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Analysis and Interpretation of Regional Gravity Data in the Swayze greenstone belt of the Superior Province, Canada

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Abstract

The Swayze greenstone belt (SGB) is an Archean granitoid-greenstone terrain located in the central part of the Superior Province in Canada. The main objective of this project consisted in doing an analysis and modelling of public regional gravity data of the Swayze greenstone belt with the aim of examining the geometry and depth extent of the geological bodies that occur in the area of this greenstone belt. Gravity data from the Geophysical Data Repository of Natural Resources Canada was used to obtain forward 2.75D gravity models along three profiles, two transversal and one longitudinal to the geological structures of the Swayze greenstone belt. Gravity forward modelling along these profiles was performed using different constraints such as mapped geological contacts at the surface and petrophysical data of different type of rocks of the Abitibi greenstone belt. The models provide an attempt to characterize the geometry and depth extent of the geological units composing the SGB, using regional gravity data.

Key words: Gravity Data, Bouguer anomaly, Gravity modelling, Swayze greenstone belt, Superior Province

Resumen

El cinturón de rocas verdes Swayze (Swayze greenstone belt - SGB) es un terreno compuesto de granitoides y rocas verdes del Arcaico ubicado en la parte central de la Provincia Superior de Canadá. El objetivo principal de este proyecto consistió en realizar un análisis y modelado de datos gravitacionales regionales públicos del cinturón de rocas verdes Swayze con el objetivo de examinar la geometría y extensión en profundidad de los cuerpos geológicos que ocurren en el área estudiada. Se utilizaron datos de gravedad del Repositorio de Datos Geofísicos de Recursos Naturales de Canadá para obtener modelos de gravedad 2,75D a lo largo de tres perfiles, dos transversales y uno longitudinal a las estructuras geológicas del cinturón de rocas verdes Swayze. El modelado de gravedad a lo largo de estos perfiles se llevó a cabo utilizando diferentes restricciones, como los contactos geológicos cartografiados en la superficie y los datos petrofísicos de diferentes tipos de rocas del cinturón de rocas Abitibi. Los modelos proporcionan una aproximación de caracterizar la geometría y la extensión en profundidad de las unidades geológicas que componen el SGB, utilizando datos gravimétricos regionales.

Palabras claves: Datos de gravedad, Anomalía de Bouguer, Modelado de gravedad, Cinturón de rocas verdes Swayze, Provincia Superior

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Introduction

The Swayze greenstone belt (SGB) is located in the western Abitibi subprovince of the Superior Province in Ontario, Canada (Figure 1). It is an Archean-age greenstone belt composed of metavolcanic, metasedimentary and metaplutonic rock types (Heather *et al.*, 1995). The SGB was a focus area of the Metal Earth project of the MERC (Mineral Exploration Research Centre, Laurentian University, Sudbury), which involved crustal-scale geophysical investigations of the Swayze greenstone belt area with reflection seismic, magnetotelluric and gravity surveys. Geological mapping was also done along the geophysical transects, to provide an up-to-date base for the interpretation of the geophysical data (Haugaard *et al.*, 2017).

The current project is focused on the analysis and modelling of public regional gravity data of the SGB that is openly available for the area of study with the purpose of contributing to the geological comprehension of the main characteristics of the upper crust in this area. Thus, the depth and geometry of the different bodies that form the subsurface structure of the SGB were investigated using gravity modelling.

Bouguer Anomaly data was downloaded from the Geoscience Data Repository for Geophysical Data of Natural Resources Canada (http://gdr.agg.nrcan.gc.ca/gdrdap/dap/search-eng.php). Three 2.75D forward gravity models are presented for selected profiles, which were obtained with the GM-SYS extension of the Geosoft Oasis montaj software.

Forward gravity modelling was done by taking into account certain constraints, such as the density contrast of the different type of rocks that crop out in the Swayze area and the mapped geological contacts at the surface. The gravity models obtained in this study are compared with other known gravity models of Archean greenstone belts from Canada, with the purpose of correlating the resulting geometry and depth extents as well as identifying if the presented models resemble the general characteristics of other Archean greenstone belts.

Regional Geology

The Swayze greenstone belt (SGB) is located in the Western part of the Abitibi subprovince of the Superior Province

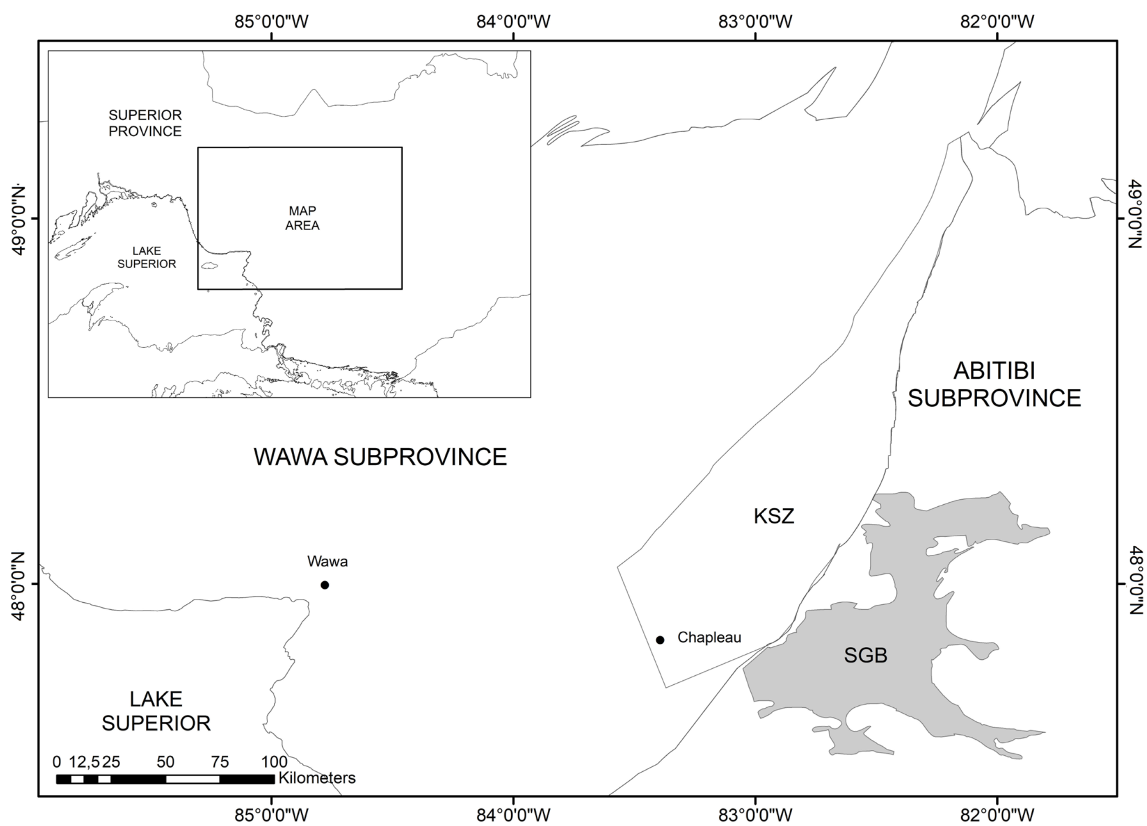

Figure 1. Sketch map of the central Superior Province showing the location of the Swayze greenstone belt (SGB). KSZ - Kapuskasing Structural Zone. The map is based on data downloaded from the ArcGIS website (https://www.arcgis.com/home/item.html?id=d87347457bc84e5c985db9e904b66b10) and from the Mineral Exploration Research Centre (MERC) website (https://merc.laurentian.ca/research/metal-earth/superior-compilation).

in Ontario, Canada. It is described as a Neo-Archean granitoid-greenstone terrain developed between 2.8 and 2.6 Ga (Jackson & Fyon, 1991). It is bounded by the (a) Kapuskasing structural zone to the west, the (b) Kenogamissi batholith complex to the east, the (c) Nat River granitoid complex to the north and the (d) Ramsey-Algoma granitoid complex to the south (Heather, 2001). The SGB consists of intrusive and extrusive rocks of ultramafic to felsic composition (Figure 2), as well as both chemical and clastic metasedimentary rocks, most of which underwent metamorphism of greenschist to sub-greenschist facies, and amphibolite facies along the boundaries of the belt with large granitoid complexes (Hastie *et al.*, 2020). Despite the SGB having similar geology and greenstone stratigraphy as others greenstone belts of the Abitibi subprovince, the SGB has been considered an area with less (significant) mineral potential (Cheraghi *et al.*, 2019).

The SGB is connected with the southern Abitibi belt by thin slivers of volcanic-sedimentary rocks associated with the Porcupine-Destor deformation zone (PDDZ) and the Ridout deformation zone (RDZ) in the northern and in the southern margins, respectively, of the Kenogamissi granitoid complex (van Breemen *et al.*, 2006). The Kenogamissi batholith complex and the Ramsey-Algoma granitoid complex mainly comprise felsic to intermediate intrusive rocks.

There are two main folds in the SGB: the Brett Lake Syncline and the Woman River Anticline which are labeled in Figure 2 and in Figure 3 with the letters BL and WR, respectively. The SGB is divided in six supracrustal groups from the oldest to the youngest: Chester, Marion, Biscotasing, Trailbreaker, Swayze and Ridout groups (Heather, 2001). For the purpose of gravity modelling in this project, this package of supracrustal groups was considered as a mafic metavolcanic body, given the fact that this rock type is dominant.

It is important to highlight that there is a lack of previous academic or exploration studies of the SGB in comparison with the Abitibi greenstone belt (Maepa & Smith, 2020). Geological work done on the SGB comprises: (1) detailed mapping of the SGB performed by Heather (2001), (2) mapping and data compilation by Ayer *et al.* (2002) and (3) remapping by Haugaard *et al.* (2017). Geophysical work, such as magnetotelluric resistivity sections, seismic surveys, including high-resolution seismic imaging and gravity surveys, was previously done, along some profiles across the SGB (Cheraghi *et al.*, 2019).

Gravity Data

In 2017, the SGB was an area of study of the Metal Earth project carried out by the MERC with the purpose of refining the geological knowledge of the Abitibi greenstone belt. To accomplish this task, the Metal Earth studies investigated the crust of the Swayze area along transects perpendicular to the strike of major structures and units, using reflection seismic, magnetotelluric and gravity surveys (Haugaard *et al.*, 2017). Nevertheless, these data are not publicly available for free use. Instead, the gravity data used in this project was downloaded directly from the Geoscience Data Repository for Geophysical Data of the Natural Resources Canada. For the downloaded gravity dataset, the original coordinates in the geographic coordinate system were converted to NAD83 UTM Zone 17. The Bouguer Anomaly dataset (Figure 3) was downloaded from the Geoscience Data Repository as a grid with a 2-*km* grid-cell size that extends between 47.5° to 48.27° N and -81.9° to -83° W, which corresponds to the area underlain by the Swayze greenstone belt and its surroundings.

Qualitative Analysis

The Bouguer gravity anomalies correspond to lateral variations in density and mass in the upper mantle and the crust that reflect differences in composition and thickness of geological bodies. High-frequency anomalies are caused by near-surface bodies of rocks that have significantly different densities. Longer wavelength anomalies are generally associated with variations in crustal thickness or deeper intra-crustal mass anomalies.

In the area of this study, the values of the Bouguer Anomaly range from -16,9 to -77 mGal (Figure 3). In the area labelled A1 in Figure 3 exists a symmetry with respect to the fold axis of the Brett Lake Syncline (BL). This also occurs in the area A2 with respect to the fold axis of the Woman River Anticline (WR). Despite their symmetry, these areas do not show significant changes in the value of the Bouguer anomaly away from the fold axes. On the other hand, the areas A3 (Kenogamissi granitoid complex), A4 (Biggs Pluton) and A5 (Nat River granitoid complex) are characterized by the lowest values of the anomaly, which indicates that the rocks underlying these areas are less dense than their surroundings. These areas correspond to granitic plutons that are less dense than the volcanic rocks they surround. There are also other small intrusions throughout the SGB but those do not represent significant gravity lows in the values of the Bouguer Anomaly.

Modelling

In order to study and understand the Bouguer anomalies caused by density contrasts between bodies underneath the

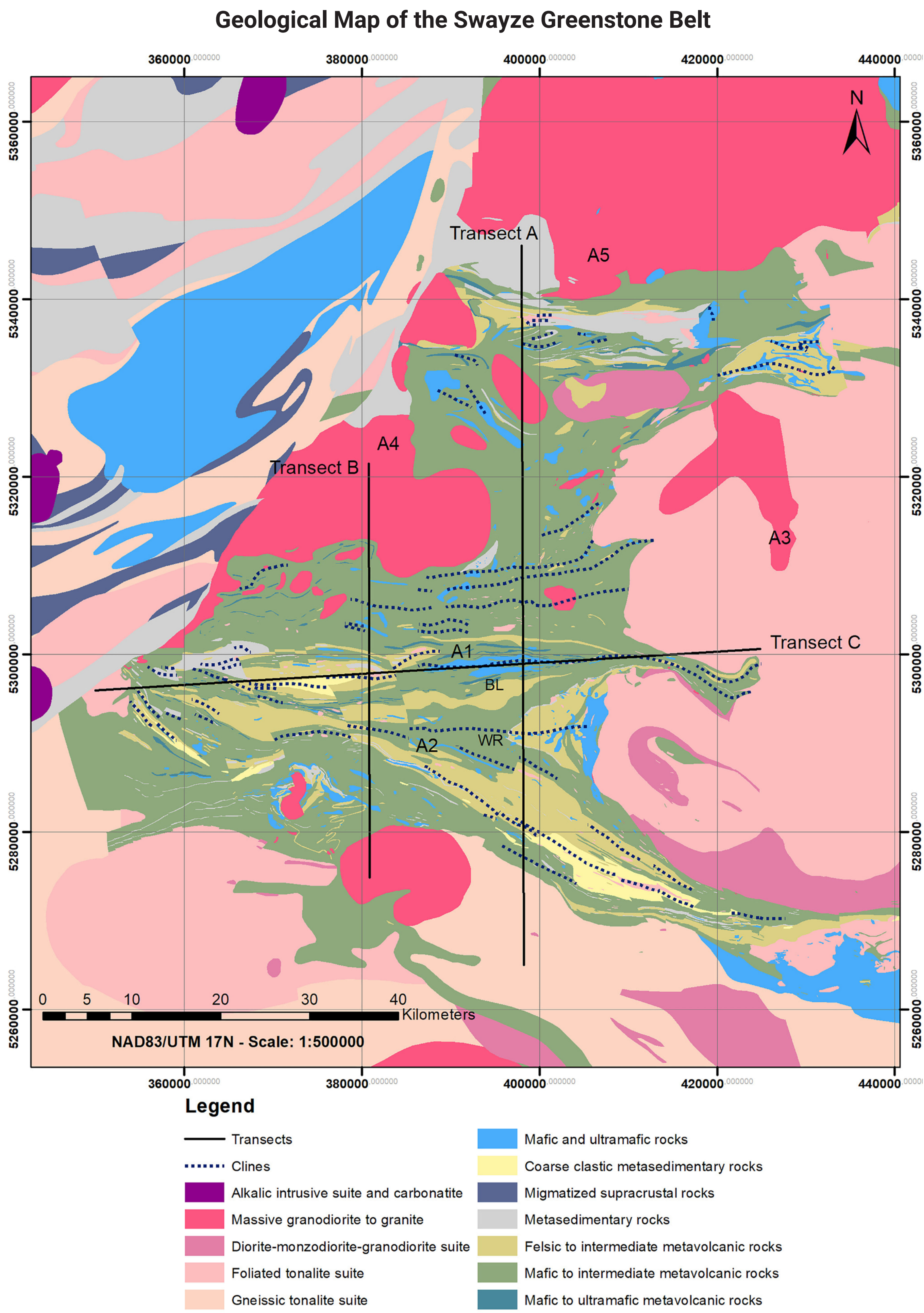

Figure 2. Geological map of the Swayze greenstone belt. Coordinate System NAD-83/ UTM Zone 17 N. The black solid lines indicate the traces of the profiles (transects) along which 2.75D forward modelling was conducted. BL and WR correspond to the Brett Lake and the Woman River folds, which are discussed in the text. In dark blue dashed lines are shown the axes of the different folds in the Swayze area. A1 to A5 indicate the different areas discussed in the Qualitative Analysis section. The digital geological dataset was downloaded in ArcGIS format from the website of the Ministry of Northern Development and Mines of Ontario: (http://www.geologyontario.mndm.gov.on.ca/mndmaccess/mndm_dir.asp?type=pub&id=MRD126-REV1).

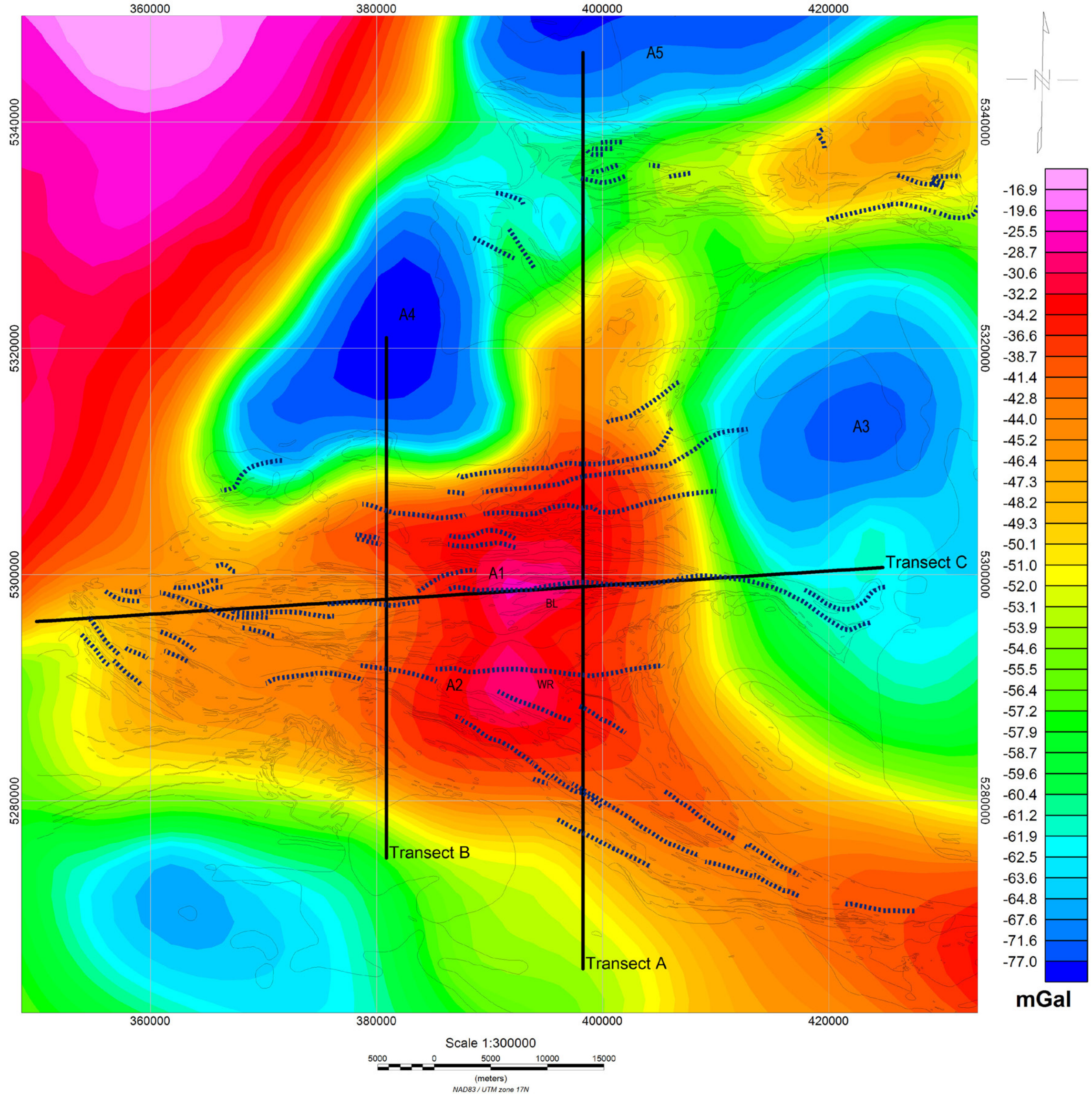

Figure 3. Bouguer anomaly map of the SGB (mGal). Coordinate System NAD-83/ UTM Zone 17 N. The black solid lines indicate the traces of the profiles (transects) along which 2.75D forward modelling was conducted, in order to study the depth and geometry of the geologic bodies and structures of the area. In grey thin lines are represented the geological contacts that occur in the Swayze area (see also the Geological Map in Figure 2). The thick dark blue dashed lines indicate fold axes in the Swayze greenstone belt area. BL and WR correspond to the Brett Lake and the Woman River folds, which are discussed in the text. A1 to A5 indicate the different areas discussed in the Qualitative Analysis section. The Bouguer Anomaly grid file was downloaded from the Geoscience Data Repository of Natural Resources Canada.

surface, a quantitative model can be constructed to fit a certain set of gravity observations, by changing, for instance, the geometry and depth extent of the model bodies. For the modelling of the selected transects (see Figures 2 and 3), the contacts between the main geological units (mafic metavolcanic rocks and granitoid plutons), the main fold location and their type as well as the densities of the types of rocks cropping at the surface were taken into account and were used as constraints. The density values of the geological units in the area of study were based on a generalized density table of the Abitibi greenstone belt published by Eshaghi *et al.* (2019). Horizontal extents of the geological bodies that extend beyond the ends of the profile were also considered, in order to model these rock bodies and resolve the calculated gravity. Furthermore, for the rock bodies intersected by the profiles, variable extents perpendicular to the strike of the transects were considered, which created 2.75D gravity models.

The density contrasts of the modelled geological bodies

Table 1. Density values (*g/cm³*) used in the forward models.

Type of Rock	Density
Mafic metavolcanic bodies	2.89 g/cm^3
Granitoid plutons	2.66 g/cm^3
Crustal back-ground	2.72 g/cm^3

were considered relative to an average upper crustal density in the Superior Province of 2.72 g/cm^3, based on previous studies (e.g. Nitescu *et al.*, 2006; Maleki *et al.*, 2021). Three gravity models were obtained with the Oasis montaj GM-SYS tool along the profiles shown in Figures 2 and 3.

For the three models, the geologic bodies were grouped into two categories with different density values, as well as density contrasts, relative to the upper crustal back-ground: mafic metavolcanic bodies, ρ=2.89 g/cm^3 and a density contrast of +0.17 g/cm^3 relative to the crustal background; granitoid plutons, with ρ=2.88 g/cm^3 and a density contrast of -0.06 g/cm^3 relative to the crustal background. The density values used in the forward models are also summarized in Table 1.

Model A

This model corresponds to a profile that is perpendicular to the general direction of the main fold axes of the SGB, such as the Brett Lake Syncline and the Woman River Anticline, in a north-south direction in the eastern part of the Swazye greenstone belt and covers a distance of approximately 81 *km*.

In Figure 4, it is observed that the highest peak of the Bouguer anomaly is located mainly on the axis of the Brett Lake Syncline. The lowest values of the Bouguer anomaly along the profile correspond to the Nat River granitoid complex north of the Swayze greenstone belt. The deepest parts of the model of the greenstone belt occurs where the Brett Lake Syncline and Woman River Anticline are located, between kilometers 45 and 55, in two roots with observed depths of 4 and 5 *km*, respectively. On the other hand, in the northern part of the profile, outcropping mafic volcanic rocks appear to extend to a depth of less than 1 *km*.

Model B

This model corresponds to a profile that is perpendicular to the general direction of the Brett Lake Syncline and Woman River Anticline in a north-south direction in the western part of the Swayze greenstone belt. It covers a distance of approximately 46 *km*. The model (Figure 5) indicates that along this profile the greenstone belt body reaches its deepest part (12 *km* depth) in the northern half of the profile (at kilometer 17), where the highest values of the Bouguer anomaly are observed. The lowest values of the Bouguer Anomaly correspond to the Biggs Pluton at the north end of the profile, which has a modelled depth of 8 *km*.

The Brett Lake Syncline and the Woman River Anticline present modelled depths of 4 to 5 *km* in the interval between kilometers 21 and 31 of the profile.

Model C

This model corresponds to a profile that follows the general direction of the Brett Lake Syncline in a west-east direction of the Swayze area. It covers a distance of approximately 75 *km*. It is observed in the Figure 6 that the highest value of the Bouguer Anomaly occurs at kilometer 41 of the profile, where the model of the greenstone belt body reaches its deepest part of about 7 *km* depth. The thickness of the mafic metavolcanic unit remains constant between the western end of the profile and the kilometer 32 along the profile, with a model depth of approximately 2 *km*.

Discussion

In the area of study, the lowest values of the Bouguer Anomaly correspond to intrusive granitoid bodies that typically have lower densities than the rocks surrounding them. The highest values of the Bouguer Anomaly correlate with metavolcanic rocks, which have undergone deformation processes often related to high strain zones, resulting in various folds with an axial plane in the west-east direction. With regards to the depth of the structures, it is observed that the Brett Lake Synclinal extends in depth between 2 to 7 *km*, whereas the Woman River Anticline extends in depth between 3 to 5 *km*.

The depth and geometry of the geological units of the SGB are comparable with those of other Archean greenstone belts such as the models presented by Peschler *et al.* (2004) of the Abitibi greenstone belt, which typically are part of the dome-and-keel structural patterns of the Archean terrains. Dome-and-keel provinces consist of synclinal keels composed of greenstone rocks that are surrounded by ellipsoidal and

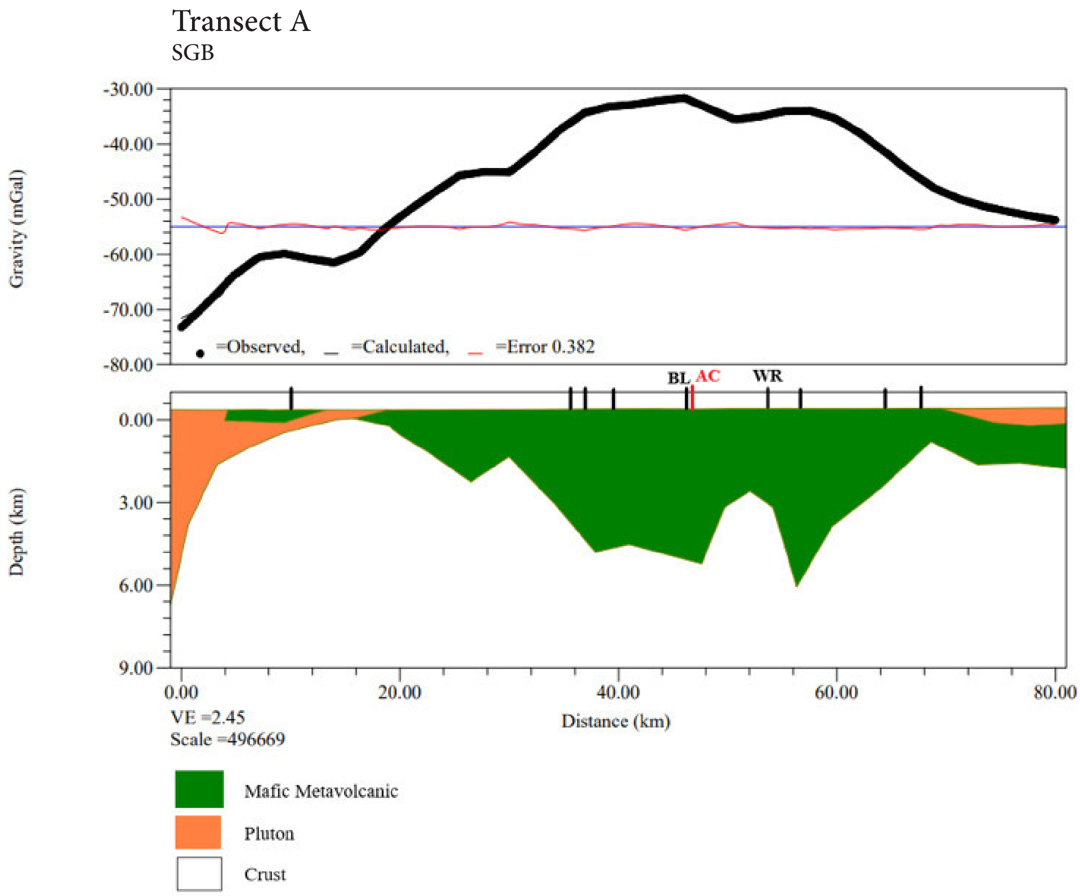

Figure 4. Gravity model along Transect A: Mafic Metavolcanic, ρ=2.89 g/cm^3 ; Pluton, ρ=2.66 g/cm^3; Crust, ρ=2.72 g/cm^3. The black vertical lines shown at the top of the model panel indicate the locations of the different fold axes crossed by the transect. The red vertical line represents the crossing location between Transect A and Transect C. WR-Woman River Anticline, BL-Brett Lake Syncline, AC-Crossing between Transect A and Transect C. The RMS error was of 0.382. The model was obtained with the GM-SYS Extension of the Geosoft – Oasis montaj software.

ovoid-shaped domes composed of gneiss, granitoid, and migmatite (Kearey *et al.*, 2009). The Archean greenstone belts are a fundamental part of this unique structural style consisting of alternating granitoid-cored domes and volcanic dominated keels, where the synclinal keels are cut by major transcurrent shear zones (Thurston, 2015). The greenstone successions feature mafic to felsic volcanic cycles of mixed tholeiitic and calc-alkalic compositions, commonly with overlying sedimentary rocks, typically in contact with younger intrusive granitic rocks (Goodwin, 1981).

Various previous studies presented gravity models of Archean greenstone belts in the Superior Province with the aim of defining their depth and geometry. Nitescu *et al.* (2006) presented models of Archean greenstone belts in the western part of the Superior Province that indicate synform-shaped, ca. 3-*km*-thick bodies of metavolcanic rocks, surrounded by thick intrusive bodies of 9 to 10 *km*. Thomas *et al.* (1986) indicated that greenstone belts are restricted to the uppermost 10 *km* of the crust and that many greenstone belts have a basin-shaped form with some having deep keels. Gupta *et al.* (1982) applied different constraints in models of the Uchi subprovince greenstone belts, in which suggest vertical extents between 4 and 9 *km* for the greenstone bodies. Gorman *et al.* (1978) presented an Archean greenstone belt model that in cross-section resembles the shape of an inverted mushroom. Grant *et al.* (1965) presented a gravity model of the Red Lake greenstone belt, which extends to a depth of 8 *km* and is basin-shaped, being underlain by granitic batholiths and gneiss. Peschler *et al.* (2004) presented different models of the Abitibi greenstone belt where the plutons have depth extents between 1 to 4 *km* and tabular shapes, whereas the greenstones bodies form keels with depths extents up to

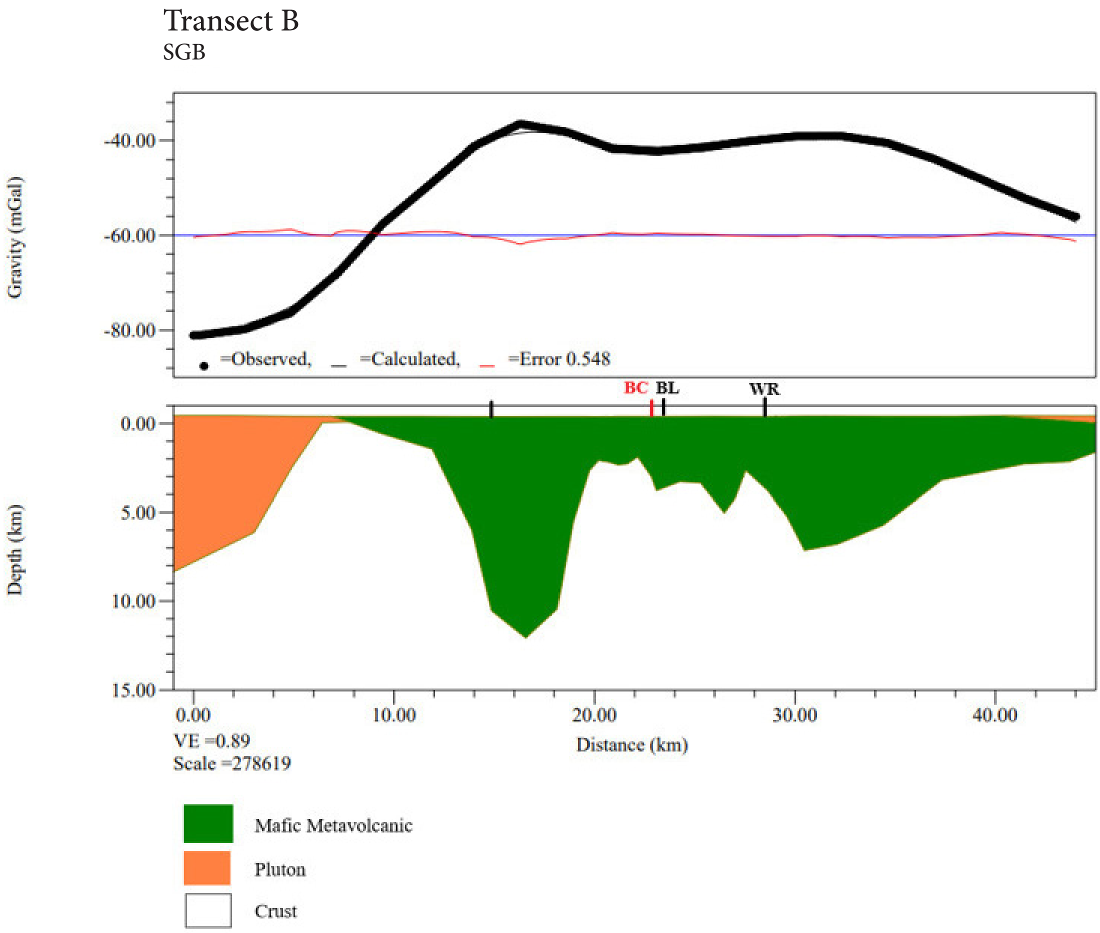

Figure 5. Gravity model along Transect B: Mafic Metavolcanic, ρ=2.89 *g/cm³* ; Pluton, ρ=2.66 *g/cm³*; Crust, ρ=2.72 *g/cm³*. The black vertical lines shown at the top of the model panel indicate the locations of the different fold axes crossed by the transect. The red vertical line represents the crossing location between Transect B and Transect C. WR-Woman River Anticline, BL-Brett Lake Syncline, BC-Crossing between Transect A and Transect C. The RMS error was of 0.548. The model was obtained with the GM-SYS Extension of the Geosoft – Oasis montaj software.

8 to 10 *km*. Maleki *et al.* (2021) presented various detailed models of the Chibougamau area in the Abitibi greenstone belt, based on gravity, magnetic and seismic data, where the mafic metavolcanic rocks have a vertical extent of 3 to 7 *km* and the plutons have depth extents to 9 *km*.

In general terms, the vertical extents of the geological units observed in the models of this project fit the range found for the Archean greenstone belts in the Superior Province. In terms of the shape of the SGB gravity models, they indicate synclinal keel shapes with steeply dipping volcanic sequences, surrounded by granitoid domes, typical of the dome-and-keel structural style.

Even though the calculated model error is less than 1% for each of the profiles analyzed in this study, the obtained models are not a complete answer on the geometry details and true depth extents of the geological units of the SGB. In order to have a better understanding of their geometry and depth, incorporation of magnetic and seismic data could constrain better the geophysical models. Moreover, a denser network of gravity data stations and an improved density database from available drill-core in the area of the SGB would provide better constraints on gravity models. Despite the limited constraints and simplifying assumptions used in this study, its results present an attempt to characterize the geometry and depth of the different geological bodies composing the SGB from public gravity data through forward modelling.

Conclusions

The gravity models obtained in this study lead to a general perspective of the geometry and depth extent of the geolog-

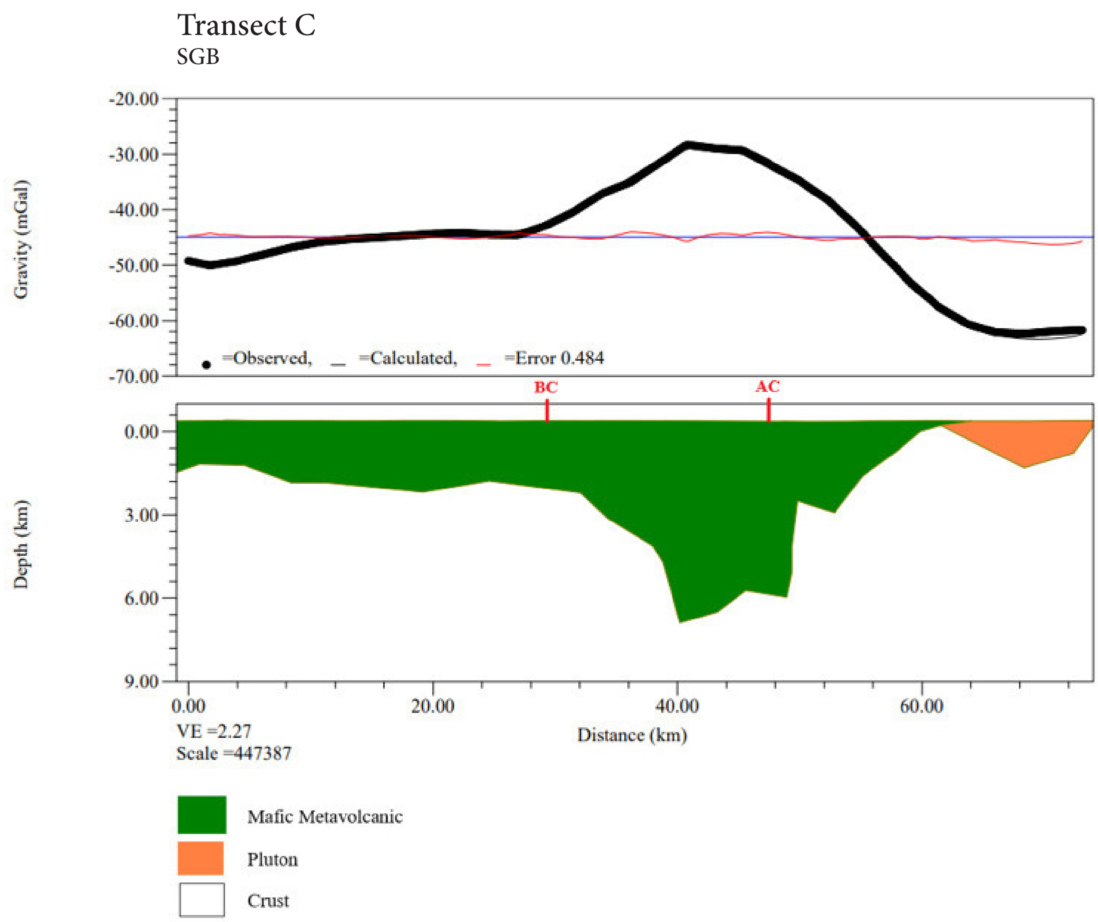

Figure 6. Gravity model along Transect C: Mafic Metavolcanic, ρ=2.89 g/cm^3 ; Pluton, ρ=2.66 g/cm^3; Crust, ρ=2.72 g/cm^3. The two red vertical lines shown at the top of the model panel and labelled AC and BC represent the crossing location between Transect A and Transect C, and between Transect B and Transect C, respectively. The RMS error was of 0.484. The model was obtained with the GM-SYS Extension of the Geosoft – Oasis montaj software.

ical units that form the SGB. The metavolcanic rocks under the Brett Lake Syncline appear to extend in depth between 2 to 7 *km,* whereas under the Woman River Anticline appear to extend in depth between 2 to 6 *km*. The deepest parts of the SGB are located in its central-southern area, extending down to modelled depths of 12 *km*. The gravity models of surrounding intrusive bodies have depth extents between 1 and 8 *km*. The geometry of the SGB and the surrounding and intruding tonalite-granodiorite plutons form a typical Archean keel-and-dome pattern.

Competing interests

There are no competing interests. The primary research data that support the findings of this study are located in the Natural Resources Geoscience Data Repository for Geophysical Data page: **http://gdr.agg.nrcan.gc.ca/gdrdap/dap/search-eng.php**. This data is publicly available.

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