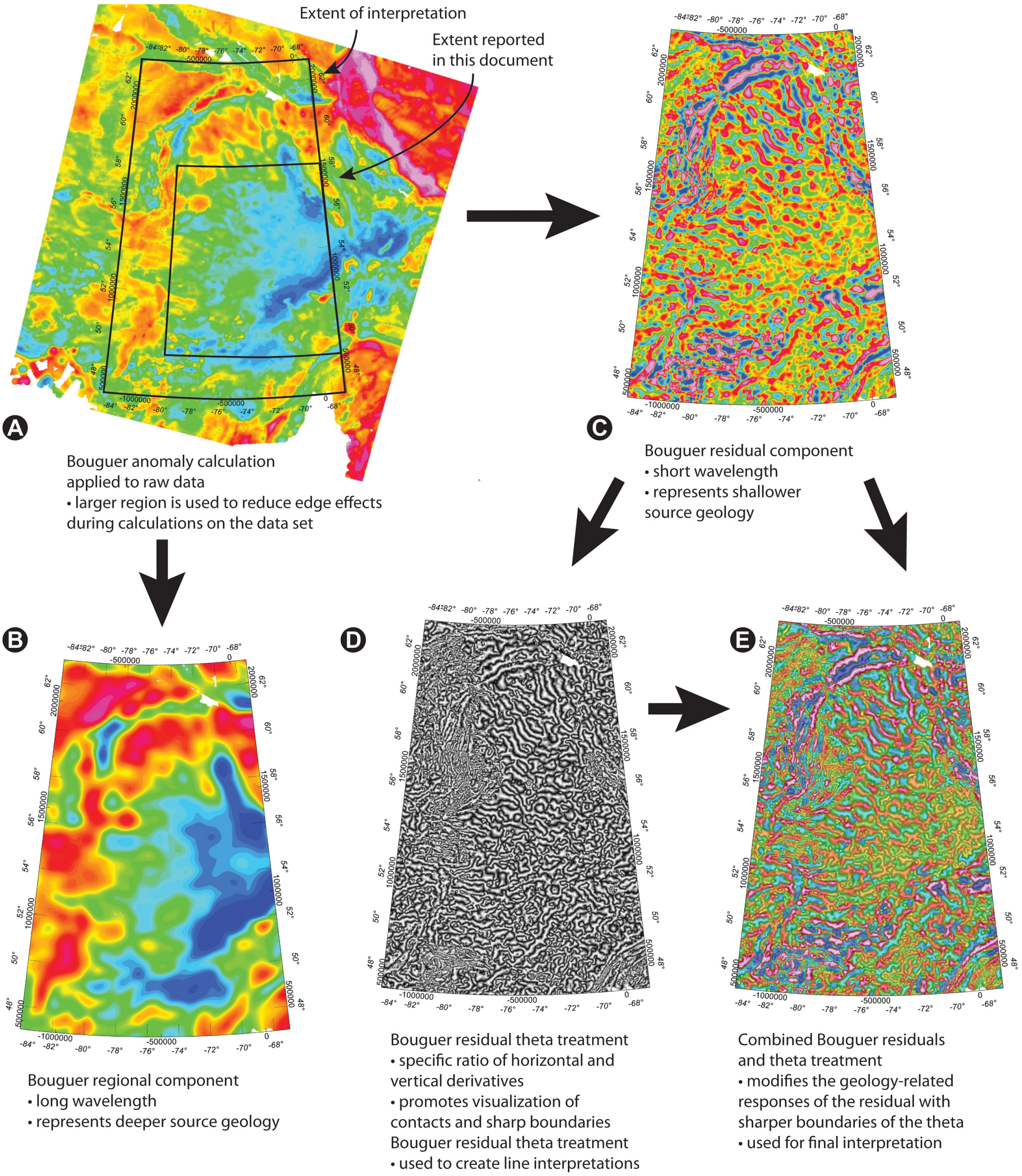

Figure 2: Flow diagram of gravity data processing. Raw data is processed for the Bouguer anomaly (A) then broken into long (B) and short (C) wavelength components. The short wavelength component, or residuals, is used to apply a theta calculation (D) which enhances boundaries. The residuals are combined with the theta (E) to create a map representing shallow source geology with improved boundaries for final interpretation.

provides one map with a gentler gradient than the Bouguer anomaly map, the regional component map (or long wavelength, Fig. 2B), and another with a rapidly changing values, the residual component map (or short wavelength, Fig. 2C). Both have a semblance to the original in the pattern of colouration, but differ on their respective level of detail.

The residual component data provides us with the core data we wish to work with for this portion of the study. It represents shallower crustal units in a region where there can be a high contrast between units. With a long tectonic history, we expect to see density differences not only due to lithological relationships, but where lithologies have been juxtaposed across structures (such as faults). To target this we have processed the residual component data set with a theta treatment (Fig. 2D). The theta treatment (Wijns et al., 2005; Cooper and Cowan, 2006) is a calculation involving the ratio of the magnitude of the horizontal gradient to the magnitude of the analytical signal (the anomaly). The effect is that it promotes a lateral contrast in the respective density representations: it helps define edges. The theta treated data represents a ratio, therefore magnitude of signal information is lost. To compensate, the theta was combined with the original residual component map to produce a plot (Fig. 2E) with improved contrast at edges, with a remnant of the original variations in magnitudes throughout the region, thus preserving lithological information as well as highlighting structures.

2.1.3 Interpreting the treated data

Line interpretations were primarily made on the theta treatment map, as it offers the best opportunity for boundary identification. Interpreted lines were hand drawn and grouped according to general orientation, the prominence of the feature, and the amount of curvature to the lineament. The identification of lineaments or features to be traced is not always immediately obvious. The point is not to follow the 'tectonic grain' of the region and trace highs and lows, but to identify subtle alignments of finer details, truncations of the grain, that define a traceable trend. Some traced features cross only fine detail, whereas others cross wider highs or lows. Such differences were accounted for in grouping.

The combined theta and residual map was used to interpret more context for lines traced on the theta treatment map. The residual Bouguer highs and lows provide context for whether a lineament or traced feature may be an important contact or fault. The relationship between a potential boundary and the natures of the bordering units can be examined.

2.2 Pseudogravity

2.2.1 Aeromagnetic data to pseudogravity

Pseudogravity data is derived from magnetic data. Under assumptions of density for the magnetized bodies the gravity potential can be calculated from its relationship with magnetic potential (Baranov, 1957; Jekeli et al., 2010). The result, applied over an entire aeromagnetic data set, is a pseudogravity map that can be treated in an identical manner to a Bouguer anomaly map. The aeromagnetic data used for this study is the Ministère de l'Énergie et des Ressources naturelles 60 m spacing data set for Eeyou Istchee Baie-James region from 2010-2011. The (squared off) extent of the data set is indicated in Figure 1.

2.2.2 Pseudogravity treatments

The original Baie-James aeromagnetic data set (Fig. 3A) was processed in a similar manner to to the gravity data, segregating the signals into long wavelength regional component (Fig. 3B) and a short wavelength residual component (Fig. 3C) using a Butterworth filter based on the slope of the radially averaged power spectrum, from the method of Spector and Grant (1970). The residual component data set was processed with a tilt angle treatment (Fig. 3D) which calculates a ratio of the horizontal and vertical gradients (Cooper and Cowan, 2006). The effect is that the gradational or sharp nature of boundaries is enhanced. This treatment is a ratio, and loses the respective absolute magnitudes of the data. The tilt map was combined with the regional (long wavelength) data set (Fig. 3E) to provide colouration representative of deeper sources. The tilt map was also combined with the residual (short wavelength) data set to provide colouration representative of shallower crustal units.

2.2.3 Interpreting the treated data

Line interpretations were focused on delineating structural domains. The tilt map was primarily used to trace structures. Trends of highly negative (dark) data bounding contrasting structural styles were traced as major possible domain boundaries. Minor boundaries, where small crossings of positive signal were necessary, were grouped together as well.

The combination tilt and residual map was used to establish context for the major and minor interpreted line boundaries. The colouration based on crustal density provided context for which units may be grouped along boundaries. The combination tilt and regional map was used to establish which domain boundaries may possibly denote major subprovince boundaries.

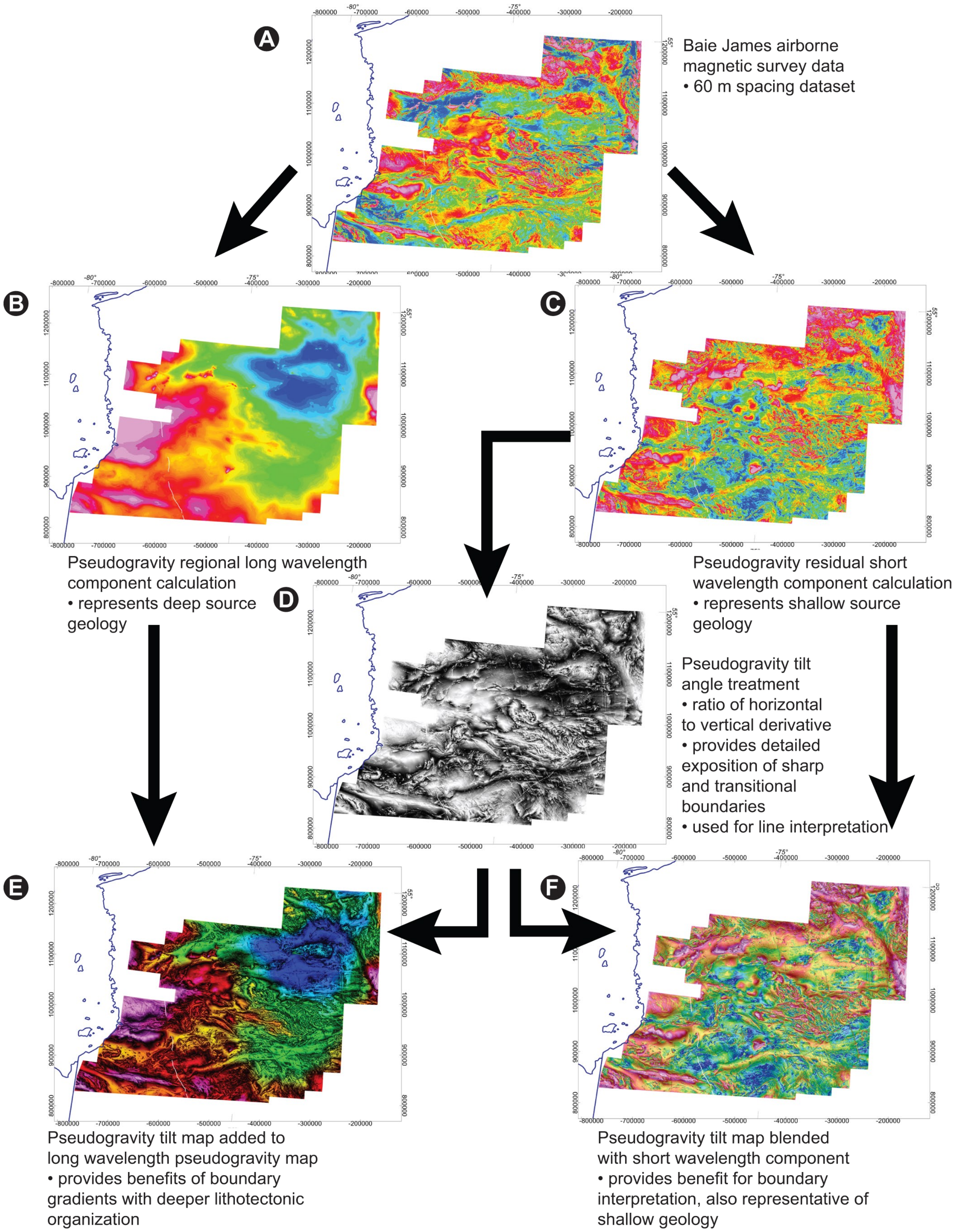

Figure 3: Flow diagram of pseudogravity data processing. Raw aeromagnetic survey data (A) is processed to calculate for pseduogravity short (B) and long (C) wavelength components. The tilt (D) angle is calculated, which is combined with the short (E) and long (F) wavelength data sets for final interpretation maps.

3 Gravity map interpretation

3.1 Theta angle treatment map

The theta angle treatment map (Fig. 4) is a grayscale map that has with high and low (light and dark) ridges that generally define the regional tectonic grain. The map has increased detail in Hudson's Bay and Baie-James, due to a high density of data points. It covers the region from the Minto block in the north, to the Abitibi and Grenville Front in the South. It covers most of the Opatica, Opinaca, La Grande, and Ashuanipi subprovinces. The tectonic grain generally trends northwest-southeast in the north, and east-west in the central subprovinces. The Grenville front can be seen trending northeast-southwest in the southeastern corner.

3.1.1 Lineament interpretation

Lineaments are recognized on the theta map by aligned truncations of ridges (positive values) following the tectonic grain. Commonly, parallel sections of troughs (negative values) appear aligned with a series of truncations, showing a trend. Occasionally, traced lineaments appear to form a semi-continuous series, even though they can be locally cut but the tectonic grain. This could be explained as intrusions that crosscut the tectonic grain, or anomalously dense material may have distorted the region, or the feature may not have originally been continuous. An example is a series that is generally aligned along the 74° meridian (Fig. 4). It is a North-South band that shows the highest density of (N-S) linear features. A geologic interpretation of this may be one of many possibilities: each segment may be a remnant of a distributed deep deformation event preserved in the deeper, dry granulite basement rocks, such as a failed N-S rift; they may be detachment structures formed as antithetic structures to E-W shear zones, and accommodated E-W extension during transpressive shearing.

Figure 4 includes a specific set of line interpretations that trace straight features. In the north, in the Minto Block, the lineaments are more obvious, are traceable for longer distances, and generally follow the tectonic grain. However, in the central Eeyou Istchee Baie-James region they are not as long, but have a higher density of shorter segments. In this region North-South structures are generally absent in maps of bedrock geology, or in the literature. The North-South band aligned along the 74° meridian (Fig. 4) cuts the Opinaca and La Grande subprovinces. There is a high density and confluence of them at the western contact between the Opinaca and La Grande subprovinces. In this region the rocks exposed at surface are mostly supracrustal, and underlying, older basement may contain structures that were covered by deposition of the La Grande and Opinaca, and throughout history affected the structural expression of the ductile deformation in the rocks of the surficial geological record. They cannot be extremely late features such as fractures or low-displacement faults, as the nature of gravimetric surveys does not differentiate regions with no large density contrast.

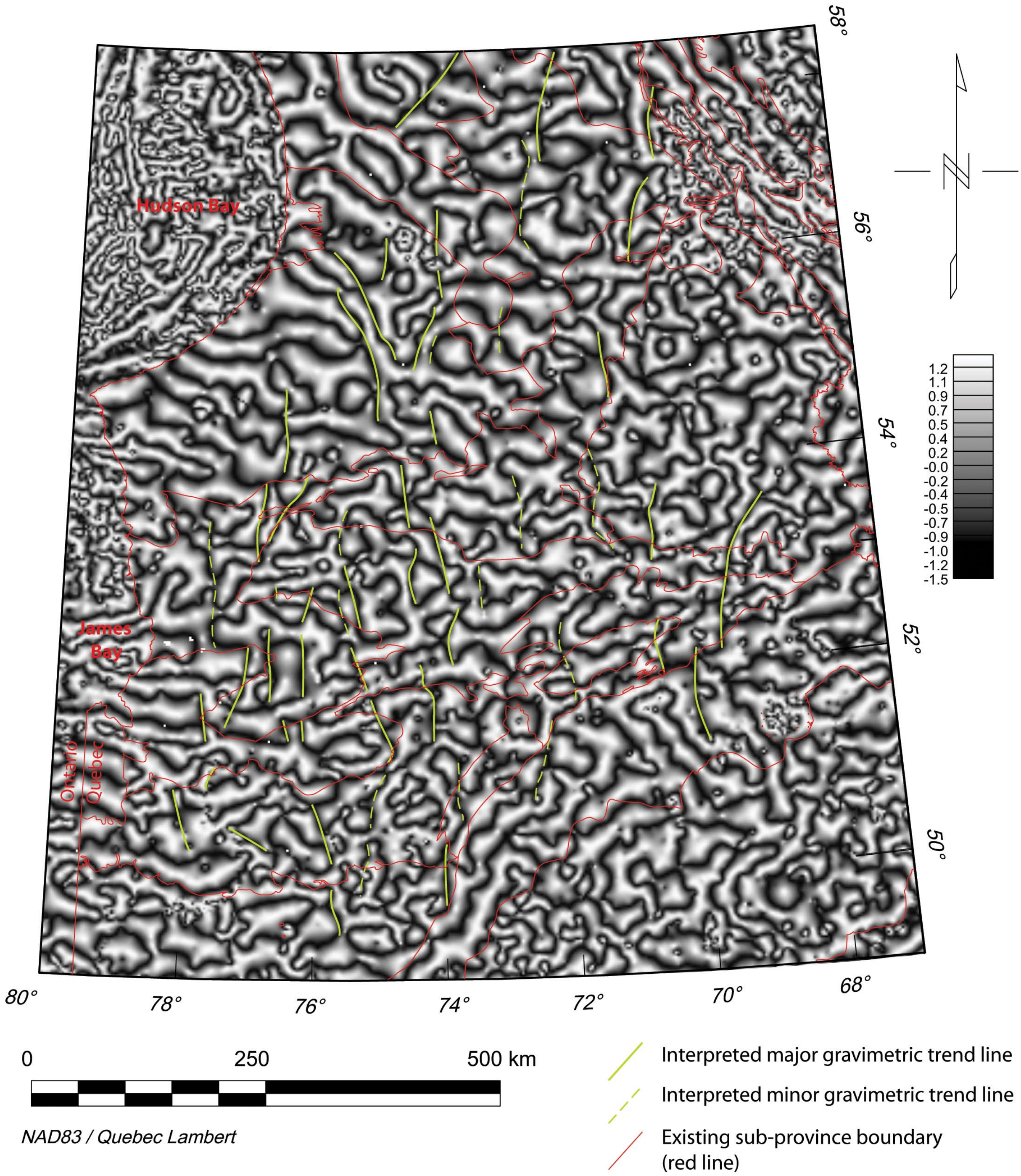

Figure 4: Gravity map with theta angle processing and lineament interpretation. The group of traced lineaments included in this map are a series of largely north-south oriented straight features.

3.2 Combination theta treatment and residuals map

The combination theta treatment and residuals map (Figure 5) provides context for further interpretation of features traced on the theta map. The texture of the map is similar to the theta map, with ridges and troughs, but with colour generally representing a component of the crustal density or lithology. For example, the Grenville front is easily identified in reds and pink in the southeastern corner. Subprovince boundaries are subtly included in

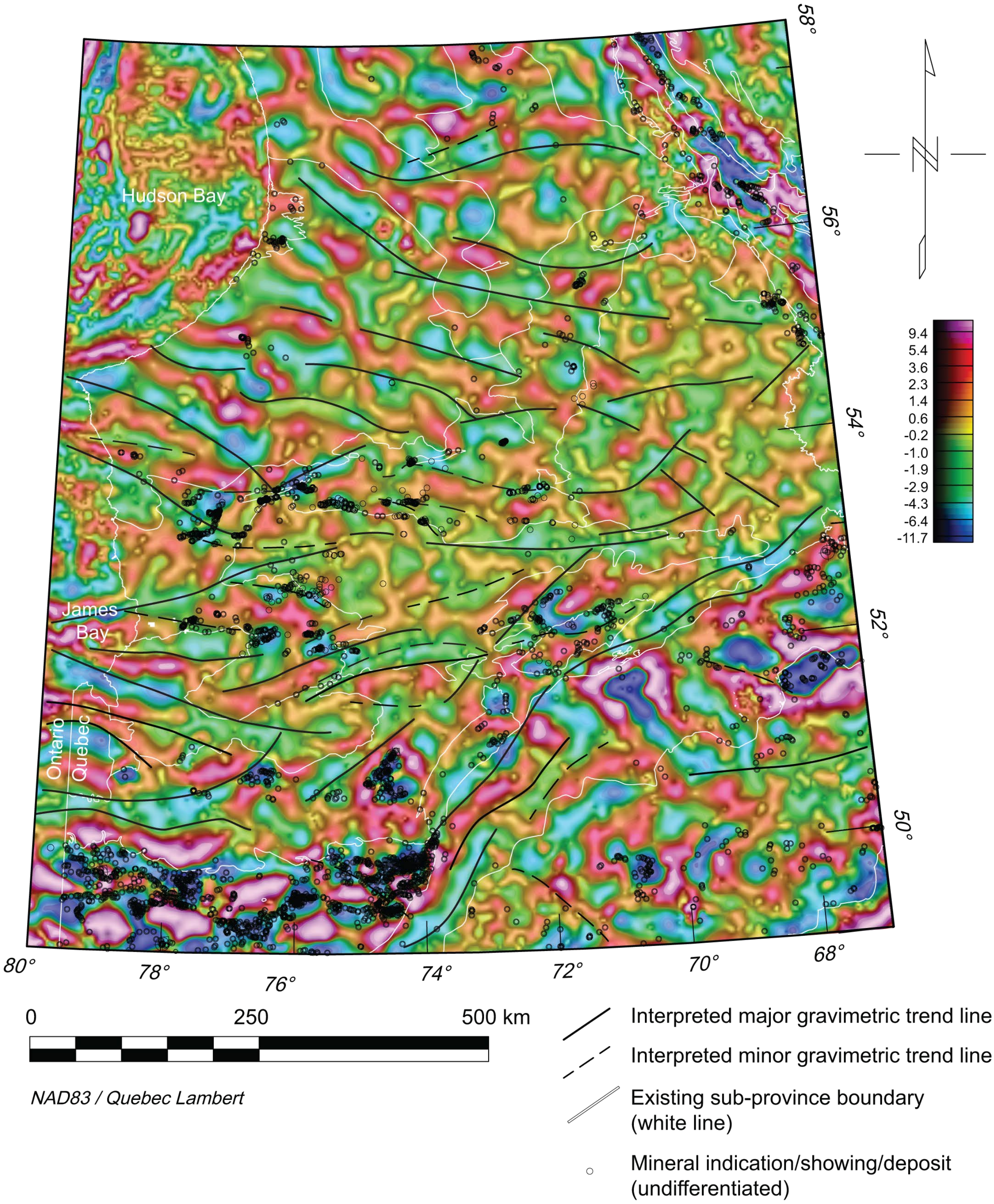

Figure 5: Combination gravity map of residuals and theta processed data. Mineral occurrences sourced from le ministère de l'Énergie et des Ressources naturelles du Québec (similarly in all subsequent figures).

white, and mineral showing/indicatons/deposits are included, undifferentiated due to the scale, as black circles.

3.2.1 Lineament interpretation

The group of features traced included in the combined theta and residuals map (Fig. 5) are generally east-west trending curvilinear structures. The curvilinear traces may be representative of such features as shear zones or regional faults, many of which are traceable as subprovince boundaries. Many of the curvilinear features span the breadth of the map and form interweaving networks. Some cross-cut others. The general network they form resembles fault systems that develop in regions that have experience protracted and pervasive strike-slip shearing, forming fault-bounded lens shaped bodies that are in contact.

Some gravimetric trend lines correlate well with subprovince boundaries, whereas some boundaries defy any correlation. If the N-S trend lines in Figure 4 are considered in conjunction with the E-W lines in Figure 5, more complete patterns of deep structures can be seen defining the subprovince boundaries. Their collective orientations and pattern do not exactly match the detailed surficial geological patterns, but they can delineate the homogenized signal representing contacts between potentially different basement. In the case of the Opinaca and La Grande, the northern E-W boundary segment of the La Grande follows the general orientation of three, well defined segments that align. The northern boundary of the Opinaca (bordering the La Grande) follows a well defined lineament in the east, yet the same lineament appears to continue and crosscut the Opinaca, bifurcating westward into the La Grande. These details speak to the relative structural timing of development or reactivation of these structures: the example given for the northern La Grande boundary implies that the boundary may be old, and has been later cut by tectonic or magmatic events (the lines are now segmented); the example given for the northern Opinaca boundary implies that the structure either developed or reactivated late, cutting the Opinaca after its formation.

Mineralization occurrences correlate very well with the trends of many major east-west curvilinear structures in the Opinaca and La Grande. Mineralization occurrences are concentrated in the central region where there are strong, well defined E-W lineaments and more extreme contrast in the gravity signal (colour changes in the maps). It is also worth noting that they concentrate where north-south oriented straight lineaments intersect and cross-cut the east-west structures.

4 Pseudogravity map interpretation

4.1 Tilt treatment map

The pseudogravity tilt map (Fig. 6) provides a detailed exposition of the subsurface structure. The tilt map appears in greyscale shaded relief, with more heterogeneous units providing higher, denser alternating contrast, and more homogeneous units providing a more subtle gradient. Many of the structural styles and patterns that are visible are characteristic of ductile deformation, consistent with the protracted history of tectonism and the high metamorphic grade for much of the region. While the pseudogravity calculation is largely reflective of density, units with high or consistent content of paramagnetic minerals may provide stronger signals. This may be the case in regions such as the western Opinaca, where the subprovince appears very light grey.

4.1.1 Lineament interpretation

The tilt angle map provides the most basic view to reliably delineate major structures and structural domains. The detailed variation in the signal produced by highly deformed units, seen as folding and sweeping fabrics, provides a basic structural style of domains between more prominent boundaries. More continuous traced features include structures bounding domains of intense ductile deformation, as well as structures crossing domains. There is considerable variation in these, but generally they are curvilinear and are oriented east-west. Long straight traces that cut through units are interpreted to be brittle fracture zones or fault systems. A series of these traverse the La Grande just north of the Opinaca, at seemingly regularly spaced intervals. The northwest trending regularly spaced Proterozoic dykes, that crosscut the region, are not traced.

Known mineralization occurrences and existing subprovince boundaries were omitted in Figure 6 to allow a focus on the structural traces. They provide a view of how complicated regions can be divided into structural domains. For example, the southern boundary between the Opinaca and La Grande, however complex, consists of numerous E-W domains with individual styles of deformation and segregated by structures that seem fairly continuous at depth. This may help in the delineation of the boundary at surface, through the grouping of units that contribute to the respective structural domain. The structure defining the northern boundary between the Opinaca and La Grande presents a different challenge. One nearly continuous structure traverses the map, and generally correlates to the existing boundary definition. The exact placement of the lineament is difficult: the structural style at the northern edge of the Opinaca is unique, yet the signal fades north and the line is difficult to place. This striking difference in homogeneity of signal between the La Grande and the Opinaca provides the most prominent distinction to bound the two subprovinces. The La Grande contains little variation, and large regions of negative signal, but the Opinaca generally a highly variable signal. The Opinaca is cut by many prominent features that subdivide the subprovince into numerous domains, each with a slightly contrasting structural style to its neighbour. This may represent internal breakup of the subprovince along internal shear zones. With regard to their orientation and structural style, they appear related to the nature of deformation along the southern contact of the Opinaca and further south. The northern contact has simpler, sweeping lineaments, and less obvious deformed internal structure.

Lineament traces produced for the tilt angle map have a close correlation to clusters of known mineral occurrences (see Figure 7). Situations favourable to correlation with mineralization include where east-west curvilinear traces bounding domains exhibiting ductile deformation intersect traces that are straight and likely delineate brittle fault zones. Also, intersection of regional-scale east-west curvilinear traces intersect north-south traces is favourable for correlation with mineralization occurrences.

4.2 Combination tilt angle treatment and residuals map

The pseudogravity blend of the tilt angle and short wavelength residuals map (Fig. 7) provides the detail of the tilt map with the density and lithology based colour differentiation of the residual map.

4.2.1 Lineament interpretation

Superimposed on the blended tilt angle and short wavelength residuals map (Fig. 7) are the N-S trend line tracings from the theta angle gravity map (Fig. 4) and the E-W curvilinear line tracings from the combination gravity map of residuals and theta angle (Fig. 5). These are applied for the sake of testing the fidelity of the gravity interpretation against the detail of the high-resolution pseudogravity map. Subprovince boundary lines are included in white, and mineralization occurrences are shown.

In this high resolution map, with tracings from the lower resolution gravity, it is apparent that major deformation domains developed along the southern boundary between the Opinaca and Opatica subprovinces. The major, arcuate E-W structure along the Opinaca and Opatica boundary is expressed in both the gravity and the pseudogravity maps, indicating that they may be more developed or older structures present as a major discontinuity between both deep and shallow lithologies. Similarly oriented traces pervade northward, traversing the Opinaca and La Grande. The northern contact of the Opinaca with the La Grande shows a correlation between gravity interpretation and major structures visible in the pseudogravity along its eastern segment. According to the overlain gravity interpretation, this boundary structure cuts through the Opinaca and does not continually define the border between these two subprovinces towards the west (Fig. 7). This may indicate that the northern boundary of the Opinaca with the La Grande is not a single continuous transcrustal structure, and instead is a composite of both deep and less penetrative structures. This may imply that the boundary was originally a primary contact, yet the severe deformation within both subprovinces is illustrated well in the pseudogravity image, and it complicates direct interpretation of the nature of the contact. The northwestern-most segment of this contact appears to have a correlation with deeper structures implied by the gravity interpretation, although the structure is oriented north-south. There is a series of north-south oriented line segments interpreted from the gravity map, and overlain on the pseudogravity they are visibly concentrated in the central domain with considerable low-signal (blue) regions. This region contains extensive plutonism intruding supracrustal rocks, and this correlation with transverse north-south structures may be suggestive of an extensional setting in its history.

The heterogeneous nature of domains within the La Grande is expected, with its duality of metavolcanic and plutonic rocks, yet the heterogeneity of signal within the lithologically homogeneous Opinaca is apparent. There is a strong divide between western and eastern Opinaca, each with distinct structural styles and pseudogravimetric signatures. This may define differences in basement, or an isograd of a paramagnetic mineral, or a change in the source of migmatite injections coming from beneath the Opinaca.

4.3 Combination tilt angle treatment and regional long wavelength map

The combination tilt angle and long wavelength pseudogravity map (Fig. 8) offers a colouration that, in a loose way, mimics subprovince boundaries. It provides a gradient map of how deeper source lithologies affect the organization of surface units. The structures of the upper crust, provided by the tilt angle component, match fairly well with the regions defined by the regional long wavelength component.

4.3.1 Lineament interpretation

The sharp gradient transitions in the regional (long wavelength) signal component were traced in this map, tending to follow obvious boundaries presented in the tilt component. The traces provide a general view of regions that may have subtly or greatly different deeper crust or mantle. These can be seen in contrast or in coincidence with regional subprovince boundaries, in white.

Within the Opinaca subprovince there is a high contrast steep gradient shift from east (in green, Fig. 8), to west (in red). There is a contrast in the associated structural styles as well, with fine detail (intrusions) and folding in the east, to a soft dome-like gradient in the west. This difference may be due to differences in the underlying basement rocks, to compositional differences in the source of injections in the east, the deformation styles, or possibly a metamorphic assemblage difference that involves the changing equilibrium state of a paramagnetic mineral. Each region outlined in Figure 8 mimics (portions of) the shape or trend of its respective subprovince, yet not exactly. The steep gradients in signal therefore indicate that the structures that form the subprovince boundaries are likely related to how the respective basements are organized or structured. For the La Grande and Opinaca, this map shows that the northern La Grande may share elements of its basement with the eastern Opinaca, and the western La Grande may share elements of its basement with the western Opinaca. This, in turn, implies that the basement geology is likely shared by the two subprovinces, and they are not exotic with respect to each other.

Groups of mineralization occurrences are noted to commonly inhabit locations near these sharp contrasting gradient lines. More specifically, there appears to be a tendency for mineralization to have occurred along major structures within the transition from positive signal (red in Fig. 8) to negative (green), hosting largely within barely negative (orange) transitional regions.

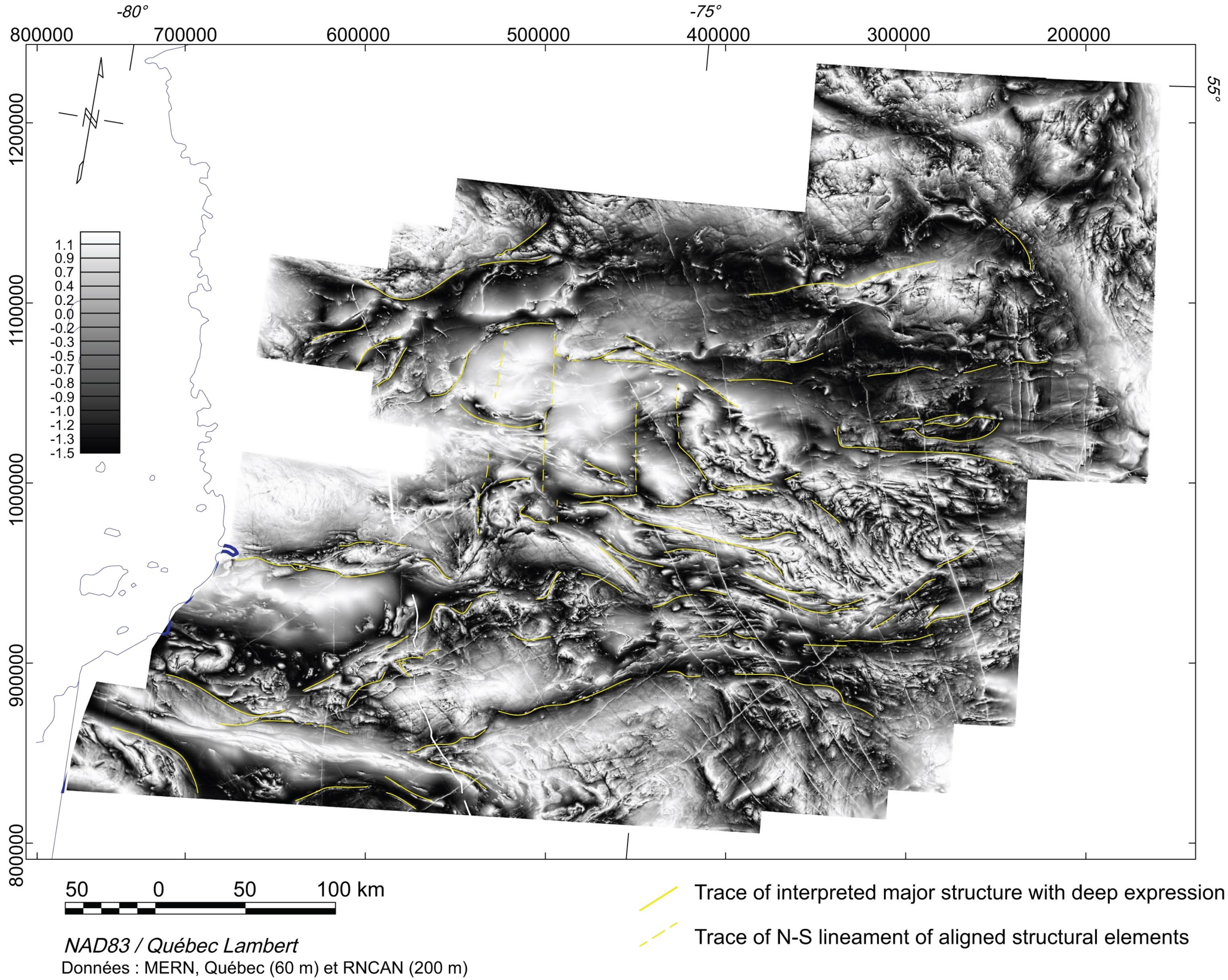

Figure 6: Tilt angle pseudogravity map on the short wavelength residuals. Interpreted lines mark significant structures, both brittle and ductile, within the Eeyou Istchee Baie-James region.

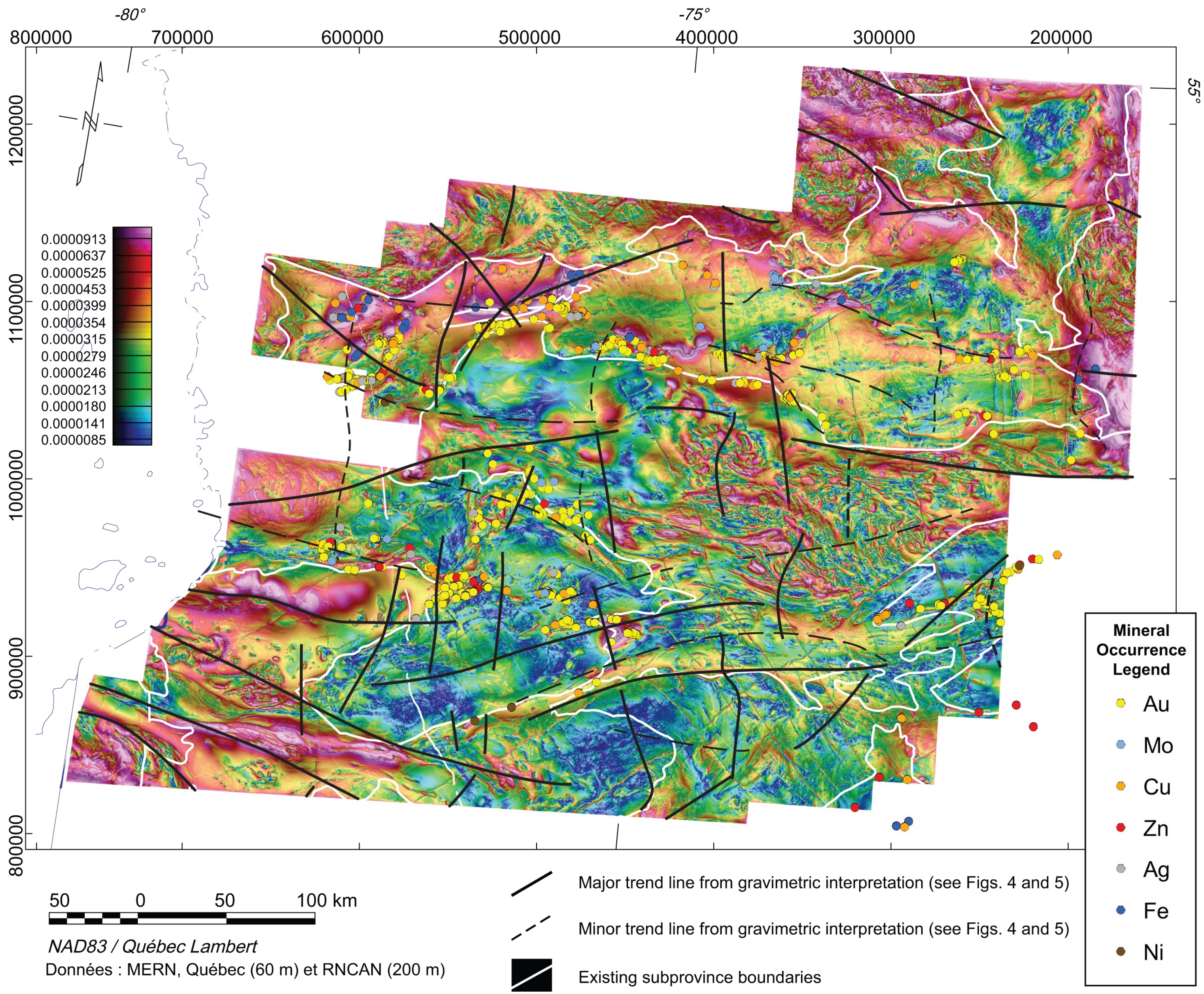

Figure 7: Blend of tilt angle and short wavelength pseudogravity residuals map. Black line tracing has been added from gravimetric survey maps (Figs. 4 and 5). Some key lines loosely correlate with major East-West structures seen in the pseudogravimetric map, indicating their depth. Most North-South lines seem to cross the tectonic grain.

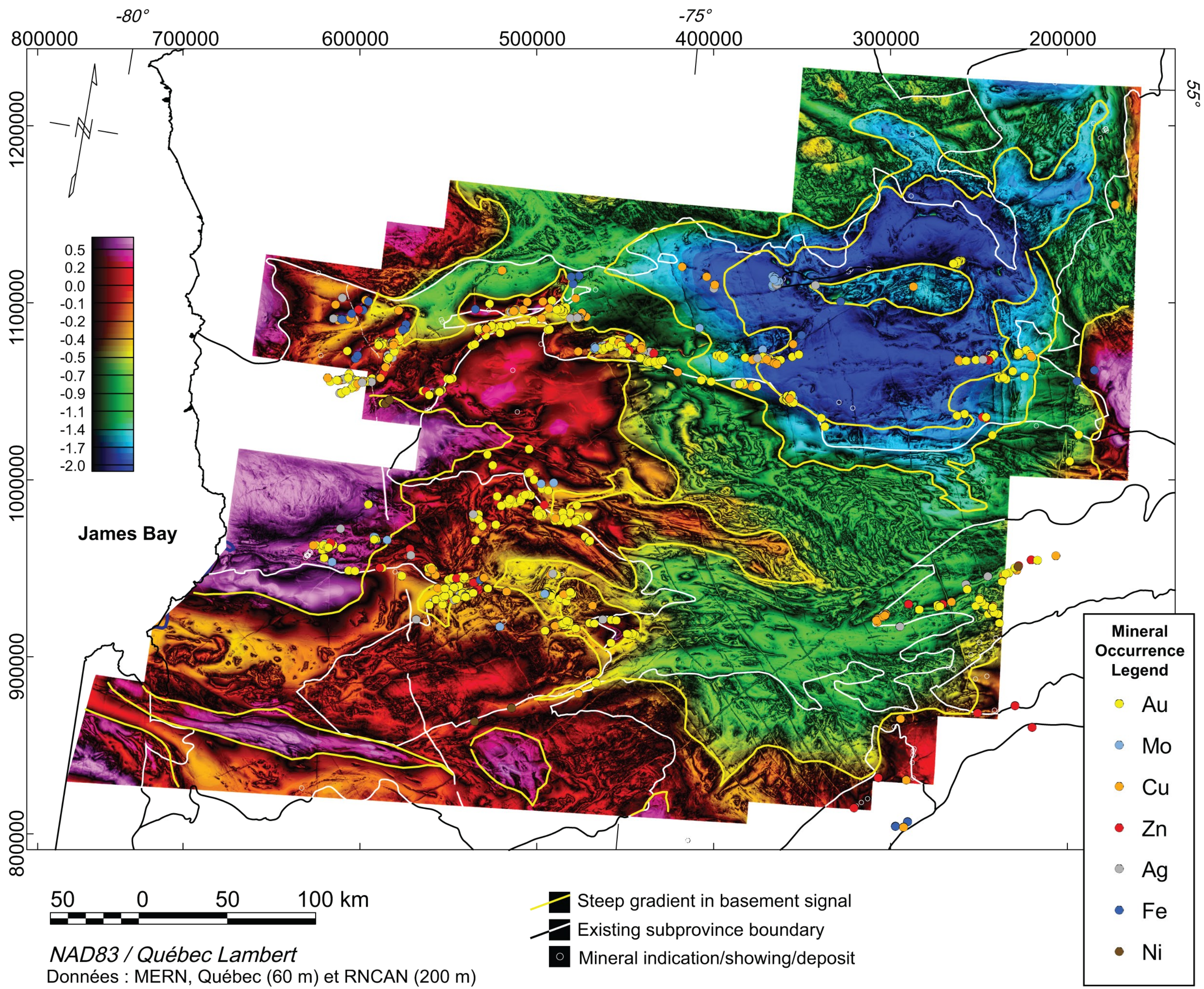

Figure 8: Combination tilt angle and long wavelength pseudogravity map. Domains are defined by yellow lines following sharp gradients of the long wavelength signal.

5 Target generation

5.1 Northeastern La Grande

Mineralization within the northeast Eeyou Istchee Baie-James region (Fig. 9) is largely known to lie just north of the contact between the Opinaca and La Grande subprovinces, within regions of deformed La Grande volcanic sequences. The combination tilt angle and

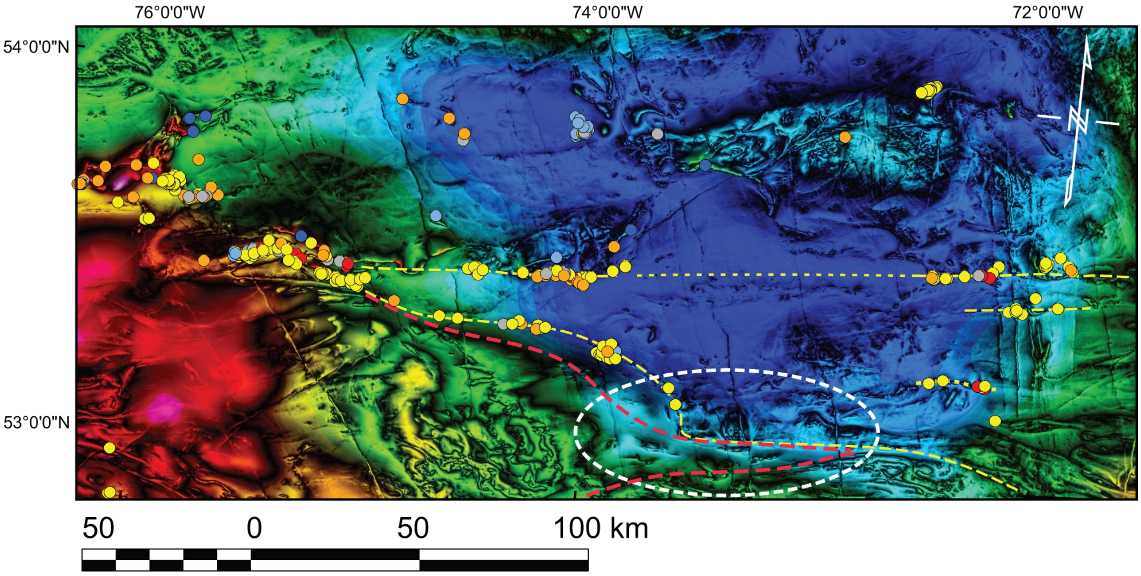

Figure 9: Exploration targets, East Eeyou Istchee Baie-James region. The base map is the combination tilt angle and long wavelength pseudogravity map from Figure 8. The legend for mineralization symbology can be found in Figure 8.

long wavelength pseudogravity map provides interpretation of which structures have deeper expressions (the shading), in conjunction with regional scale differences in the basement (the colour). The correlations that are apparent include that mineralization is hosted where there are more significant structures at transitions in the basement signal. In Figure 9 this can be seen as the clusters of mineralization situated over or near the most pronounced shading gradients (representing the significant structures with deeper expression) at the transitions between the green to blue colouration, and green to red (representing the transitions in the basement signal). There appear to be two known mineral occurrence trends aligned on two different orientations of structures (yellow dashed lines in Fig. 9). The northerly trend appears to be defined by the general E-W orientation of volcanic sequences in the region, and is divided into clusters in the west and east by plutonic rocks (within the region with finer yellow dashes). The southerly trend is defined by the La Grande–Opinaca contact, oriented NW-SE where mineralization has been observed. There is a concentration of mineralization occurrences at the intersection of these two trends, in the west. We have highlighted a region with a white dashed oval in Figure 9 that may be prospective for further mineral exploration. The interpreted potential is derived from that it exhibits a transition in the basement signal (blue to green) and is a region that hosts the convergence of major structures, including the intersection of a dextral shear zone at the northern boundary of the Opinaca and an antithetic sinistral shear zone that traverses the Opinaca. These two shear zones are roughly indicated with dashed red lines in Figure 9, yet their exact surface location is difficult to place as they are defined by wide zones of penetrative ductile deformation with a variety of structural expressions. The Éléonore mine is located at the opposite end of the sinistral shear zone, at a different confluence of structures (see below). The negative aspects are that the volcanic sequences terminate in the western part of the oval, and the region is known to have a less pronounced metamorphic gradient than other mineralized Opinaca/La Grande boundary regions.

5.2 Western La Grande and Opinaca contact

The Western La Grande and Opinaca contact (Fig. 10) is a widely mineralized region. Figure 10 illustrates three structural styles of mineralization that occur in this 'corner'

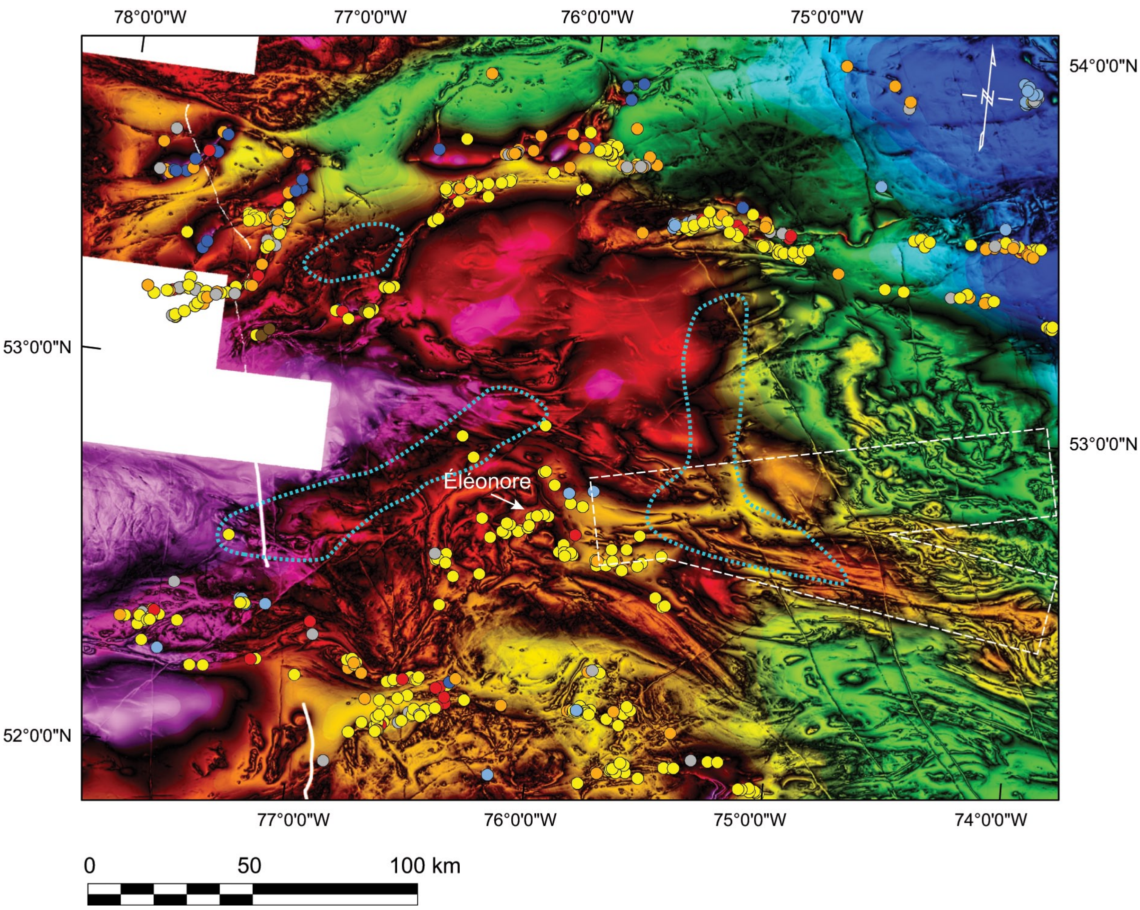

Figure 10: Mineralization analysis, West Eeyou Istchee Baie-James region. The base map is the combination tilt angle and long wavelength pseudogravity map from Figure 8. The legend for mineralization symbology can be found in Figure 8.

of the subprovince. In the eastern side lie the mineral occurrences at the intersection of two major structures, situated over a transition in the basement signal, that were outlined above. In the northwest lies a cluster of mineral occurrences that are also at a confluence of major structures. They lie along the northern-most point of the contact, where both sweeping northeast and southeast oriented structures intersect. This situation may be unique to the region. In the south, southeast trending major structures intersect minor North-South trending structures. All these regions have slightly different structural styles, yet each exhibits mineralization where the signal in the map transitions from red to green; most mineralization lies in orange coloured regions. Similarly, there are regions exhibiting mineralization that lie in transitions from red to purple. Regions highlighted in dashed blue line in Figure 10 are regions that fit these structural and geophysical correlation, and therefore have potential for mineral exploration. The exception may be in the northeast, where the 'orange transition' is very sharp, and lies within the Opinaca.

5.3 Southwestern La Grande and Opinaca contact, and the Éléonore mine

Near the southwestern contact between the La Grande and the Opinaca (Fig. 10) lies the Éléonore mine (Fontaine et al., 2015). Analysis of both the gravity and pseudogravity maps provides an interpretation of a series of trans-subprovince major structures crossing the Opinaca. The Éléonore mine (Roberto ore body) occurs at the intersection between one of these southwest oriented trans-Opinaca structures (outlined in white dashed region in Fig. 10) and north-south oriented deep structures, as outlined in the discussion of the interpretation of the combined theta and residual gravity map (Fig. 5). It is also near a major southeast oriented boundary between the La Grande and Opinaca.

Aside from the discussed region being a target for mineral exploration, the nature of the faulting involved in both the southwest and southeast orientations is not well understood. Targets for future geological mapping could include analysis of the trans-Opinaca structures, to analyze if they are shear zones with deformation existing in the exposed bedrock, or if they only created minor effects in overlying geology from the reactivation of deeper structures. Similarly, analysis of regions containing north-south oriented lineaments could be studied for the same reasons. Study of the southeast trending subprovince boundary structures would be beneficial for understanding the nature of the western contact between the La Grande and Opinaca subprovinces.

5.4 Southeastern La Grande and Opinaca contact

The southeastern La Grande and Opinaca contact (Fig. 11) remains under-studied to date. It shows strongly differing structural styles on either side of the contact (dashed white region in Fig. 11). Resulting from summer 2015 mapping and structural studies of the eastern north contact between the La Grande and Opinaca subprovinces, I have interpreted extensional deformation to have localized in a domain north of the contact (indicated with opposing arrows in the northeast corner of Fig. 11). Analysis of the pseudogravity maps

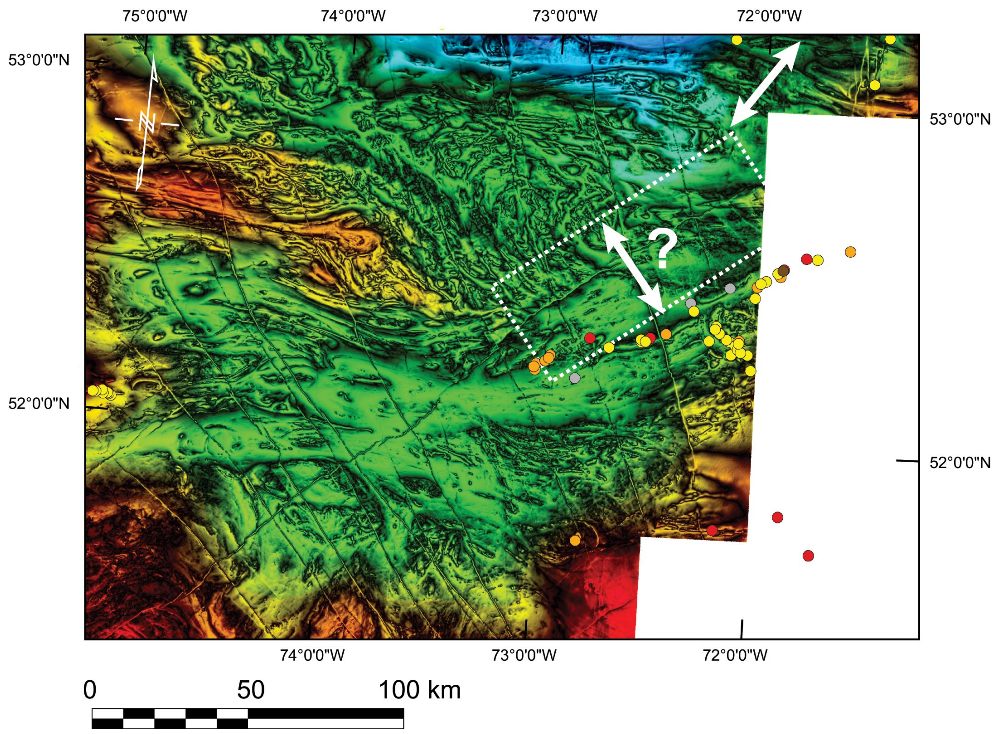

Figure 11: Mapping and exploration targets, Southeast Eeyou Istchee Baie-James region. The base map is the combination tilt angle and long wavelength pseudogravity map from Figure 8. The legend for mineralization symbology can be found in Figure 8.

for the region bounding the eastern south contact of the Opinaca and La Grande indicates a distinct contrast in structural styles on either side. This region is a target for geological and structural mapping to define whether or not extensional deformation is hosted in either subprovince. The hypothesis is that if extensional deformation exists in this region, with the extension direction oriented northwest-southeast (as indicated within the dashed region, Fig. 11), it would support an interpretation that the eastern Opinaca may represent an exhumed core complex.

The Opinaca region at the furthest south (Fig. 11, south) is structurally complex, but also defines a large structure present in all map interpretations. The continuity of structures to their east and west may influence the definition of subprovince boundaries in the region, and help define the nature of the contact between the Opinaca and La Grande. This region would be a prime location for future geologic mapping work.

6 Future work

The interpretation of these geophysical maps will continue with a focus on synthesis with existing bedrock geological maps and structural measurement data sets. This will provide a view of how deeper geophysical signals can provide an understanding of how to interpret boundary structures, and therefore provide reasons for their exact delineation. The maps provided in this report are not intended to provide exact delineation of subprovince boundaries, they are meant to provide judgement about the organization of units in the subsurface. Further work will identify specific structural signatures or patterns in the maps, for the sake of correlating lithostratigraphic units into specific domains. Consideration will be taken for where original data points used for map interpretation exist, so that re-interpretation of some units boundaries may be made. Sub-domains of subprovinces will be delineated based on contrasting structural styles that are hosted between major interpreted boundaries or linear structures. Features that are interpreted from these geophysical maps that can be identified as related to deep structures, and that may not be exposed at surface, will be noted and categorized for future analysis and for their mineral exploration potential. This work will be completed for the Superior subprovinces including the La Grande, Opinaca, and those immediately surrounding.

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