

Potential-field modelling of the prospective Chibougamau area (northeastern Abitibi subprovince, Quebec, Canada) using geological, geophysical, and petrophysical constraints

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Abstract: This paper focusses on obtaining a better understanding of the subsurface geology of the Chibougamau area, in the northeast of the Abitibi greenstone belt (Superior craton), using geophysical data collected along a 128 km long traverse with a rough southwest–northeast orientation. We have constructed two-dimensional (2D) models of the study area that are consistent with newly collected gravity data and high-resolution magnetic data sets. The initial models were constrained at depth by an interpretation of a new seismic section and at surface by the bedrock geology and known geometry of lithological units. The attributes of the model were constrained using petrophysical measurements so that the final model is compatible with all available geological and geophysical data. The potential-field data modelling resolved the geometry of plutons and magnetic bodies that are transparent on seismic sections. The new model is consistent with the known structural geology, such as open folding, and provides an improvement in estimating the size, shape, and depth of the Barlow and Chibougamau plutons. The Chibougamau pluton is known to be associated with Cu–Au magmatic-hydrothermal mineralisation and, as the volume and geometry of intrusive bodies is paramount to the exploration of such mineralisation, the modelling presented here provides a scientific foundation to exploration models focused on such mineralisation.

Key words: geophysics, potential-field modelling, 2.5D modelling, geological modelling, geological, seismic and petrophysical constraints, gravity and magnetic.

Résumé : L'article est axé sur l'établissement d'une meilleure compréhension de la géologie du sous-sol de la région de Chibougamau, dans le nord-est de la ceinture de roches vertes de l'Abitibi (craton du Supérieur), à la lumière de données géophysiques recueillies le long d'une traverse de 128 km d'orientation approximativement sud-ouest–nord-est. Nous avons construit des modèles bidimensionnels (2D) de la région à l'étude qui concordent avec des données gravimétriques et des ensembles de données magnétiques de haute résolution nouvellement acquis. Les modèles initiaux ont été délimités en profondeur par l'interprétation d'une nouvelle coupe sismique et en surface par la géologie du substrat rocheux et la géométrie connue des unités lithologiques. Les attributs du modèle ont été établis en utilisant des mesures pétrophysiques, le modèle final étant ainsi compatible avec toutes les données géologiques et géophysiques disponibles. La modélisation des données de champ de potentiel a permis de cerner la géométrie de plutons et de corps magnétiques qui sont transparents sur les coupes sismiques. Le nouveau modèle s'accorde avec les éléments connus de la géologie structurale, comme un plissement ouvert, et améliore l'estimation de la taille, de la forme et de la profondeur des plutons de Barlow et de Chibougamau. Il est établi que ce dernier est associé à une minéralisation magmatique-hydrothermale à Cu–Au et, comme le volume et la géométrie des corps intrusifs revêtent une importance capitale dans l'exploration pour ce type de minéralisation, la modélisation présentée constitue un fondement scientifique pour les modèles d'exploration axés sur ce type de minéralisation. [Traduit par la Rédaction]

Mots-clés : géophysique, modélisation du champ de potentiel, modélisation en 2,5D, modélisation géologique, contraintes géologiques, sismiques et pétrophysiques, gravité et magnétisme.

Introduction

The Metal Earth project aims to better understand the differences between greenstone belts in the Abitibi and Wabigoon belts of the Superior craton of Canada that are well endowed with gold

and base metal mineralisation from those that are less endowed, in the hope that exploration can focus on the more prospective belts, and locations within their belts where there might be deposits that have not been discovered. This new understanding

Received 27 November 2019. Accepted 3 July 2020.

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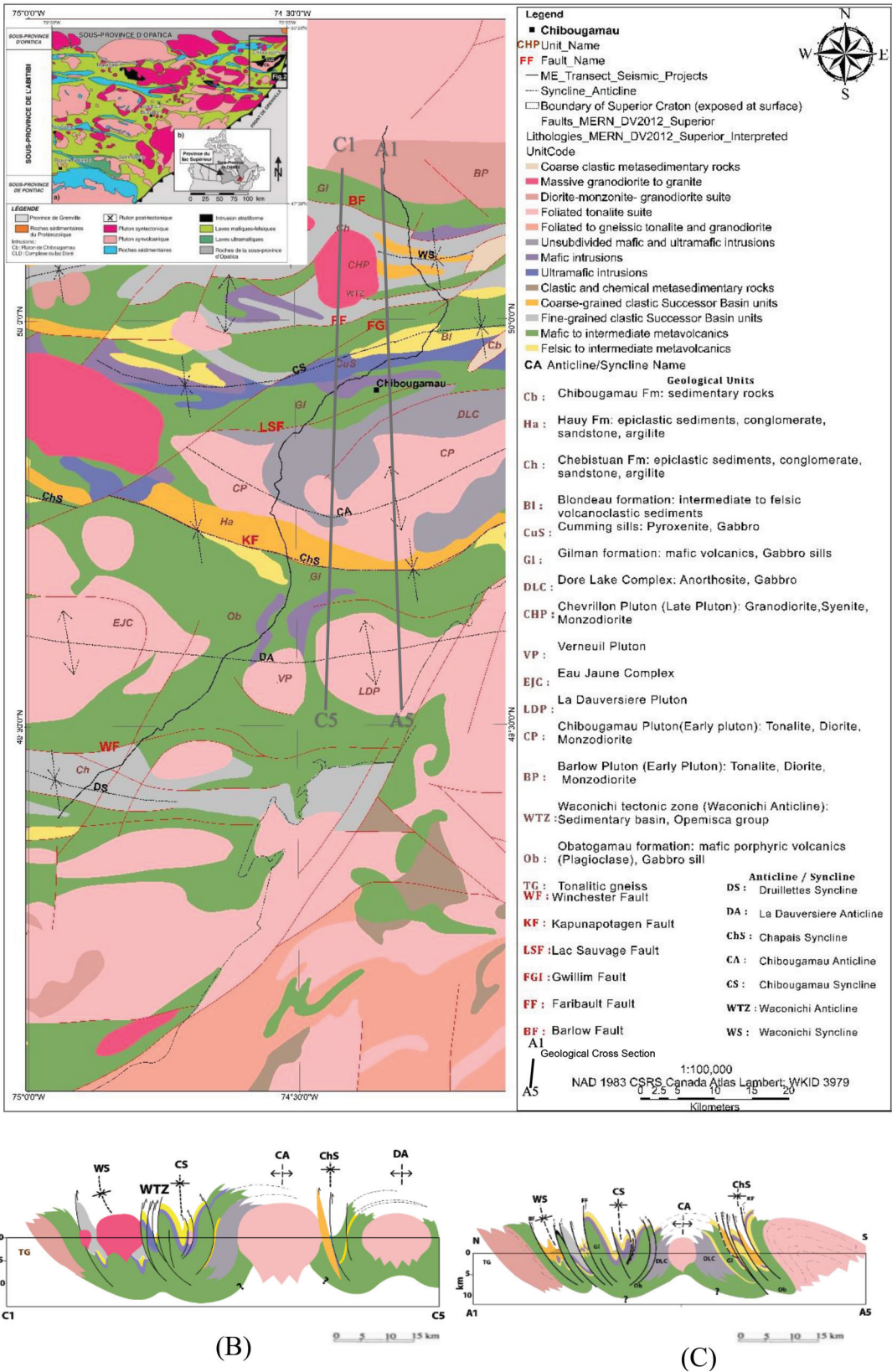
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Fig. 1. Geological map of the Chibougamau area (A), showing the distribution of the folds and faults mostly formed during the D2 regional deformation (modified after Montsion et al. 2018; Daigneault et al. 1990; Leclerc et al. 2008). The map was created using ArcGIS Desktop version 10.5. The locations of two detailed cross-sections (A1–A5 and C1–C5) are denoted by thick straight black lines. These sections are shown (B and C) and are modified from Daigneault et al. (1990). [Colour online.]



is intended to come through a combination of geological mapping (lithological and structural), geochemical and geochronological studies, mineral deposits studies, mantle studies, and deep probing geophysics.

The seismic data collected along the 128 km long Chibougamau profile as part of the Metal Earth project allows the characterisation of shallow-dipping reflective features and a number of these have been identified at depths below 5 km. Where it appears that a significant number of these reflectors terminate, major faults have been interpreted. However, the upper crust above 5 to 10 km contains very few seismic reflections, so it is termed seismically “transparent”. The lack of seismic features is most likely due to the steep dips of the geological interfaces, so seismic energy is not reflected back to the surface, or it might be due to an insufficient contrast in the seismic properties between different lithologies. Our aim is to use the gravity and magnetic data to provide information about the geology in the upper crust. In particular, this study aims at defining the geometries of the intrusive bodies, as these can generate magmatic-hydrothermal systems. The fluids associated with these systems can transport the metals and result in mineral deposits that are of interest to explorationists. A better understanding of the relationship of the plutons to mineral deposits will help to define the character of the well-endowed areas that are of interest to the Metal Earth project. We are also interested in detecting lithological contacts and major fault zones that are transparent in the seismic section. These upper-crustal structures could then be extrapolated to greater depth and associated with those evident on other geophysical data (magnetotelluric and seismic). A better characterisation of the subsurface geometry will also be useful in future studies looking to understand the tectonic history of the area.

One of the challenges in potential-field data modelling is the concept of non-uniqueness, which means that an infinite number of models can match the same observed geophysical data. A way to mitigate the impact of non-uniqueness is to constrain the model with complementary data. In this study, a set of constraints was used to construct the initial model and was also applied during modelling to ensure that the final results are realistic. These constraints include bedrock geology mapped at surface, existing geological sections, the interpreted seismic section, and petrophysical properties measurements. These data were compiled from previous studies. In the following four sections, we briefly introduce the data that provide the constraints and any conclusions that were drawn from these data and explain how they are relevant to the potential-field modelling described in the latter part of this study.

Compiled geological data

The Chibougamau (Quebec) area is located in the northeastern corner of the neoproterozoic Abitibi greenstone belt, the southern part of the Superior craton (Fig. 1, inset). The study area is in contact with the Opatica subprovince (greenstone and plutonic belts) to the north and the Grenville orogeny to the east, metamorphosed during the Grenville orogeny occurring at ~1.1 Ga (Baker 1980). The Chibougamau area is the easternmost part of the 430 km long, east–west-striking Matagami–Chibougamau greenstone belt (Wynne-Edwards 1972; Rivers and Chown 1986), and this belt has a consistent structure over its whole length according to seismic reflection profiling (Mathieu et al. 2020b). This belt was mostly metamorphosed to greenschist facies, as are most supracrustal rocks of the Abitibi greenstone belt (Jolly 1974; Faure 2015), except near intrusions (contact metamorphism) and close to the contact with the Opatica subprovince to the north (where amphibolite-grade metamorphism occurs).

The volcano-sedimentary assemblage of the Chibougamau area is mostly comprised of the ca. >2730 Ma to 2710 Ma Roy Group, which sits on ca. 2790–2760 Ma volcanic units (Chrissie and Des

Vents formations). The Roy Group is overlain by the sedimentary units of the Opémisca Group. The Roy Group consists of volcanic cycle 1, which is dominated by mafic lava flows, and volcanic cycle 2, which consists of mafic to felsic lava flows and pyroclastic rocks (Allard 1976; Gobeil and Racicot 1983; Allard and Gobeil 1984; Daigneault and Allard 1987; Leclerc et al. 2017). In the study area, stratigraphic interpretation has recently been modified using new geochemical and geochronological data (Leclerc et al. 2017) and, in this study, no reference will be made to former stratigraphic interpretation (e.g., the former Gilman Formation).

Volcanic cycle 1 of the Roy Group consists of the undated Obatogamau and ca. 2730–2726 Ma Waconichi formations (Caty 1975; Daigneault and Allard 1990; Mortensen 1993; Leclerc et al. 2017). The Obatogamau Formation is a 3–4 km thick pile of feldspar megacrysts-bearing basaltic to andesitic lava flows, which is conformably overlain by the ~800 m thick Waconichi Formation. This latter formation consists of felsic volcanic rocks and contains several massive sulfide and exhalative units such as the Lac Sauvage Iron Formation (thinly bedded siderite, pyrite, chert, and iron oxides) (Henry and Allard 1979). The Obatogamau and Waconichi formations are intruded by the Doré Lake Complex, a thick anorthosite-dominated layered intrusion with vanadiferous magnetite-rich upper units (Polat et al. 2018; Allard 1976; Mathieu 2019). Volcanic cycle 2 is composed of the Bruneau, Blondeau, and Bordeleau formations. The Bruneau Formation consists of ca. 2724 Ma mafic to intermediate lava flows (3–4 km thick) (Leclerc et al. 2008, 2011; Davis et al. 2014). It is overlain by the intermediate to felsic volcanoclastic rocks of the <2721 Ma (Leclerc et al. 2012) Blondeau Formation (2–3 km thick). Near its base, the Blondeau Formation is intruded by the three ultramafic to mafic sills of the ca. 2717 Ma Cummings Complex (Dimorth et al. 1983; Mortensen 1993; Bédard et al. 2009). The Bordeleau Formation consists of volcanoclastic deposits, arenite and conglomerate (Moisan 1992). The youngest part of the Bordeleau Formation transitions into the overlying <2692 to <2704 Ma Opémisca Group (Duquette 1982; Leclerc et al. 2012; David et al. 2006), which consists primarily of sandstones, siltstones, and polygenic conglomerates (Mueller and Dimroth 1984, 1987). In the south of the study area, the <2707 Ma or older (David et al. 2006) Caopatina Formation, which consists of volcanoclastic and sedimentary rocks, overlies the Obatogamau Formation (Mueller and Dimroth 1984, 1987).

In the study area, several large-volume intermediate to felsic tonalite-dominated plutons, i.e., tonalite–trondhjemite–granodiorite and tonalite–trondhjemite–diorite (TTD) suites are coeval with the Roy Group. These correspond to syn-volcanic intrusions (Percival and Krogh 1983; Mathieu et al. 2020a). One of these is the 2718 ± 2 Ma Chibougamau pluton (Krogh 1982), the intrusion of which induced doming of the regional tectonic fabric (Racicot et al. 1984). This TTD pluton is genetically related to Cu–Au magmatic-hydrothermal mineralisation (Mathieu and Racicot 2019; Pilote et al. 1995). To the south of the Chibougamau pluton, which occupies the core of the Chibougamau anticline, the Boisvert and La Dauversière plutons (TTG suites), as well as the Eau Jaune Complex (TTD suite), are aligned in the east–west direction along the axial trace of the La Dauversière anticline (Pitcher 1979; Castro 1986). It is possible that syn-volcanic magmatism focused along east–west-striking structures in the study area (Mathieu et al. 2020b). Large-volume syn-volcanic magmatism is followed by syn-tectonic magmatism that consists of smaller-volume intrusions coeval with the Opémisca Group. Examples of the latter are the Chevrillon pluton (granodiorite), dated at 2695 ± 3 Ma (Gariépy and Allegre 1985), the Muscocho pluton (granodiorite), dated at 2701.2 ± 1.7 – 1.3 Ma (Mortensen 1993), and undated alkaline intrusions (e.g., Saussure syenite), which intrude the volcanic and sedimentary rocks of the Roy and Opémisca groups. Syn-tectonic intrusions were emplaced during or toward the end

of regional deformation and cut steeply dipping volcanic and sedimentary units (Huguet 2019).

The Chibougamau area was mostly deformed and metamorphosed by terrane imbrication during and prior to the syn-tectonic, syn-Opémisca Group (deformation events D1, D2, and D3), as well as during the Grenville orogeny (1100–970 Ma; Rivers et al. 1989; Baker 1980; Daigneault and Allard 1990). The first phase of deformation (D1) is characterized by north–south to north–northwest-striking open synforms without associated axial planar cleavage (Daigneault et al. 1990) and may be associated with syn-volcanic faults, valleys, and other heterogeneities in the volcanic landscape (Legault 2003). The second phase (D2) initiates at ca. 2700 Ma or before, and may have continued after 2695 Ma (Leclerc et al. 2017; Mathieu et al. 2020b). This phase is associated with peak greenschist facies metamorphism and generated the main structures in the study area, including the main east–west-trending foliation and ductile–brittle faults, as well as large-scale, east-trending, open folds. The D3 deformation phase mostly induced oblique-slip movements along the D2 structures and may correspond to the waning stage of the main deformation event (D2). The last deformation phase (D4) occurred during the Proterozoic (1100–970 Ma) and is only predominant in the rocks near the Grenville Front where it mostly consists of north–northwest to south–southwest brittle and ductile–brittle faults. The folds and faults produced during the D2 regional deformation are expected to be prominent features on the geophysical data and are described in more detail. From north to south, the main structures are as follows (Daigneault et al. 1990) (Figs. 1B and 1C):

- (i) The Waconichi syncline is occupied by sedimentary rocks of the Opémisca Group, which is bordered by the east–west-trending Barlow and Faribault faults (Mueller and Dimroth 1984).
- (ii) The Waconichi anticline in the Waconichi tectonic zone (WTZ) is 1 km thick and consists of several steeply dipping tectonic panels. The southern limit of the WTZ is the Faribault fault (Daigneault 1982; Daigneault and Allard 1983, 1984, 1990; Leclerc et al. 2017).
- (iii) The Chibougamau syncline is overprinted by the WTZ and consists of steeply dipping tectonic panels. It is occupied by the Blondeau Formation and the Cummings Complex is bordered, to the south, by the Lac Sauvage fault.
- (iv) The Chibougamau anticline trends essentially east–west and curves toward the northeast near the Grenville front. The core of the anticline is occupied by the Doré Lake Complex (volcanic cycle 1) and the Chibougamau pluton (volcanic cycle 2). These intrusions induced doming of the lava pile, a feature that was then tightened during the D2 deformation event (Gobeil and Racicot 1983).
- (v) The Chapais structure is a half-syncline occupied by sedimentary rocks of the Opémisca Group and bordered, to the south, by the Kapunapotagen fault (Charbonneau et al. 1991; Daigneault and Allard 1983, 1987).
- (vi) The La Dauversière anticline is occupied by several intrusive complexes (see above). This open fold corresponds to an area where stratigraphic polarities invert from top to the north to top to the south.
- (vii) The Druillettes syncline is occupied by sedimentary rocks of the Caopatina Formation and is bounded by the east–west-striking Guercheville and Doda faults (Sharma et al. 1987; Daigneault 1996).

The Abitibi greenstone belt contains a large amount of east–west-striking faults. In the Chibougamau area, these structures have caused a repetition of the stratigraphic sequence (Daigneault and Allard 1987). Two of these structures are subvertical east–west-

striking faults, which are mostly syn-D2 structures that were still active (or reactivated) by the D3 event, and that separate sedimentary rocks from older volcanic rocks. In the Chibougamau syncline, the Kapunapotagen fault is a north-verging thrust fault (Daigneault and Allard 1984), whereas in the WTZ, the Faribault is a north-verging thrust fault (Daigneault and Allard 1983, 1984, 1987).

The geological map (Fig. 1A) is used to define the geological formations at the surface of our 2D model section. The subsurface geology is also defined by four published geological cross sections (two of which are shown in Figs. 1B and 1C; Daigneault et al. 1990) and the other two are from gravity forward modelling in the Chapais area (Dion et al. 1992).

Potential-field data

The Chibougamau transect has a total length of 128 km with a general northeast–southwest orientation. There is a total of 570 measured gravity observations along the profile collected by the Metal Earth project in 2017. In addition, publicly available gravity observations collected by the Geological Survey of Canada (GSC 2019, gravity database) were assessed and combined with our new database to provide information over a large area. New gravity stations were located along roads or within walking distance of roads, using an average spacing between observations of ~300 m (Maleki 2019). Theoretically, this will allow structures larger and deeper than about 600 m to be resolved. However, where the acquired data values show sharp variations when displayed on plotted profiles, an infill station was placed midway between the initial stations to more precisely define the sources (location, dip, and depth). Furthermore, measurements with 300 m spacing were acquired on small (900 m) traverses perpendicular to the main transect, when side road access allowed.

Quality control was performed on the compiled gravity data set and standard gravity processing were applied to the data; a density value of 2.67 g/cm³ was used when calculating the Bouguer anomaly. Then the terrain correction was applied to the data to produce the complete Bouguer anomaly used for the modelling discussed in the next sections. The complete Bouguer anomaly ranges from –87 to –34 mGal across the study area (Fig. 2A). The lowest values are associated with the Chibougamau and Opémisca plutons, while mafic–ultramafic intrusions and volcanic belts are associated with higher values.

Total magnetic intensity data sets were obtained from the Ministère de l'Énergie et Ressources Naturelles du Québec (David et al. 2006; Davis et al. 2014). The highest resolution aeromagnetic data sets with a 75 m cell size were leveled and used to generate the residual total-magnetic-field compilation shown in Fig. 2B. To the north of the Chibougamau pluton, mafic to intermediate metavolcanic rocks of the Bruneau Formation, and mafic/ultramafic intrusions of the Cummings Complex have the strongest magnetic intensity value. The Chibougamau, Verneuil, and La Dauversière plutons and Eau Jaune Complex exhibit weak magnetic intensity, while intermediate metavolcanic and sedimentary rocks have weak to moderately high magnetic intensity. Most southwest- and southeast-trending magnetic lineaments are associated with Proterozoic dykes that have a high magnetic intensity.

Different processing procedures (e.g., reduction to pole, vertical derivative, tilt angle, analytic signal amplitude) were applied to enhance the edges of magnetized bodies and near-surface lineaments to perform a qualitative geological interpretation. The objective of the magnetic interpretation was to better delineate geological boundaries and features (e.g., dykes, faults, and lithological contacts) where there is a contrast in magnetic susceptibility. The reduced-to-pole magnetic grid was used to generate the second-vertical-derivative map (Hood 1965) that is shown in Fig. 2C and is overlaid with the greyscale tilt-angle map (Miller and

Fig. 2. Potential-field gravity and magnetic data of the Chibougamau area of interest. (A) Complete Bouguer anomaly. (B) Total magnetic intensity. (C) Combination of secondnd vertical derivative and tilt angle images. (D) Simplified geological interpretation of potential-field data delineating physical property boundaries. The maps were created using ArcGIS Desktop version 10.5 and Geosoft Oasis montaj version 9.7. [Colour online.]

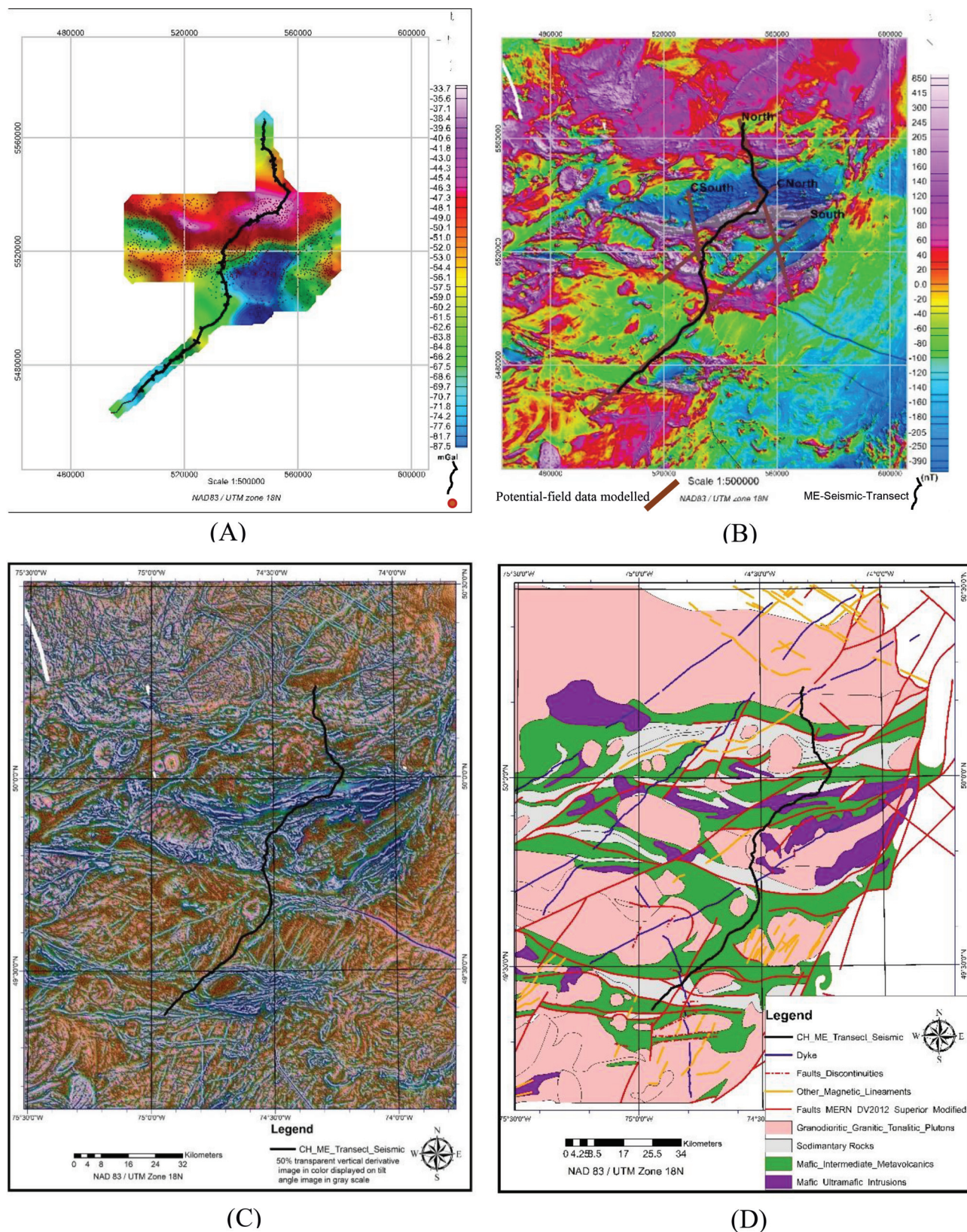
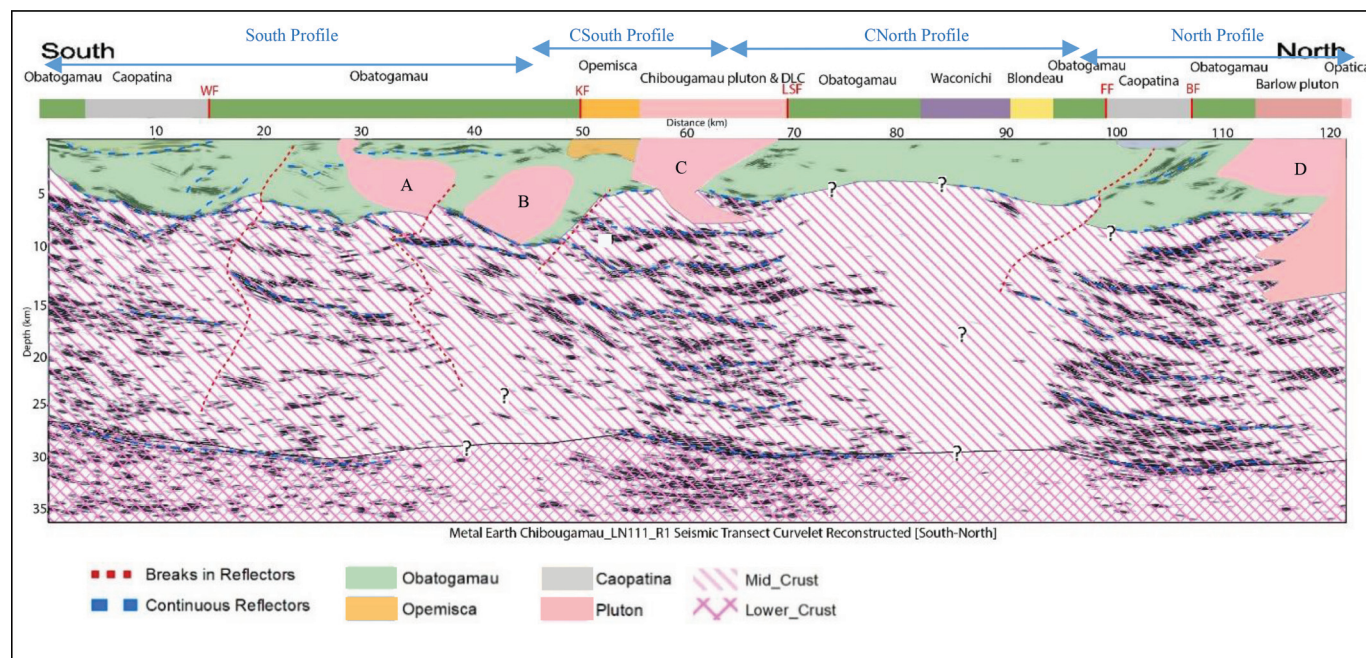


Fig. 3. Interpretation of the Metal Earth Chibougamau curvelet-enhanced seismic transect. The blue arrows on top illustrate parts that are relevant for the South, CSouth, CNorth, and North sections, which are four linear profiles that we have defined for the 2dimensional modelling, the locations of which are displayed in Fig. 4. [Colour online.]



Singh 1994). This composite map highlights magnetic/geological boundaries. The new geological interpretation of the magnetic data (Fig. 2D) provides additional geological information in areas that are covered by swamps, lakes, and till deposits. The linear discontinuities with low magnetic contrast are generally associated with major faults, while southeast- and southwest-trending mafic dykes are associated with linear, short-wavelength magnetic anomalies. The magnetic map has been used to generate a simplified bedrock geology map (Maleki 2019) to use as a constraint for the inversion. In this map, geological units with similar petrophysical properties have been grouped together (Fig. 2D). Also, features interpreted as Proterozoic dykes in Fig. 2D were added to our sections, as many of these were not evident on the geological map. Specifically, several north-south-striking dykes have been added in the southern part of the “South” model. The magnetic data also indicate that the location of the Doré Lake Complex, where the “CSouth” and “CNorth” models intersect (Figs. 2B and 4), differs from that shown on the geology map, so this should be checked on the ground if there is outcrop available.

Seismic data

Seismic data collected by the Metal Earth project across the Chibougamau area was intended to image structures from the near-surface to Moho depths, which is 37–40 km in the Abitibi greenstone belt (Winardhi and Mereu 1997; Mereu 2000). The seismic survey was acquired with a source separation of 50 m and a receiver separation of 25 m. The details of the seismic data acquisition and processing are described by Naghizadeh et al. (2019). Overall, the processing workflow was focused on robust static corrections, detailed velocity analysis, minimal trace smoothing, and high-resolution imaging. In this paper, we will use the pre-stack time migrated seismic section of Metal Earth’s Chibougamau transect to guide our potential-field modelling effort.

Previous research undertaken for Lithoprobe acquired three seismic reflection profiles across the eastern part of the Superior craton (i.e., the Opatica subprovince, the Abitibi greenstone belt, and the Pontiac metasedimentary subprovince) to define the geometry of the crustal structure at depth (Calvert and Ludden

1999). Line 48 is the closest Lithoprobe line to the Chibougamau’s Metal Earth transect and is located ~300 km to the west, in the Matagami area. The interpreted seismic section (Calvert and Ludden 1999) shows shallow reflections that dip shallowly to the north that may be associated with northward underthrusting or a subduction zone in the upper mantle below the Opatica plutonic gneiss belt (Benn et al. 1992; Sawyer and Benn 1993). Calvert and Ludden (1999) interpreted the mid-crust Abitibi belt as being composed of metasedimentary and igneous rocks with some unknown affinity units, and the Opatica belt as mainly orthogneisses. To the west of these profiles, Mints (2017) proposed that a fragment of the middle and lower crust of the Superior craton was exhumed within the north-south-striking Kapuskasing thrust fault zone. The Kapuskasing zone consists of mafic, tonalitic, and metasedimentary gneisses of amphibolite metamorphosed in the conditions of the granulites facies (Percival et al. 1992).

A preliminary geological interpretation of the Chibougamau seismic data are performed on dip coherence enhanced seismic sections (Fig. 3) generated using the curvelet transform (Candes et al. 2006). The vertical axis of seismic sections were converted from time to depth using an average velocity of 6000 m/s (Christensen and Mooney 1995). The unreflective near-surface zones labeled as A, B, C, and D are mainly interpreted as granodioritic bodies (plutons) intruded into the volcanic rocks. Some of these intrusions (A and B) do not outcrop on surface. The approximately 7 km near-surface zone (primarily shown as green) has fewer reflections than the deeper zone labeled as “mid-crust” on the section. The transition from the greenstone rocks in the near-surface to the mid-crust is shown as the top of the hatched zone in Fig. 3. Mints (2017) interpreted a feature similar to this as a decollement surface. There are some reflectors along this boundary that match with the synclines and anticlines documented in the Chibougamau area. A dimming of reflectors sometimes occurs where the seismic line bends and the assumptions implicit in the common-midpoint processing method are not satisfied. This could have a negative impact on the coherent imaging of reflections.

Within the mid-crust (Fig. 3), below an approximate depth of 7 km, the seismic images are characterized by gently dipping

Table 1. Density and magnetic susceptibility measurements in the Chapais area (Dion et al. 1992).

		Density (g/cm ³)		
Lithology	N	Interval	Mean ± SD	Magnetic susceptibility (×10 ⁻³ SI), interval
Opemisca Pluton				
Monzonite	6	2.62–2.64	2.63 ± 0.008	0.01–0.8; 2.4–4.3
Presquile Pluton				
Tonalite	3	2.74–2.82	2.77 ± 0.04	0.01; 0.2
Chibougamau Pluton				
Tonalite	12	2.60–2.73	2.67 ± 0.04	0.01–2.3; 10–40
Diorite	21	2.73–3.06	2.93 ± 0.1	0.01–2.3; 18–53
Opemisca Group				
Hauy Formation	10	2.72–2.97	2.87 ± 0.07	0.1–0.5; 1.4–3.4
Stella Formation	4	2.71–2.76	2.74 ± 0.02	0.1–0.5; 6.3–6.5
Daubree Formation	4	2.73–2.99	2.88 ± 0.11	0.01; 0.6
Cummings Complex				
Bourbeau gabbro	9	2.83–3.05	2.97 ± 0.07	0.01–0.6; 3–8
Ventures gabbro	7	2.92–3.04	2.99 ± 0.05	0.01–1.6; 12–45
Dunite	2	2.72–2.74	2.73	110; 190
Peridotite	6	2.66–2.79	2.73 ± 0.04	72–130
Pyroxenite	5	3.12–3.27	3.21 ± 0.06	0.8–8; 100
lac Doré Complex				
Anorthosite	2	2.99–3.00	2.99	0.01
Granophyre	1	2.61	2.61	0.2
Roy Group				
Blondeau Formation				
Sediments-tufs	24	2.66–2.91	2.79 ± 0.06	0.01; 1.2
Andesite	8	2.75–2.83	2.79 ± 0.04	0.01; 1.4
Gabbro dyke	6	2.85–2.98	2.90 ± 0.05	17–100
Gilman Formation				
Basalt	11	2.80–3.23	2.99 ± 0.13	0.01–1.6; 5–11
Gabbro	5	2.90–3.12	3.00 ± 0.08	0.01–1.4; 6
Andesite	3	2.71–2.79	2.76 ± 0.04	0.01; 0.4
Pyroclastic felsic	3	2.64–2.74	2.69 ± 0.05	0.01; 0.1
Waconichi Formation				
Rhyolite	2	2.63–2.66	2.65	0.01; 0.1
Obatogamau Formation				
Basalt	27	2.73–3.10	2.95 ± 0.12	0.01; 1.2
Gabbro	4	2.82–3.05	2.99 ± 0.11	0.01; 1.4
Andesite	1	2.65	2.65	0.05
Chrissie Member	2	2.68–2.74	2.71	0.01; 0.5
Tonalitic gneiss	22	2.56–2.77	2.67 ± 0.05	—

reflections, also in agreement with Mints (2017). Below the mid-crust, a zone is labeled “lower crust” on the interpreted section, following Cook et al. (2010). Within the mid-crust, reflective horizons dipping gently to the north are observed. The dips are generally slightly steeper at shallow depths and flatten near the lower boundary. Similar flattening observed by Calvert and Ludden (1999) at a boundary between the mid- and lower crust was interpreted as a lower crustal decollement.

Seismic features have been used to define the deeper parts of our 2D section, specifically the top of the mid-crust and the approximate location of the plutons (A, B, C, and D in Fig. 3).

Petrophysical data

Changes in the density and magnetic susceptibility can reflect variations in the lithology, weathering, hydrothermal alteration (Morris et al. 2007), and metamorphic grade (Cisowski and Fuller 1987; Boroomand et al. 2015). For example, higher density values are generally associated with rocks that are (i) mafic as opposed to lower-density felsic rocks, (ii) least weathered, and (iii) that have been metamorphosed to higher metamorphic grade and are thus more compacted (Telford et al. 1976).

Eshaghi et al. (2019) combined petrophysical measurements, collected by the Metal Earth project, with compiled measurements

collected across the Superior Craton and undertook a systematic characterisation at a regional scale. For the Chibougamau traverse, few outcrops were close to the Metal Earth gravity stations, and we only had three readings of physical properties. Thus, in this area, we use the values tabulated by Dion et al. (1992) based on surface and borehole samples in the nearby Chapais region (Table 1). We therefore assume that the density of the rocks of the Chapais region are similar to those of the Chibougamau region and that the magnetic susceptibility values compiled by Eshaghi et al. (2019) for rocks in the Superior craton can be used to constrain the physical properties of models in this study area.

Main conclusions drawn from these two petrophysical data sets are as follows. Younger dykes (diabase) are mafic units with a high magnetic and density values compared with the other units of the studied area. Plutonic bodies have low densities and a narrow range of density values. Sedimentary and metamorphic rocks also display relatively low-density values. However, volcanoclastic packages can show a wide range of density values. Also, felsic and intermediate igneous rocks, sedimentary rocks, and metamorphic rocks generally show low magnetic susceptibility values (Table 1).

In the sections we constructed, the mean values of magnetic susceptibility and density were assigned to specific geological units and these values were then adjusted to be consistent with

the potential-field data. These adjustments account for weathering, hydrothermal alteration, and metamorphism, and they should not exceed the maximum and minimum values measured in the field. However, sometimes the magnetic susceptibility had to be increased or decreased outside the expected range. We felt that this was likely due to normal or reversed remanent magnetisation (Telford et al. 1976), which magnetic susceptibility instruments cannot measure. We hypothesize that when we had to make the susceptibility significantly more than expected, there was normal remanent magnetisation present and when the susceptibility was less than expected, the remanent magnetisation was reversed.

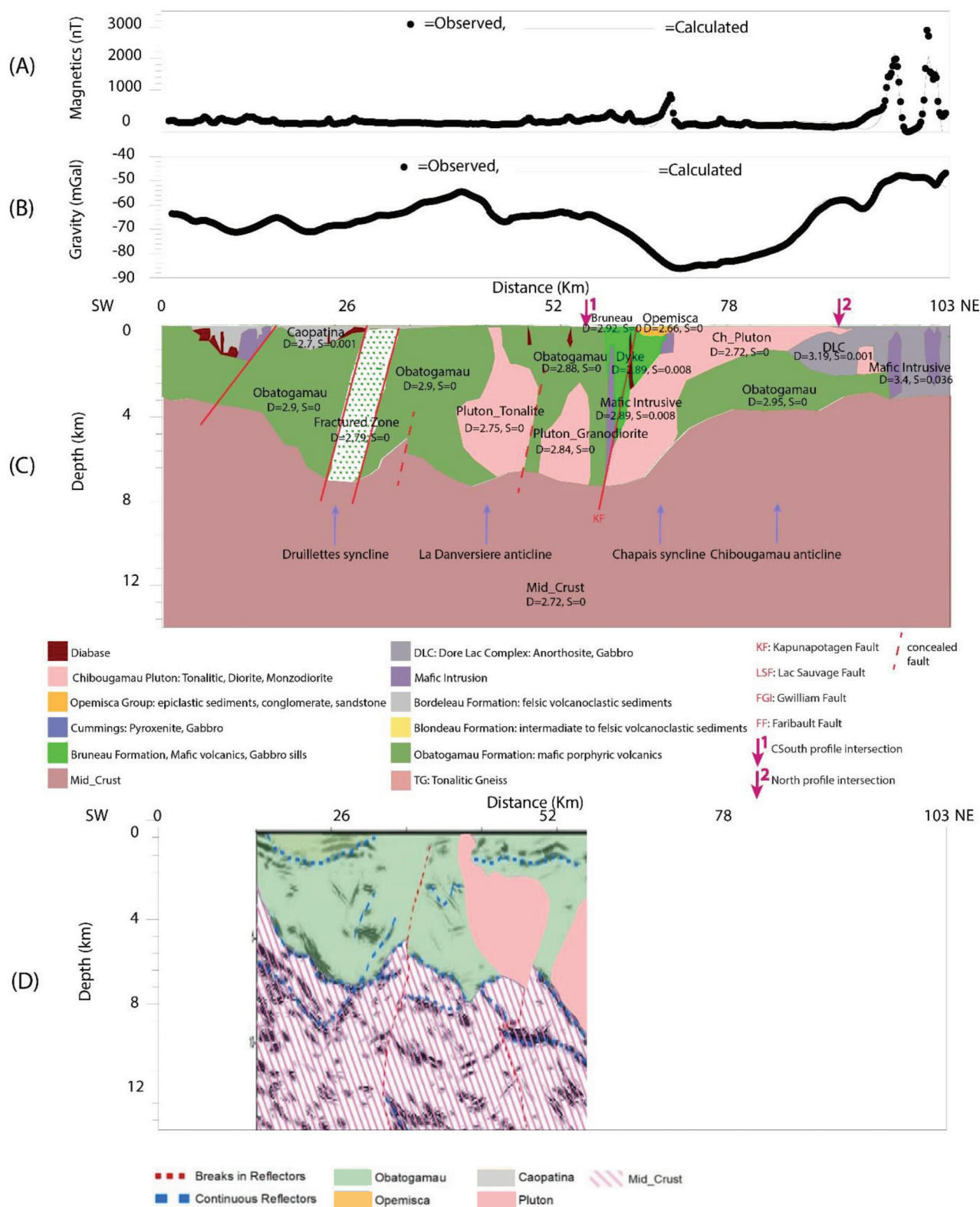


the 128 km Chibougamau seismic traverse is not straight, it has been broken into four straight profiles: South, CSouth, CNorth, and North profiles (Fig. 4). These profiles have also been extended beyond the area covered by seismic data. This was to allow more distal data from the GSC databases to be used to resolve deep structures. In this way, structures down to 7 km depth were resolved by modelling gravity and to some extent magnetic data. The geology is rarely unchanging away from the profile, so the software allows for a finite strike length on either side of the section to be specified (this is termed 2.5D modelling or a 2.5D correction). In the case of the CSouth and North profiles, the geological and magnetic interpretation maps (Figs. 1A and 2D) were used to set the strike length, on either side of the profile, to 5 km. For the South and CNorth profiles, the strike length was set to 2 km due to the structure being oblique to the profile direction.

For each profile, the complete Bouguer anomaly (includes Metal Earth and public data sets) and the residual magnetic field were forward modelled by manually adjusting the shape and physical properties of different geological units to minimize the differences between the modelled and the observed data (Olaniyan et al. 2013, 2014). We found that no variation in the depth of the Moho or lower crust was required to explain the gravity or magnetic data: all potential-field variations could be explained with adjustments to the physical properties or geometry of material in the top 7 km. When making adjustments to the model, we tried to ensure that the geological, seismic, and petrophysical constraints were respected. The final models, for each profile, are presented and discussed in detail in the following four sections.

Profile South is 103 km in length and is orientated in a south-west–northeast direction and includes the southern part of the Chibougamau seismic transect (Fig. 4). Figure 5D illustrates a part of the interpreted seismic section used as a constraint. In the south, the Caopatina Formation has a density of approximately 2.70 g/cm^3 , so it exhibits a relative gravity low (-72 mGal) compared with surrounding rocks (Fig. 5B). The Caopatina Formation forms a sedimentary basin bounded by east–west striking faults (Sharma et al. 1987). In the middle of this broad low, at kilometre 15 on the profile, there is a moderate gravity high (-64.4 mGal , 5 km wavelength) that occurs in an area where there is outcrop of underlying mafic volcanic rocks (Obatogamau Formation; $2.85\text{--}2.95 \text{ g/cm}^3$). From 18 to 28 km along the profile in the Druillettes syncline, the gravity response increases with an approximately linear trend. This could be interpreted as a thinning of the syncline, but we interpreted an underlying deeper fractured zone in the Obatogamau Formation (basalt, gabbro, andesite) with a density of 2.79 g/cm^3 , as this is consistent with truncations of units observed in the seismic section. If this source has a density higher than 2.79 g/cm^3 and closer to the density of the unfractured Obatogamau Formation, the fractured zone would be wider, while a lower density value would lead to a narrower geometry. This fractured zone is also consistent with a deformation zone observed on the surface in the Druillettes syncline. Subtle inflections, with short wavelengths from 25 to 29 km on the gravity profile could indicate fracture zones at these locations. The gravity continues to gradually increase northward from 28 to 40 km , followed by a significant (4.5 mGal) decrease from 40 to 48 km , which is interpreted to be due to a deep tonalitic pluton body (2.75 g/cm^3). At surface, this pluton corresponds to a narrower 2 km wide tonalitic outcrop on the geological map from 42 to 44 km . This plutonic body coincides with a reflector-free zone on the seismic data and is located along the same east–west trend of several tonalite-dominated plutons (Mathieu et al. 2020a) such

Fig. 5. The 2.5-dimensional geological model for profile South (C) and the corresponding magnetic data and gravity data (A and B, respectively). The measured data are the thick dotted line and the forward model data are the thin solid line. On the sections, the “D” label is associated with the density (g/cm^3) and “S” denotes the susceptibility (SI). A part of the interpreted seismic section was used as a constraint (D). Seismic constraints apply only between 12 and 56 km along the profile. The top red arrows show the location of the intersection of the South and CSouth profiles (#1), South and North profiles (#2). The blue upward arrows at the base of the section show the locations of anticlines and synclines. [Colour online.]



as the Eau Jaune Complex (TTD suite), the La Dauversière Pluton (tonalite–granodiorite), and the Boisvert Pluton (tonalite–granodiorite), all of which outcrop within the La Dauversière anticline (Fig. 4). On the part of the profile where the Bruneau Formation (light green in Fig. 5C) is shown coming close to surface (but actually does not outcrop), there is a slope down in gravity. This occurs at a zone where there are no reflectors on the seismic data. However, there is an outcrop of granodiorite off the profile (~1 km to the northwest), which may be connected with our deep feature and could explain the gravity reduction. Further to the north, there is another decrease in the gravity response, which is interpreted to be associated with two adjacent geological features. The first is the Chapais syncline, which outcrops at 62–67 km and is occupied by the low-density sedimentary rocks (2.66 g/cm³) of the Opémisca group (orange colour on the section) that overly sills of the Cummings Complex intruded into the Blondeau Formation (2.92 g/cm³). The Chapais syncline is bordered to the south by the Kapunapotagen fault. The second geological feature to the north is the Chibougamau anticline, located at 67–90 km in the section. This anticline includes the low-density Chibougamau pluton (2.70 g/cm³) composed of tonalite (2.76 g/cm³) in the center of the pluton and of denser diorite (2.93 g/cm³; Dion et al. 1992) along its margins. These different phases within the pluton are consistent with the geological observations of Mathieu and Racicot (2019). The gradual increase in gravity response to the north of the pluton is interpreted to be due to a decrease in the thickness of the Chibougamau pluton, and to the abundance of the diorite phase along its margin. The gravity data are consistent with a thickness of the northern portion of the Chibougamau pluton of about 1 km, whereas the southern portion is thicker, has a subvertical contact, and could extend to about 7 km at depth. At the northeastern end of the South profile, the geology consists of the Chibougamau anticline and the Doré Lake Complex, but the profile is semi-parallel to the anticlinal structure. Hence, the geometry and physical properties selected for the model are not reliable, as the 2.5D assumptions are not well satisfied. However, the high gravity values in this section are consistent with dense rocks composed of the main lithologies (anorthosite, gabbro, pyroxenite) of the layered Doré Lake Complex (3.00 g/cm³; Dion et al. 1992). In some parts of the profile, sharp drops in the gravity response can be explained by buried granophyre (2.61 g/cm³; Dion et al. 1992), which is the uppermost unit of the Doré Lake Complex.

The residual magnetic intensity data exhibits a relatively flat magnetic response across the South profile. However, there are some short-wavelength anomalies in the Druillettes syncline that are interpreted to be caused by mafic intrusions and diabase dykes, in agreement with the magnetic map interpretations (Fig. 2D). Between 58 and 67 km along the profile, the Cummings Complex, and mafic intrusions that underlay the sedimentary rocks of the Opémisca group have been interpreted as the source of some short-wavelength magnetic anomalies. The highest magnetic response along the South profile belongs to two anomalies (3.3 and 2 km wavelength) over the Doré Lake Complex in the northeastern end of the profile, which are modelled as two subvertical mafic intrusions with high magnetic susceptibilities. Small changes in the shapes of these bodies could result in better agreement between the model and measured data, but the precise geometries of these magnetic bodies were not considered an important part of modelling the deep structure.

Profile CSouth results and discussion

Profile CSouth is 44 km in length with an approximate south–north orientation. The location of the profile has been selected to include constraints from part of the Chibougamau seismic transect between 45 and 66 km. Figure 6D illustrates a part of the interpreted seismic section that is used as a constraint. Starting

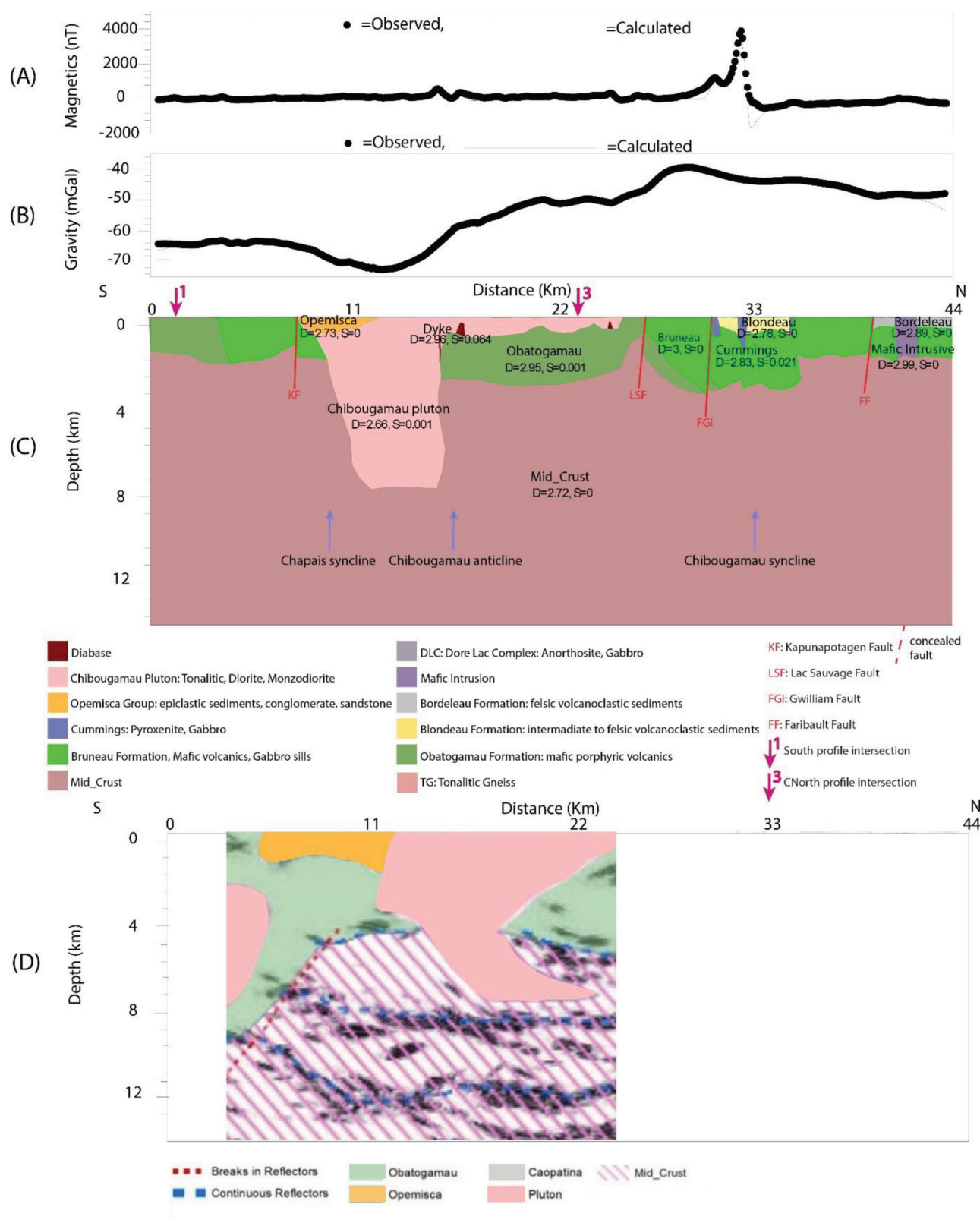
from the south, Fig. 6C shows mafic rocks of the Obatogamau and the Bruneau formations (density approximately 2.8 g/cm³), between 0 and 7.7 km, that exhibit a flat gravity response. To the north of the Kapunapotagen fault, a gradual decrease of the Bouguer anomaly is associated with the Opémisca group (density approximately 2.66 g/cm³), which is interpreted to overlie the Bruneau Formation to the south and further to the north it overlies the southern corner of the Chibougamau pluton. These lower density rocks correspond to a gradual decrease in gravity response. The lowest gravity response (−73.36 mGal) along the CSouth profile is interpreted to be due to tonalitic/dioritic rocks (2.65 g/cm³) in the Chibougamau anticline, which is consistent with an area without reflectors in the seismic profile. The thickness of the Chibougamau pluton at the centre of the Chibougamau anticline changes thickness at the 16 km mark on the profile. The portion to the north is about 800 m thick and overlies the Obatogamau Formation (2.95 g/cm³), whereas the southern thicker portion could extend to about 8 km. Some short wavelength fluctuations in gravity data between 20.5 to 25.7 km are interpreted to be due to slight changes in the thickness of the Chibougamau pluton in the thinner northern part. The smooth gradual increase in the gravity response from 25.7 km to 27 km is interpreted to be due to the gradual thinning of the Chibougamau pluton, and to a relatively thin body of the Obatogamau Formation against the fault. Further to the north toward 29.5 km, there is a steeper increase in gravity data from −46.5 to −39 mGal, which is interpreted to be due to an increase in the thickness of the denser lithologies, such as the Obatogamau and the Bruneau formations (2.95–3.00 g/cm³) with the depth extent not exceeding 3600 m. The Chibougamau syncline is bounded by two east–west-oriented faults (the Lac Sauvage fault to the south, and the Faribault fault to the north), with dominant lithologies of the Cummings Complex sills and an assemblage of Roy Group rocks (Bruneau and Obatogamau formations), having densities between 2.78 and 3.00 g/cm³. The Chibougamau syncline corresponds to broad and smooth gravity high (−40 mGal) with a moderate decrease over intermediate to felsic volcanoclastic sediments of the Blondeau Formation (density approximately 2.78 g/cm³). The far north of the profile shows a gradual smooth decrease towards the Waconichi tectonic zone with sedimentary rocks of the Bordeleau Formation and mafic intrusions of the Cummings Complex.

The residual magnetic intensity profile is moderately flat along the southern 30 km. There are some short wavelength anomalies on the northern flank of the Chibougamau anticline, which are modelled as mafic intrusions and dykes with higher magnetic susceptibilities than surrounding rocks. The highest magnetic response is recorded over the Cummings Complex and mafic intrusions with high magnetic susceptibilities in the Chibougamau syncline. The lower magnetic field values from ~32 km to the end of the profile, is interpreted to be due to sedimentary rocks in the Chibougamau syncline (Blondeau Formation), and in the Waconichi Anticline (Bordeleau Formation) with low magnetic susceptibilities.

Profile CNorth results and discussion

Profile CNorth has a total length of 54 km with a general orientation of southwest–northeast. Between 65 km and 96 km, Fig. 7D illustrates a part of the interpreted seismic section that is used as a constraint. Starting from the southwest, there are two adjacent geological features along the first 6 km of the profile resulting in a steep and linear decrease in the gravity response. The first one is the Opémisca Group with a density value of approximately 2.66 g/cm³, which is interpreted to structurally overlie the Chibougamau plutonic body. The second feature is the Chibougamau pluton, a tonalitic/dioritic intrusion (density 2.65–2.70 g/cm³) that is here interpreted to extend to 9 km at

Fig. 6. The 2.5-dimensional geological model for profile CSouth (C) and the corresponding magnetic data and gravity data (A and B, respectively). The measured data are the thick dotted line and the forward model data are the thin solid line. On the sections, the “D” label is associated with the density (g/cm^3) and “S” denotes the susceptibility (SI). A part of the interpreted seismic section was used as a constraint (D). Seismic constraints apply only from 3 to 24 km of the profile. The top red arrows show the location of the intersection of the South and CSouth profiles (#1), CNorth and CSouth profiles (#3). The blue upward arrows at the base of the section show the locations of anticlines and synclines. [Colour online.]



depth with subvertical contacts. The moderate increase in gravity response from 6 to 22 km is interpreted to be due to the gradual decrease in thickness of the Chibougamau pluton, and denser diorite phases occurring on the border of it. There are some short-wavelength fluctuations in the gravity response along the thinner northern portion of the Chibougamau pluton, which are interpreted as firstly due to depth fluctuations of the contact between the plutonic body and the underlying mafic rocks of the Obatogamau Formation, and secondly due to some hidden mafic intrusions and mafic rocks of the Doré Lake Complex (inserted to explain two 2.5 and 2 km wavelength gravity anomalies). Crossing the Lac Sauvage fault further to the north is the southern limit of the Chibougamau syncline, which is marked by an increase in thickness of an assemblage of Roy Group rocks (Bruneau and Obatogamau formations) with a density of 2.9–3 g/cm³. These result in a generally gradual increase in gravity response from 22 to 27.7 km. It should be mentioned that the sharp change in the thickness of the Roy group rocks is consistent with the seismic interpretations, but the profile is semi-parallel to the strike of geological structure, and the transect is crooked in this area. The crooked transect compromises the seismic processing and the semi-parallel traverse violates the 2.5D assumption in the potential-field modelling. The gradual increase in gravity response continues toward 32.7 km, which is interpreted to be due to the mafic intrusive body with a density value of approximately 3.2 g/cm³ that outcrops on the surface. A slight low in the gravity data at 29.5 km is observed over a location where there is an outcrop of basalt and andesitic basalts of the Bruneau Formation (2.7–2.9 g/cm³), which overlies the previously mentioned mafic intrusive body. About 2 km further to the north, the flatter gravity response is interpreted to be due to basaltic and andesitic rocks of the outcropping Bruneau Formation having similar densities. Between 34.5 to 45 km, the gravity profile is generally flat with some subtle low-amplitude anomalies. The increases are interpreted to be due to the pyroxenite, dunite, and peridotite rocks of the Cummings Complex (density 2.7–2.9 g/cm³). These rocks outcrop at a number of locations on surface. The slight decreases are interpreted to be related to intermediate to felsic volcanoclastic sediments of the Blondeau Formation (2.76 g/cm³), which also outcrop on surface. North of the Faribault fault, the gravity is reduced in the Waconichi tectonic zone as a consequence of the less dense sedimentary rocks of the Bordeleau Formation.

The residual magnetic intensity profile exhibited an overall moderate flat response along the first ~34 km (Fig. 7A). At 8, 13, and 19 km, there are some increases in magnetic response on the northern flank of the Chibougamau anticline, which are modelled as buried mafic intrusions and dykes with higher magnetic susceptibilities than surrounding rocks. These anomalies are consistent with interpreted magnetic lineaments in Fig. 2D. An alternative source for these features is hidden mafic intrusions and mafic rocks of the Doré Lake Complex with high magnetic susceptibilities. The largest magnetic anomalies are recorded over the Cummings Complex and mafic intrusions with high magnetic susceptibilities in the Chibougamau syncline from 34 to 46.5 km. Within these magnetic highs, the local lows are associated with sedimentary rocks of the Blondeau Formation (low magnetic susceptibility). There is a drop in magnetic response from ~46.5 km to the end of the profile, which is interpreted to be due to two low magnetic susceptibility sedimentary rocks; one in the Chibougamau syncline (Blondeau Formation), and the other in the Waconichi anticline (Bordeleau Formation) both with low magnetic susceptibilities.

Profile North results and discussion

Profile North is 66 km in length and runs from south to north. The northernmost 28 km section coincides with the northern

part of the Chibougamau seismic transect (Fig. 8D). The southernmost 6.5 km of Fig. 8C is covered by mafic rocks of the Obatogamau and the Bruneau formations (~2.8 g/cm³), which exhibit a smooth gravity response with a slight decrease attributed to an increase in the thickness of the Blondeau sedimentary rocks (density 2.68 g/cm³). Crossing the east-trending, south-dipping Kapunapotagen reverse fault, the Opémisca group (~2.66 g/cm³) in contact with anorthosite and gabbro of the Doré Lake Complex (2.98 g/cm³) below and to the north, results in a gradual increase in the gravity response to the north. The lowest gravity response (–74 mGal) compared with surrounding regions is interpreted to be due to tonalitic/dioritic rocks (2.65 g/cm³) of the Chibougamau pluton, which could extend to about 7.7 km with subvertical contacts. The northern portion of the Chibougamau pluton overlies the Obatogamau and Bruneau Formations (2.95–2.97 g/cm³) so there is a gradual increase in gravity response from 18 to 21 km along the profile. There is a flat part of the gravity profile with some short wavelength fluctuations from 21 to 30.3 km, which is interpreted as changes in the thickness of Roy group rocks. Further to the north, there is a subtle short-wavelength gravity high at 32.8 km and with amplitude –35.5 mGal, which is interpreted to be due to the Cummings Complex (2.9–3.05 g/cm³), which is supported by a mapped outcrop in the Chibougamau syncline. The zone covered by Blondeau sediments from 32.8 to 34.8 km shows a slight decrease in the Bouguer anomaly values. At 45.3 km, there is a gradual decrease in the gravity response that is interpreted to be due two factors: (1) a decrease in the thickness of the denser lithologies, such as the Bruneau Formations (2.9–2.95 g/cm³) with vertical extension not exceeding 2.3 km, and (2) the occurrence of sedimentary rocks of the Opémisca Group with lower density than surrounding mafic to intermediate metavolcanic rocks in the Waconichi syncline. Further to the north, there is a gravity high from 43.1 to 44.3 km, which is interpreted to be due to high density mafic intrusions in the Waconichi syncline. At 50.1 km, gravity values start to decrease. Although there is an interpreted reverse movement of the Barlow fault that results in an increase in the thickness of the denser lithologies in the footwall (Obatogamau and Bruneau formations; density 2.85–2.95 g/cm³), the measured gravity values decrease. This is likely the impact of the deep and less dense tonalitic/granodioritic rocks of the Barlow pluton (2.69 g/cm³) and the tonalitic gneiss rocks of the Opatika plutonic belt (2.66 g/cm³) that are located at the extreme end of the profile and are interpreted to extend to great depth. We have placed high-density Obatogamau Formation below the Barlow pluton, but, as there is no field evidence other higher density rocks could be used such as mafic cumulus rocks at the base of the intrusions.

The residual magnetic intensity data appear moderately flat along the first 29 km. There are some short wavelength anomalies on both the northern and the southern flanks of the Chibougamau anticline, which are modelled as mafic intrusions and dykes with higher magnetic susceptibilities than surrounding rocks. The highest magnetic response is recorded over the Cummings Complex and mafic intrusions with high magnetic susceptibility content in the Chibougamau syncline. There is a drop in magnetic data from 33 to 42.2 km, which is interpreted to be due to the two sedimentary packages; one in the Chibougamau syncline (Blondeau Formation), and the other in the Waconichi anticline (Bordeleau Formation). There is a strong magnetic anomaly from 42.7 to 44.4 km that is consistent with a mafic intrusive body with a higher magnetic susceptibility than the surrounding sediments in the Waconichi syncline.

Discussion and conclusion

Because of the non-uniqueness of potential-field data, in this study, we used various data sets (i.e., surface geology, magnetic map interpretation, interpreted seismic sections, and petrophysical

Fig. 7. The 2.5-dimensional geological model for profile CNorth (C) and the corresponding magnetic and gravity (A and B, respectively) data from this study and GSC (2019) data. The measured data are the thick dotted line and the forward model data are the thin solid line. On the sections, the “D” label is associated with the density (g/cm^3) and “S” denotes the susceptibility (SI). A part of the interpreted seismic section was used as a constraint (D). Seismic constraints apply only from 17 to 48 km of the profile. The top red arrows show the location of the intersection of the CNorth and CSouth profiles (#3), CNorth and North profiles (#4). The blue upward arrows at the base of the section show the locations of anticlines and synclines. [Colour online.]

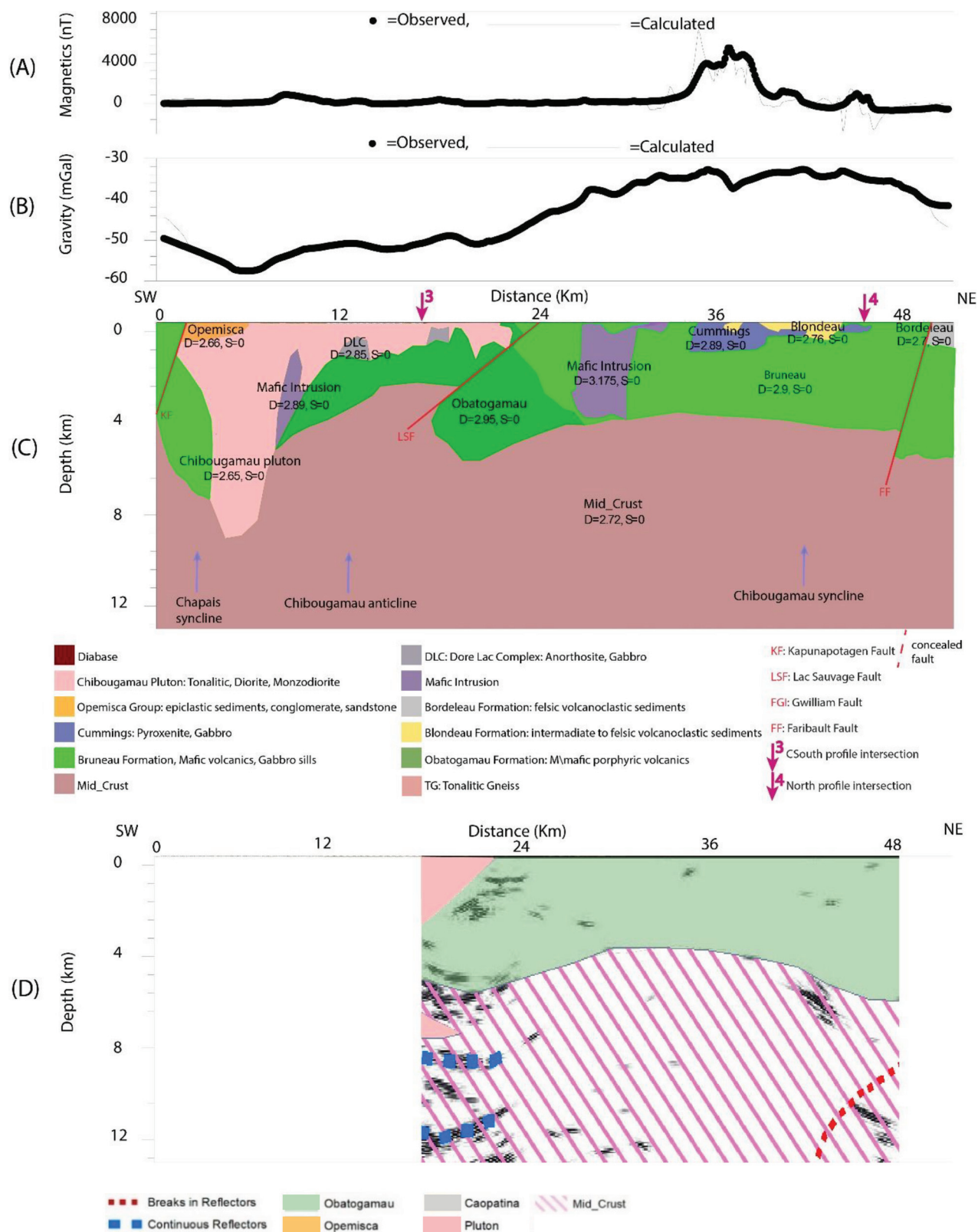
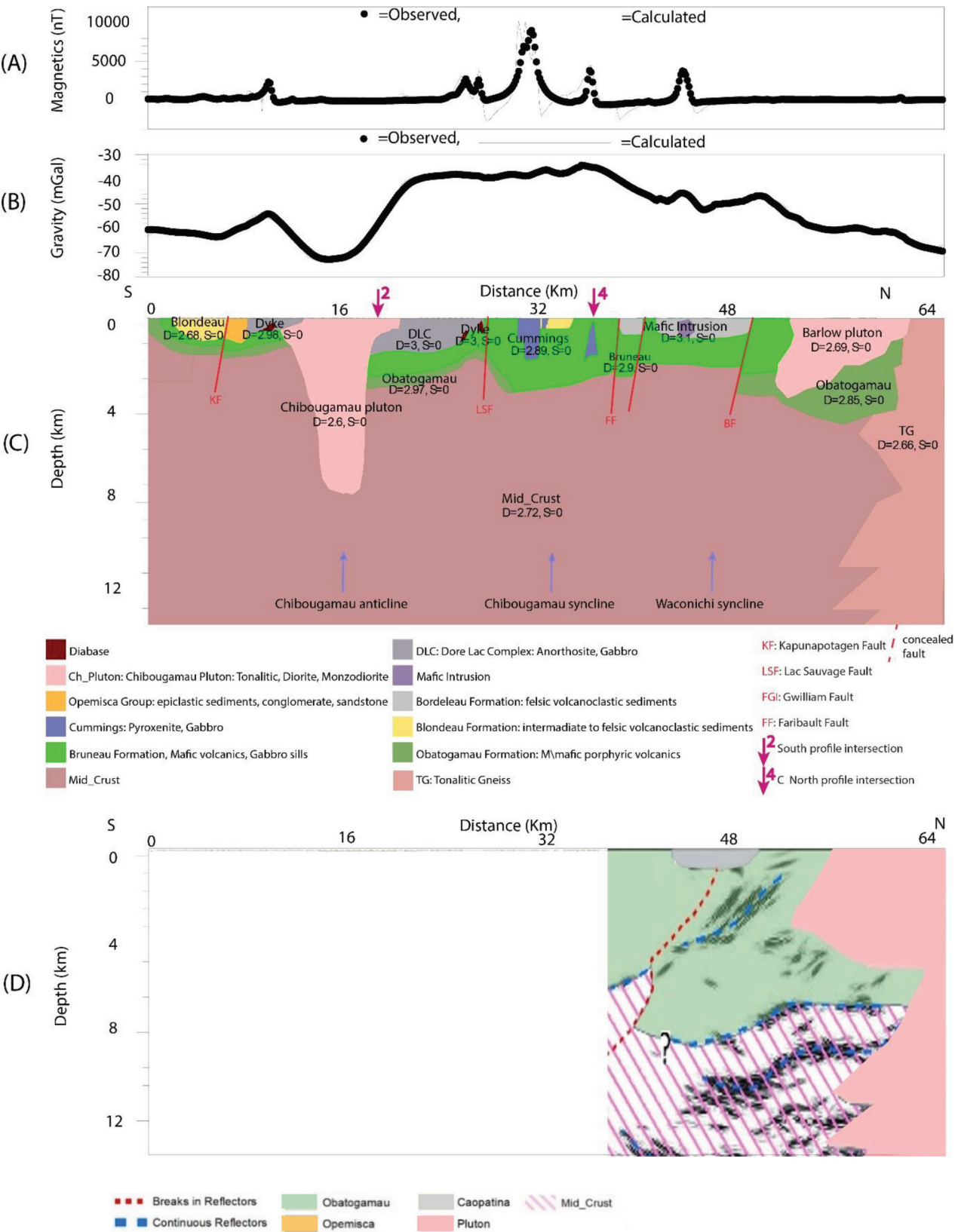


Fig. 8. The 2.5-dimensional geological model for profile North (C) and the corresponding magnetic and gravity (A and B, respectively) data from this study and GSC (2019) data. The measured data is the thick dotted line and the forward model data is the thin solid line. On the sections, the “D” label is associated with the density (g/cm^3) and “S” denotes the susceptibility (SI). Seismic constraints (D) apply only from 37.5–65.5 km of the profile. The top red arrows show the location of the intersection of the South and North profiles (#2), CNorth and North profiles (#4). The blue upward arrows at the base of the section show the locations of anticlines and synclines. [Colour online.]



measurements) to produce reliable sections that model the geometry of geological features at depth.

Our primary emphasis was on the gravity data, which was used to resolve the shape and geometry of several features, and especially plutonic bodies. This is significant, especially for the Chibougamau pluton that is associated with Cu–Au magmatic-hydrothermal mineralization. The magnetic data was used to focus on narrow planar structures (dykes) associated with magnetic contrasts. The gravity and magnetic modelling provided insights as to the shape of the plutons in areas where there were no reflections in the seismic data. When reflections are evident, subsurface structures can be interpreted with more confidence.

In the La Dauversière anticline (the South profile), a buried pluton was modelled at depth. This pluton potentially connects with an outcrop of granodiorite to the northwest of the transect. Also, in the southern part of the South profile, in the Druillettes syncline, a fractured zone is interpreted in the Obatogamau Formation, which is relevant to the seismic interpretation and to the deformation zone observed at the surface.

Acknowledgements

The authors thank Pierrick Altwegg, William McNeice, Fabiano Della Justina, Brandon Hume, Tara Smith, Kerri Campbell, and Pierre Bedeaux for their help during data collection, processing, and interpretation. The authors acknowledge that the Metal Earth project, Harquail School of Earth Sciences, Laurentian University, has provided a platform to perform this research. This work was supported by the Canada First Research Excellence Fund (CFREF). On behalf of the Metal Earth project, the authors also acknowledge Seequent for providing four Geosoft montaj licences, which allowed the processing of the magnetic and gravity data and the GM-SYS modelling presented here. The contribution number of this publication is MERC-ME-2019–225.

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