3D Seismic Wave Velocity Model for the Revell Batholith and Surrounding Region

NWMO-TR-2020-07 **October 2020**

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INRS L'Institut National de la Recherche Scientifique

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ABSTRACT

Title: **3D Seismic Wave Velocity Model for the Revell Batholith and Surrounding Region**
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Abstract

This report describes how a three-dimensional (3D) seismic wave velocity model was built for the Revell Batholith and surrounding rock units. Models were constructed at two different scales: a) local-scale model, based on the results from a 3D geophysical density model inversion, and b) a regional model that incorporates information derived from a regional bedrock geology map. The local model is nested in the regional model, and both honour the heterogeneities of the Revell Batholith and surrounding area.

Two methodologies were implemented and are explained in this report. First a well-established empirical relationship between bulk density and velocity was applied to the input data to generate the local seismic wave velocity model. The velocity distributions of each rock unit were evaluated to define histograms, means and standard deviations, which were used to perform sequential Gaussian simulation (SGS) to generate multiple realizations of the velocity distribution for the regional model. The mean ensemble of the multiple realizations were generated to produce smoother model that honours the statistics derived in each of the individual realizations.

The established workflow resulted in a robust three-dimensional seismic wave velocity model that incorporates geologically reasonable heterogeneities that can be used to evaluate seismicity. However, there remains some uncertainty in the transferability of the empirical approach applied to our site-specific rock units. The seismic wave velocity model reported here can be verified and further refined as needed as more information becomes available.
Being a required variable for spatial location and magnitude of seismic events, these models will help characterising the potential of seismic hazards in the Ignace area.

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1. INTRODUCTION

NWMO conducted Geoscientific Desktop Preliminary Assessments (Golder, 2013; Golder, 2015) to assess whether the Ignace area has the potential to satisfy the geoscientific site evaluation factors outlined in NWMO's Adaptive Phased Management (APM) site selection process (NWMO 2010). At that time, the assessment was conducted using available geoscientific information and key geoscientific characteristics that could be realistically assessed at the desktop stage. This assessment revealed that the Ignace area contains a number of areas that have the potential to satisfy NWMO's geoscientific site evaluation factors (Golder, 2013).

In 2014, NWMO initiated numerous field studies, including acquisition of high-resolution airborne magnetic and gravity data, detailed field mapping and a structural lineament interpretation. The results identified areas that appear to have favourable geoscientific characteristics for hosting a deep geological repository, which motivated subsequent stages of the site evaluation process through borehole drilling in order to address remaining uncertainties.

Of relevance for the evaluation of safety of a Deep Geological Repository (DGR) is the magnitude and spatial location of seismic events in and around the Revell Batholith. The establishment of a microseismic network is important to better understand the long-term seismic hazard of the region at the site-scale. To accurately evaluate the microseismic data emanating from such a network, it is necessary to develop a robust seismic wave velocity model that honours the regional scale heterogeneities of the area surrounding the Revell Batholith.

1.1 Objective

The objective of this work is to build an initial three-dimensional (3D) seismic wave velocity model for the Revell Batholith and surrounding greenstone belt rock units. A seismic wave velocity model can be incorporated into the analysis of microseismic data coming from a microseismic network for the area surrounding the Revell Batholith. Arrival times registered at the microseismic stations are inverted to determine seismic events locations and origin times and for doing so, an initial velocity model is required (Block et al., 1994). Historically the hypocenter location was performed with a homogeneous velocity model, but results can be significantly improved by using more detailed 3D seismic velocity models containing geologic structures, especially at large scales (Wong et al., 2010)

Models were constructed at two different scales: a) local-scale model, based on the results from a 3D geophysical density model inversion by SGL (2020), and b) a regional model that incorporates information derived from the regional bedrock geology map (Ontario Geological Survey MRD126-rev1). The local model comprises the most accurate understanding of the 3D geometry of the Batholith and surrounding greenstone belts units, based on results from a fully coupled geophysical inversion (SGL 2020). The local model is nested within the regional model, which honours the main rock units with their boundaries extended vertically to the bottom of the model.

The methodology implemented in this report is based on well-established empirical relationships between petrophysical rock properties (Brocher, 2005) followed by sequential Gaussian simulation (Journel, 1994), which is an established method in reservoir modeling for generating multiple equiprobable realizations of a property (e.g. seismic velocity), including the quantification and assessment of uncertainty. The approach is outlined in Section 3.

1.2 Model Extents

The limits of the local model (dashed rectangle in Figure 1) are 30.7 km x 31.4 km x 4.5 km (depth) and a voxel cell size of 157 m x 153.5 m x 125 m, resulting in a model with 1,600,000 cells. The extents of the model were chosen taking into consideration SGL's 3D density model. This model sits within the regional model, represented by the map boundary of Figure 1. The dimensions of the regional model are 94 km x 61 km x 4.5 km, with cell sizes of 150 m x 150 m x 125 m, making a total of 10,166,240 cells. The limits of the regional model were established to cover the area of a planned microseismic network.

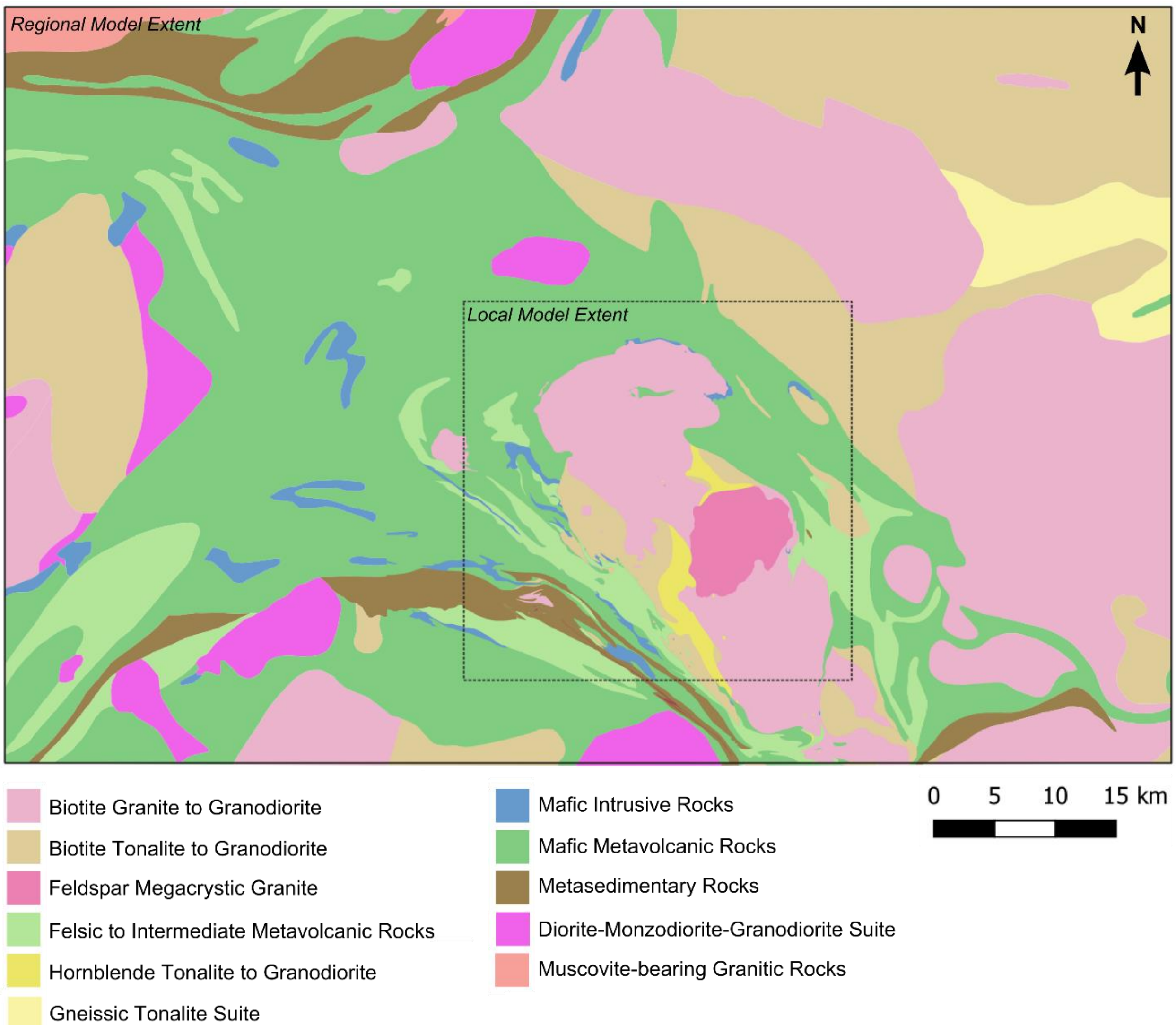

Figure 1. Bedrock geology map for the local model and the regional model extents. The local model is shown as a black dashed rectangle, with its extent consistent with the SGL 2020 geophysical model (SGL 2020). The regional model is shown as the outer limit of the map.

2. Data Sources

The following section outlines the data sources used to develop the 3D seismic velocity model

2.1 Rock Density

The 3D density model of the region provided by Sander Geophysics Ltd. (SGL, 2020) is shown in Figure 2. The 3D geophysical modelling was carried out using gravity and magnetic data (airborne magnetic dataset, ground and airborne gravity measurements), constrained by bedrock geology observations and all available petrophysical data (magnetic susceptibility and density measurements from NWMO, Ontario Geological Survey and Geological Survey of Canada). Details of the data inputs and workflows to accomplish the 3D geophysical modelling are provided in SGL, 2020. The resulting 3D density model was built in four main stages:

1) Geology interpolation stage, where a 3D geological model was constructed using geological information only, honouring mapped bedrock geology.

2) Forward modelling stage, where rock properties are assigned to the geological model, enabling replication of theoretical gravity and magnetic fields, modifying iteratively the initial model according to the misfit between predicted and observed fields.

3) Optimization stage, which identifies the most suitable rock property values and distributions in order to reduce the misfit between calculated and observed gravity and magnetic fields; and

4) Inversion stage, in which separate inversions are first performed for gravity data or magnetic data only. Once these models are optimized, a final joint inversion was performed, incorporating both data types.

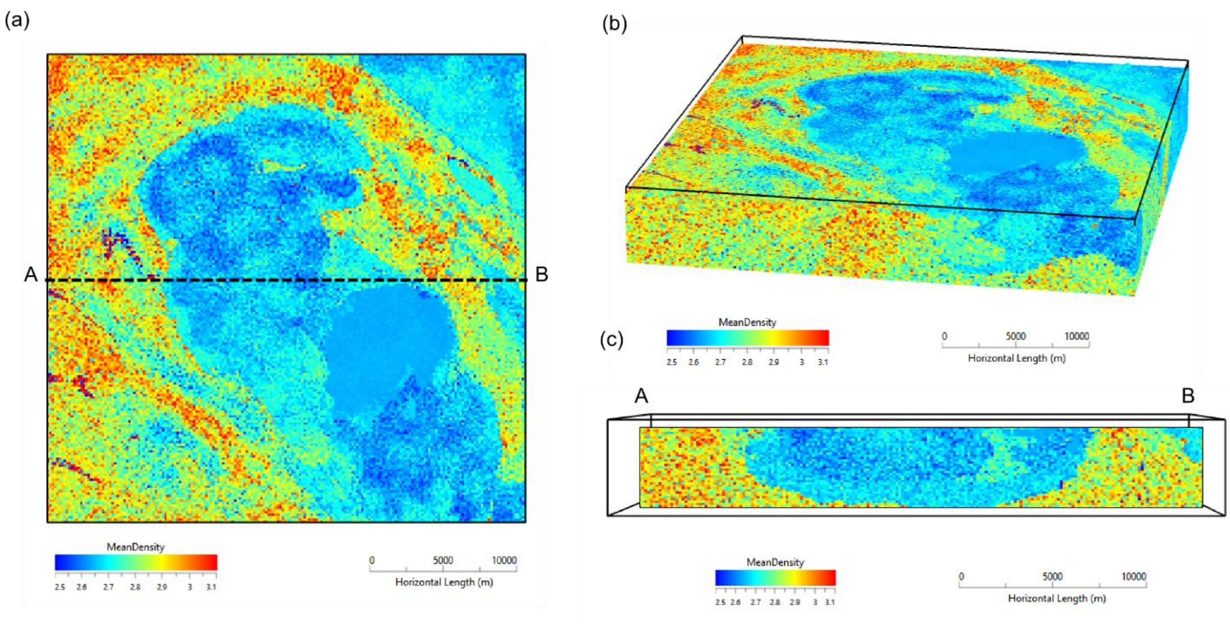

Figure 2: (a) plan view, (b) oblique view, and (c) cross-sectional view of the 3D density model provided by SGL 2020.

Table 1: Mean and standard deviation of bulk rock density for each rock unit (SGL, 2020)

	Rock Unit	Mean density [g/cm3]	St. Dev [g/cm^3]
Plutonic Rocks	Biotite Granite to Granodiorite	2.65	0.05
	Biotite Granodiorite to Tonalite	2.68	0.04
	Feldspar Megacrystic Granite	2.64	0.01
	Hornblende-biotite Tonalite to Granodiorite Gneiss	2.76	0.06
Supracrustal Rocks	Intermediate to Felsic Metavolcanic Rocks	2.80	0.10
	Mafic Metavolcanic Rocks	2.91	0.10
	Metasedimentary Rocks	2.82	0.11
	Mafic Intrusive Rocks	2.91	0.50
	Iron Formation	2.70	0.48

Mean densities and standard deviations for each rock unit from SGL (2020) are presented in Table 1. Plutonic rocks associated with the Revell Batholith comprise a range of lithologies including granite, granodiorite and tonalite. Supracrustal rocks make up the surrounding greenstone belt and are composed mainly of intermediate to felsic and mafic metavolcanic rocks, and metasedimentary rocks. Due to their similar densities and spatial distribution, the Biotite Granite to Granodiorite and Biotite Granodiorite to Tonalite were merged into a single unit, which makes up most of the Revell Batholith. Similarly, minor occurrences of mafic intrusive rocks were merged with the more abundant mafic metavolcanic rocks, and the minor iron formation unit was combined with the surrounding metasedimentary rocks prior to developing the seismic wave velocity model due to their size, similar mean densities and spatial locations.

3. Methods

Different methodologies were implemented for the two different model scales. For the local model, empirical relations between density and seismic velocities were used. By contrast, for the regional scale model, an unconditional sequential Gaussian simulation was performed. Both methods are explained in this section.

3.1 P-wave Velocity as a function of density

Seismic wave velocity and density (ρ) are strongly related variables since p-wave velocity (V_p) is defined as $V_p = \sqrt{(\lambda+2\mu)/\rho}$, where λ is a Lamé parameter and μ the shear modulus, which are both intrinsic elastic properties of the rocks (Shearer, 2019).

Several empirical methods have been developed to establish correlations between density and seismic velocity for different bedrock and sediment types, such as the Gardner equation (Gardner et al., 1974), the Nafe-Drake curve (Ludwig et al.,1970) or the Christensen and Mooney (1995) equation, illustrated in Figure 3. Although the Gardner equation is well used in literature, it was derived from sedimentary rocks and the geology of the Ignace area is dominated by plutonic and volcanic units. The Nafe-Drake curve provides an average fit between densities and velocities, for several rock types. However, it is a graphical relation, which does not provide an equation and it was determined exclusively from laboratory measurements (Salisbury et al., 2003). The Christensen and Mooney equation was derived from crystalline rocks. While it is theoretically appropriate for all rocks, it is not recommended for volcanic rocks (Brocher et al., 2005). More recently, Brocher (2005) compiled several measurements from borehole wireline measurements, vertical seismic profiles, laboratory and field measurements on hand samples, and in-situ estimates from seismic tomography studies. Using Ludwig et al.'s (1970) data, Brocher (2005) derived an empirical equation for V_p as a function of ρ with a goodness of fit R^2 metric of 0.999 where velocities range between 1500 and 8000 m/s:

$$V_p = 39.128\rho - 63.064\rho^2 + 37.083\rho^3 - 9.1819\rho^4 + 0.8228\rho^5 \qquad \text{(Eq. 1)}$$

Because this empirical model was developed specifically for a wide range of crystalline rock types, over a wide range of densities, the empirical equation presented by Brocher (2005) was chosen to build the V_p model in this study.

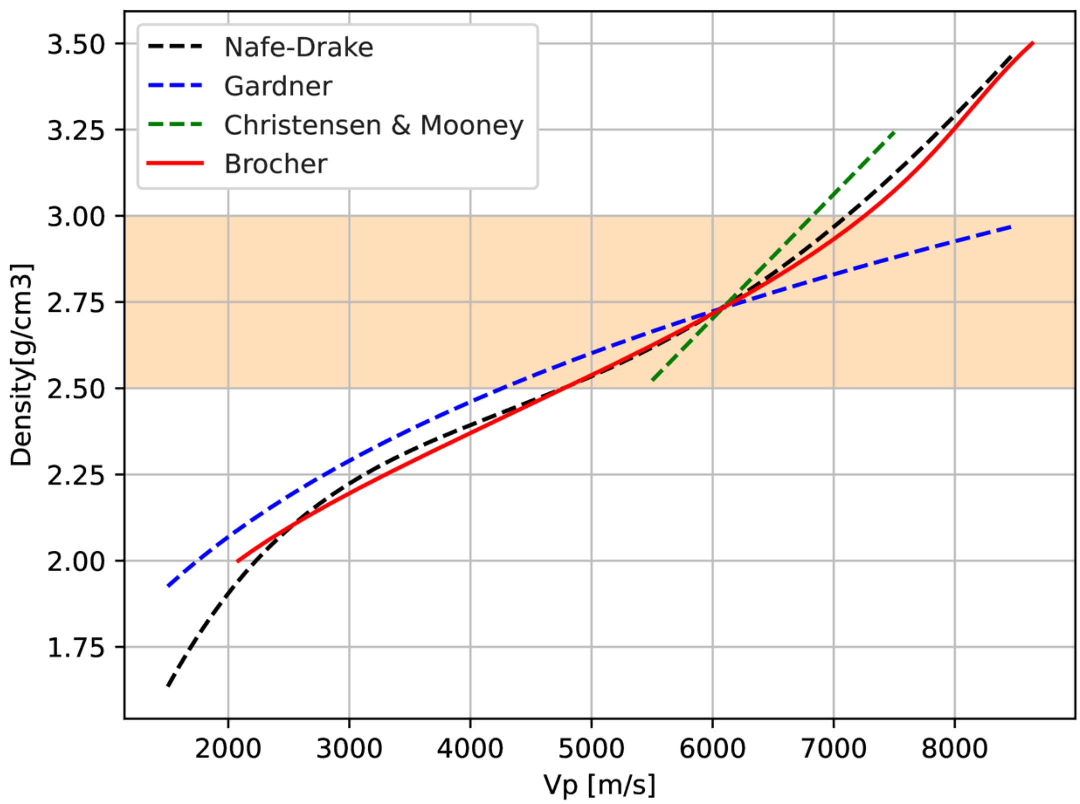

Figure 3: V_p vs density for different established empirical relationships. The density range for the Revell site is highlighted in orange.

3.2 Sequential Gaussian Simulation (SGS)

After converting the density model to seismic velocity through Brocher's equation, histograms of each rock type were evaluated within the local model and used as conditioning data to simulate V_p distributions in the extended regional model volume. Sequential Gaussian simulation (SGS) can be used to generate multiple equiprobable models honouring hard data, while preserving the theoretical variogram (Journel, 1994). Unconditional SGS was performed in GOCAD to populate the units outside the local model, reproducing their statistical properties. A variogram was modeled using the density values from the SGL model for each geological unit to use as input for the simulation. Since SGS is formulated in a Gaussian space, the input data is transformed (through normal score transformation) to follow a gaussian distribution Due to the heterogeneous nature of the SGL model, the variograms present a significant nugget effect (see Figure 4), which produces variability in property values over short distances.

With the variograms and histograms appropriately computed for each rock type within the local model, similar rock units were selected in the regional model, and V_p values were stochastically simulated, conditioned using the distribution and spatial variability of the input data.

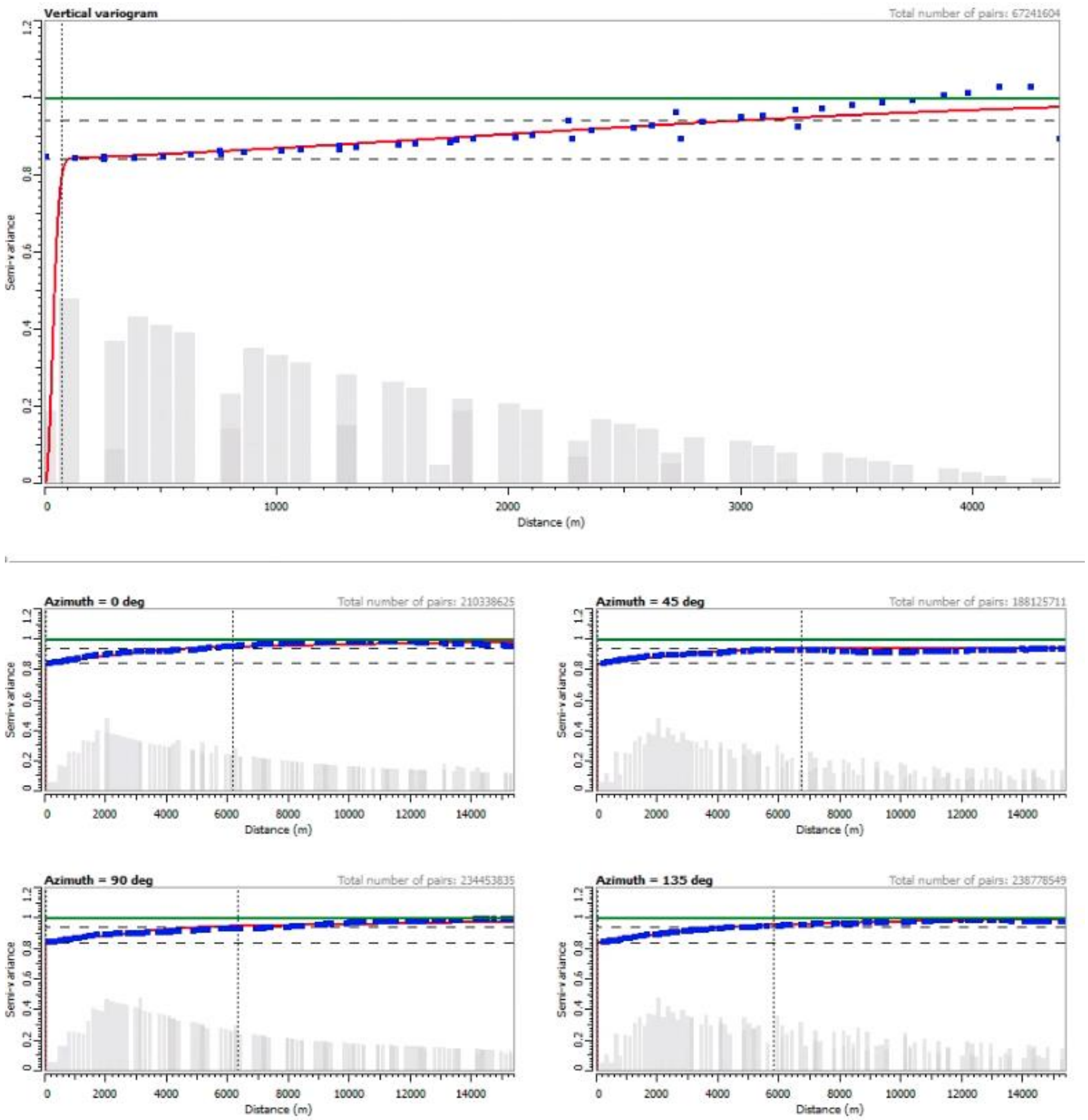

Figure 4: Experimental (blue dots) and theoretical (red line) variogram for the Mafic Metavolcanics unit.

4. Results

4.1 Local Model

To build the local model, the densities modelled by SGL (2020) were converted to seismic velocity by applying Eq.1 to each of the six rock units. According to Figure 3 and a density distribution ranging from 2.5 g/cm^3 to 3.2 g/cm^3, computed seismic velocity values mainly range between approximately 4800 m/s and 7500 m/s. Looking at the density distribution for each rock unit, some extreme values are present, and therefore a threshold was defined by the 0.01% and 99.9% percentiles as follows:

If $\rho < P0.01 \rightarrow \rho = P0.01$
If $\rho > P99.9 \rightarrow \rho = P99.9$

An example is presented in Figure 5 with the histogram of the combined Biotite Granodiorite to Tonalite and Biotite Granite to Granodiorite rock unit, indicating that the minimum and maximum values are 2.4 and 2.9 respectively. The extreme values at the tails of the Gaussian bell curve are filtered below the P0.01= 2.47 and over P0.09=2.8.

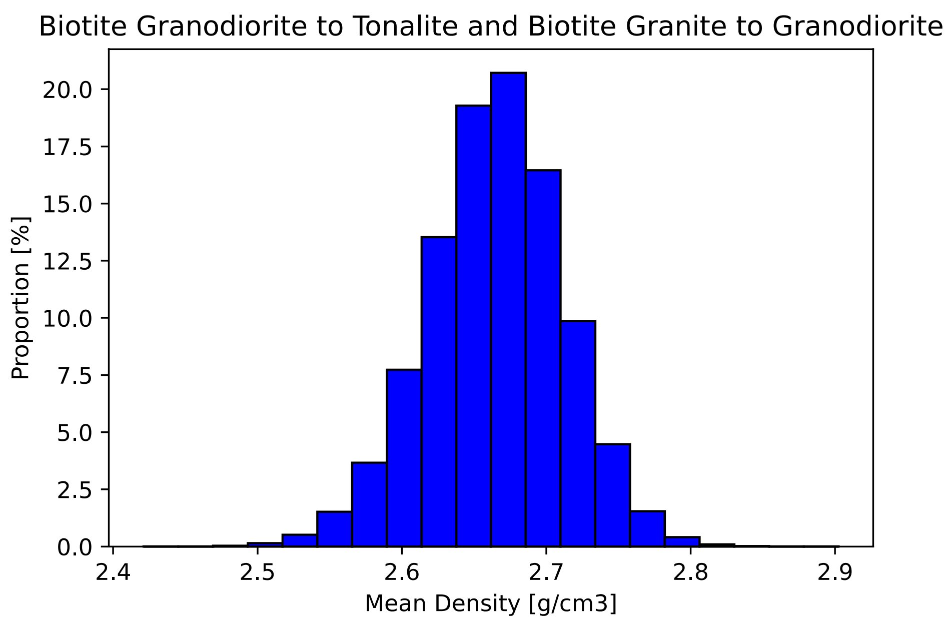

Figure 5: Density distribution corresponding to the Biotite Granodiorite to Tonalite and Biotite Granite to Granodiorite unit

The final V_p local model is presented in Figure 6 and a summary of the properties are in Table 2: Mean and standard deviation of the p-wave velocity properties (V_p) calculated for each rock unit in the local model volume. The latter is consistent with the extent of the SGL (2020) density model.. Also, the histogram of the p-wave velocity for the Biotite Granodiorite to Tonalite and Biotite Granite to Granodiorite rock unit is shown in Figure 7 to illustrate how the density distribution was honoured. This procedure was reiterated for all six rock units.

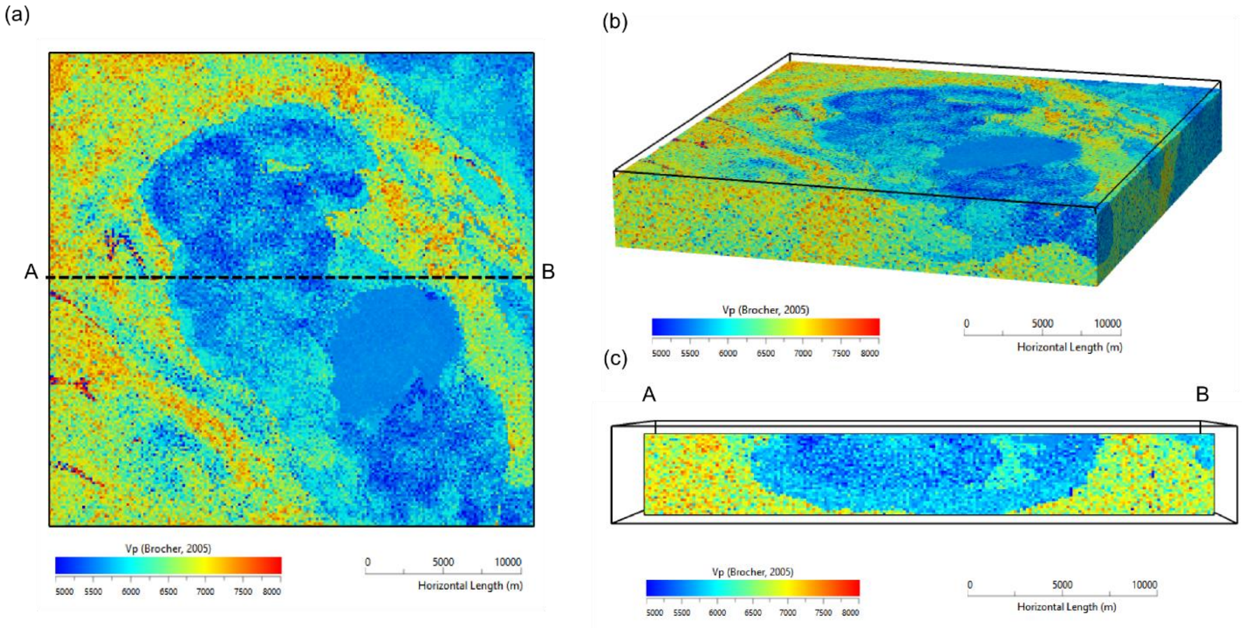

Figure 6: (a) plan view, (b) oblique view, and (c) cross-sectional view from A to B of the final p-wave velocity model at the extent consistent with the SGL (2020) density model.

Table 2: Mean and standard deviation of the p-wave velocity properties (V_p) calculated for each rock unit in the local model volume. The latter is consistent with the extent of the SGL (2020) density model.

	Rock Unit	Mean V_p [m/s]	St. Dev [m/s]
Plutonic Rocks	Biotite Granodiorite to Tonalite and Biotite Granite to Granodiorite	5717	256
	Feldspar Megacrystic Granite	5587	32.9
	Hornblende Tonalite to Granodiorite	6327	420
Supracrustal Rocks	Felsic to Intermediate Metavolcanic Rocks	6407	457
	Mafic Metavolcanic and Mafic Intrusive Rocks	6859	414
	Metasedimentary Rocks and Iron Formation	6307	467

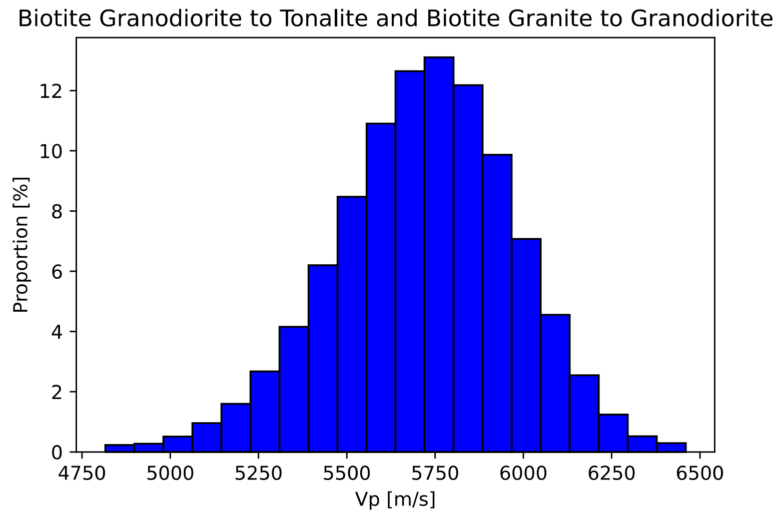

Figure 7: Velocity distribution for the Biotite Granodiorite to Tonalite and Biotite Granite to Granodiorite unit

4.2 Regional model

The Ontario Geological Survey regional bedrock geology digital database (MRD126 Rev1) was used to construct the regional seismic velocity model. Prior to developing the regional seismic velocity model, smaller geologic units mainly located within the larger mafic metavolcanic unit were removed, resulting in seven main rock units: Biotite Granodiorite to Tonalite and Biotite Granite to Granodiorite, Feldspar Megacrystic Granite, Hornblende Tonalite to Granodiorite, Felsic to Intermediate Metavolcanic Rocks, Mafic Metavolcanic and Mafic Intrusive Rocks, Metasedimentary Rocks and Iron Formation, and Diorite-Monzondiorite to Granodiorite suite. Due to lack of structural information, these main units were extended vertically from ground surface to the bottom of the model volume, in contrast to the local model where more accurate dips are defined for contacts between units. The Diorite-Monzondiorite to Granodiorite suite was not part of the six main rock units contained in the Revell local model. In order to constrain the Gaussian simulation for this unit, mean and standard deviation of bulk rock densities were obtained from the Ontario Geological Survey PETROCH Lithogeochemical Database (MRD250), from which only 23 data points were identified resulting in a mean density of 2.79 g/cm^3 and standard deviation of 0.0985 g/cm^3. These bulk densities were also transformed to velocity values using Eq 1.

After converting SGL's density model to a seismic wave velocity model using Brocher's relationship, the mean p-wave velocities and standard deviations in Table 2 in combination with those for the Diorite-Monzondiorite to Granodiorite suite were used to define histograms for each rock unit. By using the distributions and appropriate variogram models, five subsequent probable seismic velocity distributions were simulated for the rock units located outside the local model volume through unconditional sequential Gaussian simulation (SGS). The combined seismic wave velocity model for one of the realizations is shown in Figure 8, and the mean of the five realizations is shown in Figure 9. The model shown in Figure 9 is smoother and it honours the means and standard deviations of each of the realizations. All versions (the five realizations and the mean) are available and can be used according to the preferences and objectives of future users. A summary of the properties and volumes of each rock unit are provided in Table 3: Mean and standard deviation of the p-wave velocity (V_p) calculated for each unit in the regional model volume..

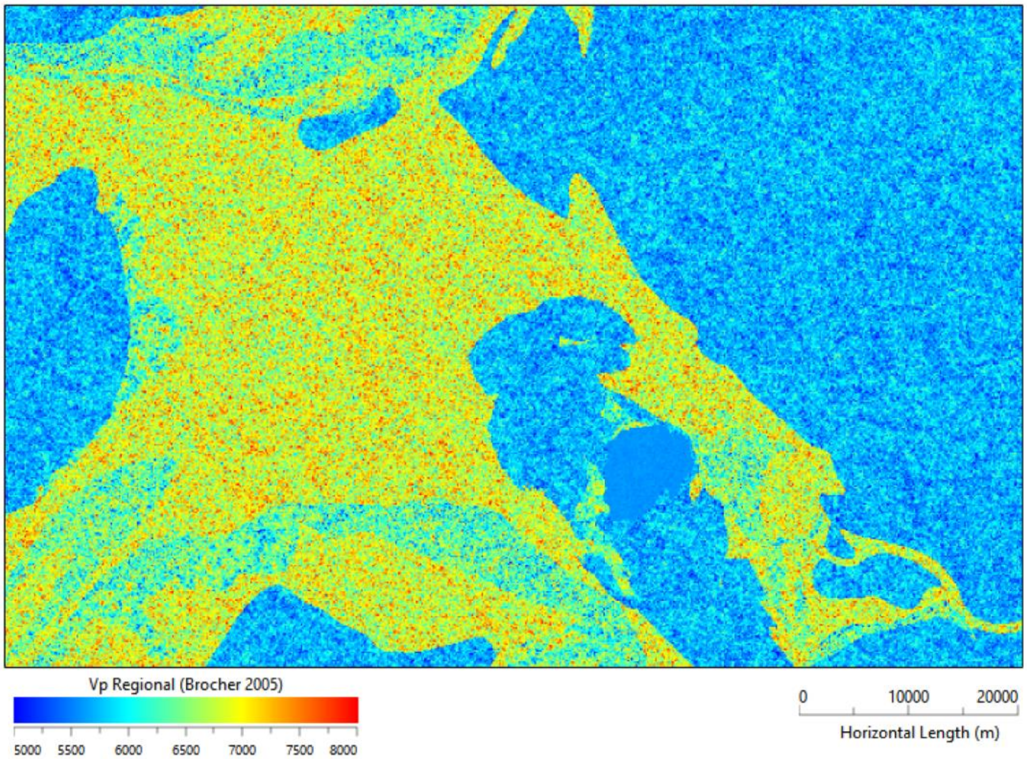

Figure 8: Plan view of the 3D regional-scale p-wave velocity model.

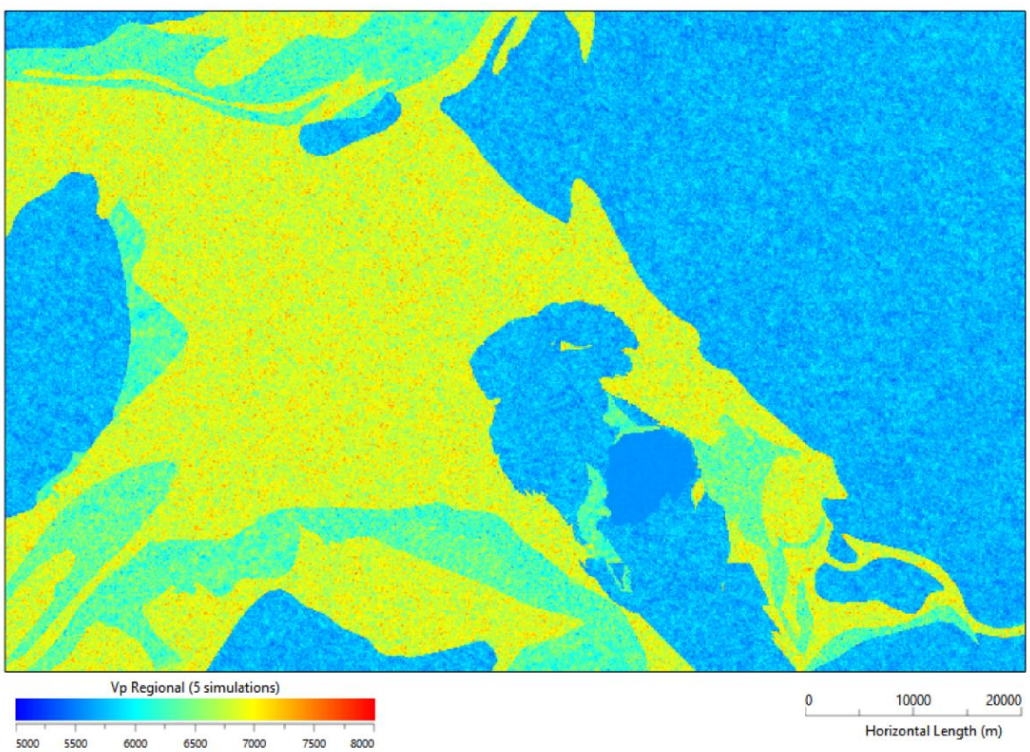

Figure 9: Plan view of the 3D regional-scale p-wave velocity model, computed as the mean of five realisations.

Table 3: Mean and standard deviation of the p-wave velocity (V_p) calculated for each unit in the regional model volume.

Rock Unit	Mean V_p [m/s]	St. Dev [m/s]	Number of cells
Biotite Granodiorite to Tonalite and Biotite Granite to Granodiorite	5716	251	4194385
Mafic Metavolcanic and Mafic Intrusive Rocks	6857	406	3765926
Metasedimentary Rocks and Iron Formation	6300	462	473238
Felsic to Intermediate Metavolcanic Rocks	6402	457	376972
Diorite-Monzondiorite to Granodiorite suite	6366	466	331887
Hornblende Tonalite to Granodiorite	6341	421	53746
Feldspar Megacrystic Granite	5586	32.9	34091

5. Discussion

We extrapolated properties from the local model to the regional model to obtain seismic velocities in a sufficiently large model volume for the purpose of evaluating seismic network measurements. While SGS is a good approach to capture spatial heterogeneity, we are building the regional model based on the spatial behavior of the local model, which may not necessarily reflect the characteristics of that adjacent area. Hence, some uncertainty remains since the distribution of the regional model may not reflect the true spatial distribution of values. In addition, a significant assumption in the regional seismic wave velocity model is that all rock unit contacts extend vertically from ground surface to the bottom of the model volume. Although this is an assumption, it is normal practice to simplify lithological boundaries to represent the main trends and significant changes in velocity, especially in complex geological models (Solutions, E. S. G., 2013).

Despite the use of empirical models being widely used to transform density data to seismic velocities, there is uncertainty in the accuracy and applicability of this empirical approach applied to our site-specific rock units. The seismic wave velocity model reported here can be further refined as more information becomes available, which may include borehole- and surface-based seismic reflection data, additional petrophysical measurements, etc.

6. Conclusions

Two 3D p-wave velocity models were built in the Ignace area. Based on SGL's density model, a local seismic wave velocity model was created by converting density values through an empirical relationship. The distributions of these V_p values were used to evaluate histograms, mean and standard deviations of each rock unit, which were later propagated to a larger region. Bedrock geology from OGS was obtained for the regional model, and the rock unit boundaries were draped onto bedrock and extended vertically to the bottom of the model volume. Variograms were computed within the local model and used along with the histograms to populate the regional model through unconditional SGS.

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