PETROLOGY AND GEOCHEMISTRY OF THE BELLS MILL ROAD ULTRAMAFIC BODY, PHILADELPHIA PA

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Abstract

A petrographic and geochemical assessment of the Bells Mill Road ultramafic body was conducted to examine its alteration history and to test hypotheses on the source of the ultramafic protolith. The Bells Mill Road ultramafic body is located in the Piedmont region of southeastern Pennsylvania within Wissahickon Valley Park at the intersection of Bells Mill Road and Wissahickon Creek. The Bells Mill Road ultramafic body is one of several altered ultramafic bodies scattered throughout the Pennsylvanian Piedmont province. The local area is host to rocks that are metamorphosed from greenschist to amphibolite facies during accretion onto the continental margin during the Taconic orogeny (450-470 Ma) that overlay a basement composed of higher grade metamorphic rocks of Grenville age (1.0-1.2 Ga).

The geologic history of the Pennsylvanian Piedmont has been thoroughly studied, but the origin of the ultramafic bodies remains a source of contention. There are several competing hypotheses to explain the protolith of these ultramafics, namely: oceanic crust (ophiolite), diapiric mantle, and arc-related magmatic differentiates. Geologic mapping of the body has shown the following lithologic zones: serpentine-talc rock, talc-tremolite schist, anthophyllite-chlorite schist, chlorite schist, and talc-serpentine schist. Spinel chemistry was obtained using EDS and whole-rock chemistry was obtained using ICP-MS and XRF. Elemental concentrations of spinel minerals reveal significant metamorphism (greenschist to amphibolite facies), altering the inherited protolith signals. However, plotting whole-rock trace element concentrations on multiple petrogenetic discrimination diagrams confirms an island arc origin. A minority of samples exhibit a mid-ocean ridge basalt affinity on petrogenetic diagrams, however, these rocks are rich in Al-phases (garnet, kyanite, and corundum), which may suggest a high level of recrystallization/metasomatism altering inherited signals. The ultramafic body is most likely the ultramafic differentiate of an arc-related magma system.

Introduction

The Bells Mill Road ultramafic body is part of a set of exotic rocks located in the Pennsylvanian Piedmont that have evaded proper characterization and scientists remain uncertain about their exact origin. Published geologic maps that contain coverage of the ultramafic bodies (Bascom et al., 1909; Weiss, 1949; Amenta, 1974; Amenta et al., 1974; Berg and Dodge, 1980; Bosbyshell, 2006; among others), contain contradictory information pertaining to the precise locations and contact relationships between the ultramafic bodies and adjacent rocks. Furthermore, all of the geologic maps for this region lump the ultramafic bodies as single units and do not differentiate between the various lithologies within the ultramafic bodies. Field work on the Bells Mill Road body revealed complex zonation that has not been adequately characterized.

Limited studies have been conducted on the ultramafic bodies in the Pennsylvanian Piedmont (Busé and Watson, 1960; Carnes, 1990; DeSantis, 1978; Roberts, 1969; Zarnowsky, 1995). Furthermore, these studies present contradictory information related to the lithologies and alteration zones within the bodies as well as varied contacts for the ultramafic bodies with respect to adjacent rocks. Previous studies on the ultramafic bodies included limited structural data for the ultramafic bodies. Addressing these discrepancies and omissions for the ultramafic bodies is essential for understanding the Paleozoic tectonic evolution of the Central Appalachian Mountain Belt.

Regional Geology

The basement rocks in the region are Precambrian gneisses (Baltimore Gneiss) that were metamorphosed during the Grenville orogeny approximately 1000 Ma (Wagner and Crawford, 1975). The Baltimore Gneiss can be observed approximately 1 km northwest of the Bells Mill Road ultramafic body, once crossing over the Rosemont shear zone (Figure 1 and 2). Regionally, the Rosemont fault separates the Baltimore Gneiss from the Wissahickon Formation, a pelitic to quartzofeldspathic schist with interspersed amphibolite layers. Ultramafic pods are found within the Baltimore Gneiss and Wissahickon Formation throughout the Piedmont Province and the pods are elongated, which trend parallel to major structural features trending generally northeast.

The Baltimore Gneiss is interpreted to have sedimentary and igneous origins and experienced its peak metamorphism at granulite facies during the Grenville orogeny approximately 1000 Ma (Wagner and Crawford, 1975). During rifting of supercontinent Rodinia in the late Proterozoic and the opening of an ocean basin, the Baltimore Gneiss served as the bedrock of the Laurentian continental margin as carbonate and siliclastic sediments were unconformably deposited. Shortly after, an island arc developed under an eastward dipping subduction zone on the eastern margin of the Laurentian continent (Crawford and Mark, 1982;

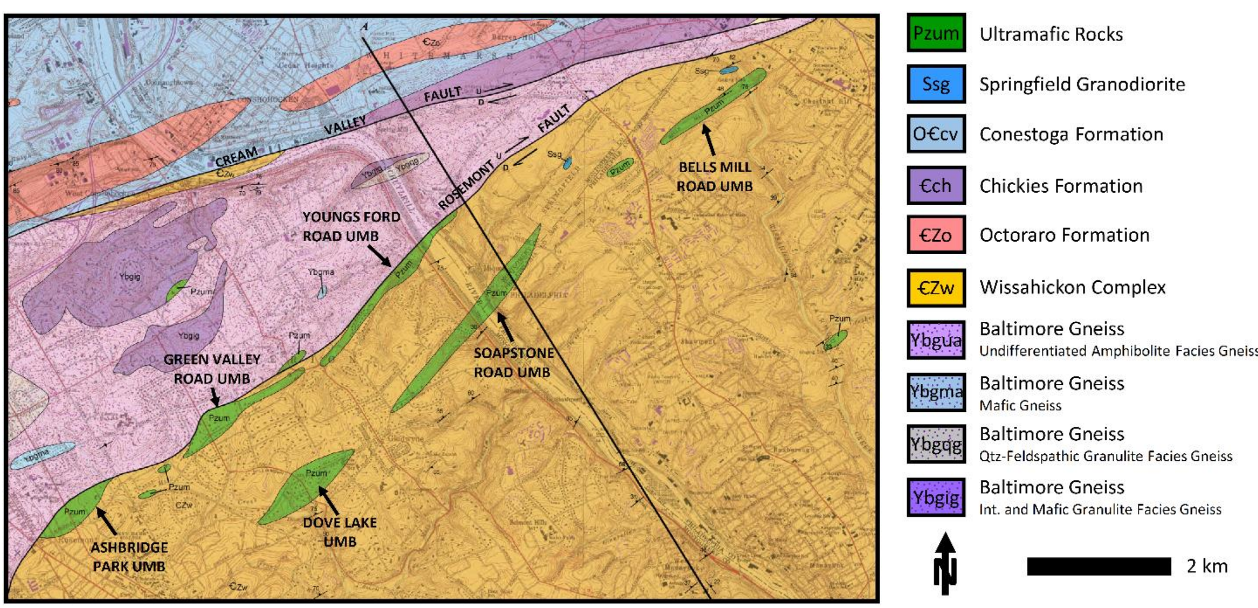

Figure 1. Map of the Bells Mill Road vicinity with regional ultramafic bodies labeled (modified after Bosbyshell, 2006).

Wagner and Srogi, 1987). The Wissahickon Formation was originally deposited in the marginal basin enclosed by the Laurentian continent and the offshore island-arc (Crawford and Crawford, 1980; Wagner and Srogi, 1987). Before or during the late Ordovician Taconic orogeny, a series of ductile nappes and thrust sheets were transported west as the island arc was accreted onto Laurentia (Crawford et al., 1999). New interpretations suggest the Taconic arc may have been accreted near the North Appalachians (i.e., New England) and transported by transcurrent faulting to its present location by the Late Paleozoic (Bosbyshell et al., 2016). The crustal thickening during the Taconic orogeny and high heat flow from the accreted island arc complex deformed the region into the Devonian (~385 Ma) from greenschist to amphibolite facies with grades increasing from the northwest to southeast toward the proposed core of the arc complex, the Wilmington Complex (Wagner and Srogi, 1987). After or during peak metamorphic conditions, the thick crustal orogen began to isostatically uplift. The later Alleghenian orogeny during the late Paleozoic appears to have had little effect on the rocks of the Piedmont Province; however, shortly after, erosion began to unroof the buried rock to expose the Piedmont units.

Ultramafic pods are scattered throughout the Baltimore Gneiss and the Wissahickon Formation ranging in size from 0.5 to 2.5 km long and 0.2 to 0.7 km wide. Geologists have speculated on the origins of the ultramafic bodies and offered a number of possible hypotheses: dikes of metapyroxenite and metaperidotites (Bascom et al., 1909; Busé and Watson, 1960); diapiric mantle intrusions (Weiss, 1949; Amenta, 1974; Amenta et al., 1974); and oceanic crust ophiolite sequences or ophiolite fragments within an accretionary prism (DeSantis, 1978; Wagner and Srogi, 1987; Carnes, 1990; Faill, 1997). Research conducted on the State Line serpentinites, ultramafic bodies approximately 80 km southwest of the Bells Mill Road ultramafic body, show a close association with the Baltimore Mafic Complex and have been interpreted to be part of a large layered mafic intrusion (McKague, 1964; Hanan and Sinha, 1989). The possibility of the ultramafic bodies in the Philadelphia region being related to a large layered mafic intrusion has not been ruled out. The age and emplacement history of the ultramafic bodies are unknown, however, they are believed to have been emplaced prior to or during metamorphism of the country rock based on seemingly conformable trends of the contacts, foliations, and lineations. Additionally, the lack of hornfels aureoles around the ultramafic bodies would support the pre- or syn-metamorphic age of the ultramafic bodies.

Field Relationships and Lithologies

Field work, petrography, and whole-rock geochemistry has been completed to understand the nature of the alteration zones, deformation history, and the potential protolith of the Bells Mill Road ultramafic body. The Bells Mill Road ultramafic body is an elongate unit (~0.25 by 1 mile in dimensions) emplaced within the Wissahickon Formation of southeastern PA and is oriented parallel to regional foliations (NE-SW trending). Foliations, textures, and contacts within the body all follow a general northeast-southwest trend with steep dips from ~70° to vertical and varying in dip direction (northwest to southeast). Direct contact between the body and the country rock is not observable.

The body can be separated into five distinct lithologic units: serpentine-talc rock, talc-tremolite schist, anthophyllite-chlorite schist, chlorite schist, and talc-serpentine schist. The units are layered within the body and the best exposures reveal an interweaving/duplication of units (Figure 2). Some shear is present in the rocks, however, only on microscale and large shear indicators are absent on outcrop scale. Duplication of units and shear indicators may suggest the body was thrusted and stacked during emplacement.

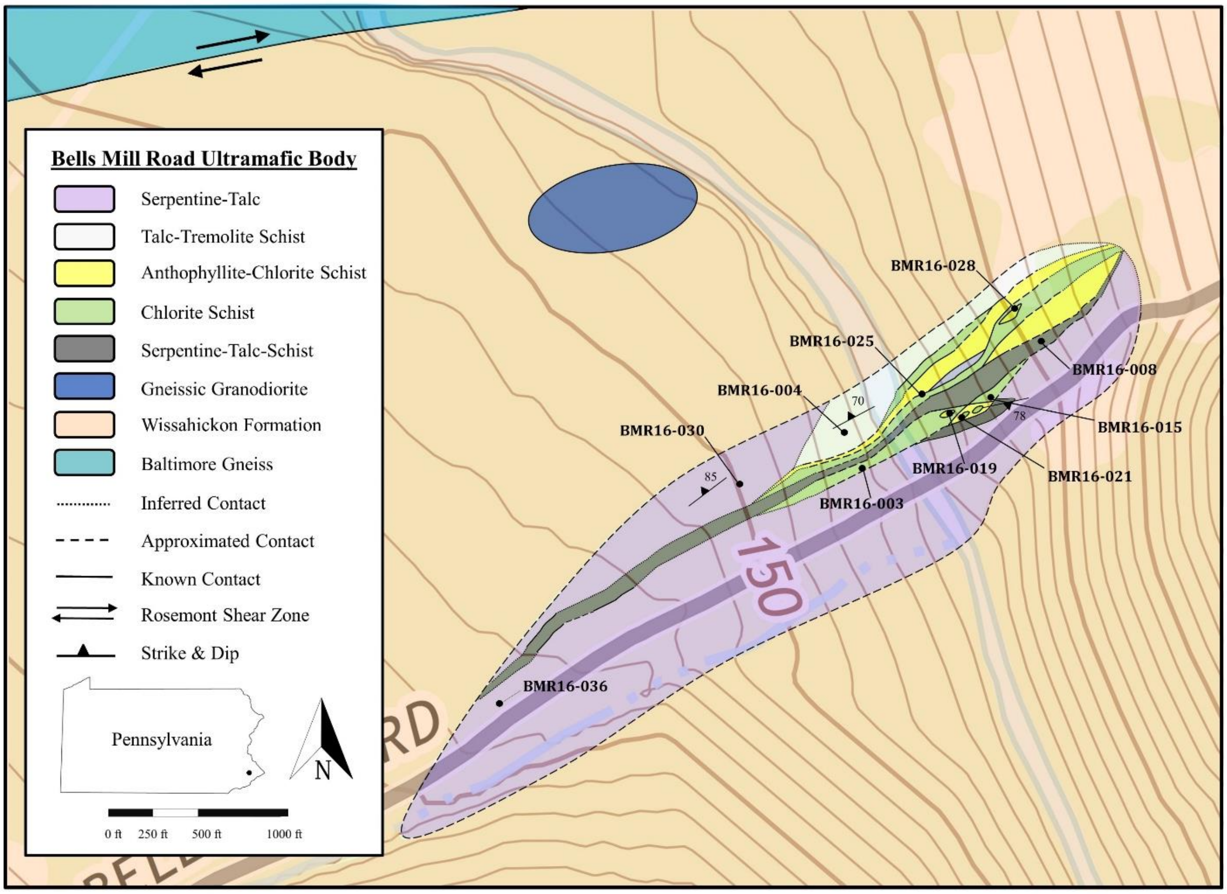

Figure 2: Geologic map of the Bells Mill Road ultramafic body. The lithologic zones of alteration are defined as: serpentine-talc, talc-tremolite, anthophyllite-chlorite schist, chlorite schist, and talc-serpentine schist (Simboli et al., 2017)

Serpentine-talc rock

The serpentine-talc rock is most abundant unit within the body and encompasses the outside edge of nearly the entire body. The serpentine-talc rock is characterized by large inclusions of serpentine surrounded by a matrix of talc, anthophyllite, and magnesite. The serpentine inclusions range in size from 1 to 10 cm and provide hand samples a spotted appearance (Figure 3). Most of the serpentine inclusions are oblong and seemingly randomly orientated. Most inclusions are rounded but, increase their angularity with increasing size. In thin section, the serpentine inclusions have mesh textures serpentine suggesting the replacement of olivine (O’Hanley, 1996). Other serpentine textures are present (i.e., chysotile

Figure 3. Serpentine-talc rock textures seen in outcrop. The black is serpentine inclusions surrounded by a matrix of talc, anthophyllite and magnesite.

veining, bastite), however, they are minor. Accessory phases within the serpentine inclusions include: magnetite, hematite, chromite, awarite, and millerite (DeSantis, 1978).

Overall, the rock is matrix-supported with most serpentine inclusions surrounded by the matrix. The serpentine inclusions can range from 30% to 60% of the rock, but most samples maintain an approximate 50% ratio of inclusion to matrix. The grey matrix is a complex network of talc, anthophyllite, magnesite with minor amounts of chlorite and opaques, likely magnetite, chromite, and ferritchromite. Talc is the dominant mineral in the matrix and defines the schistosity with dispersed acicular anthophyllite. Magnesite porphyroblasts are common but have ragged grain boundaries with clear centers.

Talc-tremolite schist

The talc-tremolite schist is a massive, fine-to-medium grained, grey rock located mainly in the northerly portions of body. In hand sample the rock's schistosity is revealed by white stringers of tremolite (Figure 4). The talc-tremolite schist appears only in the northern half the body and pinches out with many units near the center of the exposed body.

Figure 4. Talc tremolite schist hand sample view.

Anthophyllite-chlorite schist

The anthophyllite-chlorite schist consists of anthophyllite, chlorite, talc, and occasional relic orthopyroxene. The chlorite is fine grained making up the matrix with large acicular anthophyllite throughout the sample. The anthophyllite is often kinked or distorted exhibiting brittle deformation. At the contact with the chlorite schist unit, the anthophyllite becomes coarser grained splaying blades into the chlorite schist (Figure 5). The presence of orthopyroxene may be relic from the protolith.

Figure 5. The contact between chlorite schist (upper green) and anthophyllite-chlorite schist (lower beige)

Chlorite schist

The chlorite schist is a fine to medium grained green rock with several diverse layers in several locations. The majority of this lithologic unit is overwhelmingly chlorite in composition, however, some locations have scattered layers of magnesite (Figure 6), magnetite (see Spinel Mineralogy section), and Al-rich phases (Figure 7) all restricted to specific field locations and not representative of the lithology. Magnesite present

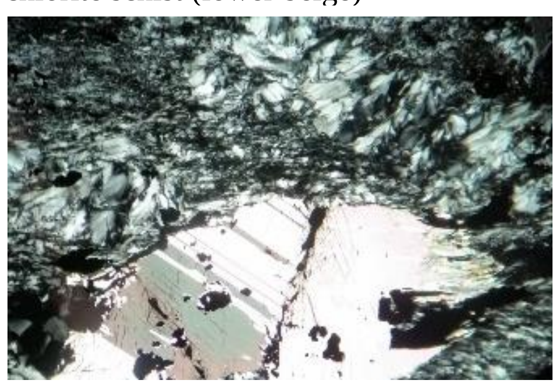

Figure 6. Thin section photomicrograph in XPL of the chlorite schist with a large magnesite grain. FOV = 1 mm

as porphyroblast up to 1 mm and occasionally exhibiting deformation twinning (Figure 6). Magnetite in the chlorite schist occurs as layers up to 10 cm thick of magnetite porphyroblasts from 0.01 to 1 cm. In one unique location there is a layer of chlorite rock containing porphyroblasts of garnet, kyanite, and corundum (Figure 7). The presence of such high-Al phases in an ultramafic body suggests a large amount of component exchange and metasomatism. The Al-rich layer occurred with a magnetite rich layer as well.

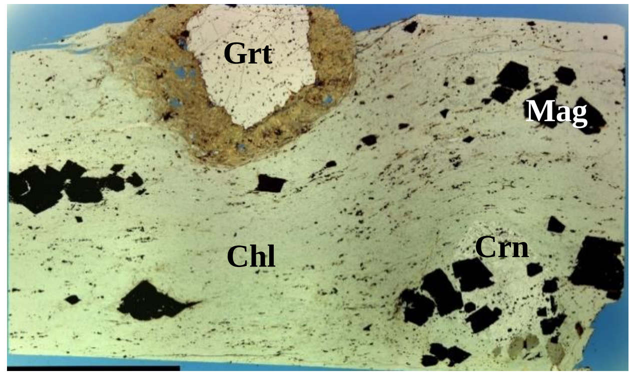

Figure 7. Thin section photomicrograph in PPL of sample BMR17-015 showing Al-rich phases within the chlorite schist. FOV = 4 cm

Talc-serpentine schist

The talc-serpentine schist is a fine to medium grained rock with magnesite scattered throughout specific locations as well as anthophyllite. The talc, serpentine and anthophyllite define the foliation while the magnesite is porphyroblastic. Most samples containing magnesite develop a strong 1 to 2 cm weathering rind that bleached the silicates a dirty bright white and a rusty red-brown replacing the magnesite. The weathered rock becomes extremely soft and crumbles with the strike of a hammer.

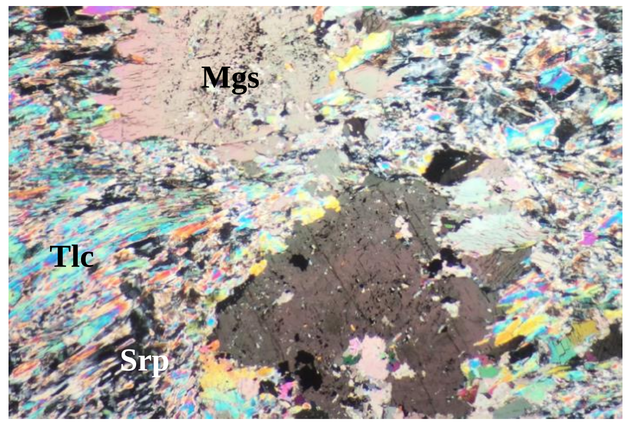

Figure 8. Thin section photomicrograph in XPL of sample BMR17-008. FOV = 1 mm

Spinel Mineralogy:

Spinel minerals, particularly magnetite and chromite, are common in mafic and ultramafic rocks over a wide range of conditions. This group of oxides, specifically chromites, was one of the first mineral systems to be used as petrogenetic indicators as reported by Irvine (1965). Chromites can be one of the first minerals to crystallize in a mafic or ultramafic magma including unfractionalized signature of the magma. Chromites are refractory and relatively resistant to alteration especially when compared to the silicate minerals within these systems. However, pervasive alteration can change inherited geochemical signatures and metamorphism must always be assessed prior to applying spinel compositions on petrogenetic diagrams.

Large Cr-rich spinels from samples showing the least apparent alteration were analyzed for geochemical evidence of tectonic origin. Cr-rich spinel were analyzed using energy dispersive spectroscopy electron probe microanalysis (EDS-EPMA) on the microprobe at the National Institute of Standards and Technology (NIST) following the methods of Mengason et al. (2017). Quantitative values were arrived at using standards-based multiple linear least squares fitting with DTSA-II software from NIST. Individual spinel grains were selected for anlaysis based on size and position in the sample (either thin section or epoxy mount). Transects of the grain in at least one direction were performed and apparent 'plateau' values were averaged for plotting in discrimination diagrams.

Spinel minerals in samples from Bells Mill Road examined were from the following lithologic units: talc-serpentine schist (BMR16-008), serpentine-talc rock (BMR16-030 and BMR16-036), and chlorite schist. All examined spinels from the chlorite schist were found to be nearly pure magnetite and therefore not plotted on the below diagrams (Figures 10, 11, and 12) as this study focused on Cr-rich spinels. Along with Bells Mill Road samples (BMR) plotted on the diagrams below were samples from other regional ultramafic bodies. Sample SRP16-011A is serpentinite from an ultramafic body near Newtown Square, PA. Sample SRP16-024 is serpentinite from an ultramafic body at Strode's Mill in southern West Chester, PA. In addition, Cr-rich spinel compositions of Smith and Barnes (2008) from the Goat Hill Serpentine Barrens in southwestern Chester county, part of the State Line Serpentinite, are plotted for comparison.

Spinels from Mid Ocean Ridges (MOR) show a more limited range in Cr:Al ratio compared to those from volcanic arcs (Arc) (Figure 9 for reference). The core compositions of spinel from nearby serpentinite units and from Goat Hill Serpentine Barrens plot largely outside of the MOR field and within the Arc field (Figure 10). However, the BMR samples are significantly Al-depleted and plot outside of all fields. This correlates well with the reported petrogenesis of the State Line deposits being closely related the Baltimore Mafic Complex (McKague, 1964; Hanan and Sinha, 1989; Smith and Barnes, 2009).

Two core compositions from BMR16-008 are more highly oxidized and depleted in Al by alteration. They can be described as 'ferritchromite' with rim compositions plotting as metamorphic magnetite overgrowth (Figure 10). The core compositions from BMR16-030 and -036 are just slightly Cr-enriched compared to their rims and have homogenized with their magnetite overgrowth (Figure 10). All of these spinels have undergone significant alteration and no-longer reflect initial compositions. However, it is possible to use their elemental concentrations to assess metamorphic grade and confirm the syn-metamorphic nature with the adjacent Wissahickon schist.

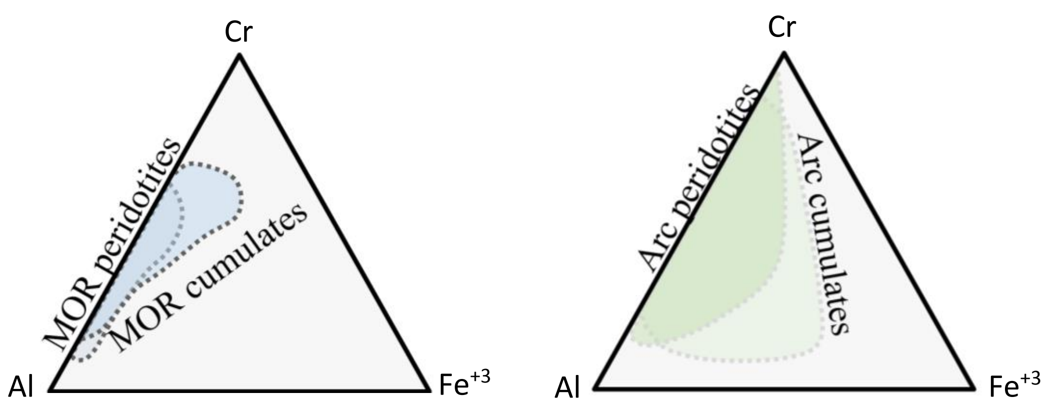

Figure 9. Fe^{3+}-Cr-Al ternary diagram in atomic % (as below). Fields encapsulate data from Arai et al. (2011)

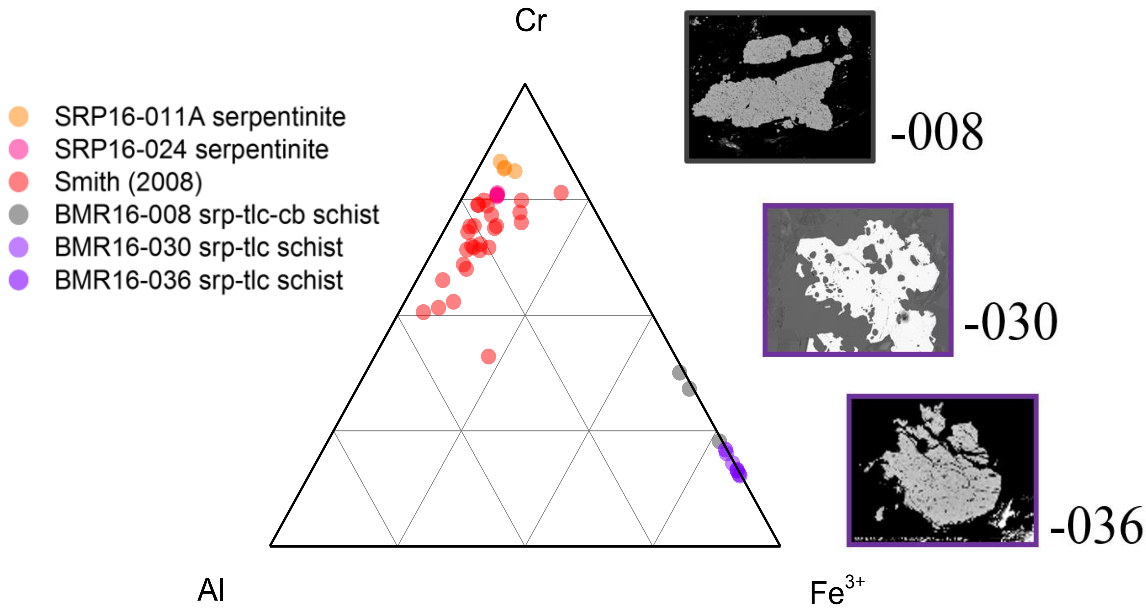

Figure 10. Core compositions taken from cross-grain transects of Cr-rich spinels. Fe^{3+} calculated from total Fe assuming charge balance and full site occupancy. Backscatter images of the spinels are shown on the right.

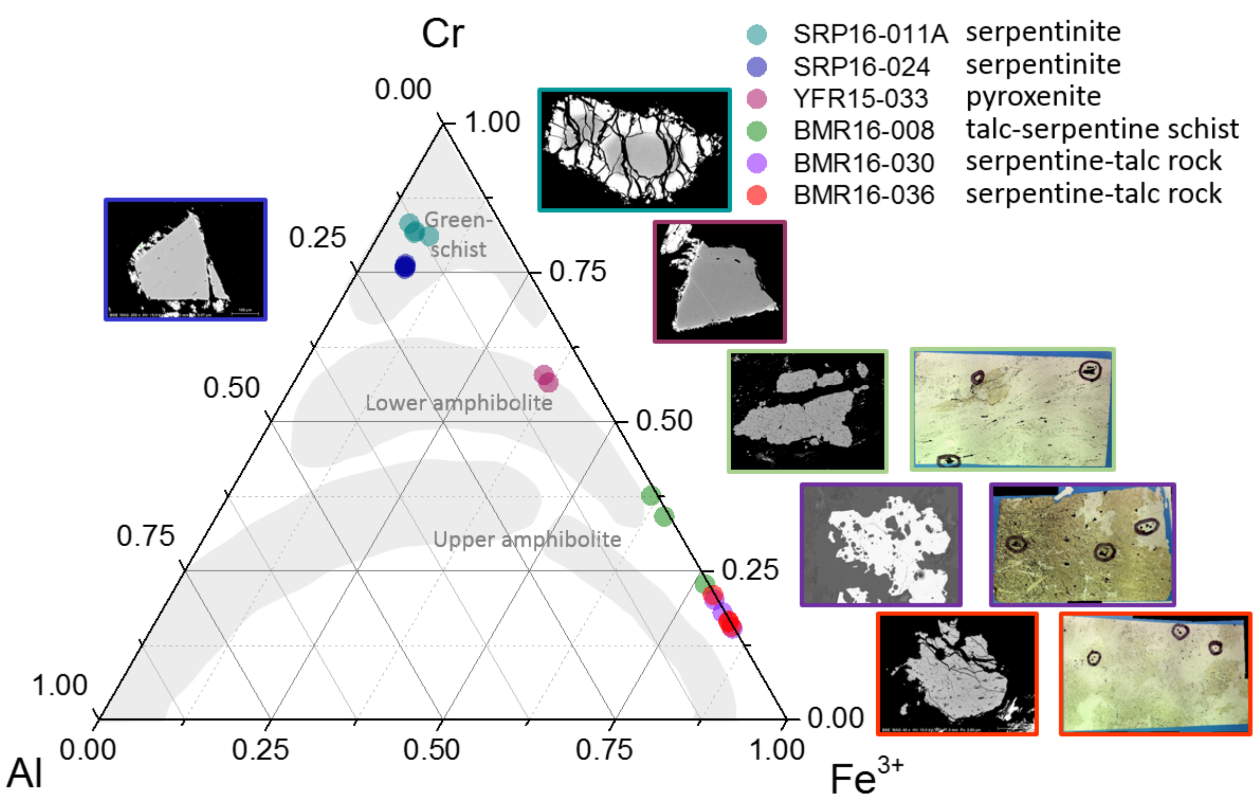

Figure 11. Chromite composition from chlorite schists of this study and related units. Data from chlorite schists plot in the field of ferritchromite and Cr-magnetite. Fields of composition for different metamorphic facies after Evans and Frost (1975) and Suita and Streider (1996).

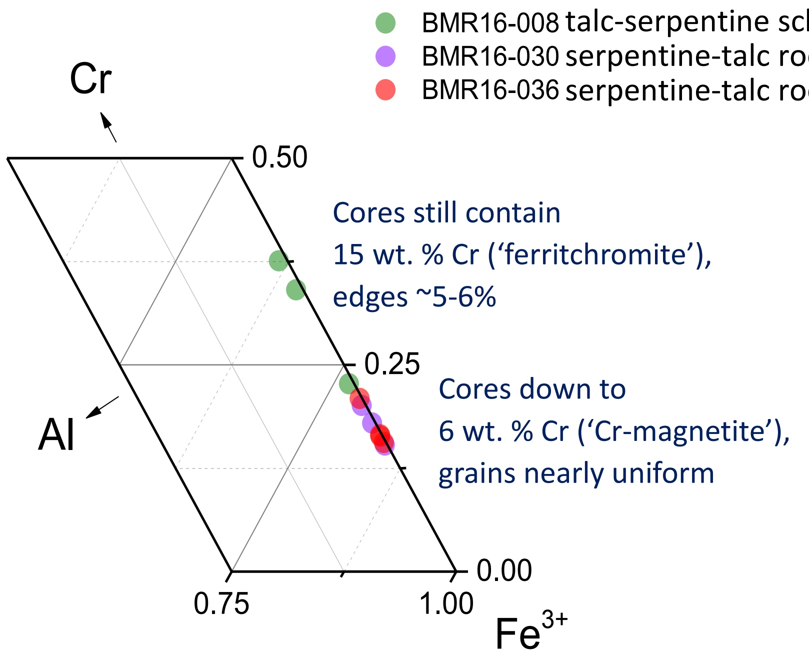

Figure 12. Cr-rich spinel in samples plotted approaches magnetite in composition. Elevated Cr concentration in cores indicates initial igneous origin and lack of full homogenization. Possibly represents initial conversion to 'ferritchromite' and later ongoing replacement by magnetite.

Spinels from Bells Mill Road and spatially related metamorphosed mafic/ultramafic rocks can give context to the metamorphic grade and history of these altered samples. Figures 11 and 12 show spinels from samples plotted with respect to reported metamorphic grades associated with spinel compositions (Evans and Frost, 1975; and Suita and Streider, 1996)

Based on plots shown above and interpretations detailed by Barnes (2000), Barnes and Roeder (2001), and Gonzalez-Jimenez et al. (2009), the generalized chromite alteration sequence is as follows:

- Low-temperature serpentinization sees some overgrowth of 'ferritchromite' or magnetite and minimal alteration of core.
- Lower Greenschist facies sees Mg loss during Fe^{2+}↔Mg^{2+} exchange with olivine, growth of "ferritchromite" rim and gradual loss of Ti, Cr, and Mg from the core to the rim progressing inward from the contact.
- Upper Greenschist facies sees effective loss of Al by fluid-mediated reaction to form chlorite along with an increase in Fe^{3+}, reflecting increasing fO_2 and the Mg^{2+}/Fe^{2+} ratio no longer buffered by olivine.
- Lower Amphibolite facies sees continued Cr, Mg, and Al loss and increase in Fe^{3+} with a shrinking miscibility gap between chromite and magnetite diminishing above 500°C and closing above ~550°C.

Geochemistry

Major and trace abundances have been measured by ICP-MS and XRF on all of the lithologies present at the Bells Mill Road ultramafic body (geochemistry of representative samples are present in Table 1). Mineral modal abundances were found by point counting >600 points per slide and are compatible with major element geochemistry. Major minerals present are represented in Table 1. All samples exhibit elevated concentrations of chromium, cobalt, and nickel, which is typical for ultramafic rocks.

Plotting the trace elements on petrogenetic discrimination diagrams is common practice in igneous petrology where inherited signals are sustained due to minimal disturbance from alteration. The rocks of the Bells Mill ultramafic body have been significantly altered through possibly multiple stages of deformation, making it difficult to plot on discrimination diagrams, particularly if the elements plotted are mobile/incompatible. Application of discrimination diagrams to metamorphic systems requires the use of elements that are relatively immobile/compatible within rock. Although large fluxes of fluid significantly alter the parent rocks, some trace element concentrations can remain unaltered retaining geochemical signatures that are inherited from their initial crystallization (Deschamps et al., 2013).

A combination of igneous and metamorphic petrogenetic discrimination diagrams have been used to plot the trace elements of relatively immobile elements for mafic to ultramafic systems to determine the potential origin of the Bell Mill Road ultramafic body. Two mafic igneous systems designed for basaltic systems (Figure 14: i.e., Shervais, 1981 and Pearce and Cann, 1971) and two metamorphic systems for serpentinites (Figure 15: i.e., Deschamps et al., 2013) have been used to test hypotheses of possible protolith origins. Geochemical discrimination diagrams can be used to identify tectonic origin. These diagrams are not specifically designed for ultramafics, however, consistent results were observed. It can be inferred that the source of magma originated from a subducted island arc setting. Figure 14 shows several samples plotting in the MORB field suggesting an ophiolite setting for the

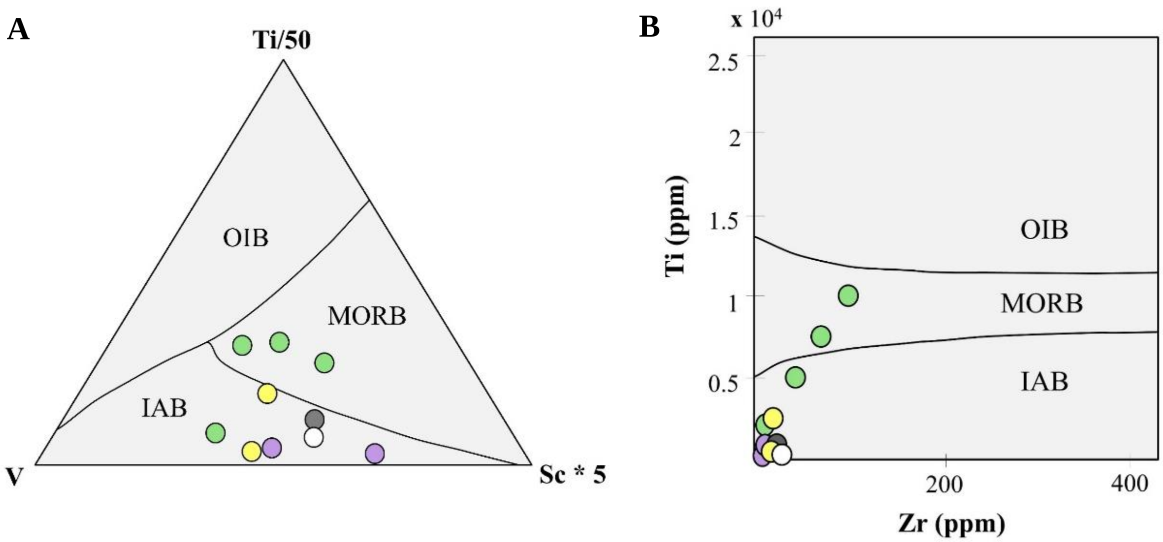

Figure 14: Petrogenetic discrimination diagrams for basaltic igneous systems (**A)** after Shervais, 1981; (**B**) after Pearce and Cann, 1971. IAB – Island Arc Basalt (arc related magmatism), OIB – Ocean Island Basalt (mantle derived hot spot activity), and MORB – Mid-Oceanic Ridge Basalt (oceanic floor derived ophiolite). Colors correspond to mapped lithologies in Figure 2: purple – serpentine-talc rock, white – talc-tremolite schist, yellow – anthophyllite-chlorite schist, green – chlorite schist, and grey – talc-serpentine schist.

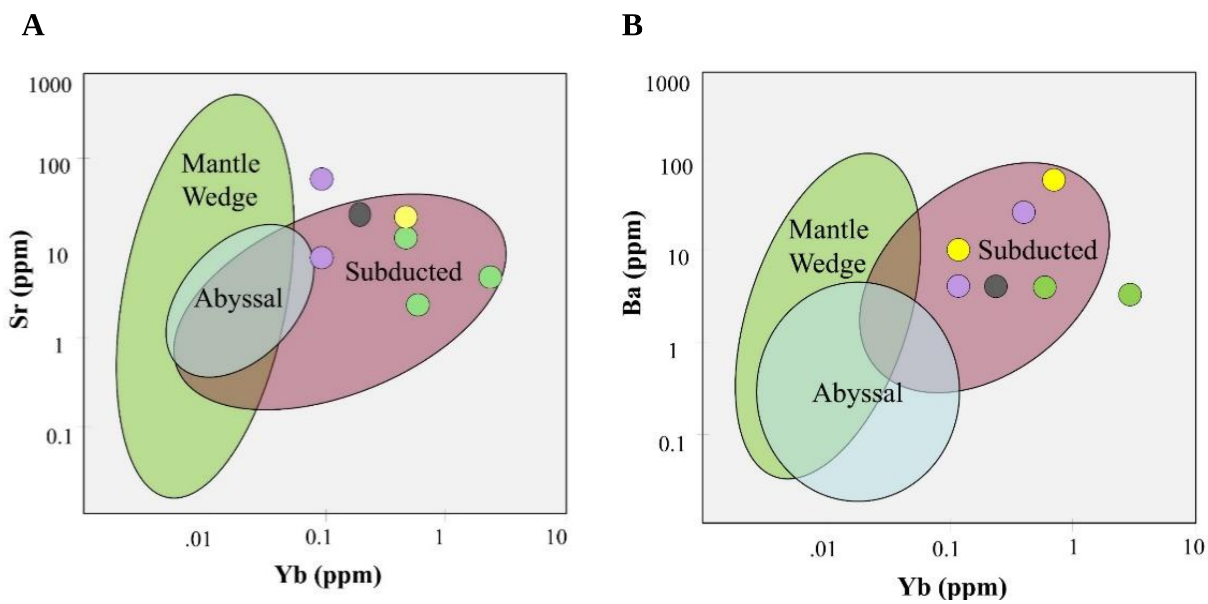

Figure 15: Petrogenetic discrimination diagrams for serpentinite systems (**A & B)** after Deschamps et al., 2013. Abyssal serpentinites represent oceanic floor derived ophiolite, Mantle wedge represent diapiric mantle derived material, and subducted represent arc related magmatism. Colors are described in the figure above.

protolith. However, all samples plotting in the MORB field were from the chlorite schist, which display significant metasomatism/component exchange as evidenced by the presence of garnet, corundum, and kyanite in some samples. The presence of these minerals in limited zones suggests localized significant component exchange with fluids derived from the Al-rich country rock. It is unclear why this would drive compositions toward the MORB field but they did have a consistent deviation.

Conclusions

The Bells Mill Road ultramafic body shows several distinct alteration zones with the following lithologies: serpentine-talc; serpentine-talc-carbonate; talc-tremolite; chlorite schist; and anthophyllite-chlorite schist. Shearing appears present exhibited by duplication of units and shear-induced microstructures (shear banding, pressure shadows, deformation twins, etc.). Chromites have undergone significant alteration and no-longer reflect initial compositions. A small minority of samples show a mid-ocean ridge basalt affinity, but these rocks are rich in Al-phases (garnet and corundum) which may suggest a high level of recrystallization/metasomatism altering inherited signals. Interpretations of petrogenetic discrimination diagrams suggests that the ultramafic body is most likely a differentiate of an arc-related magma chamber.

	BMR16-003 Chlorite schist	BMR16-004 Talc-Trem schist	BMR16-008 Talc-Serpentine schist	BMR16-028 Anthophyllite Chlorite schist	BMR16-036 Serpentine-Talc rock
Major Elements in Wt%					
SiO_2	23.22	53.45	39.48	42.87	41.41
Al_2O_3	12	3.13	1.22	7.34	1.21
Fe_2O_3(T)	29.77	6.5	6.92	8.7	7.11
MnO	0.046	0.089	0.053	0.131	0.055
MgO	24.27	25.09	32.1	29.25	34.97
CaO	0.01	6.38	1.22	1.28	0.35
Na_2O	< 0.01	0.05	0.02	0.03	0.02
K_2O	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
TiO_2	0.297	0.048	0.074	0.366	0.017
P_2O_5	< 0.01	< 0.01	< 0.01	0.02	< 0.01
LOI	9.04	4.67	18.08	8.73	13.54
Total	98.65	99.42	99.16	98.72	98.69
Trace Elements in ppm					
Cr	20	2220	2200	1620	2060
Co	100	68	80	79	96
Ni	150	1280	1700	1540	2150
Sc	36	12	9	20	7
V	343	49	36	122	40
Ba	< 2	5	5	29	< 2
Sr	< 2	9	32	31	10
Y	< 1	15	2	5	< 1
Zr	5	15	3	10	< 2
Zn	70	60	40	60	30
Ga	10	4	2	7	1
Nd	0.6	3.3	0.5	1.3	0.2
Sm	0.2	1.5	0.2	0.4	< 0.2
W	2	2	2	2	2
Mineral Modal Abundances in %					
Srp	-	6%	20%	-	53%
Chl	90%	-	1%	34%	4%
Tlc	-	49%	40%	17%	25%
Ath	-	15%	18%	42%	13%
Tr	-	27%	-	-	-
Opx	-	3%	-	5%	-
Mgs	-	-	19%	1%	4%
Opaques	10%	-	2%	1%	1%

Table 1: Geochemistry and modal mineral abundances of representative samples from each of the lithologic zones at the Bells Mill Road ultramafic body.

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