YGS Miscellaneous Report MR-26

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Front cover: Carbon mineralization (white crust) on ultramafic tailings at the Clinton Creek mine, western Yukon. Photo credit: Greg Dipple, UBC.

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# Regional scale 3D modelling of magnetic data to assess carbon mineralization potential of serpentenized ultramafic rocks in the Yukon

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## Abstract

Serpentinized ultramafic rocks contain minerals that are highly reactive with $CO_2$. These rocks are becoming increasingly recognized for their potential to act as atmospheric $CO_2$ sinks. Carbon mineralization locks $CO_2$ in carbonate minerals and stores it over geological time scales. This is a naturally occurring process but one that can be accelerated through increasing the available surface area of serpentinized material, or through injection of $CO_2$-enriched fluids into serpentinized rock substrates. The Yukon has significant occurrences of ultramafic rock throughout the territory, covering a mapped areal extent of approximately 2000 $km^2$. This work represents a preliminary attempt to review territorial opportunities for carbon mineralization via ultramafic rocks. Regional scale magnetic data which can help identify serpentinized parts of ultramafic bodies was used to remotely locate prospective ultramafic rocks in the Yukon, and to model targeted bodies in 3D to derive their volumes and estimate their $CO_2$ mineralization capacities. Local volumes of serpentinized rock modelled within the depth interval of 0 to -4000 m range up to 361 $km^3$, and total capacity estimated for all modelled sites in the Yukon from 0 to -4000 m depth is >1600 $GtCO_2$. In order to meet emissions-offset targets required to mitigate climate change, such natural carbon sinks providing potentially large storage capacities must be considered part of the solution. Results of this study, based on regional-scale public datasets, are meant as a guide to direct future investigations with higher resolution mapping, data collection, and modelling, together with necessary consideration to existing land ownership, land use, infrastructure, and access.

## Plain language summary

This report provides a first assessment of the potential for capturing atmospheric carbon ($CO_2$) in altered ultramafic rocks in the Yukon. Ultramafic rocks contain more than 18% magnesium (as MgO). Magnesium combines readily with carbon in the atmosphere to form an inert carbonate mineral (magnesite, $MgCO_3$). Altered ultramafic rocks, also called serpentinite for their green colour, are most effective for this reaction and commonly contain the mineral magnetite that can be detected in regional magnetic surveys throughout the Yukon. Using geological maps and regional magnetic data, three-dimensional models were constructed to evaluate potential volume of reactive serpentinite at more than 90 locations throughout the Yukon. Using these models, it is estimated that more than 1600 gigatonne (Gt) of $CO_2$ could be captured if all serpentinite was exposed to, or injected with, atmospheric carbon. Individual sites have estimates ranging from less than 2 Gt to more than 500 Gt of potential $CO_2$ capture; values that could contribute to meeting emissions targets for greenhouse gases.

# Introduction

Solutions are urgently needed to offset anthropogenic global $CO_2$ emissions and meet the goal of avoiding a 1.5°C global temperature increase and the accompanying negative impacts on climate and the human population (Allen et al., 2018). Science, technology, and engineering bodies are leading the way in developing means and technology to both reduce $CO_2$ emissions, and capture and store atmospheric $CO_2$ Much of this work has focused on carbon capture and storage technologies where $CO_2$ is captured and then stored typically in sedimentary basins, including in depleted oil and gas reservoirs (Raza et al., 2019). An alternative means of directly capturing and storing carbon is through carbon mineralization (Fig. 1), where $CO_2$ reacts with cations, primarily $Mg^{2+}$ and $Ca^{2+}$, in certain mafic and ultramafic rocks, to form mineral carbonates (e.g., Lackner et al., 1995). Serpentinized ultramafic rocks, which typically have high magnesium (Mg) contents, are particularly effective in mineralizing atmospheric $CO_2$ (Power et al., 2013a). Serpentinized ultramafic rocks are found world-wide in many different geological environments, and there is potential for large scale $CO_2$mitigation via mineralization of these rocks or material derived from them.

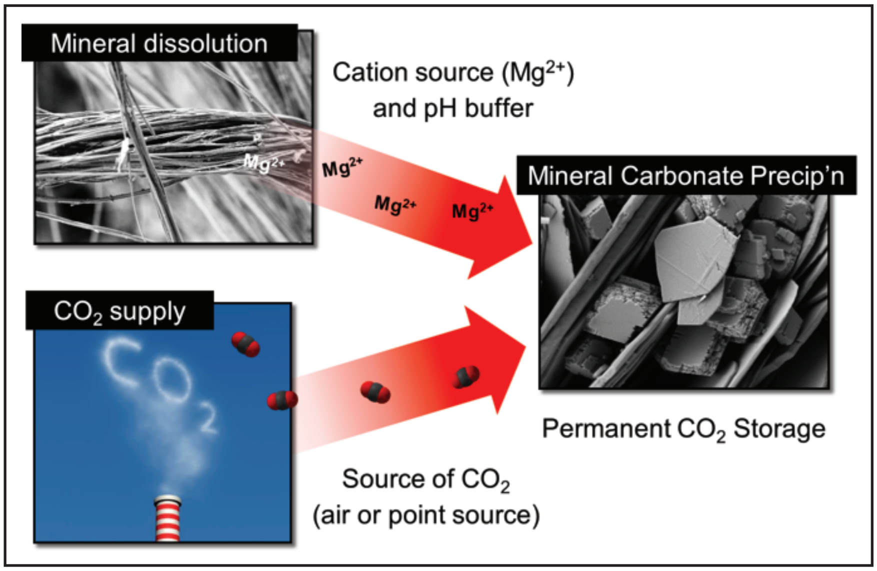


**Figure 1.** *Labile $Mg^{2+}$ cations in high Mg rocks, like serpentinized ultramafic rock, have a high reactivity with $CO_2$, and bind with it to crystallize magnesium carbonate minerals. These minerals are naturally stable over geological time. Photomicrograph at top left shows chrysotile fibers from Clinton Creek, Yukon. Photomicrograph at right shows magnesite and hydromagnesite carbonate sediments from the Atlin playas, northern British Columbia.*

Serpentinized ultramafic rock mined for commodities like nickel (Ni), copper (Cu), cobalt (Co), and platinum group elements (PGE) provides an excellent substrate for carbon mineralization. Such mines have an opportunity to offset $CO_2$ emissions generated during their production using mine waste, or mine tailings, in a process known as ex-*situ* carbon mineralization (e.g., Wilson et al., 2014; Vanderzee et al., 2019; Power et al., 2020). Deep ultramafic rock reservoirs may provide a separate medium for $CO_2$ storage via injection of fluids mixed with captured $CO_2$. This process is referred to as *in-situ* carbon mineralization, where a high pressure and temperature environment significantly enhances capacity for $CO_2$ storage (Kelemen et al., 2011).

The Yukon has significant occurrences of ultramafic rock, with the mapped and inferred extent of ultramafic and related bodies in the Yukon bedrock geology database (Yukon Geological Survey, 2022) totaling 2025 km$^2$ (Fig. 2). Some of these occurrences are known hosts to nickel, copper, and platinum group minerals, with mineral exploration companies actively investigating their mining potential. There may be future opportunities in the territory to utilize ultramafic rocks for ex-*situ* or *in-situ* carbon mineralization. To understand the carbon mineralization potential at the territory-scale, public geological data and magnetic data were assessed to first determine distribution, and then estimate the volume of serpentinized ultramafic rocks in the Yukon. Mineral explorers and groups interested in carbon capture via mineralization can use outcomes of this assessment as a guide to inform more detailed work on individual prospective ultramafic units.

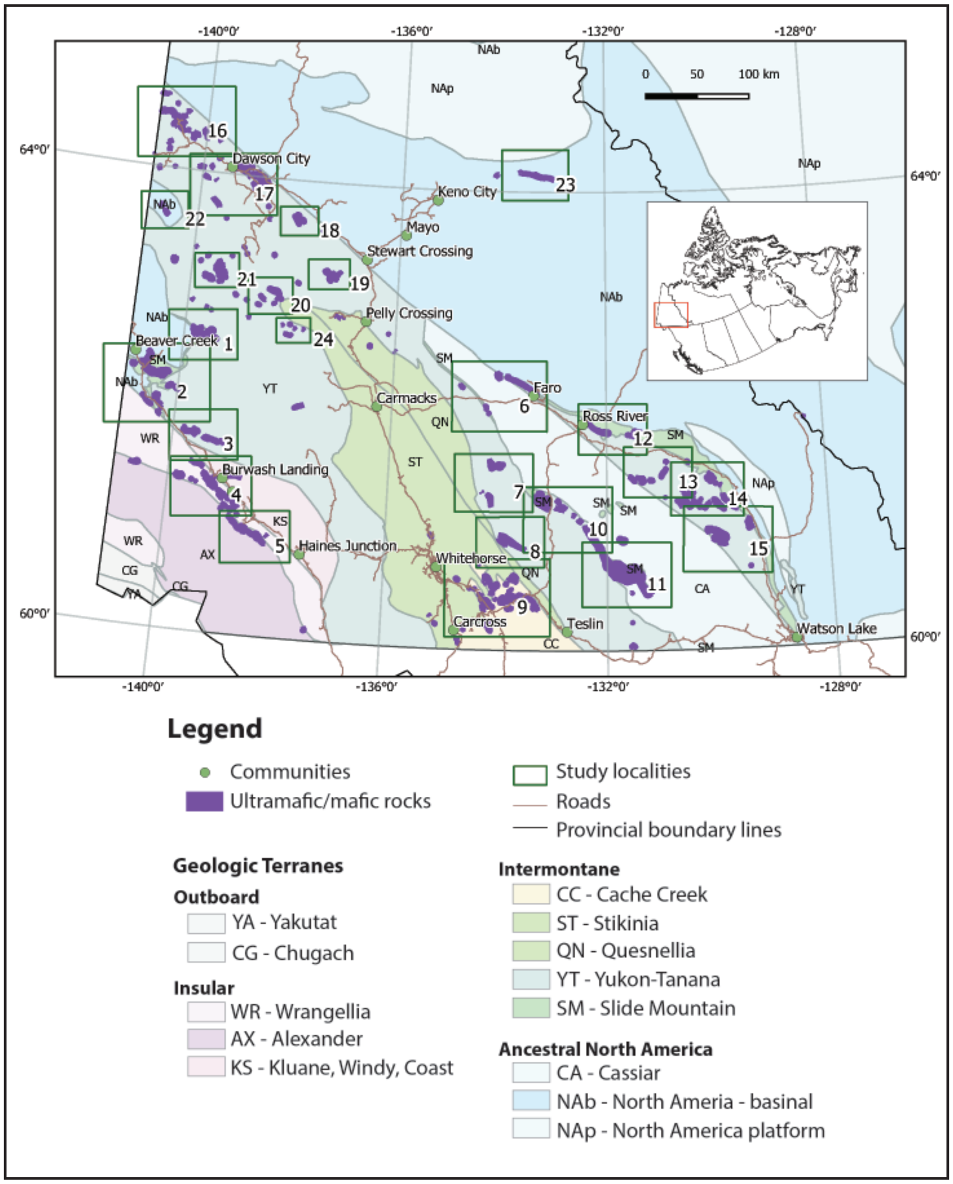
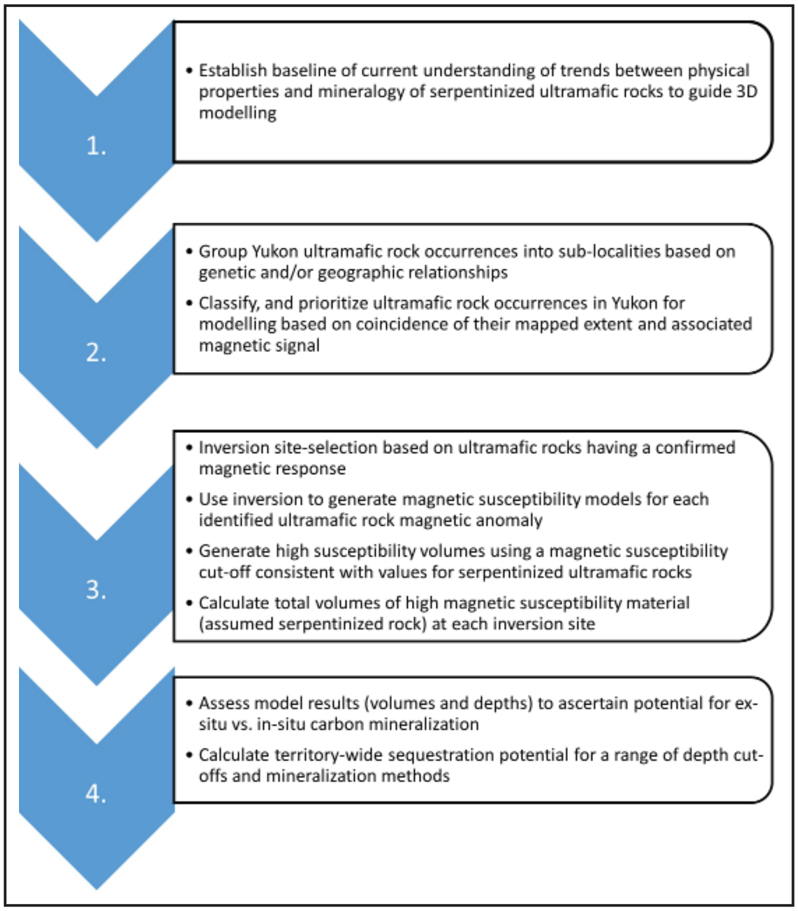


**Figure 2.** *Ultramafic rock localities in the Yukon investigated and modelled for this project. Ultramafic rock polygons extracted from the Yukon bedrock geology database (Yukon Geological Survey, 2022). Cordilleran terranes from Colpron and Nelson (2011).*

## Scope of work and workflow

This work is modelled after a Geoscience BC-supported project lead by the Mineral Deposit Research Unit (MDRU), the Bradshaw Research Initiative for Mining and Metals (BRIMM), and the Carbon Mineralization Laboratory at the University of British Columbia (Mitchinson et al., 2020). The British Columbia Carbon Mineralization Potential (BC CaMP) project was initiated to estimate the $CO_2$ storage capacity of serpentinized ultramafic rocks in British Columbia using magnetic inversion modelling methods. A similar workflow to that used for the BC CaMP project was applied to the Yukon and is outlined in Figure 3.



1.
- Establish baseline of current understanding of trends between physical properties and mineralogy of serpentinized ultramafic rocks to guide 3D modelling

2.
- Group Yukon ultramafic rock occurrences into sub-localities based on genetic and/or geographic relationships
- Classify, and prioritize ultramafic rock occurrences in Yukon for modelling based on coincidence of their mapped extent and associated magnetic signal

3.
- Inversion site-selection based on ultramafic rocks having a confirmed magnetic response
- Use inversion to generate magnetic susceptibility models for each identified ultramafic rock magnetic anomaly
- Generate high susceptibility volumes using a magnetic susceptibility cut-off consistent with values for serpentinized ultramafic rocks
- Calculate total volumes of high magnetic susceptibility material (assumed serpentinized rock) at each inversion site

4.
- Assess model results (volumes and depths) to ascertain potential for ex-situ vs. in-situ carbon mineralization
- Calculate territory-wide sequestration potential for a range of depth cut-offs and mineralization methods

**Figure 3.** *Generalized project workflow culminating in estimation of regional-scale carbon mineralization capacities of serpentinized ultramafic rocks in the Yukon.*

The objective of this assessment is to use regional scale, publicly available geological and geophysical data to locate and model highly $CO_2$-reactive serpentinized ultramafic rocks in the Yukon to estimate their volumes and their notional $CO_2$ mineralization storage capacities. This represents a preliminary attempt to review territorial opportunities for carbon mineralization using ultramafic rocks. Using regional scale data, the resulting models are developed at a relatively coarse scale. Individual sites of interest would ultimately require detailed mapping and modelling with higher resolution data to more accurately assess distributions and volumes of serpentinized ultramafic rock.

## Carbon mineralization and ultramafic rocks

Carbon dioxide from the atmosphere is reactive with cations in solution. From this reaction, carbonate minerals are formed. This process is known as carbon mineralization. Magnesium from brucite and serpentine minerals in serpentinized ultramafic rocks is loosely bound and particularly highly reactive with $CO_2$, forming magnesium carbonates that can lock up significant amounts of $CO_2$, and store it over geological timescales (Lackner, 2003).

This process happens naturally at slow rates but can be accelerated if rock surface area is increased, such as through crushing and milling that occurs during ore processing at mines (Wilson et al., 2009, 2014; Turvey et al., 2018). Serpentinized ultramafic mine tailings can be very efficient at capturing $CO_2$. Wilson et al. (2014) determined that approximately 11% of $CO_2$ emissions from the Mount Keith nickel mine in Western Australia were offset passively through carbon mineralization occurring in its tailings (Fig. 4). This is an example of *ex-situ* carbon mineralization (Power et al., 2013b). This significant emission offset has attracted the interest of mineral exploration and mining companies who are making greater efforts and seeking various means to reduce their $CO_2$ emissions. Since critical metals like nickel, copper, and cobalt are often hosted in ultramafic rocks, there is a very exciting and realistic opportunity to both mine critical metals while simultaneously offsetting emissions and decarbonizing the critical metals supply chain.

***Figure 4.*** *Mineral carbonates forming on serpentinized ultramafic rock tailings at the Mount Keith nickel mine in Western Australia. Image from Power et al. (2014).*

Carbon mineralization is also speculated to happen at accelerated rates at high temperatures and pressures present at depth within the crust. Early research and modelling have been done to assess carbon mineralization processes and rates via injection into deep (>2 km) ultramafic rock bodies (Kelemen and Matter, 2008). This style of injection-driven carbon mineralization, or *in-situ* carbon mineralization, shares similarities with the CarbFix Project in Iceland where $CO_2$ in solution is mixed with water and injected into basalt formations (Matter et al., 2011; Snæbjörnsdóttir et al., 2020). In Iceland, basalt provides cations ($Mg^{2+}$, $Ca^{2+}$, and $Fe^{2+}$) for carbon mineralization, and importantly, it provides pore space for carbonate mineral crystallization. Ultramafic rocks, and especially serpentinized ultramafic rocks, are significantly more reactive than basalt, however, they lack the high porosities of the Holocene basalts in Iceland, and mineralization of carbonate minerals will depend on availability of internal fracture networks to provide volume for accommodation of new minerals (Kelemen and Matter, 2008). Carbon mineralization by injection into deep ultramafic rocks has not yet been widely demonstrated or proven, however, several collaborators including Geoscience BC, University of British Columbia, and CarbFix are currently evaluating sites based on BC CaMP project results for a pilot *in-situ* carbon mineralization study in British Columbia (Steinthorsdottir et al., 2024).

## Physical rock property signatures of ultramafic rocks in British Columbia and the Yukon, and remote detection using geophysics

Three-dimensional modelling and volume estimation of serpentinized ultramafic rock bodies in the Yukon was guided by an understanding of the behaviour of physical properties of ultramafic rock in various states from least-altered fresh igneous rocks, through variably serpentinized, to carbonate-altered. Physical property trends in ultramafic rocks were analyzed for British Columbia and Yukon samples by Cutts et al. (2020, 2021). Data from Cutts et al. (2020, 2021) show a consistent decrease in density of ultramafic rocks with increased serpentinization (Fig. 5). This is due both to destruction of higher density primary olivine and pyroxene minerals in favour of less dense serpentine minerals and brucite, and an increase in porosity with serpentinization. An increase in magnetic susceptibility occurs during serpentinization due to the formation of magnetite. If serpentinized rocks then become carbonated, a reversal in the trends is seen. Density increases with decreasing pore space and the formation of typically dense carbonate minerals, and magnetic susceptibility decreases corresponding to a breakdown of magnetite.

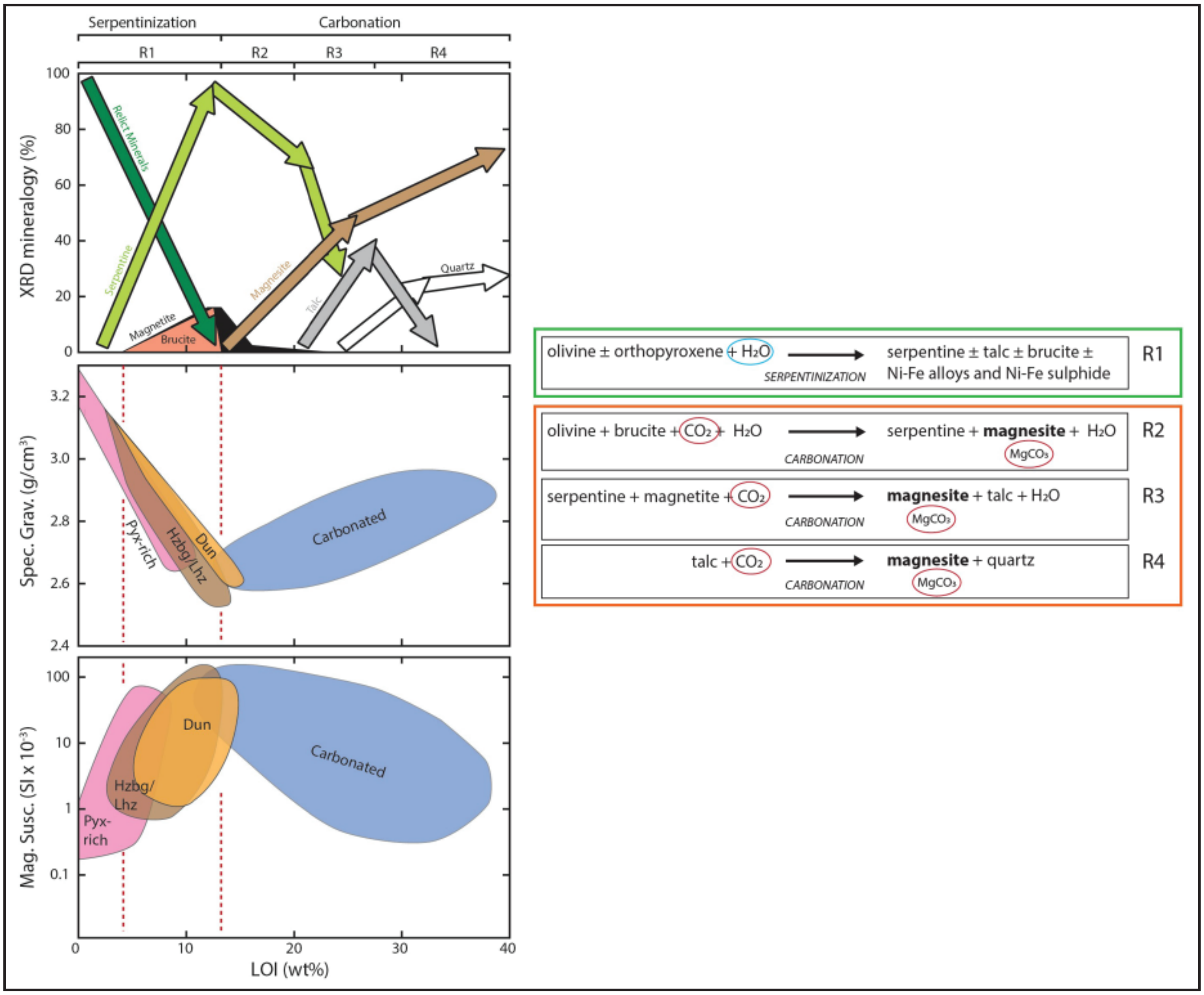


**Figure 5.** *Density and magnetic susceptibility trends correlated with serpentinization and carbonation of ultramafic rocks from British Columbia and the Yukon (figure from Mitchinson et al., 2020). Loss on ignition (LOI) tracks alteration of the rock initially to serpentinite and then to carbonate. Peak serpentinization occurs at approximately 13 wt% LOI, after which further increases in LOI are correlated with carbonation of the rock. Red dashed lines mark the LOI window where highly reactive brucite forms during serpentinization.*

The results of physical property data analysis indicate that serpentinized ultramafic rocks have unique physical properties allowing them to be potentially distinguished from unserpentinized or carbonated ultramafic rocks, and other surrounding rocks. By extension, it should be possible to remotely explore for serpentinized ultramafic rocks using data from gravity surveys, which respond to density variations within the Earth's crust, and from magnetic surveys, which respond to the magnetic susceptibility of rocks. For this preliminary assessment of serpentinized ultramafic rocks in the Yukon, magnetic data is used to identify magnetically susceptible (and likely serpentinized) ultramafic rocks. There is excellent potential to use gravity as a tool to remotely detect and model serpentinized rocks, based on the clear trends in density data from ultramafic samples. At this time however, publicly available regional gravity data is too coarse (gridded to a 2 km interval) to be effective in modelling individual ultramafic bodies or serpentinized domains within them. If higher resolution gravity datasets are eventually collected over ultramafic rock districts or individual bodies, analyzing and modelling them in an integrated manner with magnetic data will lend confidence to identification and volume estimation of serpentinized rock domains.

## Ultramafic rocks in the Yukon

The following section describes major ultramafic rock occurrences and their distribution in the Yukon. They are here subdivided into: 1) ultramafic rocks that represent basal sections of ophiolites, or accreted slivers of oceanic lithosphere; 2) ultramafic rocks that are intrusive in nature; and 3) origin unknown or unclassified ultramafic rocks. The distributions of these various ultramafic assemblages are shown in Figure 6.

### Ophiolitic and tectonically emplaced ultramafic rocks

#### *Northern Cache Creek (Atlin) terrane*

Ultramafic rock bodies in the northern part of Cache Creek (Atlin) terrane in south-central Yukon (orange polygons on Figure 6) occur mainly along alpine ridges between Whitehorse and Teslin, as well as east of Carcross. Exposures are generally fresh and comprise harzburgite, dunite, pyroxenite and lherzolite. Locally, the ultramafic rocks are more serpentinized and intruded by gabbro, or comprise carbonate-altered pyroxenite (listwaenite). The ultramafic rocks are in structural contact with underlying mafic volcanic and volcaniclastic rocks of the Joe Mountain formation. Northwest of Teslin, ultramafic rocks are intruded by Early Cretaceous granodiorite on Hayes Peak. Ultramafic rock bodies generally coincide with prominent positive magnetic anomalies that closely approximate the mapped extent of the units, indicating that they are serpentinized to the extent that they should be suitable candidates for carbon mineralization.

#### *Slide Mountain terrane*

Ultramafic rocks associated with the Slide Mountain terrane form small bodies within basalt, chert and argillite that occur along the boundary between Yukon-Tanana terrane and continental margin rocks of Ancestral North America (red polygons on Figure 6). In the Yukon, their main occurrences are found: (1) in the Finlayson Lake area, northeast of the Tintina fault; (2) in the Wolf Lake area southwest of the Tintina fault; and (3) in the Wellesley Lake area of western Yukon. The rocks consist of variably serpentinized harzburgite tectonite and minor dunite, associated with pyroxenite, gabbro, diabase, and rare throndhjemite. Most ultramafic occurrences coincide with magnetic highs indicative of extensive serpentinization and secondary magnetite development.

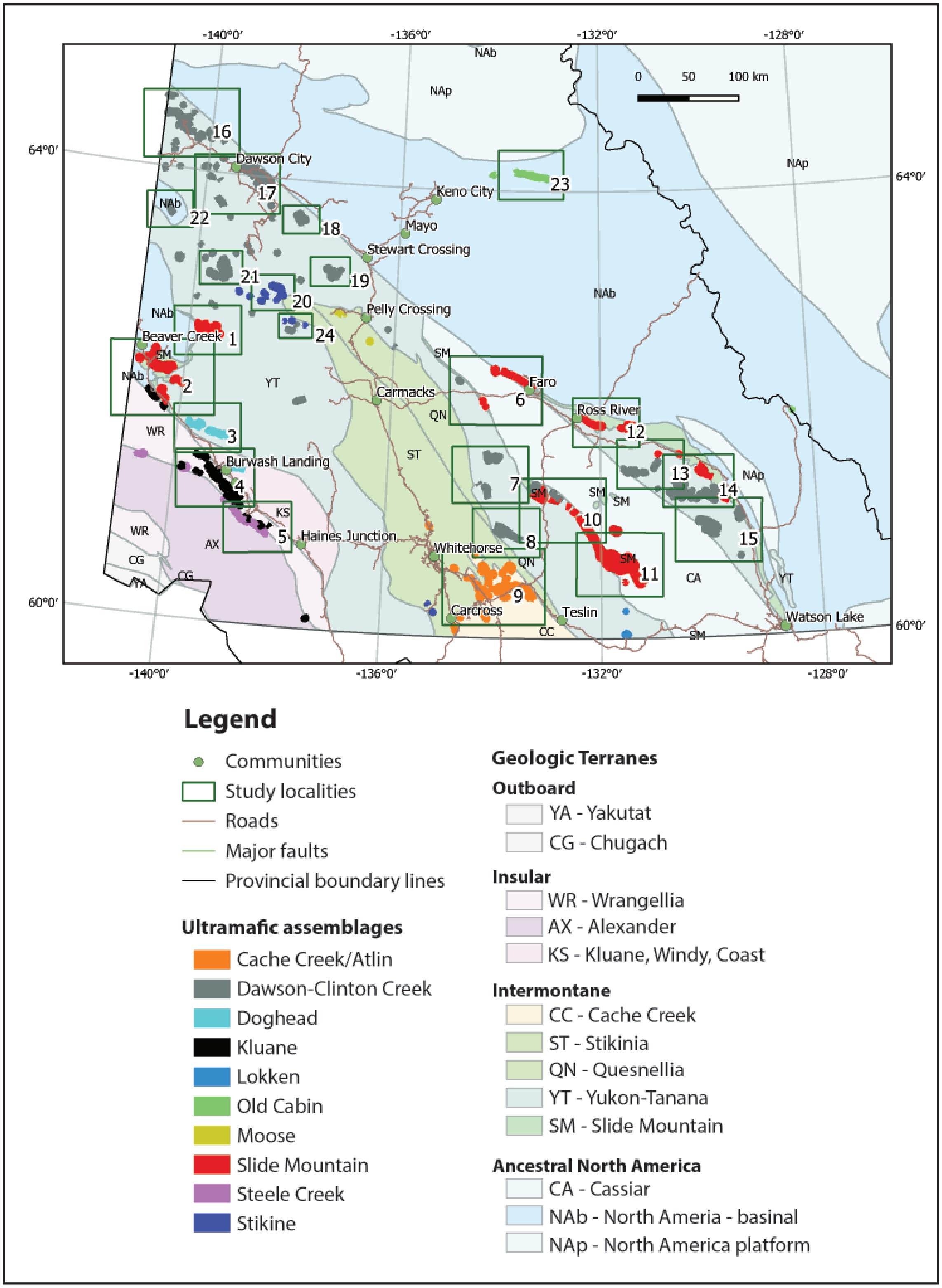


***Figure 6.*** *Distribution of ultramafic rock assemblages in the Yukon, derived from the Yukon bedrock geology database (Yukon Geological Survey, 2022). Cordilleran terranes from Colpron and Nelson (2011).*

### *Dawson-Clinton Creek assemblage*

Ultramafic rocks imbricated within the Yukon-Tanana terrane in western and south-central Yukon are assigned to the Dawson-Clinton Creek assemblage (dark grey polygons on Figure 6). These rocks had previously been assigned to the Slide Mountain terrane. Main exposures are found near Dawson City, at Clinton Creek near the Alaska border, and at Dunite and Tower Peaks north of Teslin. Smaller occurrences of serpentinized rocks throughout the Yukon-Tanana terrane may also be related to the Dawson-Clinton Creek assemblage; prominent exposures occur at Australia Mountain, Flat Top and Mount Stewart south of Dawson, and in the Finlayson Lake area of southeast Yukon. In most cases, the rocks are strongly deformed and altered to serpentinite; harzburgite, dunite, pyroxenite and gabbro are locally preserved in least altered exposures. Ultramafic rocks of the Dawson-Clinton Creek assemblage are typically coincident with strong, positive magnetic anomalies.

### *Doghead assemblage*

Ultramafic rocks of the Doghead assemblage consist of variably serpentinized, deformed and metamorphosed peridotite, gabbro and trondhjemite occurring as klippe overlying Yukon-Tanana terrane (light blue/cyan polygons on Figure 6), and as isolated 1 - 500 m-scale lenses (boudin) within Kluane Schist near Burwash Landing; gabbro and trondhjemite occur as deformed dikes cutting peridotite. Ultramafic exposures generally coincide with magnetic highs.

## Intrusive

### *Kluane ultramafic suite*

A suite of Late Triassic mafic to ultramafic sills intrude upper Paleozoic volcanic and sedimentary rocks of Wrangellia southwest of the Denali fault (black polygons on Figure 6). The sills are feeders to overlying Upper Triassic Nikolai basalt and are associated with Ni-Cu-PGE mineralization. They consist of a thin gabbroic marginal zone at the base, overlain by mela-gabbro, clinopyroxenite, olivine clinopyroxenite, peridotite and dunite. Kluane ultramafic suite rocks typically are associated with positive magnetic responses.

### *Alaskan-type*

Alaskan-type intrusions are poorly documented in the Yukon. Small, convergent margin-related, mafic-ultramafic plutonic bodies intrude island arc terranes of Yukon-Tanana, Quesnellia and Stikinia, and parts of the Insular terranes south of Haines Junction. In general, the plutons consist of hornblende gabbro and diorite, clinopyroxenite, and minor serpentinized dunite. Most prominent ultramafic phases occur in plutons of the Early Jurassic Lokken suite that intrude the Yukon-Tanana terrane east of the Teslin fault (blue polygons on Figure 6).

## Other mafic-ultramafic rocks

### *Ultramafic rocks within the Dawson fault zone*

Slivers of ultramafic rocks occur discontinuously within the Dawson fault zone of east-central Yukon. The most continuous exposures northeast of Mayo have a strike-length of ~30 km and are up to 1 km in width (green polygons on Figure 6). These may be feeder intrusions to volcanic rocks of the Cambrian Old Cabin Formation. The rock varies from strongly sheared serpentinite to pervasively quartz-carbonate altered listwaenite. The serpentinite is strongly magnetic and corresponds to magnetic highs, while the listwaenite is generally associated with magnetic lows.

### *Unclassified ultramafic rocks*

Several ultramafic occurrences do not fall into the other ultramafic rock classifications used here and detailed descriptions of their petrology and alteration are limited in the literature. They occur in the Yukon-Tanana, Cassiar, and Quesnel terranes, or along terrane boundaries. The unclassified ultramafic occurrences have a small areal extent and thus are volumetrically insignificant in the overall carbon mineralization capacity for the Yukon.

## Site selection for modelling

For this work we assumed that ultramafic rocks correlated with positive magnetic anomalies contain magnetite that was formed during serpentinization. Weakly magnetized, or non-magnetic ultramafic rocks are assumed to have not undergone serpentinization or were subsequently carbonate-altered, a process leading to magnetite destruction. This is a broad assumption since it is both possible for fresh ultramafic rock to contain magnetite, and for serpentinized rock to lack magnetite depending on protolith and local site fluid history (Cutts et al., 2021). Nonetheless, considering bulk sample trends, these assumptions seem reasonable at a regional scale. Future local scale investigations, however, should involve detailed analysis of site-specific mineralogy and physical properties to guide modelling.

In a preliminary screening done to determine sites for 3D inversion modelling and serpentinized rock volume estimation, each ultramafic polygon from the Yukon bedrock geology database (Yukon Geological Survey, 2022) was assigned a classification based on whether there was a correlated positive magnetic response in the magnetic data (Yukon-Alaska 100 m residual total field data, Geological Survey of Canada, 2019). The same classification scheme that was used for the BC CaMP project was used here (Mitchinson et al., 2020). Classes “A”, “B”, and “C” were assigned to polygons that have a clear spatial association with positive magnetic anomalies (Fig. 7). Approximately 85% of the aerial extent of mapped ultramafic rocks in the Yukon have a positive magnetic response (Table 1). This suggests that a significant proportion of Yukon ultramafic rocks are serpentinized. Magnetic anomalies associated with these presumed serpentinized rocks were modelled using inversion. Other polygons, where a correlative relationship to a positive magnetic response is unclear, or there is no magnetic response, were assigned classes “D”, “E”, “F”, “X”, and “ND” (Fig. 7; Table 1). These bodies were not followed up with 3D inversion modelling.

Based on the preliminary assessment of the presence and coincidence of magnetic responses, twenty-four ultramafic rock localities, or geographic clusters of ultramafic rock bodies, were focused on for 3D magnetic inversion modelling. From the 24 localities, 90 sites in total were selected for 3D modelling.

## Geophysical inversion to model serpentinized rock bodies in 3D

Geophysical inversion methods were used to model the magnetic ultramafic bodies in 3D. Geophysical inversion is used to recover physical property models of the Earth that predict a set of observed data. The magnetic 3D inversion code used for modelling is from Simulation and Parameter Estimation in Geophysics (SimPEG), an open-source geophysical data modelling code repository (Cockett et al., 2015). The magnetic data used was the Yukon-Alaska 100 m gridded residual total field magnetic data compilation from the Geological Survey of Canada (2019).

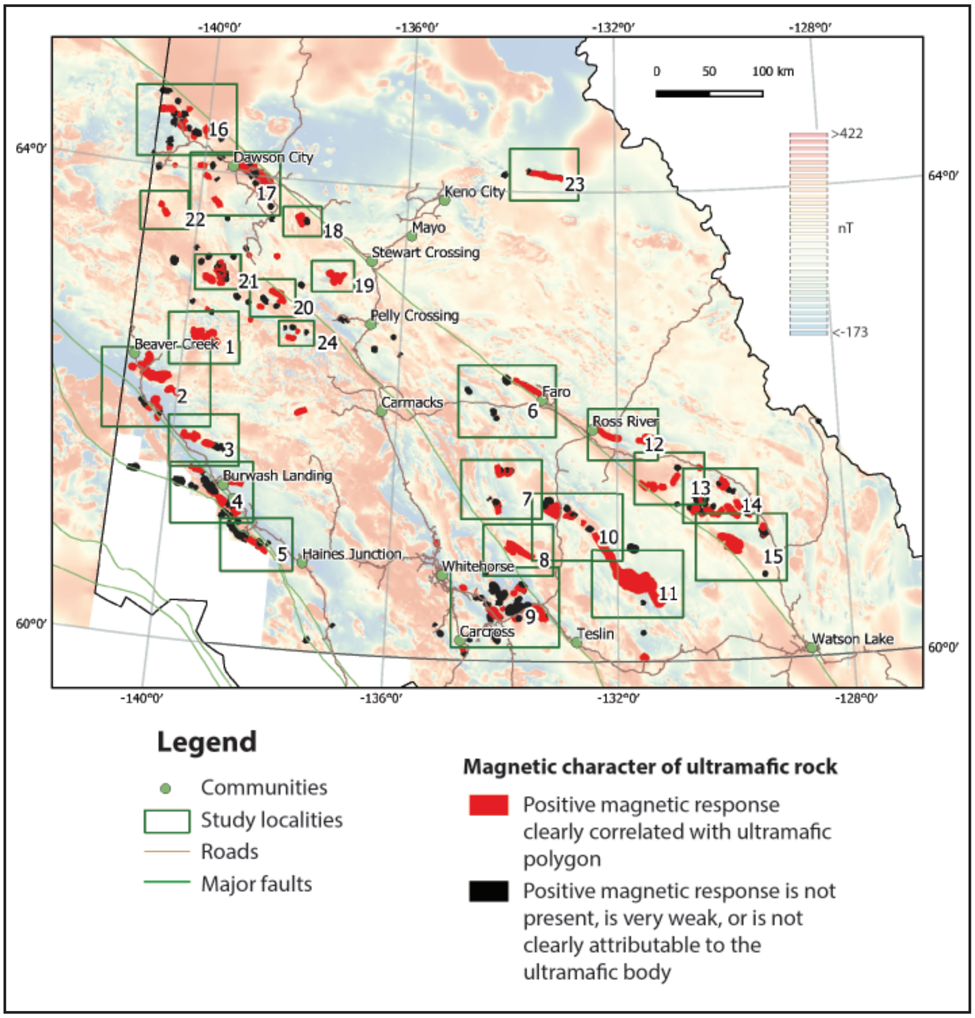


***Figure 7.*** *Distribution of mapped and interpreted ultramafic units from the Yukon bedrock geology database (Yukon Geological Survey, 2022) coloured based on the mapped polygons correlations with positive magnetic anomalies. Overlain on residual total field (RTF) magnetic data (Geological Survey of Canada, 2019).*

The geophysical inversion routine is captured in a series of Jupyter Notebooks (available on request from the first author), and only a general summary is provided in this report. The inversion methodology developed during the BC CaMP project, was modified for this project. One notable modification is that a regional magnetic response removal step was added before individual sites were modelled. This was to better separate out the magnetic signal caused by local ultramafic bodies and to improve modelling of the individual sources. Following removal of a regional magnetic signal, local inversions were run as a bulk process. To expedite the work, the process of creating the topographic data file, the observed magnetic data file, and the 3D inversion mesh, were automated. The magnetic data and topographic data resolution were determined based on the geographic area covered, and the inversion mesh and cell sizes were similarly automatically defined to avoid overly large and intensive inversion problems. The size of the local models ranged from about 4 km to about 30 km on their long edge in plan view, with magnetic data down-sampled to approximately 1000 data points for inversions, and 4 horizontal mesh cells per data point. An uncertainty of 2 nT was applied to the observed magnetic data.

***Table 1.*** *Classification system for ultramafic rock polygons from the Yukon bedrock geology database (Yukon Geological Survey, 2022) based on spatial correlation with positive magnetic anomalies.*

| Classification | Description | Confidence that magnetic anomaly is related to mapped ultramafic unit | Number of polygons represented | Total area (km$^2$) of mapped polygons within class |
|---|---|---|---|---|
| A | Positive magnetic anomaly well-correlated spatially to mapped ultramafic polygon | High | 69 | 494 |
| B | Positive magnetic anomaly extends beyond mapped ultramafic polygon | High | 24 | 24 |
| C | Irregular or patchy positive magnetic anomaly contained within a mapped ultramafic polygon | High | 117 | 1186 |
| D | Polygon with offset positive magnetic anomaly (may be due to the ultramafic or adjacent unit) | Low | 113 | 99 |
| E | Can't isolate/differentiate a distinct magnatic signal from surrounding magnetic material | Low | 17 | 77 |
| F | Very weak to no magnetic signal correlated to the mapped ultramafic polygon | None | 115 | 115 |
| X | Generally small polygon of varied magnetic response, overall insignificant contribution to ultramafic rock volume | None | 63 | 1 |
| ND | No magnetic data coverage | None | 5 | 29 |
|  |  | **Total** | 523 | 2025 |

There are many physical property models that can explain an observed geophysical dataset. Typically, geophysical inversion code includes parameters that establish boundaries on the inversion to limit results, forcing them to be simple and smoothly varying in space, and for model values to be within specified ranges. However, while this necessarily reduces the vast number of models down to those that make physical and geological sense, this still leaves a large number of possible model outcomes.

One way to sample a range of inversion results is to use ℓp-norm pairs to vary the smoothness of the outcome and to control the model values (Fournier and Oldenburg, 2019). ℓp norms for $p=2$, is the standard for typical unconstrained inversions, and generate smooth bodies with lower model values. When $p<2$, the result is a more compact model, with higher model values concentrated in smaller volumes. For this project, to explore the model space, five different models were ultimately generated for each site by varying ℓp norms pairs (one term related to smallness, or closeness to a reference model, and a second related to smoothness), with varying reference models guiding the inversion. Inversion results for each site were reviewed to ensure model objectives are met and to evaluate 3D distributions and ranges of magnetic susceptibility values. On review, two ℓp norm/reference model configurations consistently yielded results with compact but not overly blocky appearances, and these two were selected for final volume calculations. The first configuration (“Model 1”) used regional-scale inversion results as a reference model, and applied ℓp norm pair ℓ2-ℓ0. The second configuration (“Model 2”) again used the regional inversion model as a reference model, and applied ℓp norm pair ℓ2-ℓ1. Certain inversions failed, which was due, either to the inability to fit the observed data within the imposed constraints, or else to incomplete magnetic data coverage.

Appendix A presents data and modelling results as maps and sections. Appendices B and C contain details of individual inversion outcomes. High magnetic susceptibility bodies recovered for some of the interpreted and mapped ultramafic polygons are significantly larger than what is expected based on map patterns and field relationships. This may be caused by magnetic remanence. Magnetic remanence is a retained magnetization within a rock, locked in when magnetic minerals crystallize or recrystallize, that may preserve a magnetization direction different from Earth's current inducing field. If remanent magnetization within a body aligns with the inducing field, it may result in higher-than-expected measured magnetic amplitudes.

Synthetic modelling studies carried out during the BC CaMP project indicated that remanently magnetized serpentinized ultramafic rocks in British Columbia may cause very strong magnetic anomalies that cannot be explained by the typical ranges of magnetic susceptibilities found in serpentinized rocks (Mitchinson et al., 2020). Unrealistically high magnetic susceptibilities and depths unsupported by geological evidence were required to fit the observed data. This indicates that when remanent magnetization is present, application of unconstrained inversion techniques may lead to geologically unrealistic models. Recovered volumes of high susceptibility material are expected to be overestimated in these cases. Ultramafic bodies suspected of being remanently magnetized would be more accurately modelled if detailed physical property data, including natural magnetic remanence, were collected from the rocks. This should be a consideration for future investigations of any of the Yukon sites modelled in this report.

## Estimating carbon mineralization capacity of serpentinized ultramafic rocks in the Yukon

High magnetic susceptibility volumes, which are assumed to represent the most strongly serpentinized parts of the modelled ultramafic units, are derived from a magnetic susceptibility cut-off value of 0.04 SI. A lower cut-off value of 0.02 SI was used for volume determination for the BC CaMP project, which was based on physical property analyses documented in Cutts et al. (2020) and correlates with the first quartile value for magnetic susceptibility for samples that were determined to be >60% serpentinized (generally, highly reactive rocks for $CO_2$ capture). This cut-off value did not effectively isolate realistic bodies from the local Yukon inversion models, capturing too large a portion of the model cells. It was not explored whether this was due to the modified inversion methodology used here, or if serpentinized ultramafic rocks in the Yukon inherently have higher magnetic susceptibilities. The dataset presented in Cutts et al. (2020) that was used to decide cut-off values for the BC CaMP project was composed of mainly samples from British Columbia; Yukon samples made up only 16 of the 441 samples. More mapping and physical property analyses of Yukon ultramafic rocks would be required to determine what magnetic susceptibilities would be representative of strongly serpentinized volumes of Yukon ultramafic rocks. These values might also be found to vary between ultramafic rock protoliths and assemblages. The median volume of two models ("Model 1" and "Model 2" described in Section 8) was used as the representative volume of 'serpentinized' material from which to estimate the capacity for ultramafic rock at each inversion site to mineralize $CO_2$.

The BC CaMP project investigations showed that using relatively coarse publicly available magnetic data for inversion may result in somewhat smooth model results that see the core volumes of high susceptibility material sitting at greater depths than expected (Mitchinson et al., 2020), in some cases, not reaching the surface where serpentinized rock is known to occur. This should be a consideration for the Yukon project as well, and this has implications on the calculations of carbon mineralization capacity per depth interval. Near surface capacity maybe be underestimated, and at depth capacity is potentially overestimated. Choice of magnetic susceptibility cut-off will obviously also affect the estimated volumes. More work should be done to test estimated volumes, such as for example, completing forward modelling exercises as in Mitchinson et al. (2020), or testing the methodology on ultramafic bodies with known dimensions.

Since the amount of $CO_2$ that can be sequestered via carbon mineralization in ultramafic rocks depends on whether the mineralization reactions are happening near-surface or at depth, two calculations were used to estimate mineralization capacity. For material modelled within 2 km of the surface, it is feasible that this rock might be accessed by surface mining and an ex-*situ* carbon mineralization scenario is applicable. The reactivity of brucite and serpentine minerals in ophiolitic rocks with $CO_2$ was investigated at the Baptiste nickel deposit in British Columbia by Vanderzee et al. (2019), who determined that 2.3 wt% of MgO is available for reaction with $CO_2$ at surface conditions if the serpentinized rock is crushed and exposed to the atmosphere. Assuming a density of 2800 kg/m$^3$ for serpentinite (Cutts et al., 2021), and using magnesite mineral stoichiometry, it is possible to derive a $CO_2$ reaction capacity of 0.02 tonnes $CO_2$ per tonne (0.0563 Gt per km$^3$) of serpentinized rock (Mitchinson et al., 2020).

At depths greater than 2 km, *in-situ* carbon mineralization may be possible. At these depths and pressures, rapid reaction kinetics are expected if internal fluid pathways allow and the rock is not carbonated (Kelemen and Matter, 2008). All Mg within the ultramafic body could be completely converted to magnesium carbonate ($MgCO_3$, magnesite). This means we only need to estimate the total wt% MgO content of the ultramafic rock host to calculate sequestration capacity. Using magnesite mineral stoichiometry, a $CO_2$ reaction capacity of 0.426 tonne $CO_2$ per tonne (1.2348 Gt CO2 per km$^3$) is derived.

Table 2 shows the estimated $CO_2$capacities at varying depths from surface based on modelled volumes and the above assumptions regarding reactivity of Mg contained within the host rock. Appendix C details the estimated volumes and $CO_2$ mineralization capacities per inversion site

***Table 2.*** *Serpentinite volume and carbon sequestration capacity for all of the Yukon based on volumes of high susceptibility material modelled at varying depths from surface. Detailed data found in Appendix C.*

| Depth interval (km) | Serpentinite volume (km$^3$) | Sequestration capacity (Gt $CO_2$) | Method |
|---|---|---|---|
| 0 to 0.5 | 360 | 20 | *ex situ* |
| 0 to 1 | 729 | 41 | *ex situ* |
| 0 to 2 | 1477 | 83 | *ex situ* |
| 2 to 4 | 1239 | 1530 | *in situ* |

## Discussion and considerations

This study represents a preliminary assessment of locations and volumes of serpentinized ultramafic rocks in the Yukon that could be used to capture and store atmospheric $CO_2$. Several assumptions were made for this assessment, as such, large uncertainties are expected.

The largest volume of high magnetic susceptibility ultramafic rock was modelled at ultramafic study locality 1 (Appendices A-C), specifically at inversion site 1.2, in west-central Yukon. The large mantle massif here is known as Harzburgite Peak, which has previously been interpreted from geological mapping to have a significant structural thickness of 5 km (Canil and Johnston, 2003). Within 0 - 4000 m depth (depths feasible for either ex-*situ* or *in-situ* carbon mineralization), ~360 km$^3$ of high susceptibility material was modelled using a magnetic susceptibility cut-off of 0.04 SI. The carbon mineralization capacity for the same volume was calculated at 238 Gt $CO_2$. This is a significant capacity when considering the Yukon's typical annual $CO_2$ emissions of between 0.6 and 0.7 Mt (Government of Yukon, 2023). The total $CO_2$ mineralization capacity for all bodies modelled from 0 to 4000 m depth is 1613 Gt $CO_2$. While this study indicates that a large $CO_2$ mineralization capacity may exist for ultramafic rocks in the Yukon, it is not realistic, nor expected, for $CO_2$ capture by ultramafic rocks to occur on this scale, as it would require accessing and reacting all serpentinized material in the territory. This work is meant instead to evaluate individual sites for carbon capture potential and to motivate further assessment of these sites. More detailed 3D inversion modelling should be carried out at local sites of interest. This should be done with higher resolution magnetic and gravity data, to best discern serpentinized material from unserpentinized or carbonated ultramafic rocks. Constrained and joint inversions using physical rock property data may provide a promising technique for remote determination of rocks of interest (Heagy et al., 2022). Magnetic remanence is a concern and must be accounted for in local site-scale modelling to provide more accurate volume estimates. More rock property data should be collected to understand controls on geophysical response, and to determine if there are consistencies or differences in geophysical response between different ultramafic suites and protoliths in the Yukon. At the site scale, rock conditions may be expected to be unique, and local distribution of serpentinized material and relationships to neighbouring rocks, mineral reactivity, and physical access to the reactive material, will play important roles in determining how efficient the rock is for capturing $CO_2$.

In terms of site selection for further analysis of ultramafic bodies for $CO_2$ sequestration capabilities, the locations where the greatest volumes of serpentinized ultramafic rocks were modelled are possibly of highest interest (Appendices A-C). However, other important factors will influence whether a particular site can, or should be, followed up for potential future development, including land use and ownership, physical access, and access to existing infrastructure and power sources.

As suggested in the above example of Harzburgite Peak, development of a single ultramafic site with permissive properties for carbon mineralization, using either *ex-situ* or *in-situ* methodologies, could be impactful in terms of $CO_2$ mitigation. If capture and storage is via mine tailings $CO_2$ mineralization, it may be possible to completely offset mine-related emissions (Vanderzee et al., 2019; Power et al., 2020). Although the technology is not yet proven, *in-situ* injection-driven methods have the potential to mineralize significant carbon in deep ultramafic reservoirs. A pilot *in-situ* mineralization study envisioned for southern British Columbia (Steinthorsdottir et al., 2024) could be a model for future in-situ studies and project development in similar ultramafic rocks in other parts of Canada or globally.

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# Appendix A - Ultramafic site locality maps and inversion results

# Appendix B – Inversion result notes and considerations for future analysis

# Appendix C – Estimated inversion volumes and $CO_2$ mineralization capacities per depth interval

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