1. Introduction

There are many planets in the universe, but current scientific knowledge contains more information about some planetary bodies than others since gathering data is not easy based on existing technologies. There is relatively tiny that humans know about the universe, and thus, there is still a far way to go. Scientists knew more about our solar system and planets near Earth-like Moon and Mars. However, those planets have different thermal histories from Earth since they have different compositions and internal structures. Earth is a unique terrestrial planet in our solar system, which recycles at the surface (Guerrero, 2020). This recycling is known as plate tectonic driven by mantle convection, where heat from the core is transferred to the surface (Guerrero, 2020). Another way to transfer heat is conduction through the mantle in terrestrial planets (Guerrero, 2020; Schubert et al., 2001; Turcotte & Schubert, 2014). For planets without active plate tectonic, the heat moved by mantle convection is not as efficient as on Earth (Guerrero, 2020) since heat transfer is mainly by volcanism and conduction (Shahnas & Pysklywec, 2020). Besides active or inactive plate tectonics, some planets have active plate tectonics; however, instead of having all the lithosphere take parts in mantle convection, only the one with a weaker, warmer lid is involved, referred to as the stagnant lid (Robert, 2018). The stagnant lid is a more common tectonic style in our solar system (Robert et al., 2018). Also, this existence of a stagnant lid at the surface of the planets would cause the cooling efficiency to be lower (Shahnas & Pysklywec, 2020). This cooling efficiency would influence the surface heat flux, and it would increase when the Rayleigh number increase (Shahnas & Pysklywec, 2020). Rayleigh number is an expression of fluid, $Ra = \beta g A L / \kappa \nu$; in the mantle where heated from the core and cooled from the surface (Stevens et al., 2011). In this mathematical equation, $\beta$ is the thermal expansion coefficient, $g$ is the gravitational acceleration, $A$ is the difference of temperature between the bottom and top layers, $L$ is the thickness, $\kappa$ is thermal diffusivity, and $\nu$ is kinematic viscosity (Stevens et al., 2011).

Scientists have noticed many features that could influence mantle convection, such as rheology, internal heating, mantle transitions, phase transition, viscosity variations, compositions, and geometry of the planets (Shahnas & Pysklywec, 2020). However, scientists have marginally understood the relationship between mantle convection and planetary surfaces but no clear understanding of core size and its importance (Guerrero, 2020). Serval studies have investigated the influence of curvature on mean mantle temperature and convection in bottom-heated situations (Guerrero, 2020). Jarvis et al. (1995) found that with a fixed Rayleigh number of $10^3$, the mean mantle temperature would decrease as curvature increased. Conversely, the mean mantle temperature would close to the mean bounding surface temperature when the curvature decrease (Jarvis et al., 1995). Another study also reported a similar result with low Rayleigh numbers. Thus, interpreting those concepts together might help understand exoplanets better and other habitable planets like Earth. This study aims to use deep learning algorithms to estimate the mean mantle temperature of rocky planets with different core sizes, $f$, internal heating, $H$, Rayleigh number, $Ra$, and surface heat flux, $F$. The curvature or core size of a planet is the ratio of the planet's inner radius to the planet's outer radius, $f = R_{\text{inner}} / R_{\text{outer}}$ (Shahnas & Pysklywec, 2020).

2. Methods

Many researchers have used machine and deep learning algorithms to train models when those sample data cannot be elaborated mathematically. Indeed, those input sample features could be used to find patterns or relationships, and then the researchers could make predictions for unseen sample data based on those patterns and relationships. In this study, we use deep learning algorithms to train our samples in Python programming.

By modelling the relationship between curvature, internal heating, Rayleigh number, and surface heat flux, we could then use our model to estimate the mean mantle temperature of planetary bodies. The input training data is from the numerical mantle convection models by Shahnas et al. (2008). We have three training data sets from models with rigid surface boundary conditions with no plate tectonics. Each set of data include 60 samples. The first data set is the training data with three features: curvature, internal heating, and Rayleigh number. The Rayleigh number we used is the same as Shahnas & Pysklywec used in their convection models (2020), ranging from $10^4$ to $10^7$, internal heating values.
between 0 to 40, curvature between 0.1 to 0.9. Similarly, the second set of data has three features: curvature, internal heating, and surface heat flux. The surface heat flux is calculated as $F = \alpha Ra^\beta \theta^\gamma$ (Shahnas & Pysklywec, 2020), where $\alpha$ is the thermal expansion coefficient, $Ra$ is the Rayleigh number, $\theta$ is the dimensionless temperature. Even though the second set of data is missing the Rayleigh number in the inputting features, the neural network could still learn due to the equation used to calculate the surface heat flux. The last set of data contains all four features.

First of all, we train our first data set. Using permutation script in Python, we first shuffle data before using them in training. Then, we use the MinMaxScaler function to scale the Features to a given range between zero and one. After the data is shuffled and scaled, we split them into a test set and train set. We set the test sample to be 0.2, which means 20% of the whole sample will be randomly taken out, and we would not touch those data when we train our model. Then come to the critical part of our research, we need to define and fit the final model with parameters. We play with different parameters of layers, nodes, and epochs many times to get the best parameters, but in each hidden layer, we use the Relu activation function. Also, the final output node is one with a linear activation function. The best parameters in our model should be the parameters that consistently result in high $R^2$ accuracy in both whole data and test data. Also, the accuracy in the whole and test data should be close to each other to be validated. We would set the number of Iteration to be lower to save time for the computer to get the results, and once we find a good set of parameters, we increase the number of Iteration to 500 to get more random training. Then we start to use the second set of sample data with $f$, $H$, and $F$ without changing the model parameters. Finally, we use the last set of sample data with all four features, $f$, $H$, $Ra$, and $F$, and get the results.

3. Results

We tried over 100 experiments and ended up with 80 nodes in the first hidden layer and 40 in the second hidden layers. The number of epochs we used is 500, and the learned models are trained with a 500 random training set. We get the average predicted mean mantle temperatures of test data and trained whole data and their $R^2$ accuracy values. After that, we plot the $R^2$ accuracy data for the index number of Iteration with both $R^2$ accuracy and average $R^2$ accuracy in a single graph. We repeat the step for both whole and test data in every three cases. Figures 1 and 2 shows the model accuracy results of predicted mean mantle temperature with input features of curvature, internal heating, and Rayleigh number for whole and test data. The accuracy for both data is shown as scatter points. They close to each other, and the average accuracies are relatively stable. The average scores are shown as lines, and the values are 0.999 and 0.993 for the whole and test data, respectively. In the second case, with input data of curvature, internal heating, and surface heat flux, we get slightly lower accuracy. However, both whole and test data are close together, and the mean accuracy is stable. The average scores are 0.994 and 0.984 for the whole and test data, respectively. In the third case, with input data of curvature, internal heating, Rayleigh number, and surface heat flux, both whole and test data are close together, and the mean accuracies are stable. The average scores are 0.993 and 0.985 for the whole and test data, respectively.

![Figure 1](image1.png)

**Figure 1:** The $R^2$ accuracy results for predicting mean mantle temperature of whole data specified in the text. The scatter points are accuracy values from each Iteration, and the line is the average accuracy.

![Figure 2](image2.png)

**Figure 2:** The $R^2$ accuracy results for predicting mean mantle temperature of test data specified in the text. The scatter points are accuracy values from each Iteration, and the line is the average accuracy.
4. Discussion

Even though the predicted mean mantle temperature accuracy is high in all three cases, they change slightly each time we run the code due to randomly distributed sample data. We tried to limit the error of getting low accuracy data by running the code with the exact parameter several times and take the lowest accuracy data if the accuracy is high and stable each time. Our research only tried one and two hidden layers, but future studies could use more hidden layers, and higher accuracy might be obtained. Also, the number of epochs and Iteration could increase if computer speeds are appropriate.

We only used a maximum of four features in our models. However, heat transfer is much more complex and includes many more affecting viscosity variations and phase transitions. Another limitation in our study is we only used 60 samples, and which is relatively small. Future studies could include those complexities as additional features and train with more sample data to get higher accuracy.

5. Concluding remarks

We used deep learning algorithms to estimate the mean mantle temperature of rocky planets with original data of curvature, internal heating, Rayleigh number, and surface heat flux. The input data used are 3-D-spherical mantle convection models done by Shahnas & Pysklywec (2020). The curvature ranges from 0.1 to 0.9, internal heating is between 0 to 40, and Rayleigh number from 104 to 107. We trained three data sets, and we first used curvature, internal heating, and Rayleigh number as our training sample. We used 20% of unseen sample data not using in training to test the accuracy of our models. The accuracy scores for the mean mantle temperature are 0.999 for the whole data and 0.993 for the test data with original curvature data, internal heating, and Rayleigh number. The accuracy for input data, curvature, internal heating, and surface heat flux is 0.994 and 0.984 for the whole and test data, respectively. Finally, the accuracy for all the four features, curvature, internal heating, Rayleigh number, and surface heat flux, is 0.993 for the whole data and 0.985 for the test data. Future studies could try with more layers, include more complex features and train with more samples.

References


1. Introduction

The Bushveld Complex is the largest layered mafic intrusion in the world, covering approximately 65,000 km$^2$ (Yuan et al. 2017) (Figure 1). This complex was emplaced at approximately 2.06 Ga, and it contains world-class deposits of magmatic platinum-group elements (PGEs) such as platinum, palladium, and iridium, as well as high-grade deposits of vanadium and chromium, among others (Yuan et al. 2017).

The Bushveld Complex has been the subject of decades of research; however, there are still lingering questions about the magmatic origins of the later lithologies of this complex. One main question revolves on whether the concentrations of minerals of interest form from the magmas they are hosted in or are transported from a deeper part of the melt. In this study, we attempted to determine this by comparing the chemistry of massive and disseminated magnetite samples taken from the Bushveld Complex. Similar geochemical signatures between the two magnetite types could indicate a single source, presumably the host melt, while the opposite could point to different sources. Additionally, it has not been established how many analyses are needed to provide a statistically robust representation of the geochemistry of the magnetite sample, thus in this study we performed more than the usual number of analyses to establish how many analyses are needed to provide a robust dataset.

A greater understanding of how the different forms of magnetite in the Bushveld Complex formed will help exploration geologists in the area. This is important because the Upper Zone is rich in the critical element vanadium. Vanadium is important in the production of high-strength steel alloys that are used in the oil and aerospace industry, and vanadium redox-flow batteries are becoming a strong contender for large-scale energy storage (Kelley et al 2017).

This study will be compared to two papers in particular; the first of these papers had studied trace element composition in ~four massive samples from the Bushveld Complex (Dare et al 2014). These magnetite samples were analyzed using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS), the same analytical method used in this study. The other paper conducted geochemical analysis of massive and disseminated titanomagnetite from the Bushveld Complex which was achieved using X-ray Fluorescence (XRF) and electron microprobe analysis (Klemm et al 1985). Our new data will work to assess the data reported by Klemm et al (1985) using a modern technique, while also investigating a wider range of elements that is available with LA-ICP-MS.

2. Methods

Massive and disseminated magnetite samples were taken from 24°48′40″S, 29°58′28″E (Magneets Hoogte, South Africa). The massive magnetites were collected from the Main Magnetite Layer, while the disseminated ones were obtained from the area approximately 10 m above it.

We prepared the samples for analysis by first cutting them using a diamond saw to provide a flat and fresh surface. To keep them stable, we mounted these samples in 2.5-cm epoxy resin blocks, which we then polished until flat surfaces of magnetite were exposed. Samples were polished with progressively finer diamond polishing compounds to an end grit of 1 µm diamond. We performed reflected light (RL) microscopy on the finished samples to accomplish three things, the first of which was to locate the magnetites themselves on the disseminated samples (since they are surrounded by norite, and thus it is difficult to locate the magnetite using the naked eye). Second, we used RL to locate areas of interest within the massive samples; we identified eight sites in the massive magnetite samples and ten sites in the disseminated samples for analyses. Finally, we used RL to determine the magnetite textures present in the samples. Finally, we analyzed the trace element composition of these samples using an NWR
193nm excimer laser coupled to an Agilent 7900 triple quadrupole ICP-MS at the University of Toronto.

The ICP-MS was tuned to achieve 100,000 cps sensitivity on 115In in NIST-610 with a 25 μm spot size, 10 Hz repetition rate, and ~5.75 J/cm² laser fluence. Three different standards were used to calibrate the machine throughout the data collection process. The primary standards used were in-house GSD-IG (Guillong et al., 2005) and BCR-2 standards (Rocholl, 2007). Meanwhile, the secondary standard was a magnetite standard from the Bushveld Complex (obtained from Barnes & Savard of the Université du Québec à Chicoutimi).

The standards were analyzed with a 75 μm spot size, 10 Hz repetition rate, and ~5.75 J/cm² laser fluence. Meanwhile, most of the samples were analyzed with a 35 μm spot size. The same repetition rate and laser fluence as the standards were used on all samples. There were two sets of spacing between the ablation spots for the sample: one had the spots adjacent to one another (which we will now refer to as Adjacent), while the second had the spots more evenly distributed throughout the sample (now referred to as Across). The closely spaced analyses were done to determine the homogeneity of the individual magnetite crystals while to more widely spaced samples was to obtain a measure of the range of possible magnetite chemistry.

We analyzed the following isotopes: 23Na, 24Mg, 27Al, 29Si, 30K, 44Ca, 45Sc, 47Ti, 49Ti, 51V, 53Cr, 55Mn, 57Fe, 64Co, 65Ni, 69Ga, 71Ga, 75As, 89Y, 90Zr, 93Nb, 107Ag, 114Sn, 116Sb, 140Ce, 146Nd, 157Gd, 172Yb, 178Hf, 181Ta, 197Au, 206Pb, 207Pb, 208Pb, 209Bi, 232Th, and 238U. The dwell time was set to 0.02 for 27Al, 47Ti, 49Ti, 51V, and 57Fe, while the dwell time was set to 0.03 for the rest of the isotopes. Total data acquisition for each sample was approximately 85s; this included 25s of background acquisition before the laser was turned on, followed by 60 s of sample acquisition during ablation. We used Sills data reduction software (Guillong et al., 2008) to correct for drift, instrumental bias, as well as to calculate the ppm concentrations from the raw counts per second data.

3. Results

LA-ICP-MS analyses of the massive magnetite samples have revealed that 57Fe, 49Ti, 47Ti, 27Al, 51V, and 24Mg are the most abundant isotopes with average values at around 588000, 74600, 74500, 15800, 9100, & 5000 ppm, respectively. On the other hand, the analyses have shown that 57Fe, 49Ti, 47Ti, 27Al, 29Si, and 55Mn are the most abundant isotopes in the disseminated magnetites with mean values of 600273.9, 84586.39, 84333.3, 6532.169, 3074.494, & 3053.14 ppm, respectively.

Further data processing revealed that most of the data from both magnetite types do not follow a normal distribution; this has required us to do a log-transformation of the data to a normal distribution when calculating further statistics and comparing data. Figure 2 shows an example of the data histogram before and after log-transformation; we see that the histogram is more normally distributed after the transformation. We used Shapiro-Wilks tests to statistically determine whether the data had a log-normal distribution or not.

Using these tests, we have observed that when analyzing the data from each magnetite type as a whole, the data distribution is non-normal. However, when we ran these tests on each individual magnetite sample (i.e., one Shapiro-Wilks test for only the data from massive magnetite sample 3D, another test for data only from disseminated sample 1A, etc.), we were able to observe more log-normal distributions.

We also compared the normality of the data based on the spacing of the analysis spots; we have discovered that both spacing types Across and Adjacent both yielded approximately the same number of normal and non-normal data distributions in the massive samples. Conversely, the data from the disseminated samples have shown that the Adjacent spacing have

![Figure 2. Sample histograms showing the data distribution before and after log-transformation](image-url)
yielded more normal data distributions than that of the Across spacing type.

One of the main points of this study was to check the data presented by Klemm et al. (1985).

**4. Discussion**

We have observed large differences in the geochemistry of the two magnetite types, especially when we look at the values obtained for $^{24}$Mg, $^{27}$Al, $^{45}$Ti, $^{49}$Ti, $^{51}$V, among others. We argue that these large differences are evidence that the disseminated magnetite from our study area had a different source from the massive magnetite. One could argue that the differences in these elemental compositions are the result of partitioning, where these elements are depleted only because they were preferentially partitioned into the massive magnetites as they crystallized; however, we do not think this is the case. The disseminated samples were taken from the area closely above the Main Magnetite Layer where the massive samples were obtained. There would not have been enough massive magnetite crystallized to cause the drastic decrease we observed.

Since most of the data are not normally distributed, we decided to use the median and the median absolute distribution (MAD) as a more robust measure of the center of the data. It is here where we found large differences between the elemental compositions of the two magnetite types. For example, the median Ti and V values for the massive samples are 75000 & 10400 ppm, respectively; compare this to the 24700 & 3740 ppm median values for the disseminated Ti and V.

Looking at Figure 4, we can see that our data is similar to what Klemm et al. have observed. Noticeable outliers however are the disseminated magnetite MgO and Cr$_2$O$_3$ values – they are different from the expected data by orders of magnitude. Also, Klemm et al. have stated that, though fairly similar, the average V$_2$O$_5$ value of the massive magnetite was smaller compared to the disseminated magnetite; we have observed the opposite. We have also noted that a large difference between the certain trace element concentrations of the two magnetite types (such as Nb and Yb) – elements that Klemm et al. did not analyze. Our mean massive magnetite data is also similar to the mean data obtained by Dare et al. (2014). As we have pointed out earlier however, the data obtained did not follow a normal distribution, and as such, using the mean to draw conclusions about the data is not as statistically powerful as expected. Assuming that the non-normality observed also affected the other studies – an assumption that we argue is acceptable since both studies ran analyses on a small number of samples – it would have been better if both studies used a different and more robust measure for the central tendency of the data (e.g., the median).

This study also set out to determine how many analyses are needed to obtain a statistically robust presentation of the geochemistry of the magnetite samples. For the massive magnetite samples, we have observed that, despite the samples being more heterogenous than expected, around ten spot analyses per sample are enough to be able to obtain a statistically
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robust result. Furthermore, the spacing between the analytical sites is not that important with this magnetite type. The analyses of the disseminated magnetite are a different story though, as we have observed much more variability in the data we obtained. As such, we conclude that more analyses must be done when studying disseminated magnetite samples to get a statistically robust result. Also, there is a possible correlation between the normality of the results and the Adjacent spacing of the analytical sites; this is something that could be expanded upon in future studies.

5. Concluding remarks

We argue that the disseminated and massive magnetites of the Upper Zone of the Bushveld Complex came from different sources. We point to the large differences in the geochemistry between the two magnetite types to support this argument. Klemm et al. (1985) have argued that the differences observed between magnetite types are the result of just magma evolution; however, we contend that such drastic evolution is unlikely in our samples given their close proximity to one another in the field. Furthermore, Klemm et al. missed large differences in the certain trace element compositions, which was data that modern analytical methods such as LA-ICP-MS were able to provide.

Furthermore, we contend that around ten analyses per sample would be able to provide a statistically robust representation of the geochemistry of massive magnetites. However, more analyses must be done to obtain this robust representation in disseminated magnetites; this number of analyses could be the subject of a future study.

Finally, we posit that geologists must be more cautious in their own analyses and assuming the normality of their data. We believe that taking a few extra steps to check for normality would help these scientists ensure their results be more statistically robust and sound.

References


1. Introduction

Short-duration metamorphism refers to metamorphic events driven by a thermal event less than 10 Ma in duration in the context of continental collisions. Few records of Precambrian short-duration metamorphism have been reported (Viete and Lister, 2017). This could simply be a result of preservation bias and the traditional geochronology whose time resolution is associated to the age of the rock. Alternatively, the lack of such features in the Precambrian rock record could hint for the impact of secular cooling and change in mantle composition on the style of metamorphism (Palin et al., 2020).

Diffusion speedometry is a promising candidate to overcome the presented challenge as its time resolution is independent of the age. Diffusion is a temperature- and pressure-dependent process that tends to homogenize chemical heterogeneity of mineral zones. The longer event a mineral underwent, the more smeared its compositional zoning is. Thus, with necessary assumptions of the mineral’s growth zonation, the timescale can be derived by diffusion simulation of the observed compositional profiles (Viete and Lister, 2017; Ganguly, 2010; Smit, Scherer, and Mezger, 2013; Chakraborty, 2006 etc.).

In this study, we investigate the retrograde eclogite near Mattawa, Ontario. We examine the petrography, conduct systematic analyses of mineral compositions and bulk rock geochemistry. We apply a range of modern methods to further confirm eclogite facies condition and construct a metamorphic p-T-t path with more constraint timescale, including: (1) phase equilibria analysis with contours for garnet composition and reconstructed sodic clinopyroxene composition; (2) Zr-in-Rutile thermometry (Kohn 2020); and (3) garnet diffusion speedometry at the inferred p-T path. We hypothesize that the metamorphic event recorded by retrograde eclogite near Mattawa, Ontario is short-duration metamorphism, and it could potentially be evidence of operative tectonics similar to modern plate tectonics in Mesoproterozoic era.

2. Geologic Setting

The Grenville Province located on the southwestern margin of Canadian Shield hosts lithologic units of diverse ages and metamorphic grades. The metamorphic terranes of Grenvillian ages extends north to Caledonia of Northern Ireland, Scotland, and the Sveconorweigian Province in Scandinavia. High grade metamorphic rocks in the Grenville Orogeny poses as a suitable target for studying the duration of metamorphism for its extremely well studied overall lithotectonic settings amongst other Precambrian orogenies. One of the pulses of collision and accretion within the Grenville Orogeny, the Ottawan Orogeny, was characterized by high grade metamorphism at midcrust level followed by extensive lateral transportation along the Allochthonous Boundary Thrust. Massive anorthosite massifs, peralkaline intrusions, dike swarms, and extensive A-type granite intrusions distinguish Grenville Province from Phanerozoic orogens (e.g., Rivers et al., 2012). This anomalously hot orogeny might reflect the prolonged heating of sub-continental mantle under a long-lived supercontinental insulating lid (Cawood and Hawkesworth, 2014).

Mattawan Domain is a part of the Algonquin domain in the allochthonous belt (Figure 1). The lithotectonic unit is interpreted as a klippe to the north of the Allochthonous Boundary Thrust that separates the parautochthonous Tomiko terrane to the northwest from allochthonous terranes. The presence of mafic garnet-pyroxene gneisses, or retrogressed eclogites, distinguish Mattawan Domain from the adjacent Tomiko Terrane. Major rock types of Mattawan Domain include quartz monzonite plutons, intermediate gneisses, and pods or layers of metagabbroic rocks associated with meta-anorthosite. These mafic gneisses crop out as large screens within intermediate to felsic gneisses in the study area, suggesting that it was likely derived from mafic
enclaves or dikes hosted in the felsic country rock. The host felsic gneisses are both texturally and compositionally heterogeneous, mainly fine-grained tonalitic to granodioritic with the mineral assemblage of quartz + plagioclase + K-feldspar + biotite + garnet. The Mattawa domain is characterized by younger Nd model ages (<1.7 Ga; Holmden and Dickin 1995; <1.8 Ga; Dickin and Guo 2001) than the supracrustal rocks from Tomiko Terrane (1.9-2.9 Ga, Dickin and Guo 2001), which confirms its allochthonous origin and limited interaction with older crustal rocks. The metagabbro consists of garnet porphyrblasts with polycrystalline plagioclase corona hosted in diopside + clinopyroxene symplectite matrix with various degrees of amphibolite facies retrogression; this assemblage is interpreted to be derived from eclogite facies rocks.

### 3. Sample Description and Mineral Chemistry

The studied samples are collected along Route 553, to the north of Mattawa, Ontario. The outcrop is a road cut with ~70m exposure with mafic pods of retrogressed eclogites enclosed in felsic to intermediate gneiss. Within the mafic gneiss, sparse felsic veinlets are observed suggesting some degree of partial melting. No evidence of melt segregation was observed on the outcrop.

Samples of the least retrogressed mafic gneiss were collected for this study and they consist of garnet porphyrblasts surrounded by polycrystalline plagioclase corona hosted in a matrix of lamellar clinopyroxene + plagioclase symplectite (Figure 2). The symplectite matrix appears green in hand sample. Various amount of amphibole + biotite patches are present in association with the degree of retrogression. Large flakes of amphibole and biotite are randomly oriented. Smaller amphibole grains replace symplectite and crosscut clinopyroxene and plagioclase grain boundaries. Accessory phases include rutile, ilmenite, andapatite, present as inclusions in garnet, and in the cores of amphibole. Samples with least retrogression were selected for chemical analysis.

**Figure 2** Photomicrograph of the petrographic thin section taken under 10X and plain polarized light.

Quantitative wavelength-dispersive spectrometer (WDS) analyses, energy-dispersive spectrometer analyses (EDS), and backscattered electron (BSE) imaging were carried using the JEOL JXA-6230 electron microprobe at the University of Toronto. The operating conditions were 10 and 15 kV (garnet) accelerating voltage and 10 nA or 50 nA (garnet and rutile) beam current. Amphiboles and feldspars were analyzed using a defocused electron beam (5 μm) to minimize beam damage. The chemical maps were made at 15 kV, 100 nA, and 200 ms dwell time. Trace elements in rutile were counted for 100-200s on peak to optimize counting statistics. Mineral standards used were well-defined natural and synthetic minerals.

#### 3.1. Symplectite

The symplectite consists of fine-grained lamellar intergrowths of clinopyroxene + plagioclase and late amphibole. On average, the relative modes of plagioclase, clinopyroxene, and hornblende are 50%, 38%, and 12% respectively, estimated based on BSE image analyses (e.g., Figure 3). The compositions of the clinopyroxene grains in the symplectite intergrowth range from diopсидic to omphacitic with Na/(Na+Ca) ratios 0.16-0.29 (cpx ternary, pyroxene table). The Na content decreases toward grain boundaries (Figure 3), suggesting slight Na loss during decompression. The plagioclase associated with symplectite is mostly oligoclase in composition with average An# of 16. Small euhedral grains of amphibole crosscut clinopyroxene – plagioclase grain boundaries. With average 6.1 Si pfu and 0.6 Mg/(Mg+Fe$^{2+}$), they plot in the pargasite/tschermakite field.

Symplectite is inferred to be pseudomorphous after Na-rich clinopyroxene precursors, and the decomposition reaction is largely isochemical (Anderson and Moecher, 2007). We used the modal abundances of clinopyroxene, plagioclase, and hornblende to calculate reintegrated compositions of symplectite to approximate that of the original clinopyroxene. The reintegrated compositions have Na/(Na+Ca) ratios around 0.5.
3.2. Garnet
Chemical mapping was conducted on several representative garnets; larger garnet grains with closer to euhedral form were selected to minimize the effect of retrogressive resorption. A manganese rich core is present in all the garnet grains that were chemically mapped. In sample XCG6DB (Figure 4), some garnet grains are anhedral, and their cores display features non-concentric chemical zoning in Ca and Mg, both of which could be a result of multiple garnet grains recrystallized into one during prograde. While the degree of resorption varies among grains, the resorption front is commonly associated with higher Ca and lower Mg concentrations.

4. Phase Equilibria Simulation and Thermobarometry
Metamorphic P-T-t history was reconstructed by phase equilibria analyses using the THERMOCALC software (Version 3.45; Powell and Holland, 1988) and an internally consistent thermodynamic dataset ds62 (Holland and Powell, 2011). The pseudosection is calculated in the model chemical system of Na2O-CaO-K2O-FeO-MgO-Al2O3-SiO2-H2O-TiO2-Fe2O3 (NCKFMASTH). The bulk rock composition is estimated from the results of X-ray fluorescence. Water is first estimated based on bulk-rock analysis, and then adjusted to excess on the solidus.

The calculated phase equilibrium diagram for sample XCG6DB is presented in Figure 5. The phase assemblage relations are heavily dependent on pressure with a few exceptions of temperature-controlled reactions, like the wet solidus. The large field of L+o+g+bi+ru+hb at 16-22 kbar matches the inferred peak assemblage. The main retrograde reactions as the pressure decreased are the breakdown of omphacite accompanied by the formation of plagioclase feldspar, and the conversion from rutile to ilmenite. Amphibole
is stable in the entire calculated P-T field. The observed retrograde assemblage of di + g + bi + ru + ilm + hb + pl + q is stable at ~12-14 kbar and ~700-750 °C.

Relevant compositional isopleth contours are plotted in the P-T field of interest. The garnet $X_{GRS}$ isopleths contours and the observed garnet $X_{GRS}$ profile suggests that the prograde growth of garnet mostly happened above the solidus along an isobaric heating path. Mg# isopleths shows that Mg# increases with temperature and pressure, thus the point with highest $X_{PRP}$ and lowers $X_{ALM}$ on the profile is interpreted to represent the peak metamorphic temperature. The Na/(Na+Ca) isopleths of clinopyroxene shows that Na/(Na+Ca) in clinopyroxene increases with pressure and decreases with temperature and is more dependent on pressure than temperature.

We apply the zirconium-in-rutile thermometer calibrated by Kohn 2020 to constrain the peak metamorphic temperature. The P-T curve calculated from the measured Zr concentration in rutile inclusions in the garnet is plotted in Fig. 6 with standard error. Together with the phase equilibrium analysis, we confirm the eclogite facies peak metamorphic condition, and reconstructed a P-T path of nearly isobaric heating at around 21 kbar reaching peak P-T condition of ~860 °C and 22 kbar, followed by simultaneous decompression and cooling to near solidus condition.

5. Diffusion Simulation
We conduct multicomponent diffusion modeling for garnet zonation with an attempt to constrain the durations of the peak metamorphic conditions. The diffusion equations are numerically solved by a finite-difference algorithm. We chose 2 representative profiles to conduct the diffusion modelling (See Fig 4. for location). In sample XCG6DB, assuming minimal resorption, the duration of high temperature condition of 800 °C at 16 kbar is constraint to be less than 0.2 Ma.

6. Discussion
6.1. Uncertainties with diffusion modelling
Uncertainties in the result of diffusion modelling arise from several assumptions. First, we assumed the garnet profiles were taken on a cross section that passes through the center of the garnet. This assumption is likely not valid in the case for sample XCG6DB since the high Mn core is not located in the center of the chemical map. However, a not perfectly radial profile would result in a longer diffusion length scale geometrically and thus overestimate the diffusion time (Ague and Baxter, 2007). The constraint on the upper limit is valid.

Another source of uncertainty is the assumption on the initial condition. The initial conditions were all assumed to be step functions. The timescale estimated from a gradational initial condition would only be shorter (Ague and Baxter, 2007), therefore the upper limit constraint holds regardless.

6.2. Short-duration metamorphism
The short-duration metamorphism recorded in the Grenville Orogeny is bizarre to say the least. Eclogites and HP granulites associated with the Allochthonous Boundary Thrust in the western Grenville are interpreted to be hot nappes extruded in early Ottawan phase (Rivers et al., 2009). The Ottawa orogeny itself is characterized by protracted periods of heating, which lead to a weakened mid-crust and subsequent collapse (Rivers et al., 2009). However, the time of peak
metamorphic conditions determined from U-Pb analyses of metamorphic zircon and monazite in rocks of similar path in the allochthonous High Pressure belts are in the 1000 Ma order of magnitude (Rivers et al., 2009).

To fully understand the discrepancy between the existing literature and this study on the timescale of the HP metamorphism, future work is needed. U-Pb dating of the Mattawa mafic gneisses can provide a consistent metric of comparison; and a closer examination on the felsic country rock might shed more light on the petrogenesis of the mafic enclaves.

7. Conclusions
In this study, we examined the retrograde eclogite near Mattawa, Ontario in detail. We confirmed the peak metamorphic condition to be ~20 kbar at 860 °C in eclogite facies, in a supersolidus plagioclase assemblage through phase equilibrium analysis, consistent with the Zr-in-rutile thermometer. Despite the high temperature, chemical zoning in garnet is partially preserved. Forward modeling of diffusion profiles in garnet constraints the duration of peak metamorphic stage to be ~0.2 Myr, suggesting a short-duration regional metamorphism within the overall protracted Grenville orogenesis. Very few examples of Precambrian short-duration regional metamorphism have been reported, and this result could potentially be evidence of operative tectonics similar to modern plate tectonics in Mesoproterozoic. To gain a better understanding of the mechanism of the short-duration metamorphism, a closer examination of the felsic country gneiss is required.

References
1. Introduction

In geophysics, magnetic surveys are conducted by measuring the magnetic fields generated by magnetized objects in the subsurface against Earth’s ambient magnetic field. The internal magnetic moments of most magnetically susceptible materials will align themselves with a strong external magnetic field, but will have no inherent magnetic field otherwise. Other materials, called ferromagnetic materials, maintain a permanent magnetic field which will remain constant even after the object or external field changes orientation or location (Reynolds, 2011). This permanent magnetization is often called remanent magnetization.

In magnetic data, unless taken above one of Earth’s magnetic poles where field lines are vertical, anomalies will generally appear as a peak and trough side by side, with the source buried somewhere in between. Magnetic data is much easier to analyze when the peaks lie directly over the sources in a radial pattern. Thus, one of the most common data processing techniques used on geomagnetic data is reduction to the pole (RTP). RTP Transforms the data to how it would look had it been collected at the North Pole, achieving this desired effect. However, this does not work on remanent magnetization, as remanent fields will have different orientations than induced fields.

Remanent magnetic effects in the subsurface of the Earth can both make magnetic data very challenging to interpret and increase the ambiguity in inversions of the data. This is because while subsurface anomalies with purely induced fields will have a known magnetization direction, remanent magnetic fields can have any orientation, making it harder to gain information on the size, depth, and shape of the anomaly.

There are multiple ways of dealing with remanent magnetization effects in magnetic data. This paper will explore a method called normalized source strength, or NSS. NSS is a scalar quantity and as such is insensitive to direction. It is also inversely related to displacement from the source, so it should peak directly over the source in a relatively flat survey area (Pilkington & Beiki, 2013). Placing the peaks directly over the source allows depth to be estimated using the half width at half maximum (HWHM) length (Clark, 2014). This will also be explored in this paper, although it is not the focus.

In order to evaluate the effectiveness of NSS in mitigating remanent magnetization, I will create NSS maps of two different survey areas: one is a small shallow lake in the Deep River area of Ontario, and the other is a forensics site containing buried human-made objects with known locations and depths. This should allow us to evaluate the use of NSS in near surface investigations where it has not been thoroughly tested, as to date, available studies have used it almost exclusively on data from large-scale aeromagnetic surveys. I will then compare these NSS maps to RTP maps of the two areas to see if significantly more information can be gained by adding NSS as a data processing step.

2. Methods

The first survey was taken over Lake Ogilvie, which is a small human-made lake located about 10 km Northwest of the town of Deep River, following the Ottawa River. It was originally a creek, but it became flooded during the construction of a nearby road. The geology of the area is strongly influenced by glaciation that occurred during the Pleistocene, while the bedrock mostly consists of Precambrian rock of the Grenville Structural Province (Gartner & Vandine, 1980). The second survey was performed at a forensics site located in Southern Ontario, approximately 25 km Northwest of Pearson International Airport. The survey area contained three buried handguns and rifles and three empty graves, all of varying depths.

Total magnetic intensity (TMI) data was collected at both survey sites. The data was first gridded, and then an upwards continuation was applied. Upwards continuation transforms the data to how it would look had it been taken at a higher elevation, filtering out shallow, high amplitude/low wavelength anomalies (Ganiyu et al., 2012). Diurnal corrections were deemed unnecessary after looking at the base station data and finding that changes in the ambient field were negligible over the course of the survey. Then, an RTP was performed.

Finally, the NSS maps were constructed from the upwards continuation data. NSS is a quantity derived from the eigenvalues of the magnetic gradient tensor (MGT) (Pilkington & Beiki, 2013). However, in order
to find the components of the MGT, the magnetic field strength vectors had to be calculated from the TMI data. This was done using Fourier analysis, as outlined by Clark and Schmidt (1998). After this, directional derivatives were taken to construct the MGT, and the NSS could finally be found at each point.

3. Results

The processed data from the Lake Ogilvie survey can be seen in Figure 1. Figure 1a shows the RTP data, while Figure 1b shows the NSS data. Three strong anomalies appear along the western edge of the lake (Points A, B, and C). Points A and C are noted to be metal railings on docks, while the point B is thought to either be a large boulder, potentially containing magnetite or another ferromagnetic material. As can be seen in Figure 1a, remanent magnetization in these three anomalies is clear due to the distinct peak/trough pattern. The peaks are shifted directly over the anomalies in Figure 1b, giving the desired radial pattern. One of the most distinct features in Figure 1a is the gradient from low values of TMI along the West side to high values on the east. Interestingly, this is not really evident in Figure 1b. Peaks from induced magnetic fields should appear in approximately the same location on both maps. Thus, two of the peaks on the eastern shore (points E and F), as well as a large portion in the Southern portion of this high TMI zone (area G) are caused by induced magnetization. Points E and F are thought to be boulders containing magnetic minerals, while area G is thought to be a section of the lake with a thinner sediment layer, making the bedrock appear closer to the surface. The bedrock in the area is noted to contain magnetite as an accessory mineral, which would greatly increase the magnetic susceptibility of the bedrock (Duesterhoeft et al, 2021). The rest of this high TMI zone has a relatively weak NSS, leading to the lack of an NSS gradient in Figure 1b. This large distinction between the maps means that there is likely remanent magnetization in the area, and the remanent/induced fields are overlapping in Figure 1a to produce the gradient pattern. The biggest example of this can be seen at points D1/D2. The peak at point D1 on the RTP map has no apparent analogue on the NSS map. This means that there must be remanent magnetization. In fact, a very small peak at point D2 on Figure 1b corresponds to point D1, as it appears directly between point D1 and a small low TMI area directly Northeast of point D1 on Figure 1a. Thus, the actual source of this anomaly is buried at point D2, and the shifted peak in the RTP data overlaps with the peak at point E, undergoing superposition and creating a strong peak that is not directly over any anomaly.

Figure 2 shows the processed data from the forensics test-site. Figure 2a shows the RTP data, while Figure 2b shows the NSS data. The strong anomalies at the very top of the map are the bottom edges of magnetic fields coming from concrete rebar and an oil drum, respectively. The objects were buried on the grids seen in Figure 2. Line R denotes rifles, and line H denotes handguns. The rifle buried at 0.6m is the strongest anomaly on the map, and it clearly shows strong remanent magnetization, as can be seen in Figure 2a. This is fully corrected for on the NSS map, creating a very radial peak, very close to the true location of the buried rifle. The handgun buried at a depth of 1.2m also appears clearly in the NSS data. On the RTP map, this
handgun is extremely unclear. It seems to appear in the middle of a somewhat soft TMI gradient, without the distinct peak-trough pattern of a typical magnetic anomaly. A fairly radial peak appears on the RTP map along the 1.2m line at around y=2.5m, indicating the presence of a magnetically induced anomaly at this (incorrect) location. The NSS data clears this ambiguity up and gives the true location of the object.

The rifle of depth 1.2m appears much more clearly on the NSS map as well, although it does not have the distinct radial pattern due to its close proximity to the much stronger anomaly caused by the shallower rifle. The handgun of depth 0.6m also appears in the NSS data, although not as clearly, and the deeper guns don’t appear at all.

Depth could now be estimated using the HWHM method. A roughly radial anomaly signature is required for this. Thus, this can only be tested on the 0.6m deep rifle and the 1.2m deep handgun. It is important to remember that an upwards continuation of 0.5m has been applied here, so the anomalies appear in the data as though they have been buried 0.5m deeper than in reality. Thus, for the purpose of these calculations the “true” depths for the objects will be 1.1m and 1.7m, respectively. The rifle’s depth was estimated to be 1.01m, giving a percent error of 8.18%, while the handgun’s depth was estimated to be 2.3m, giving a percent error of 26.1%. Clearly, this method only works in certain perfect circumstances, so it is fairly unpractical.

4. Discussion

These two case studies show that valuable information can be learned from adding NSS to the analysis. NSS clearly did a very good job of mitigating the effects of remanent magnetization. For the data from both surveys, the size, shape, and depth of the permanently magnetized anomalies were almost impossible to gauge from the RTP data alone due to the irregular shapes of the anomalous fields. NSS was successfully able to shift these fields into a more radial pattern, placing the peaks over the sources. Even without knowledge of the true locations of the sources, as is the case at Lake Ogilvie, this was clear since the peaks on the NSS map appeared directly between where the peaks and troughs appeared on the RTP map.

On top of this, as seen in the map over Lake Ogilvie, remanent magnetization is not always immediately obvious even after RTP. This occurs in areas where a lot of anomalous fields are overlapping, making remanent magnetization extremely hard to differentiate from induced magnetization by eye. Point D1 is a good example of this, as it strongly resembles an induced magnetic field due to its radial nature and ambiguous relationship with the magnetic low to its Northeast. In fact, the calculation of NSS completely changes how this area would have been interpreted. If the NSS had not been calculated, interpretation of the TMI gradient would have made up a significant part of data analysis, and larger, deeper anomalies likely would have been tested for as potential causes. However, the NSS maps show that this gradient is really just caused by the overlap of a couple of induced fields and a remanent field that happen to be on the Eastern side of the lake. However, NSS should not be used alone. This is because it is impossible to tell if the anomalous magnetic field is induced or remanent. This information is extremely important, as it can strongly affect predictions on what the material of the source is. Thus, NSS and RTP should be used together and compared to each other to maximize the effectiveness of the analysis.

In order to confirm my theories on the nature of the sources of the magnetic anomalies under and around the lake, further investigation would have to be undertaken. Performing other geophysical surveys, such as a GPR survey to measure lake depth/sediment...
thickness would greatly add to the accuracy of the interpretation of the geology of the lake.

NSS also shows great promise at locating buried human-made objects for use in forensics. This makes sense, since many shallow buried objects (such as weapons) will contain iron or other ferromagnetic components. These purified ferromagnetic materials will have extremely strong remanent magnetization – much stronger than any ore found in nature. This makes NSS extremely well suited for the task. The data from the forensics test-site further shows how the close proximity of multiple magnetic sources with different magnetization directions can lead to extremely ambiguous data, and that NSS can greatly clarify it. In addition, as stated before, the use of NSS allowed a HWHM depth approximation to be made. In order for an accurate estimation to be made, the anomaly had to be extremely radial, and far stronger than its surroundings, limiting the practicality of this technique. However, since human-made metal objects will have far stronger remanence than natural metal-bearing objects, if a single metal object is being searched for, this could be a viable way to estimate the depth, as its magnetic signature will drown out the magnetic field generated by its surroundings.

5. Conclusion

Overall, NSS was found to be extremely effective at removing the effects of remanent magnetization on geomagnetic data. This study tested it for near surface applications, including a shallow human-made lake featuring strong shallow remanent and induced magnetic anomalies, and on a forensics site with shallow buried human-made objects with known depths/locations, and strong remanent magnetization. This shows that NSS isn’t just able to mitigate the remanence of deep, long wavelength anomalies. NSS was able to remove remanence to such an effective degree that it shed light on areas where remanence would not have been immediately noticeable. Adding NSS as a data processing step can therefore completely change the interpretation of the data, and make it more accurate. NSS was also shown to be potentially useful for depth estimates without inversion, although more research needs to be done in this area. Another area that could use further investigation would be the comparison of NSS to the analytical signal method of mitigating remanence. Analytical signal is known to make assumptions about the shape and location of the sources (Pilkington & Beiki, 2013) making NSS theoretically superior, but a more in depth investigation would be beneficial. Another area that could use further research would be the comparison of NSS inversion to RTP/TMI inversion. Inversion of NSS data has been studied (Pilkington & Beiki, 2013), but according to my research, direct comparisons have not been made.

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References


Schmidt, P. W., and D. A. Clark. "The Calculation of Magnetic Components and Moments from TMI: A
1. Introduction

The Reykjanes Ridge is a spreading ridge that presents an opportunity to track the evolution of rifting centers at an asymmetric slow-spreading plate boundary. The ridge spans the northern ~1000 km of the Mid Atlantic Ridge and has been spreading at a full spreading rate of ~20 mm/year. A unique feature of the ridge is that it spreads obliquely to the spreading axis: a consequence of the change in spreading direction from ~125 to ~100 degrees due to the failure of the triple junction between the Greenland, Eurasian, and North American plates 37 Mya (Martinez et al., 2020). Along with the sudden change in orientation, disjunct ridge segments were formed and separated by transform faults which have been continuously eliminating through strike-slip motion from north to south, thereby re-establishing the original linear geometry of the ridge. The southern extent of the ridge is the latest to reorganize but remains in a state of active tectonic deformation as demonstrated by the gradual lengthening of spreading segments and migration of non-transform discontinuities wakes (NTOW) which are analogues of pseudofaults that form by ridge propagation (Hey et al., 2017). Investigating the geodynamic control on the style and extent of rift-valley volcanism is possible with the application of a novel remote-predictive geological mapping method based on interpretations from newly acquired bathymetric and acoustic backscatter data. Notably, the bathymetric data in the southern extreme of the Reykjanes Ridge provides significant high-resolution coverage of both on-axis and off-axis regions, allowing the precise and detailed monitoring of the evolution of the ridge for up to 13 years Mya.

The acoustic backscatter data aids in the interpretation of geologic features and terrains whose distribution and morphology reflect both present-day and historic ridge dynamics. This analysis will produce new insight of the on-going first and second order deformation of the Reykjanes Ridge, its controls, and its effects on rift valley volcanism and potential locations of hydrothermal venting. This has implications for sea-floor economic geology and exploration. Specifically, providing insight into the key tectonic settings that produce environments conducive to high volume and focused magma supply or the lack thereof. The more information we gain from these studies, the more effective sea-floor exploration campaigns will be.

2. Methods

The geologic mapping in this study closely follows the remote predictive mapping technique used in previous papers on rifting centers (Anderson, 2017, Klischies 2019, Palgan, 2017). The multibeam bathymetry data comes from the R/V Marcus G. Langseth (MGL1309) cruise, with a gridded resolution of 50 x 50 m recorded by the Kongsberg EM122 multibeam echosounder. The data was rendered into ArcMap 10.7.1 and enhanced with hill shade and slope shade texture to add contrast for interpreting geologic structures and terrain.

Acoustic backscatter data was collected from the same cruise and was used to determine relative ages of the crust. Moderate to high backscatter intensities are reserved for newly erupted lava flows including both hummocky and sheet flows. Low backscatter intensities represent older and sedimented terrain (Anderson, 2017, Klischies 2019).

Regional structures including fault zones (FZ), NTOWs, and reorganization boundaries were mapped according to their location in the magnetic surveys.
2.1 Linear Structures

Linear structures are classified into four categories: major faults, minor faults, eruptive fissures, and lineaments. **Major faults** are elongated structures that exceed a thrust of 100 m. **Minor faults** have a thrust that is less than 100 m. **Eruptive fissures** are elongated structures with a high slope angle on both sides of the raised scarp. **Lineaments** are features with a linear geometry but an ambiguous slope.

2.2 Geologic Terrain Mapping

Classification of geologic terrains relied on previous geologic mapping undertaken in the Marianas back-arc by Anderson et al (2017). This system uses discrete-time categories: Neovolcanic terrain and Old Crust. The former is limited to the axial valley, while the former encompasses all other regional terrain.

The Neovolcanic terrain has three subcategories: Hummocky, Smooth and Sedimented Neovolcanic terrain. The **Hummocky terrain** is made up of hummocky and pillow lava flows which result in an irregular morphological pattern in the bathymetry formed from multiple dike injections. The **Smooth terrain** is distinguished from the hummocky terrain by its smooth bathymetry and low rugosity backscatter. This represents effusive flow. The **Sedimented terrain** is characterized by low backscatter intensity and smooth, even bathymetry. The categorization of the old crust follows the same principles as the Neovolcanic terrain. A new category: **Old Sedimented Basins** was also added to distinguish sedimented flows from concave basins.

Point-sourced volcanics were divided into three broad categories. **Flat-topped volcanoes** have flat and wide summit compared to its base. **Volcanic cones** have distinct conical and highly pointed summits. **Cratered volcanoes** have a distinct depression on the summit visualized by concentric darker slope shade values. **Axial Volcanic Ridges (AVRs)** are axial-valley bound, elevated features that are an amalgamation of Neovolcanic terrain, point-sourced volcanics and linear structures.

3. Results

3.1 Lineament Density Mapping

More than 15,000 polylines features were mapped across the southern study area. These features were sorted according to their orientation in 20-degree bins (i.e., 10 – 30 degrees azimuth) and the ArcMap Lineament Density Tool was used to calculate the prevalence of these binned linear features. The darker shaded areas represent the highest lineament density, while lighter tones represent the lowest with null colors representing no data (Figure 3).

The average orientation of spreading centers along the ridge, defined by the long axis of AVRs is 21 degrees azimuth. The average orientation of the axial valley is 40 degrees azimuth. These orientations are visualized by the black and red lines respectively in Figure 3. Almost 70 percent of all linear structures fall near these orientations (10 – 70 degrees azimuth). Furthermore, the region between the two oppositely facing INTOWs have few N/S trending structures compared to other coeval zones in the study area (Figure 3a, 3b). Linear structures located in the 10-15 km wide axial valley are more N/S trending on average compared to those off-axis which trend more towards the NE/SW (Figure 3c, 3d). There is also significant overprinting, that is, structural trends typically dominating off-axis (30 – 70 degrees azimuth) are also abundant in the axial valley (Figure 3c, 3d). All but one lineament density map converges on a consistent high lineament density locus in the center of the two oppositely facing INTOWs (Figure 2).

![Figure 2. Lineament density maps sorted by binned linear structures. Dark = high lineament density, light = low lineament density.](image-url)
volcanism is abundant (Figure 4a). However, there is a marked decrease south of this boundary. Moreover, a 16 km segment of the axial valley north of the large central cratered volcano is barren of any significant point source volcanism. Volcanoes reappear south of the central downwards pointing INTOW marking a central segment that is dominated by hummocky and smooth terrain.

Overall, there is a greater abundance of sedimeted terrain and sedimeted basins on the Eurasian plate than the North American plate between the two INTOWs (Zone 3 and 4, Figure 4a). A different pattern emerges between INTOWs and NTOWs since in Zones 1, 2, 5, and 6 there’s more hummocky and smooth flow on the Eurasian plate but less in the southern area in between Zone 1 and 2 (Figure 4a). In addition, the first ~20 km of the North American plate from the valley bounding fault to the western extent of a fault cluster is heavily tectonized in comparison to the Eurasian plate (Figure 4b). This fault cluster zig zags to match the bend in the axial valley in this area.

3.3 Segment Scale Mapping

A total of five AVRs were mapped in the center of the southern study area. These five were chosen because of their proximity to the INTOWs and each had a distinct orientation to the regional structure (i.e., AVR-2 and AVR – 4, cross- cut the INTOW traces). The AVRs were described by their dimensions and morphology (Figure 4).

**Figure 3.** Remote-predictive geologic maps. Map 3a illustrates the terrain mapping. Map 3b illustrates terrain mapping, faults and point sourced volcanics.

**Figure 4.** Sample of key characteristics of AVRs mapped in detail along the southern axial valley.

4. Discussion

Based on the linear structures alone, the Reykjanes ridge appears to be actively deforming despite having mostly reorganized back to its original linear geometry. This is supported by the evidence for polyline orientational changes progressively off-axis into older terrain. While a kinematic procession of gradual structural rotation cannot be deduced yet, younger crust is dominated by N/S trending structures and older crust is dominated by NE/SW trending structures. This suggests that the overall stress field has changed, and newer tectonic and magmatic processes happen along a N/S direction instead of an older NE/SW orientation. These older trends haven’t disappeared yet because they’re still prevalent in the axial valley. This can be accredited to structural inheritance which suggests that older ridge geodynamics may still influence modern spreading. A similar argument is made for the NTOWs which extend from the former FZs.

The change in fault orientation off-axis in the central ridge segment also supports a recent shift in ridge orientation. This zig-zag fault pattern follows the axial valley bounding faults on both plates (Figure 5). These faults regain their linearity further off-axis. Based on the distance from the spreading center and spreading half-rate assuming symmetrical plate spreading, the orientation of the axial valley has changed in the last 2 million years. The INTOWs bounding the ridge segment could be involved in this second-order tectonic deformation, but more time-series analysis is needed for a causal link.

The geologic mapping of Neovolcanic terrain and point-source volcanoes provides another line of evidence for the interaction between INTOWs and the evolution of the ridge. In the central ridge segment between oppositely pointing INTOWs, there is a
preference for hummocky and pillow lava style volcanism with minimal point source volcanoes. This is in direct contrast with both northern and southern extents of this segment beyond the central bounded segment. High-volume hummocky-style flow is usually indicative of repeating dike intrusion with low magma supply while point source volcanism usually indicates focused effusion with a large magma supply (Colman et al., 2012).

This segment is also the locus of most populated lineament density bins (Figure 3). Due to the abundance of lineaments in this center, it could be a magmatically robust center with both eruptive fissures and magma conduits through pre-existing faults. The latter would increase the segment’s crustal permeability and would allow for more magma to reach the surface. In turn, this would increase the likelihood of finding hydrothermal vent sites, since crustal permeability has been cited to determine the style of hydrothermal venting (Anderson et al., 2017, Pałgan et al., 2017, Klischies et al., 2019).

5. Conclusion

Contrary to previous assertions about the ridge’s linearity north of the Merlin NTO, second-order ridge deformation is active along the southern Reykjanes Ridge. With possible causal links to the NTOWs and INTOWs, a new evolutionary stage of the ridge can now be defined using the exceptional bathymetry coverage in this region. This new deformational stage could be linked to active magmatic and tectonic processes along the ridge. Further work could include integrating the geophysical data sets (i.e., magnetics, gravity and seismic) with the bathymetry to correlate regional features. This work will lead to a better understanding of sea-floor processes at slow-spreading ridges and contribute to the expanding knowledge framework of tectonic and magmatic conditions for hydrothermal vent systems.

References


1. Introduction

Mining has a rich history in Nash Creek, NB, however, there have been few cohesive models that have combined historic and modern data. The creation of a three-dimensional model using the aforementioned data could shed light on the unknowns of the Nash Creek Deposit. This paper aims to create a geologic model that could elucidate the structural geology, mineralization constraints, and the shape of the deposit.

The Nash Creek Deposit (NCD) is an Ag-Pb-Zn volcanogenic massive sulphide (VMS) deposit. It is primarily hosted in the Archibald Settlement Formation and Sunnyside Formation (Walker 2010). These formations are host to a centralized region of intense clay alteration and silicification that is then surrounded by an area of carbonate, hematitic, and potassic alteration (Eugene 2020). The Nash Creek Deposit is bounded by a graben, which was active at the time of the deposit’s formation (Lentz 2006).

1.1. Regional Geology

![Figure 1. The geology of the Nash Creek Deposit (Walker 2010)](image1)

The NCD lies in the northeast of New Brunswick in the Jacquet River Syncline. This is located withing the Chaleur Bay Synclinorium, one of fifteen tectonic belts in NB. The other important belts that make up this region are the Charlo-Jacquet River Area, Connecticut Valley-Gaspe Synclinorium, the Rocky Brook-Millstream Fault, and the Gander Zone. (Wilson 2004).

![Figure 2: Map of Orogeny (Wilson, Van Staal, Kamo. 2017)](image2)

The NCD formed during the oblique convergence of Laurentia and Ganderia, in an extensional setting which was dominated by the bimodal volcanism and a marine transgression (Lentz 2006). The ore deposits in New Brunswick were formed by three events during the Appalachian Orogeny: 1) the collision of Avalonia and Laurentia, 2) the closure of the Rheic Ocean through northward subduction, which formed oceanic plumes, and 3) the oblique convergence mentioned above (Murphy 2005). The graben that confines the NCD was formed during this transtensional event. The zircons found in the units of the NCD date the formation of the deposit to the formation of the Nash Creek Graben.

1.2. Nash Creek Deposit Characteristics

The Nash Creek Deposit is a sulphide deposit split between two main mineralization zones: The Hickey zone and the Hayes zone. They are both postulated to occur at about 250 meters depth. The deposit is estimated to have 14.4 million tonnes of 2.9% Zn, 0.6% Pb, and 20.3 g/t Ag (Eugene 2020). The sulphide mineralization is confined by a strata-bound replacement style mineralization (Eugene 2020), which fills the stockwork and auto-breciated rocks. The mineralized breccia has strong correlations to intraclast chlorite, zinc, and lead relationships. The lapilli topped pyroclastic layers formed a mineralization conduit for hydrothermal fluids (Lentz 2006).
1.3. Stratigraphic Context

**Big Hole Brook Formation**

This formation is made up of parallel laminations in a range of thicknesses, interlayered with cross bedding. It is primarily a micaceous fine-grained sandstone and siltstone and the upper boundary is an unconformity.

**Sunnyside Formation**

In this formation there are layered vesicular flows, interbedded mafic tuff and pillow basalt, and earlier in the formation is comprised of intercalated massive and reworked hyaloclastite interlayered with mafic flows.

**Archibald Settlement Formation**

This formation is comprised of flow banded rhyolite, red rhyolitic clasts in the pyroclastic unit, and green felsic flows.

**Jacquet River Formation**

This formation is primarily made up by marine sandstones and siltstones that are interbedded with limestone and mafic flows. The mafic flows are completely contained within the sedimentary rocks.

**Mitchell Settlement Formation**

The youngest part of this formation is distinguishable due to its red hue and is comprised of a weathered mafic flow. The next section is a micaceous sandstone, and the oldest section is a mafic volcanic breccia.

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2. Methods

2.1. Data Cleaning and Collation

Evaluated data to ensure there was no anomalies in core logs to create the best chance for an accurate generalized model. If there were any major uncertainties and a conclusion could not be made as to the meaning of the core logs, the section of core in question was excluded from the dataset.

Python (3.8) was used to create a program to retrieve and collate Digital Terrain Models with vertical accuracy of 2.5 m and horizontal resolution of 70 m from the Government of New Brunswick website.

2.2. Mineralization occurrences at depth and per lithology.

A program was created using Python to sort the mineralization occurrences at depth and by lithology. The mineralization occurrences were normalized by the total number of occurrences at each depth (Figure 6).

2.3. Leapfrog Setup

Drillhole data was imported in four steps: 1) Collar (containing drillhole number, the location of the drillhole X, Y and Z coordinates and the maximum depth of the drillhole), 2) Survey (containing drillhole number, depth, dip and azimuth values), 3) Intervals 1 (containing drillhole number, from and to depths, column measurements, and lithology) and 4) Intervals 2 (containing drillhole number, from and to depths, column measurements). Imported topography data as points and used these data to construct a topography mesh.

2.4. Lithologies

Due to the large variety of companies and geologists involved in logging the core there was a large variety of lithology names used for the same units. Therefore, each lithology appearing in the model uses a new definition created by analyzing the most common phrases and explanations of the units. Each core log was then sorted into one of the generalized units, (Andesite, Basalt Breccia, Basalt Dykes, Basalt Flows, Basalt scoria, Basalt Tuff, Faults, Mineralization, Mineralization next to faults, Overburden/Casing, Rhyolitic flows, Rhyolitic Breccia, and Sand/Siltstone).

2.5. Deposit Modelling

A geologic model was created following importation and cleaning of the data. The model’s extents were set to coincide with the furthest extents of the boreholes. The surface chronology was determined through

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*Figure 3: Idealized stratigraphic column created from literature.*
analysis of the stratigraphic context and visual clues. The model was then rendered.

3. Results

3.1. Cross-section of the Ore Deposit model

![Figure 4. Cross-section East to West facing North at 53072000 Northing.]

The most consistently high ratio of mineralization happens depth ranges of 250-295 m and 495-555 m (Figure 6).

3.2. Ore Body model

![Figure 5. Aerial View of ore body (pink and yellow) of Nash Creek Deposit with Borehole locations. (Black Squares) (The area of established drill holes indicated by a white ring)]

The current known extents of the deposit and likely shape of the ore body are indicated in Figures 4 and 5, respectively. Pink regions indicate mineralization that is not directly associated with faults, and yellow regions mineralization that is associated with faults.

3.3. Normalized Number of Mineralization Occurrences at

![Figure 6. Normalized mineralization occurrences at depth]

The most consistently high ratio of mineralization occurs at depths ranging from 250-295 m and 495-555 m (Figure 6).

3.4. Number of Mineralized Occurrences per Lithology

![Figure 7. Number of Mineralization Occurrences Per Lithology]

The primary lithologies that confine mineralization are Basalt Flow, Flow Banded Rhyolite, Basalt Breccia, Basalt Tuff and Scoria (Ordered respectively from most likely to least likely to host mineralization) (Figure 7).

4. Discussion

The mineralization of the Nash Creek Deposit primarily occurs in the basalt flows, basaltic breccia, and the flow banded rhyolite (Figure 7), which are the primary lithologies of the Sunnyside and Archibald
5. Concluding remarks

1. This study created a preliminary model of the Nash Creek Deposit.
2. The likely mineralization constraints are the breccia and flow basalts and not the faults.
3. The shape and known extent of the deposit was elucidated and aligns with the recent arguments of a thin flow surface.
4. Mineralization is present at two depth ranges (250-295m and 490-555m)
5. Drilling should extend away from the well-established deposit area to the surrounding area and potentially deeper to determine definite deposit extents and ore body shape.
6. Moving forward a goal is to create a better understanding of the fault systems, using geologic models and historic maps.
7. Future research should include an analysis using hard rock seismic to determine more exact locations of faults, in order to conclude the relationship between silver and the fault system.

References


1. Introduction

Sea ice in the Arctic regions has been rapidly declining over the past few decades. This is due to environmental factors affecting the climate in these Arctic/sub-Arctic regions. Most of these factors can be traced back to anthropogenic causes which include ocean acidification, warming seawaters, and increased CO$_2$ atmospheric concentrations. A pristine marine organism that once thrived in cold Arctic seawaters that can help capture a glimpse into the rapid climatic changes in the Arctic, is coralline algae, *Clathromorphum compactum*. What makes this calcium-carbonate organism a crucial indicator in determining paleo-temperatures is the fact that it grows in annual layers, similar to that of tree rings that can be dated back centuries due to its long lifespan (Adey et al., 2013). These growth layers can undergo laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), to collect magnesium-to-calcium (Mg/Ca) isotope ratios to determine a sea ice proxy at the time of each annual growth layer (Halfar et al., 2008).

This study was done to understand how rapidly changing environmental factors have affected sea ice extent in the Arctic. It explores the relationship between the seasonal extent of sea ice over the past 40 years by comparing satellite data collected in the Arctic Bay region against the coralline algae sea ice proxy data. By understanding and visualizing past climatic data, trends are realized and better understood for future climate models.

2. Methods

In order to understand how the chemical Mg/Ca isotope analysis identifies a sea ice proxy for satellite comparison, both qualitative and quantitative analyses were conducted beforehand. The three samples used in this study include 19AB-10, 19AB-40, and 19AB-55.

2.1 Sample Collection, Cutting, & Polishing

Samples were collected through an Arctic expedition in August 2019 in Arctic Bay, Nunavut by Dr. Jochen Halfar. Samples were collected between 10-15m depth below the ocean surface using a rock hammer to chip off coralline algal samples. Samples were brought to the University of Toronto Mississauga (UTM) lab where they underwent a vertical cut to identify annual growth layering. The samples were then mounted onto glass slides and cut once more to create a thick section slide. The sample was then polished through a grinding machine to correct for smoothness and then underwent several rounds of disk polishing with 9-micron and 3-micron polishes. This process was repeated for each of the three samples in this study.

![Sample 19AB-40 collected from Arctic Bay indicating laser transect lines and growth direction.](image1)

2.2 Imaging & Laser Ablation

Once samples were fully polished, they were put under a high-resolution microscope to capture very detailed scans of each. Laser transect paths were then chosen and drawn onto the sample in the software program,
GeoTS, and calculated through two reference points. This data, along with the samples, was then brought to a lab at the University of Toronto St. George (UTSG), for laser ablation analysis. Samples then underwent laser ablation alongside hourly calcium carbonate (NIST610) calibrations.

2.3 Data Collection & Processing

After the laser transects were completed, batch files were obtained from each transect done. This data, which obtains elemental isotope values for the sample, was then put through Microsoft Excel macro spreadsheets designed specifically for calcium carbonate observations. The Mg/Ca isotope ratio was calculated, and graphs were created for each transect line. The overlap between transect lines was investigated further and taken into account to determine how many years of overlap were present and would be accounted for in the overall age model.

2.4 Collecting Satellite Sea Ice Data

The comparison for the coralline algal annual growth increments was plotted against sea ice data collected from the National Snow and Ice Data Center (NSIDC). In order to find this information, the Climate Explorer database was used to find the NSIDC sea ice data ranging from the years 1981-2019. The coordinates for the Arctic Bay region were put into the software to create an area of reference for the sea ice data. The area covered was between 70°N - 74°N and 270°E - 274°E. This is shown in Figure 3.

2.5 Calibrating & Normalizing Data

In order to accurately compare satellite sea ice data to annual growth calculations, normalizing data is a process used to calculate and compare unitless values. This method examines overall trends rather than absolute values calculated previously. It takes each value into account and adjusts it to the mean of the data to either show positive or negative trend correlations. This data can then be compared to other normalized data to determine positive or negative correlations between the observed variables. This is shown in Figure 4.

3. Results

3.1 Growth Increments & Sea Ice Data

Seasonal algal growth layers were calculated in microns per year from each low value to the next which is represented in Figure 2. The low value examined represented the lowest value in that growing year. It was determined that over the past 40 years, sea ice has declined in the Arctic Bay region. This is shown in Figure 3 with an overall decline since 1981 to 2019 when the samples were collected. The data also shows that alongside this declining trend, it also seems like the annual growth layers are also declining in recent years.

3.2 Normalized Data

The calculated normalized growth rate for the coralline algae was plotted against the normalized data for the sea ice cover. Even though some areas were seen to have a negative correlation, overall, there is a positive correlation between the two variables. It should be noted that the primary growth y-axis is flipped to examine if a negative correlation between the variables is present.

4. Discussion
Since coralline algae is a marine calcium carbonate flora, it uses photosynthesis to grow. This means that when there is more sea ice cover, not as much sunlight is able to penetrate through to the algal. Therefore, this means that in the colder winter months, less growth will occur and during the summer months when the sea ice breaks up, more sunlight is able to penetrate the oceans surface, thereby having higher growth increments. This trend was seen in all of the samples investigated in this study. All three samples, 19AB-10, 19AB-40, and 19AB-55 showed low winter growth and high summer growth anomalies. As seen in Figure 2, the average growth for each year was determined and then compared against the sea ice coverage in that area. Figure 3 shows how the average growth increments per year has been declining since 1981. To determine if there is a correlation between the variables, the primary growth y-axis was inverted. Interestingly, what was determined in this study was that even though growth increments have been declining since 1981, so has sea ice coverage. As mentioned before, one would think that as more sea ice melts, there should be an inverse relationship correlating with more growth increments since there would be more available sunlight (Halfar et al. 2013). This shows that the sea ice proxy isn’t the only reason that the coralline algae growth has declined over time. Other factors that can affect the growth must be considered to properly understand how the growth relationship isn’t the sole factor.

Some factors might include increased phytoplankton in the water column. Since the phytoplankton also require sunlight to photosynthesize, this also means that as sea ice melts, there will be more abundances of phytoplankton absorbing incoming sunlight (Halfar et al., 2011).

Another factor that should be taken into consideration is that with a rapidly changing ecosystem, the biodiversity that live in the Arctic regions have to adapt to their surroundings. This would affect entire food webs in the Arctic region; one particular species would be sea urchins (Rasher et al., 2020). Due to a hyperabundance of the main herbivore in the Arctic regions, sea urchins are detrimental since they graze on the topmost layer of the coralline algae degrading its structure (Rasher et al., 2020) This makes it harder to capture climate data when observing the sample in a lab.

A final factor to consider is that the warming of Arctic ocean water has made calcium carbonate organisms harder to grow and survive. The extent of this damage is better understood when looking at how coralline algae build their skeleton using high magnesium-calcite (Chan et al., 2020). Due to magnesium-calcite being much more soluble in higher temperatures, this will affect the annual growth rate of the coralline algae as the ocean waters get warmer (Chan et al., 2020).

5. Conclusion

Understanding and interpreting past climatic data is an important step to help predict future climate trends. By looking at historical climate archives and realizing ongoing trends, it enhances our understanding of the extent the climate in the Arctic is negatively changing. Seasonal data shows that over the past 40 years, sea ice has been melting at alarming rates. It seems like the growth rate of the coralline algae in the Arctic Bay area is also negatively affected by environmental factors as well. While finding that it’s inconclusive that sea ice coverage is directly affected the growth rate of the coralline algae, it does play a factor in the overall biodiverse structure in Arctic Bay. Due to these findings, it’s clear that more research needs to be done on growing algal samples from other regions in the Arctic to fully understand the damaging effect climate change is having on the Arctic ecosystem.

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References


Scurci: Sea Ice Extent in the Arctic over 40 Years


U.S. Climate Resilience Toolkit Climate Explorer, Arctic Bay (2020)