MINERAL PARAGENESIS OF A PARTIALLY SERPENTINIZED DUNITE IN EAST DOVER, VERMONT

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Abstract

Ultramafic rocks exposed on the Earth’s surface offer a rare opportunity to directly study the petrology of the upper mantle. The Appalachian Mountains of Vermont contain variably serpentinized ultramafic rocks that mark the suture zone for the Ordovician Taconic Orogeny. In southern Vermont, the serpentinized ultramafic rocks were subsequently metamorphosed to amphibolite facies during the Devonian Acadian Orogeny. Key localities of partially serpentinized ultramafic rocks and their surrounding lithologies in East Dover, Vermont were sampled to better understand the mineral petrogenesis and metamorphic history of the East Dover meta-dunite. This thesis documents the first occurrence of podiform chromitite, platinum group minerals, arsenic minerals, and metamorphic olivine in ultramafic rocks from the Vermont Appalachian Mountains. Rare chromitite occurs as pods within the dunite and is highly brecciated. Cr# (Cr/Cr+Al) is extremely high in podiform chromitite (0.7 - 0.9) suggesting that it formed via fluid/melt-rock interaction during partial melting of upper mantle peridotite in a supra-subduction zone setting. Rare inclusions of platinum group mineral alloys were found as inclusions in podiform chromitite. Many of these platinum group minerals contained arsenic. Small nickel arsenide minerals are common in serpentinized ultramafic rocks. Whole rock geochemical analyses (XRF) indicate much higher concentrations of arsenic in the more serpentinized samples, suggesting that arsenic was introduced into the ultramafic rocks during serpentinization. In the meta-dunite, the composition of olivine ranges from Fo92 in spinel inclusions to Fo96 in neoblastic olivine. Olivine neoblasts likely formed from serpentine dehydration during peak metamorphic temperatures associated with regional metamorphism during the Devonian Acadian Orogeny. Decussate amphibolite and late stage coarse acicular serpentine likely formed as the region slowly cooled following Devonian orogenesis. Recent
near-surface lateritic weathering produced local areas of nickel mineralization. Chromite, 
platinum group minerals, and nickel minerals do not appear to occur in quantities sufficient for 
exploitation from the East Dover area. Our findings illustrate the need for an investigation into 
the mineralogy of other ultramafic bodies in Vermont to better understand the relative timing of 
mineral petrogenesis and the societal implications of the presence of arsenic bearing minerals in 
ultramafic rocks.
MINERAL PARAGENESIS OF A PARTIALLY SERPENTINIZED DUNITE IN EAST DOVER, VERMONT

by

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B.A., University of Vermont, 2013

Thesis
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Introduction

The Earth’s mantle, the portion of the Earth beneath the crust and above the core, comprises 84% of Earth’s volume and is dominated by ultramafic minerals (Ringwood 1970). Opportunities to directly study mantle material are limited to 1) igneous rocks sourced from the mantle (e.g., basalt/kimberlite and the xenoliths and xenocrysts they contain) or 2) places where mantle material is exhumed during orogenesis (e.g., variably serpentinized ultramafic rocks). Serpentinized ultramafic rocks exposed at the Earth’s surface therefore offer a unique opportunity to study the petrology of the Earth’s upper mantle and the process of serpentinization. Since partially serpentinized ultramafic rocks preserve minerals derived from their upper mantle protolith (e.g., peridotite), analyzing these relict minerals and their alteration products is the only way to directly study and understand the evolution of the Earth’s upper mantle.

The Appalachian Mountains of Vermont contain a belt of partially to fully serpentinized ultramafic rocks that mark the suture zone for the Ordovician Taconic Orogeny (Figure 1) (Stanley et. al., 1984, Ratcliffe et. al., 2011, Honsburger et. al., 2017). These ultramafic rocks are interpreted to be remnants of fragmented supra-subduction zone ophiolites that were obducted onto the Laurentian margin (Coish and Gardner 2004, Pinet and Tremblay 2016). Vermont’s largest ultramafic body is a 1.5 by 5km partially serpentinized meta-dunite that crops out in East Dover (Figure 2). This ultramafic body is of interest because its many exposures offer a unique opportunity to study the mineralogy and metamorphism of rocks that were once part of the Earth’s upper mantle. In addition, the East Dover ultramafic body records a polymetamorphic history spanning multiple Paleozoic orogenic events (i.e., partial melting and melt-rock interaction prior to serpentinization, serpentinization during the Ordovician Taconic Orogeny,
regional amphibolite facies metamorphism during the Devonian Acadian Orogeny). The ultramafic rocks in Vermont were mapped as early as Hitchcock et al. (1861), and their origin has been studied as recently as Coish and Gardner (2004) and Honsberger et al. (2017). However, details about the effects of metamorphism on ultramafic rocks from Vermont are not well constrained. Some questions that remain unanswered are: How many episodes of serpentinization affected the ultramafic rocks in Vermont? Why do the ultramafic rocks in Vermont lack pyroxene as a major phase (dunite vs. lherzolite)? What are the effects of regional amphibolite facies metamorphism on rocks with an ultramafic bulk composition, particularly serpentinized ultramafic rocks? This study attempts to answer those questions, and combines field work, petrographic analysis, electron microprobe analysis, Raman spectroscopy, and whole rock geochemical analyses to determine the petrogenesis and metamorphic history of the East Dover ultramafic body. Aspects of the pressure-temperature evolution of this polymetamorphic terrane are revealed by analyzing both primary igneous and secondary metamorphic minerals, identifying previously undocumented minerals, and analyzing surrounding lithologies.

**Serpentinization**

A discussion about the process of serpentinization is a necessary introduction into the metamorphism of ultramafic rocks. Serpentinization is a metasomatic process by which ultramafic minerals (olivine and pyroxene) are hydrothermally altered to form serpentine group minerals. The general serpentinization reaction is (Hess 1933, Johannes 1968):

\[
2\text{Mg}_2\text{SiO}_4 + 3\text{H}_2\text{O} = \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4 + \text{Mg(OH)}_2
\]

forsterite + water = serpentine + brucite
Serpentinization typically occurs in the mantle wedge above a dehydrating subducting slab in subduction zones, but can also occur when lithospheric mantle from a subducting slab is incorporated into an accretionary prism, or it can occur on the ocean floor (mid-ocean ridges) where water is in direct contact with hot mantle material (Miyashiro et al., 1969, Reynard 2013, Honsberger et al., 2017). In subduction zones, the fluid required for serpentinization can be brought into a subduction channel via hydrous oceanic sediments or produced through the dehydration of hydrous minerals (Moody 1976 and references therein). Serpentinization produces three phyllosilicate serpentine minerals: antigorite, chrysotile, and lizardite (Hess 1933, Ulmer and Trommsdorff 1995). Lizardite and chrysotile are the low pressure/temperature stable serpentine minerals that commonly form on the ocean floor (known as abyssal serpentinites), or in near surface environments dominated by brittle deformation. Antigorite forms at higher pressures and medium temperatures and is commonly found in ultramafic rocks altered in subduction zones and subsequently exhumed above sea level to form ophiolites. If an abundance of iron, carbon dioxide and oxygen is available, serpentinization is accompanied by the production of magnetite, brucite, and carbonate minerals such as magnesite (Schwartz et al., 2013).

Prior to the development of the theory of plate tectonics, the origin of serpentinized ultramafic rocks within mountain belts (Alpine serpentinite) was not clear to geologists, who interpreted them as intrusive igneous rocks (e.g., Bain 1936). Alpine serpentinite is now interpreted to represent hydrated mantle sections of obducted ophiolites (Evans 1977, Coish and Gardner 2004). Depending upon how much water is available, and the size of the ultramafic block being altered, serpentinization may only partially alter ultramafic minerals. In this case, serpentine minerals will be concentrated along grain boundaries and fractures in ultramafic
minerals (e.g., olivine, pyroxene). Serpentinization reactions are exothermal and result in a volume increase of the protolith by up to 40% (Guillot et. al., 2015). This volume increase results in strained, and often fragmented primary igneous minerals (e.g., olivine, pyroxene, and spinel). In addition, fully serpentinized ultramafic rocks can contain up to 13 wt.% H₂O and therefore are important conduits for transporting water and volatiles to mantle depths (Scambelluri et. al., 1995; Hattori and Guillot 2007). Hence, the process of serpentinization has an active role in the dynamic evolution of subduction zones, and due to its unique properties (rheological weakness and relatively low density compared to anhydrous peridotite) serpentinite often constitutes a large component of accretionary tectonic mélanges.

**Ophiolites, Supra-Subduction Zones, and Dunite**

An ophiolite sequence is an idealized model of oceanic lithosphere (approximately 10km thick but may be > 20km), which contains from top to bottom: oceanic sediments (structurally highest), mafic pillow lavas, sheeted dikes, layered gabbro, and ultramafic upper mantle composed of peridotite (structurally lowest and often serpentinized) (Dilek and Furnes 2014). Ophiolite sequences are commonly emplaced onto continental margins via obduction during collisional orogenesis, and many ophiolite sequences are interpreted to be supra-subduction zone ophiolites (Pearce et. al., 1986).

Pearce et. al., (1986) defined supra-subduction zones (SSZ) as having “the geochemical characteristics of island arcs but the structure of oceanic crust and are thought to have formed by seafloor spreading directly above subducted oceanic lithosphere”. This seafloor spreading is presumably caused by slab rollback associated with the initiation of subduction, where partial melting of the upwelling asthenosphere typically produces boninitic magma (boninites are Mg rich andesites that are enriched with large ion lithophile elements). The boninitic magma erupts
on the ocean floor and creates an ‘infant arc/pre-arc’ or causes spreading in the fore-arc region if an arc has already developed (Kim and Jacobi 2002). There are additional models for the generation of supra subduction zone ophiolites as outlined by Kim and Jacobi (2002), which involve the subduction beneath a previously active ridge, or subduction of the ridge itself. Nevertheless, it is known that supra-subduction zone ophiolites have characteristically depleted mantle sections (rich in dunite from the partial melting to form boninites), island arc geochemistry (with initial boninitic magma generation), and the structure of an ophiolite. Since SSZ ophiolites form in an advancing fore-arc setting, they are commonly obducted to passive margins, hence most obducted ophiolites are of SSZ origin and contain abundant dunite in their mantle section (Pearce et. al., 1986; Kim and Jacobi, 2002; Tremblay and Pinet, 2016).

Dunite is an igneous rock and is specifically a type of peridotite containing 90% or more olivine (containing little to no pyroxene, as opposed to the pyroxene rich lherzolite or websterite). Dunite typically forms as the residue (mantle restite) leftover from partial melting of peridotite (pyroxene preferentially goes into a melt before olivine) (Winter 2013). Dunite may also contain spinel, garnet, and nickel-rich sulfide minerals.

Geologic Background

Tectonic Setting
The tectonic history of Vermont is dominated by several orogenic events. Determining the tectonic history of this region has been challenging, as structures and mineral assemblages of early tectonic events are often overprinted or completely replaced by younger minerals and textures. Nevertheless, Vermont and its neighboring states have been a natural playground for structural geologists and petrologists to study orogenesis for over 150 years (as early as
Hitchcock et. al., 1861). One major area of interest in the study of Vermont geology is the Paleozoic orogenesis, beginning with the Ordovician Taconic Orogeny where an eastward dipping subduction zone produced a chain of volcanic islands that eventually collided with the eastern margin of Laurentia (proto-North America). In Vermont, the suture zone of the Taconic collision is marked by slivers of altered ultramafic rocks. The ultramafic rocks represent pieces of depleted upper mantle peridotite that were incorporated into the Taconian accretionary prism, a tectonic mélangé of oceanic lithosphere, volcanic debris from the approaching volcanic arc, and pieces of the fore-arc mantle. These slivers of ultramafic upper mantle peridotite were partially to fully hydrated (serpentinized) in the Taconian subduction zone via hydrous sediments from the subducting slab (and also from the dehydration of hydrous minerals). In southern Vermont, subsequent amphibolite facies metamorphism during the Devonian Acadian Orogeny overprinted many existing structures and mineral assemblages formed during the Taconic Orogeny (Ratcliffe and Armstrong 1999). Studying the petrogenesis of ultramafic rocks in polymetamorphic terranes provides information about: the composition and evolution of upper mantle rocks, partial melting and arc volcanism, the process and mineralogy of serpentinization, and how rocks with an ultramafic bulk composition respond to regional metamorphism.

**Grenville Orogeny and the Iapetus Ocean**

The Grenville Orogeny produced Vermont’s oldest rocks, which are Middle Proterozoic (approximately 1300 Ma) para- and ortho-gneisses of the Mount Holly Complex (Skehan 1961, Ratcliffe and Armstrong 1999). The rocks are interpreted to represent sediments, lava flows, and intrusive igneous rocks that formed the supercontinent known as Rodinia. These rocks crop out as exposed basement in the southern Green Mountains of Vermont (i.e., Green Mountain Massif, Figure 1) (Skehan 1961, Ratcliffe and Armstrong 1999). Neoproterozoic rifting of Rodinia led to
seafloor spreading (Iapetus Ocean), which separated Laurentia from Gondwana around 615 Ma (Kamo et. al., 1989; Ratcliffe et. al., 2011). During the early Cambrian to Early Ordovician (575-475 Ma) the Iapetus Ocean was a major depositional basin where ocean sediments and eventually carbonate reefs were deposited along the Laurentian passive margin (Ratcliffe et. al., 2011 and references therein). Relatively undeformed sedimentary rocks from this time presently crop out as sandstone, limestone, dolomite, and shale in the Champlain and Vermont Valleys of western Vermont (Ratcliffe et. al., 2011, Figure 1).

**Ordovician Taconic Orogeny: Origin of the Rowe Formation**

There has been considerable debate over the details concerning events that took place during the Ordovician Period (505-438 Ma), especially regarding the structure and evolution of the Taconic Orogeny. All models for the Taconic Orogeny in New England suggest that an eastward dipping subduction zone formed off the coast of Laurentia in the Late Cambrian/Early Ordovician where an approaching island arc system eventually collided with, and sutured to, the Laurentian margin. Iapetan oceanic lithosphere incorporated into the Taconian accretionary prism currently crops out in the Rowe-Hawley Belt (Rowe Formation in Southern Vermont) and consists of greenstone, amphibolite, and meta-pelitic schists containing lenses of partially to fully serpentinized ultramafic rocks (Ratcliffe et. al., 2011). The Moretown formation, which lies structurally above the Rowe Formation, was interpreted by Stanley and Ratcliffe (1985) as fore-arc basin deposits. The Taconic volcanic arc was initially referred to as the Bronson Hill Island Arc, which currently crops out in western New Hampshire (Stanley and Ratcliffe, 1985). However, Karabinos et. al., (1998) claimed that the ages for the Bronson Hill Arc were too young (454-442 Ma) to represent arc magmatism associated with the Taconic Orogeny. They argued that the Taconic Orogeny formed due to the collision of an older arc called the Shelburne
Falls Arc (485-470 Ma) presently located west of the Bronson Hill Arc. Furthermore, Karabinos and others (1998) also argued that the Bronson Hill Arc formed above a younger, westward dipping subduction zone, east of the Shelburne Falls Arc (Figure 3). However, Ratcliffe et. al., (1998) initially argued against this hypothesis and claimed that the Taconic Orogeny was “long lived” and involved the collision of many arc terranes (not one giant arc, but a chain of islands with varying size and shape). Furthermore, they suggested that the Bronson Hill Arc and the Shelburne falls arc are “not temporally or spatially discrete” (Ratcliffe et. al., 1998).

A groundbreaking study by Macdonald et. al., (2014) used U-Pb geochronology on detrital zircons to show that the Moretown Formation (Figure 2, Map unit Om) was a Gondwanan derived exotic block (rather than Taconic fore-arc deposits). They revealed that the Moretown formation contained abundant 535-650 Ma detrital zircons (Gondwanan ages), while the Rowe formation contained abundant 950-1500 Ma detrital zircons (Grenville ages) (Macdonald et. al., 2014, Karabinos et. al., 2017). They suggested that the Shelburne Falls arc resulted from eastward dipping subduction beneath the Moretown Terrane. Furthermore, they suggested that the boundary between the Rowe Formation and the Moretown Formation marks the principal Iapetan suture zone, correlative with the Red Indian Line in Canada separating rocks of peri-Laurentian affinity from rocks of peri-Gondwanan affinity (Macdonald et. al., 2014). The younger Bronson Hill Arc also intruded the Moretown Terrane but was the result of westward dipping subduction after a subduction polarity reversal as collision continued (Karabinos et. al., 2017).

In summary, the most current model for the Taconic orogeny suggests that during the Early Ordovician, the Iapetus Ocean began to close and oceanic lithosphere connected to the eastern margin of Laurentia began to subduct (eastwards) beneath distal fragments of Gondwana,
known as the Moretown Terrane, forming the Shelburne Falls Arc (Figure 3a) (Macdonald et. al., 2014, Karabinos et. al., 2017). After subduction consumed the oceanic lithosphere between the Moretown Terrane and Laurentia (via slab rollback), eastward subduction ceased, and a new westward dipping subduction zone formed under the eastern margin of the Moretown Terrane, producing the Bronson Hill arc (Figure 3b). In the Late Ordovician, as collision progressed, accretionary wedge material (meta-sediments, meta-basalts, serpentinized upper mantle) and island arc terranes (Shelburne Falls and Bronson hill arcs, intruded into the Moretown Terrane) were thrust westward onto the Laurentian margin (via obduction) as imbricate thrust slices of lithotectonic units (Stanley et. al., 1984; Ratcliffe and Armstrong, 1999; Tremblay and Pinet, 2016). This collision marked the end of the Taconic Orogeny.

**Devonian Acadian Orogeny**

Collisional tectonics continued well into the Devonian period (408-360 Ma) with the Acadian Orogeny resulting in the accretion (westward thrusting) of the Avalonian terrain above the Taconian accreted rocks. As this collision occurred, multiple generations of fold structures (including the doming of Middle-Proterozoic basement) and foliation development overprinted many of the structures formed during the Taconic Orogeny, especially in southern and eastern Vermont (Ratcliffe and Armstrong 1999, Armstrong and Tracy 2000). Acadian regional metamorphism in Southern Vermont reached garnet-amphibolite grade in the Rowe Formation with temperatures of 540 °C and pressures of 8.2 kilobars at approximately 390 Ma, with higher pressure/temperature conditions (650°C, 9.0 kilobar) to the east toward the New Hampshire border (Ratcliffe and Armstrong 1999, Armstrong and Tracy 2000). Armstrong and Tracy (2000) also report higher temperature estimates for the region (600°C) and showed that peak
temperatures were reached following peak pressure conditions associated with the Acadian Orogeny in the vicinity of East Dover.

**Geology of the Vermont Ultramafic Belt**

The origin of Vermont’s ultramafic rocks has been debated for as long as they have been known, with hypotheses ranging from intrusive igneous stocks to pieces of fragmented ophiolites (e.g., Hitchcock 1961; Hess 1933; Skehan 1961; Stanley et. al., 1984). However, in the last 20 years geochemical, petrologic, and structural data has strengthened the argument for a supra-subduction zone (SSZ) ophiolite origin for ultramafic rocks in the northern Appalachian Mountains (Kim et. al., 2003; Coish and Gardner, 2004; Tremblay and Pinet, 2016). Partial to complete sequences of SSZ ophiolites have been found in Quebec (e.g., the Thetford Mines Ophiolite and the Boil Mountain ophiolitic suite) along strike with the ultramafic rocks in Vermont (Tremblay and Pinet 2016). In addition to their tectonic position, all northeastern ultramafic rocks have the geochemical signature of supra-subduction zone ophiolites (Tremblay and Pinet, 2016). These ultramafic rocks have a dunitic protolith and are highly depleted in large ion lithophile elements that would have preferentially gone into a boninitic partial melt (Coish and Gardner, 2004; Kim and Jacobi, 2002). Furthermore, boninites have been found in Late Cambrian/Early Ordovician oceanic deposits of the Rowe/Hawley belt (accretionary wedge and fore-arc deposits) in southern Vermont and western Massachusetts (Kim et. al., 2003). Kim and Jacobi (1996) cite these boninites as evidence for extensional magmatism above an incipient subduction zone, as fore-archs (and back arcs) are the only place where boninites are known to form (Kim and Jacobi, 1996, 2002; Kim et. al., 2003). These authors also note that fore-arc extensional magmatism was not as widespread as arc volcanism during the Taconic Orogeny and was a rather localized phenomenon, affecting sections of the Taconic arc.
After, or during the period of fore-arc extension, the depleted mantle sections of the oceanic lithosphere were hydrated above the subducting slab, either as portions of the mantle wedge, or in the accretionary prism. This resulted in partial to complete serpentinization of the ultramafic rocks (depending on the size of the mantle block) that were incorporated into the accretionary prism. During serpentinization (and after emplacement into the accretionary prism) metamorphic reactions between the ultramafic rocks and the surrounding material (meta-pelites and meta-basalt) resulted in the development of blackwall zones, a metasomatic rind (sheath surrounding the ultramafic body) composed mainly of talc, carbonate minerals (magnesite), chlorite, amphibole, and magnetite (Sanford 1982, Ratcliffe et. al., 2011). Some of the smaller ultramafic bodies were fully steatized (altered to talc-carbonate/blackwall) while the larger bodies were ‘shielded’ from complete metasomatic blackwall alteration.

$^{40}$Ar/$^{39}$Ar hornblende ages of 505-490 Ma from the Belvidere Mountain Complex record the oldest estimate for the onset of subduction zone metamorphism in Vermont during the Taconic Orogeny (Laird et. al., 1984, Castonguay et. al., 2012). Slivers of partially serpentinized ultramafic rocks also occur within the fault bounded Belvidere Mountain Complex, indicating that subduction initiated serpentinization of fore-arc mantle peridotite was also occurring by that time (Kim and Jacobi 2002; Laird et. al., 1984).

**Geology of the East Dover Area**

The East Dover meta-dunite is the largest ultramafic body in Vermont. Relict phases (olivine and chrome spinel) are still abundant and contain a geochemical signature indicative of a supra-subduction zone origin (Coish and Gardner 2004, Kim et. al., 2003). East Dover is located in the Appalachian Mountains of southern Vermont, east of the Middle-Proterozoic Green Mountain Massif (Figure 1), and just west of the Acadian Chester Dome. Ultramafic rocks
(Figure 2, Map unit CZu, CZutc) typically occur within Cambrian to Ordovician schists, phyllites and mafic rocks of the Rowe Formation, interpreted to represent the Taconic accretionary prism. Rocks of the Rowe Formation (Map units CZra, CZras, CZrgs, CZrs) generally occur west of (structurally below) the large meta-dunite body in East Dover. Ordovician schist, gneiss, and granofels from Moretown Formation (Moretown Terrane, Map unit Om) occur to the east (structurally above the meta-dunite), separated by the East Dover Fault zone, a Taconian mylonitic thrust fault (Ratcliffe and Armstrong 1999, Ratcliffe et. al., 2011). The Moretown Formation also contains slivers of serpentinized ultramafic rocks and the contact between the Moretown and the Rowe formations marks a major suture zone between the Taconian accretionary prism and the Moretown Terrane (which includes the Shelburne Falls, and Bronson Hill Arcs). This suture zone is interpreted to continue along strike with the Red Indian Line in the Quebec Appalachians (Macdonald et. al., 2014). The mineral assemblage of the meta-dunite consists of olivine + serpentine (antigorite) + spinel + chlorite + magnetite. A metasomatic alteration zone (blackwall zone) composed of amphiboles, schistose talc, and chlorite can be found along the contact of the meta-dunite with Rowe Formation. Surrounding lithologies of the Rowe Formation include meta-volcanic epidote-amphibolite schist to the west, and chlorite-rich pelitic schist and phyllite to the east.

The East Dover ultramafic body is a North-South trending partially serpentinized dunite. It is unique compared to other ultramafic bodies in Vermont because of its large size (approximately 1.5 km wide and 5 km long) and because it is only partially serpentinized, preserving mineral assemblages inherited from the dunite protolith (Hoffman and Walker 1978, Ratcliffe and Armstrong 1999). Some areas within the body contain up to 95% olivine with abundant chrome spinel (Hoffman and Walker 1978). The olivine in the East Dover dunite
displays recrystallization textures (e.g., grain boundary area reduction/annealing, subgrain
development, kink banding, undulose extinction) and its composition ranges from Fo$_{90}$ to Fo$_{97}$
(Hoffman and Walker 1978). High Mg$\#$ (Mg/Mg+Fe) in olivine and high Cr$\#$ (Cr/Cr+Al) in
spinel have led to the interpretation that the East Dover meta-dunite represents a highly depleted
mantle residue that formed in a supra-subduction zone setting (Coish and Gardner 2004). The
exact timing of initial serpentinization has not been constrained for Appalachian ultramafic
rocks, as there are few geochronometers applicable for rocks with an ultramafic bulk
composition (Cooperdock and Stockli 2016).

**Tectonic and Geologic summary**

In the Neoproterozoic, the Iapetus ocean separated Laurentia from Gondwana. By the end
of the Cambrian the Iapetus ocean began to close, forming an eastward dipping subduction zone
and volcanic island arc in the approaching Moretown Terrane. Ultramafic rocks from the Iapetus
oceanic lithosphere were incorporated into the accretionary prism (Rowe Formation) and were
obducted to the Laurentian margin along with arc volcanics during the Taconic Orogeny.
Taconian rocks were subsequently deformed to garnet-amphibolite grade during the Acadian
Orogeny when continental collision culminated in orogenesis to eventually form the Appalachian
Mountains (Stanley et. al., 1984, Ratcliffe and Armstrong 1999). Ultramafic rocks, now exposed
within these mountains, occur as lens-shaped fault-bounded slivers varying in size from meters
to kilometers long (Ratcliffe et. al., 2011).
Methods

Key Localities and Field work

Key localities in the East Dover ultramafic body (meta-dunite, Figure 2) were sampled along with representative surrounding lithologies to further understand the tectonic evolution of the region. Reconnaissance field work in Fall 2017 revealed sparse outcrops concentrated in streams with a thick covering of glacial till and foliage throughout the field area. Using ArcGIS software, a model was created (using digital elevation data, surficial geologic data, and river/stream data) that generated polygons representing possible areas of bedrock outcrops (areas of high slope, thin surficial covering, and adjacent to streams and rivers). This new layer was superimposed on the 2011 Bedrock Geologic Map of Vermont (Ratcliffe et. al., 2011) and used as a basis for field work in 2018 and 2019. Using this map layer as a guide, several key localities were sampled throughout the East Dover ultramafic body and its surrounding lithologies.

Figure 2 shows a newly created Bedrock Geologic Map of the East Dover Meta-dunite locality, largely based on the work of Skehan (1961) Ratcliffe and Armstrong (1999) and Ratcliffe et. al., (2011). Key localities are labeled and marked with white boxes. New lithologic units were assigned to the area to reflect the local geology, and contacts were adjusted to reflect new outcrops.

Adams Brook South

The Adams Brook South (ABS) locality consists of partially serpentinized dunite, talc-carbonate rock, amphibolite, and highly altered (sheared, and chlorite rich) pelitic schist. This locality begins where Adams Brook empties into the Rock River and continues north until its junction with Bemis Brook. Near the junction with the Rock River, the lithologies consist of highly-altered coarse amphibolite and garnet bearing pelitic schist. Continuing north along
Adams Brook, an outcrop of talc-carbonate and acicular/fibrous tremolite-rock can be observed in the streambed before grading into partially serpentinized dunite. Massive partially serpentinized dunite is well exposed in ledges and in the streambed until the junction of Adams Brook and Bemis Brook is reached, where highly weathered/silicified dunite and hydrous nickel bearing silicates (nickel laterite) can be found in ledges on the east side of Adams Brook (Figure 4a).

Adams Brook North

The Adams Brook North (ABN) key locality begins at the junction of Adams Brook and Bemis Brook, and continues until it reaches the Elwin Meadows Trail on the northwest corner of the study area (Fig 2). From the junction of Bemis Brook and Adams Brook, exposures of variably-weathered partially serpentinized dunite are abundant. Faulting and jointing are some common structural features in this locality. Approximately 500 meters from the surrounding Rowe Formation, highly sheared serpentinite grades into talc-carbonate schist (and chlorite-magnetite schist) with local isoclinally folded magnetite layers (Figure 4b). These lithologies dip steeply (70°) to the east and are extremely sheared. A small outcrop of coarse amphibolite separates the ultramafic rocks from pelitic schist of the Rowe Formation, just south of Jockey Hollow Road. Abundant garnet bearing pelitic schist outcrops are found here, and some are intensely sheared.

Bemis Brook

The Bemis Brook (BB) locality begins where Bemis Brook empties into Adams Brook, and continues north until it crosses North Street (Figure 2). Bemis Brook contains numerous outcrops of partially serpentinized dunite, including highly faulted and fractured zones. Intensely
foliated outcrops of the Rowe Formation occur close to North Street, but no talc/serpentine rich lithologies were located here.

**Rock River and Roadcut**

The E-W trending Rock River cuts through the center of the East Dover meta-dunite, and exposures are abundant and highly variable. Zones of talc-carbonate schist occur along the western and eastern boundary of the meta-dunite in the Rock River. Along the west side, outcrops are highly sheared and dip (60°) to the east. Within the dunite body, a massive texture is dominant. Surface coatings of white brucite are common. Glacial activity has carved many gorges into the meta-dunite, and locally (west of the junction with Adams Brook) a glacial tillite cemented by magnesium silicate (similar to those described by Ruiter and Austrheim 2018) crops out where it reaches over 1 meter in thickness. Locally, a folded mylonitic fabric defines a chaotic foliation. Rare faulted magnetite layers, and very rare podiform chromitite can also be found at this locality (Figure 4c, 4d). A zone of silicified serpentinite and hydrous nickel silicates occurs just east of the firehouse in East Dover. For approximately 300 meters, a roadcut parallels the Rock River. This roadcut was sampled and described by Coish and Gardner (2004) and is composed of variably serpentinized dunite that is highly weathered. Small veins of calcite can be seen throughout the roadcut.

**Taft Brook**

Outcrops of fully serpentinized dunite occur on the west-central side of the ultramafic body in the vicinity of Taft Brook. These outcrops occur in a road cut (at the junction of Taft Brook Road and Dover Hill Road) and continue behind the roadcut. Magnetite/chrome spinel are more resistant to weathering compared to the surrounding serpentinite and visibly stand out
against the brown weathered matrix. Amphibolite from the Rowe Formation (map unit CZra) crop out to the west of the road cut, indicating a contact buried under the foliage (Figure 2).

**Hunter Brook**

The Hunter Brook locality contains abundant outcrops of the Moretown Formation, the Rowe Formation, and partially serpentinized dunite. Hunter Brook is another small tributary of the Rock River, and outcrops of the Moretown Formation are exposed within the final 1 km of the Brook (south of Rock River). Outcrops of the Rowe Formation (Map unit CZrs) are abundant east of the Moretown Formation (~1 km SE of the Rock River, Figure 2). Partially serpentinized dunite crops out in several locations in the Hunter Brook (and in the surrounding forest) 1.5-2 km from the Rock River. Boulders containing faulted magnetite layers are abundant in the riverbed (Figure 4e). Fine grained amphibolite of the Rowe Formation continues to the west of the meta-dunite.

**Elwin Meadows**

An east-west trail transects the north end of East Dover meta-dunite in the vicinity of Elwin Meadows. Beginning at the end of Adams Hill Road, the trail offers few exposures of the meta-dunite (0.5 km North of the trail is a small ledge where meta-dunite can be found, Figure 2). However, near the center of the trail (~400 meters west of Adams Hill Road) a ridge exposes coarse grained amphibolite and garnet-amphibole bearing pelitic schist from the Rowe Formation (map unit CZras), which appears to be enclosed within the boundary of the meta-dunite body (Figure 4f).

A small open pit quarry is located at the end of Adams Hill Road at the northeast corner of the ultramafic body near the entrance to the Elwin Meadows Trail. Massive-partially serpentinized dunite makes up the bulk of this quarry, along with amphibole bearing talc schist. This quarry is currently posted as private property and trespassing is forbidden. Fortunately,
some areas of Adams Brook have been rebuilt using material from this quarry, so samples collected from large quarried blocks in Adams Brook South allowed for analysis of the quarry material.

**Petrographic analysis**

Representative samples collected from each key locality were made into thin sections for petrographic analysis. Polished thin sections of key samples were purchased from Quality Thin Sections, and others were handmade using a Buehler PetroThin Thin Sectioning System at Syracuse University. Transmitted and reflected light microscopy was used to identify mineral assemblages and textures for each thin section. Photomicrographs and detailed thin section descriptions were used to identify targets for electron microprobe and Raman analyses.

**Electron Probe Microanalysis (EPMA)**

Polished thin sections and polished epoxy mounts of key samples were prepared and carbon coated for analysis with the Cameca SXFive electron microprobe at Syracuse University equipped with a LaB6 cathode and five wavelength dispersive spectrometers. Qualitative identification of minerals was performed using the Bruker Quantax Electron Dispersive Spectrometer (EDS) attached to the SXFive electron microprobe. Quantitative spot analyses of key samples were performed using wavelength dispersive spectroscopy (WDS). For quantitative analyses, the five wavelength dispersive spectrometers were tuned, and elements were standardized on a variety of natural and synthetic materials (including metals). WDS spot analyses on all minerals were performed using a 20 nA beam current and 15 kV accelerating voltage. WDS maps were also collected from regions of interest within the samples using a 15 kV accelerating voltage and a beam current of 50 nA for garnet and 100 nA for spinel. For spinel Fe$^{3+}$ was calculated as a portion of the total Fe by stoichiometry. Complex peak position
corrections were needed to accurately analyze minerals composed of platinum group elements (PGEs) due to overlap in X-Ray spectra of many PGEs (Osbhar et. al., 2015).

**Raman Spectroscopy**

Thin sections and hand samples containing serpentine were analyzed with a Renishaw Raman spectrometer to determine the dominant serpentine polymorph in the East Dover meta-dunite. A 532 nm laser was used and targets were using a 100x objective. Band position was calibrated on a silicon metal standard prior to analyses.

**Whole Rock Geochemistry**

Four samples representing varying degrees of serpentinization (as well as spatial variation) were selected for whole rock geochemical analysis by X-ray Fluorescence spectroscopy (XRF) at the Hamilton College Analytical Laboratory. Samples were cleaned, crushed, powdered, and analyzed on site at Hamilton College.

**Results**

**Mineralogy of the Ultramafic Rock Units**

The ultramafic body (meta-dunite) in East Dover is over 5km in length, is exposed between 260m and 460m in elevation, and is variably serpentinized (Figure 5a, 5b, 5c, 5d) (ranging from 5-100 percent serpentinization/steatization). Petrographic analyses revealed olivine, chrome spinel, and orthopyroxene as major mineral phases inherited from the upper mantle protolith while serpentine, magnetite, talc, and amphibole represent the major mineral phases interpreted to have formed during Paleozoic orogenic events. The map unit CZu represents the large meta-dunite, which is composed of olivine, chrome spinel, serpentine, and
magnetite, with lessor amounts of pyroxene, calcite, tremolite, and talc. Map unit CZutc represents all variations of talc dominated lithologies, which are composed of talc, magnesite, serpentine, magnetite, chrome spinel, amphibole, and chlorite. Whole rock geochemical analyses of 4 representative samples are shown in Table 1 and Table 2. Sample TB02 is fully serpentinized (approximately 90% serpentine), samples EDQ04 and AB02 are partially serpentinized (approximately 40% serpentine), and sample HB03 is weakly serpentinized (approximately 10% serpentine).

**Spinel**

Chromium rich spinel (chromite) is a ubiquitous accessory phase in the meta-dunite and is relict from the peridotite protolith. Spinel grains can be subhedral, but are most often disseminated and occur in all variations of ultramafic rocks in East Dover, including the most altered samples (in fully serpentinized, and fully steatized samples) (Figure 5e, 5f). Rare occurrences of massive podiform chromitite also occur in the meta-dunite and can be recognized by a massive habit, and by its alteration product kammererite, a purple-colored chromium-rich clinochlore (Figure 6a, 6b). Many spinel grains contain small inclusions of silicate minerals (olivine, pyroxene), sulfide minerals (pentlandite), or rare micro-inclusions of arsenides and platinum group minerals/alloys (Figure 6c, 6d, 6e, 6f).

Most spinel grains are intensely brecciated (Figure 6b). Fe$^{3+}$ enriched spinel (magnetite/ferritchromite) often fills the interstices between fragmented spinel, or surrounds spinel grains imparting a zoned texture that can be observed in both reflected light and X-ray maps (Figure 7). Ferritchromite rims surround nearly all spinel grains. A diffuse boundary exists between the ferritchromite and the chrome spinel (Figure 7).
A large variation in mineral chemistry exists between spinel from podiform chromitite, disseminated spinel, and spinel from talc schists from the East Dover area. The most significant variation occurs in aluminum, magnesium, and chromium content. Overall, spinel from podiform chromitite has the highest chromium content (>60 wt.%) and lowest aluminum content (<0.01 wt.%). Spinel from different localities also shows strong variation (Table 3 and Table 4). Spinel from talc bearing lithologies was also highly variable, with aluminum ranging from 9-23 wt.% between localities. Magnesium content was lowest in talc bearing lithologies and highest in podiform chromitite. Disseminated spinel had less variation in mineral chemistry with intermediate values (Mg# 0.5-0.3, Cr# 0.6-0.8) falling between talc schists and podiform chromitite (Figure 8).

Olivine

Olivine occurs as a major phase in all but the most intensely serpentinized/steatized samples in the East Dover meta-dunite. In some localities it composes over 90% of the mineralogy. The initial grain size of the dunite protolith was greater than 2 mm (Figure 5c) as indicated by optical continuity of fractured grains. Olivine recrystallization textures are common including kink banding, undulose extinction, and grain boundary area reduction. Petrographic analysis revealed at least three olivine types based on textures preserved from the East Dover ultramafic body (Figure 9). Olivine textural types also vary in their chemical composition (Table 5).

Type 1 olivine occurs as inclusions in spinel (Figure 9a, 9b). Inclusions in both podiform chromitite and disseminated chrome spinel crystals have similar compositions. The forsterite component of the olivine inclusions ranges from Fo_{92} - Fo_{93}. Nickel concentrations in type 1 olivine reach as high as 4000 ppm and chromium concentrations up to 3000 ppm. Inclusions
occur within the spinel host, and only those inclusions that did not appear recrystallized, and not within fractures were analyzed.

Type 2 olivine is serpentinized olivine, the most abundant olivine type in the East Dover ultramafic body (Figure 9c, 9d). Serpentinized olivine is highly fractured and is typically surrounded and penetrated by coarse acicular or fine feathery serpentine (antigorite). Some grains of olivine can be over 4 mm in diameter and show evidence of recrystallization. Kink banding, undulatory extinction, and grain boundary area reduction (polygonal texture) are common features of the serpentinized olivine. The forsterite component of Type 2 olivine ranges from Fo_{94}-Fo_{95}.

Type 3 olivine occurs in vein-like structures that cross-cut regions of serpentinized olivine (Type 2) (Figure 9e, 9f). Type 3 olivine often displays a unique “comb-like” habit with individual flat crystals perpendicular to the vein (Figure 9f). Seams of disseminated magnetite typically occur along the boundaries of the olivine veins. Serpentine occurs rarely in association with type 3 olivine, and is always extremely coarse and acicular, with blades that just penetrate the outer edges of the veins. Olivine veins can be up to 4 mm thick (and can be seen at the macroscopic scale) and individual crystals within the veins can be over 1 mm in diameter. Elongate olivine grains are also typical in the veins, sometimes displaying a comb-like structure, and other times occurring in a matrix of non-elongate olivine. The forsterite component of Type 3 olivine approaches pure forsterite with a range between Fo_{95}-Fo_{97} (Figure 10).

**Pyroxene**

Pyroxene is exceptionally rare in the ultramafic rocks from East Dover. One crystal of enstatite was found as an inclusion in chrome spinel during analysis of Type 1 olivine. Rare diopside grains were found in one sample in the Adams Brook South Locality, within 100 meters
from the Rowe Formation to the east. These diopside grains are highly altered, some are partially replaced with serpentine, and contain calcite veins (Figure 11a, 11b). Bastite texture, a pseudomorph of serpentine and magnetite after pyroxene, is also uncommon, but present in samples from the same locality as the diopside (Figure 11c, 11d). In the bastite texture, magnetite typically nucleates along old cleavage planes in original pyroxene while the rest of the pyroxene is serpentinized. One bastite textured grain (Figure 11e, 11f) is composed of magnetite, olivine, and diopside without serpentine.

**Serpentine**

Multiple morphologies of serpentine are recognizable in the meta-dunite. Bladed serpentine is the most common (Figure 5a), and individual crystals range in size from extremely fine grained (Figure 9c) to over 1 mm in length. Nearly all ultramafic samples contain some serpentine (apart from talc-chlorite dominated lithologies), however the percent serpentinization can vary greatly from outcrop to outcrop. Meta-dunite outcrops near Hunter Brook vary in degree of serpentinization from 5 – 100% in a single outcrop, with serpentine dominating the more sheared regions.

Antigorite, the high pressure polymorph of serpentine, is the only polymorph of serpentine recognized in this study from the East Dover meta-dunite. Throughout the ultramafic body, veins of sheared/fibrous serpentine (as much as 10 cm thick locally) have the textural appearance of chrysotile but are truly antigorite as confirmed by their Raman spectrum (Figure 12). Electron microprobe analyses of serpentine from the East Dover meta-dunite are magnesium rich but can contain up to 4 wt.% iron (highest iron concentrations were found in serpentine contained in talc-schists). Aluminum concentrations serpentine minerals ranged from 0-7 wt.%. Arsenic concentrations in serpentine are as high as 70 ppm.
Magnetite

Magnetite is widespread in ultramafic rocks in East Dover and most commonly occur as reaction rims around pre-existing chrome spinel (Figures 5, 6, 7). In some cases, grains of disseminated spinel are completely replaced by anhedral magnetite. Magnetite can be massive, forming layers several centimeters in thickness. In the Adams Brook North Locality, isoclinally folded magnetite layers up to 7 cm can be found enclosed in highly sheared talc carbonate schist along the western contact of the meta-dunite with the surrounding Rowe Formation. In addition to disseminated and massive magnetite layers, euhedral magnetite (up to 1cm in diameter) occurs locally in chlorite dominated metasomatic alteration zones around ultramafic bodies (blackwall zone).

Sulfides

Sulfide minerals are an accessory phase found in all varieties of ultramafic rocks in the East Dover area. They are typically small (50-100 μm), anhedral, and disseminated throughout each sample (Figure 13a, 13b). They are abundant in the more serpentinized material, but also occur as inclusions in chrome spinel, indicating their presence prior to serpentinization. All measured sulfides were nickel sulfides except for rare grains of cobalt sulfide (cobaltpentlandite, Co₉S₈) and a lead-arsenic sulfosalts that were found as inclusions in sulfides and chrome spinel respectively (Table 6). Electron microprobe analyses revealed three distinct nickel sulfides in rocks from the East Dover ultramafic body. These include heazlewoodite (Ni₃S₂), as well as pentlandite ((Fe, Ni)₉S₈) and millerite (NiS). Heazlewoodite (Figure 13a, 13b) is found only within the more serpentinized material, while millerite and pentlandite occur almost exclusively as inclusions in chrome spinel.
Arsenic

Arsenic bearing minerals, previously undocumented in Vermont, are found in ultramafic rocks from East Dover in close association with sulfides (sometimes as inclusions) and as inclusions in chrome spinel. Three distinct nickel arsenide minerals were identified (Table 7). Arsenic bearing platinum group minerals will be discussed in the platinum group minerals section. Orcelite (Ni_{4.77}As_{2}) and maucherite (Ni_{11}As_{8}), occur as small (<50 μm) amorphous grains throughout the ultramafic rocks as inclusions in sulfides (Figure 13c, 13d), or as isolated grains in proximity to sulfides (Figure 13e). Nickeline (NiAs) also occurs as small (<50 μm) anhedral grains exclusively as inclusions in chrome spinel (Figure 13f).

Platinum Group Minerals

Several platinum group minerals (PGM) were found as inclusions in spinel from the East Dover meta-dunite (Figure 6c, 6d, 6e, 6f). All analyzed PGMs came from podiform chromitite collected in the Elwin Meadow locality on the East side of the ultramafic body in partially serpentinized dunite. Other podiform chromitite (from Adams Brook/Rock River) did not appear to contain platinum group minerals. All PGMs were micro-inclusions with an average diameter of 10 micrometers. Representative electron microprobe analyses for PGMs from the East Dover meta-dunite are shown in Table 8. The most common PGM was ruthenium arsenide (RuAs, ruthenarsenite), and several grains were identified. Others included Os-Ir-Ru alloys and Platinum Antimonide (PtSb_{2}, geversite).

Talc

In East Dover, talc is found in talc-schists (steatite) that grade into sheared serpentinite along the contacts of the East Dover ultramafic body. These talc bearing schists are most common along the northwest contact (Adams Brook North Locality) with the Rowe Formation,
but also occur locally along the Eastern contact. Three distinct types of talc-bearing rocks were recognized from East Dover.

The first (and most abundant) is a talc-carbonate schist with rust colored magnesite porphyroblasts. Carbonate porphyroblasts range in size from sub-millimeter to multi-centimeter in diameter. Abundant fine (up to 2mm) euhedral magnetite occurs in both the talc matrix and in the carbonate porphyroblasts (Figure 4b). Fine grained, foliated (often mylonitic) talc is mixed with variable amounts of chlorite and serpentine. The carbonate porphyroblasts are typically anhedral and sheared, although some large groups of euhedral carbonates occur in the Adams Brook North locality. Some carbonate porphyroblasts nucleate around preexisting chrome spinel. Small veinlets of white-green talc also occur in the talc-carbonate schist and are common where the schist grades into chlorite magnetite schist, occasionally marked by coarse euhedral magnetite and/or chlorite porphyroblasts.

The second talc bearing schist is dominated by fine grained, foliated talc and contains abundant amphibole porphyroblasts and small disseminated magnetite. The foliated talc is mylonitic with a fabric that mimics the regional N-S trend (dipping 60-70 degrees East) at each locality where the amphibole talc schist is encountered. At the outcrop scale, these schists transition from nearly monomineralic foliated talc, to nearly monomineralic amphibolite before grading into fine grained chlorite schist, similar to the Ca-Amphibolite-Chlorite zone described by Sanford (1982) from Newfane, VT (5km north of the East Dover ultramafic body).

The third talc bearing schist comes from one outcrop in Adams Brook South Locality. It is exposed in the brook near the junction with the Rock River. This schist contains 30% talc, 40% serpentine, 15% olivine, 10% magnesite, and 5% magnetite. It resembles most fully serpentinized ultramafic samples from this region, but upon examination in thin section it
contains abundant talc. This outcrop is only meters away from massive, partially serpentinized
dunite.

**Amphibole**

The amphibole crystals that are found in talc bearing rocks are dark green, euhedral, and
prismatic. Individual crystals can approach 5 cm in length. Quantitative electron microprobe
analyses reveal that the amphiboles in these talc schists are Ca and Mg rich-actinolite, and do not
show core-rim zonation. Actinolite crystals are coarser and more prismatic in the talc dominated
lithologies and are finer grained and in monomineralic acicular masses where talc schist grades
into chlorite amphibolite.

Rare occurrences of tremolite were also discovered within the meta-dunite body in the
Elwin Meadows Locality. All occurrences of tremolite from this locality occurred adjacent to
calcite, and sometimes as inclusions within calcite crystals. Crystals of tremolite were fibrous,
and small (100-200 μm).

**Chlorite**

Two distinct varieties of chlorite are associated with the ultramafic rocks in East Dover.
The first is a chromium rich chlorite (kammererite) that is found in samples containing abundant
chrome spinel (Figure 6a, 6b). This chlorite can be recognized in hand sample by its purple
color, and in thin section by its anomalous blue interference colors. Kammererite nearly always
surrounds podiform chromitite, and also occurs in veins and cracks between spinel grains. The
second variety of chlorite is fine-grained, massive, green, magnesian chlorite found in talc-
carbonate zones. These chlorite schists always contain large (up to 1 cm) euhedral magnetite,
small (20-30 μm) zircon, and are only found near the contacts of the meta-dunite with the
surrounding Rowe Schist.
**Nickel Silicate**

Several zones of intensely weathered, partially serpentinitized, dunite occur in the East Dover area (Figure 4a). These areas can be recognized by a rusty clay-like matrix of weathered serpentinitized dunite that has been replaced by quartz and nickel rich serpentine/clay minerals (garnierite). The garnierite occurs in vein-like structures that cross-cut the weathered dunite. Locally, cavities filled with drusy quartz are common, as are veins of lime-green quartz within serpentinite. These veins contain tiny inclusions of nickel rich serpentine, as confirmed by EDS. One major occurrence of nickel silicates is located at the junction of Adams Brook and Bemis Brook, and another East of the firehouse located in the Rock River.

**Mineralogy of the Rowe Formation**

The Rowe Formation in East Dover is composed of meta-volcanic epidote-hornblende-biotite-plagioclase-quartz amphibolite and meta-pelitic muscovite-biotite-plagioclase-quartz-garnet schist (Figure 14a-f). These major lithologies vary locally in both texture and composition. For example, in the vicinity of Elwin Meadows pelitic schist often contains coarse amphibole while other localities contain no amphibole minerals. The pelitic schist is often garnet bearing, but textures vary. Fractured/sheared garnets over 2 cm in diameter occur locally in Adams Brook North. Euhedral garnets 1 cm in diameter occur in Hunter Brook. Euhedral garnets 3 mm in diameter occur in the amphibole bearing pelitic schists in Elwin Meadows. Generally, garnet bearing pelitic schist (Map unit CZrs) occurs east of the meta-dunite, while fine-grained epidote plagioclase amphibolite (Map unit CZra) occurs to the west of the meta-dunite, interlayered with the sheared large garnet pelitic schist (Map unit CZrgs) (Figure 2). Although most outcrops of amphibolite are fine grained and strongly foliated, coarse hornblende amphibolite is common within 50 meters of ultramafic rocks. All variations of the Rowe
formation grade into one another at the outcrop scale, but the general trend of the units is shown on the map (Figure 2). The only outcrops from the Rowe Formation that were analyzed by electron microprobe came from the Hunter Brook Locality. Here the dunite body crops out between outcrops of amphibolite (to the west) and pelitic schist (to the east) in a 500 meter stretch of the Hunter Brook.

**Garnet**

Electron microprobe spot analyses and X-ray intensity maps (Figure 15) show that the garnets from the small garnet bearing schist (Sample HB06 from the Hunter Brook locality, map unit CZrs) are almandine rich. The cores are slightly enriched in manganese compared to the rims (cores are ~2 wt.% higher in manganese), and the rims are slightly depleted in calcium compared to the cores (Figure 15). The composition of the garnet core is 64% almandine, 16% grossular, 14% spessartine, and 6% pyrope. The composition of the garnet rim from is 72% almandine, 13% grossular, 8% pyrope, and 7% spessartine. Garnets are often full of inclusions, and inclusion trails often display a fabric that does not mimic the surrounding foliation. Common inclusions in garnets are quartz, ilmenite, plagioclase, epidote, apatite, and zircon. Garnets from the large garnet schist (Adams Brook North Locality, map unit CZrgs) were not analyzed as part of this study.

**Muscovite**

Muscovite is widespread in the pelitic schist units in the East Dover area (Figure 14). At the microscopic scale the foliation is often defined by the parallel orientation of muscovite grains, which are elongate and approximately 0.5 to 1 mm in length. At the macroscopic scale, the foliation dips 50-70 degrees to the east (steeper along the eastern boundary with the ultramafic rocks) and strikes N-S. Electron microprobe WDS spot analyses of muscovite from
the Hunter Brook Locality show that the muscovite contains elevated sodium (>1 wt.% Na₂O), iron (3 wt.% FeO), and magnesium (0.8 - 1 wt.% MgO) (Table 9). Muscovite does not occur in the inclusion trails within garnet.

**Biotite**

Coarse grained biotite cuts across the dominant east dipping foliation in many lithologies from the Rowe Formation, including the garnet and amphibole bearing lithologies. In the Hunter Brook Locality, biotite can be identified macroscopically and appear as stubby flat grains 1-2 mm in length. Biotite grains typically contain small inclusions of zircon with pleochroic halos. Biotite does not occur in the inclusion trails within garnet. Electron microprobe analyses of biotite from the Hunter Brook Locality show that the biotite is annite rich, with 10 wt.% MgO and 19 wt.% FeO and have TiO₂ concentrations of 1.6 - 1.8 wt.% (Table 10).

**Chlorite**

Chlorite is present in nearly all lithologies from the Rowe formation. Texturally, it occurs near biotite grains, as a replacement after garnet, or along the muscovite rich foliation planes (Figure 14c). Electron microprobe analyses of chlorite from within the dominant muscovite defined foliation is relatively iron-rich (25 wt.% FeO).

**Plagioclase**

Un-twinned plagioclase is common in the pelitic schist units of the Rowe Formation. It occurs in quartz-rich domains (not in mica-rich domains) and in pressure shadows near garnets. Plagioclase from the Hunter Brook Locality is enriched in the albite component (8 wt.% Na₂O) relative to the anorthite component (3 wt.% CaO) and is also relatively aluminum rich (22 wt.% Al₂O₃). Plagioclase also occurs (in association with quartz) in the fine grained and coarse grained amphibolite units of the Rowe Formation.
Amphibole

Amphibole is the dominant mineral in the more mafic units of the Rowe Formation (Figure 14). In the fine-grained units (CZra), a strong foliation defined by the preferred orientation of 100 μm hornblende is dominant. This foliation is locally crenulated, and coarse hornblende (300 μm) occurs within these zones. Adjacent to ultramafic bodies, coarse non-foliated amphibolite occurs with statically recrystallized hornblende (up to 3 cm in length) imparts a decussate texture observed in both hand sample and in thin section. These decussate textured amphibolites also occur as irregular lenses in pelitic schist of the Rowe Formation. In the more pelitic schist samples, amphibole is less common. However, in the large garnet-bearing lithologies (CZrgs, CZras), coarse tabular amphibole cross-cuts the dominant foliation imparting a decussate texture (possible garbenschiefer texture).

Quartz

Quartz is ubiquitous in all lithologies of the Rowe Formation. In hand sample, lenses and quartz boudins are common in the pelitic schists, while veins and thin quartz layers are common in lithologies dominated by mafic minerals. Some of the quartz layers in amphibolite are folded. Where decussate amphiboles are common, quartz displays a polygonal texture with prominent 120 degree triple junctions (grain boundary area reduction) indicative of static recrystallization. Quartz also occurs as inclusions in garnet.

Accessory Minerals

Units of the Rowe Formation contain several accessory minerals. The most common accessory phase in the amphibolite unit is epidote, which occur as small rounded grains. In the strongly foliated amphibolite, epidote shares a similar orientation with amphibole, and also occurs within domains of quartz. Near ultramafic rocks where the amphibolite is coarse grained,
epidote occurs as poikiloblasts within the decussate hornblende. In the more pelitic samples, epidote is common in the mica rich matrix, as well as inclusions within garnets.

Other accessory phases in all lithologies include magnetite, pyrite, calcite, apatite, and zircon. Ilmenite is present in the pelitic schist samples. Ilmenite, apatite, and zircon also occur as inclusions in garnets.

**Thermobarometry**

Titanium concentrations in biotite from the Rowe Formation were used to estimate temperatures using the Ti-in-biotite thermometer (Luhr et. al., 1984, Wu and Chen 2015). The sample was collected 50 meters east of the meta-dunite in the Hunter Brook Locality and analyzed (WDS spot analyses) using EPMA. Results indicate slightly higher temperature estimates (590 °C ± 50 °C). These temperature estimates are within error of those reported by Ratcliffe and Armstrong (1999) of 540 °C using garnet biotite thermometry. Pressure estimates for the same sample were determined using the garnet-biotite-muscovite-plagioclase (GBMP) geobarometer of Wu (2015). Compositions of relevant minerals were determined using WDS spot analyses on the electron microprobe. Garnet rim compositions were used for this calculation, as the rims are more likely to have approached chemical equilibrium with the surrounding matrix minerals as compared to the garnet core compositions. Pressure estimates obtained using this geobarometer are 8 kbar (± 1.2 kbar). The pressure/temperature estimates and mineral assemblages preserved confirm the region was metamorphosed under upper amphibolite facies conditions.
Discussion

The ultramafic rocks in the vicinity of East Dover are unique in their size, mineralogy, and texture compared to most other ultramafic rocks in Vermont. Ultramafic bodies throughout Vermont rarely reach over 1 km in length and are often intensely sheared, serpentinized, and/or steatized (metasomatically altered to talc-carbonate rock) (Ratcliffe et. al., 2011). In contrast, the East Dover meta-dunite is only partially serpentinized, preserves textures and minerals of its mantle protolith, and is approximately 5 km in length. Smaller ultramafic bodies in southern Vermont were fully serpentinized and/or steatized during subduction, obduction, and accretion to the Laurentian margin during the Ordovician Taconic Orogeny, or were altered by metasomatism during the Devonian Acadian Orogeny. The relict mineral phases in the East Dover meta-dunite such as olivine, orthopyroxene, and spinel give insight into the evolution of the upper mantle, while the more serpentinized/steatized samples provide details about the metasomatic alteration of the upper mantle. Key metamorphic events that altered the East Dover ultramafic body are summarized in Figure 16.

Partial Melting and Fluid/Melt-Rock Interaction

Partial melting of the Earth’s upper mantle produces magma at mid ocean ridges by adiabatic decompression and in island arcs by flux melting (induced by the dehydrating subducting slab). High degrees of partial melting in the upper mantle can produce basaltic to boninitic melts (Zhou et. al., 1994, Kim and Jacobi 2002). During partial melting of the upper mantle in a suprasubduction zone setting, lherzolite loses pyroxene and forms dunite through prolonged fluid/melt-rock interaction (Keleman et. al., 1992) (Figure 16a). Massive-podiform chrome spinel (chromitite) can also crystallize directly from the melt where it is typically enclosed within dunite (Zhou et. al., 1994). During fluid/melt-rock interaction, spinel and olivine
in the residual mantle become deficient in aluminum and iron respectively, making their chemistry useful in determining the petrogenetic history of their host rocks (Dick and Bullen 1984, Barnes and Roeder 2001). Highly siderophile elements such as nickel and platinum group elements (PGE) are more compatible with solid phases and do not concentrate in the melt (Becker and Dale 2016 and references therein). Furthermore, experiments involving the formation of platinum group minerals in peridotite have shown that the nucleation and growth of spinel creates local areas of extremely low oxygen fugacity, allowing for the formation of reduced metal alloys that become inclusions as the spinel grows (Finnigan et al., 2008) (Figure 16b). The occurrence of platinum group minerals, spinel with low aluminum concentrations, the lack of pyroxene as a major phase, and olivine with a high forsterite component are all characteristics indicative of high degrees of partial melting in the upper mantle.

The composition of spinel grains from the East Dover meta-dunite is highly variable, especially in spinel that occurs in talc schists. However, disseminated spinel (in serpentinitized dunite) and spinel from podiform chromitite is depleted in aluminum as shown by its high Cr# (Cr/[Cr+Al]). Some spinel grains within podiform chromitite from Adams Brook North have a Cr# greater than 0.9, which indicates that the spinel formed from a depleted partial melt. Coish and Gardner (2004) found similar results from their analyses of chrome spinel (high Cr#) throughout the East Dover meta-dunite but did not distinguish podiform chromitite from disseminated spinel. Furthermore, several platinum group minerals were found as inclusions in spinel from podiform chromitite from the East Dover meta-dunite. Although small (<20 μm in diameter), these inclusions represent the first documented occurrence of platinum group minerals in Vermont. These platinum group minerals provide a natural analog for the experimental results of Finnigan et al., (2008) who showed that spinel growth (during fluid/melt-rock interaction)
creates local areas of low oxygen fugacity that promotes growth of platinum group minerals. Other minerals that form under low oxygen fugacity conditions in the upper mantle are nickel sulfides and arsenides (Ishimaru and Arai 2008, Finnigan et. al., 2008). Nickeline and the sulfide minerals millerite and pentlandite also occur as inclusions in chrome spinel (mostly in podiform chromitite) and are therefore considered to be relict phases that also formed during partial melting events that depleted the peridotite before serpentinization.

Further evidence of a highly depleted origin for the East Dover meta-dunite is the ubiquitous high forsterite component of olivine, and near absence of pyroxene. Inclusions of olivine in chrome spinel had the lowest forsterite component (Fo92) and are interpreted to represent olivine that formed in the upper mantle in response to melt-rock interaction during partial melting. Coish and Gardner (2004) reported olivine with a similar high Mg# from the East Dover meta-dunite. Unaltered pyroxene was only found in one sample from this study and occurs as an inclusion in the core of a chrome spinel. All these data support an interpretation that the upper mantle protolith of the East Dover ultramafic body experienced high degrees of partial melting, and formed podiform chromitite (with inclusions of PGMs, arsenides, and sulfides) and dunite through melt-rock interaction prior to serpentinization. Furthermore, boninites occur along strike with the East Dover meta-dunite (Red Indian Line) in Quebec (Thetford Mines Ophiolite) and the Bay of Islands Ophiolite in Newfoundland (Macdonald et. al., 2014). Boninites typically form from partial melting of previously depleted mantle (leaving behind a highly depleted restite largely composed of dunite and chromitite) and thought to form from supra-subduction zone extensional magmatism caused by subduction initiation and slab rollback (Shervais 2001; Kim and Jacobi 2002; Reagan et. al., 2010). Boninites also occur in ophiolites such as the Oman
Ophiolite, New Caledonia, Papua New Guinea, and occur today the Izu-Bonin-Mariana Fore-arc southeast of Guam (Kim and Jacobi 2002 and references therein).

**Mineralogy of Serpentinization**

The initiation of serpentinization is known to produce highly reducing conditions with extremely low oxygen and sulfur fugacities (Frost 1985). However, in fully serpentinized ultramafic bodies, once olivine is completely consumed, oxygen and sulfur fugacities increase and talc and pyrite begin to form (Eckstrand 1975, Frost 1985). Therefore, highly reduced sulfur-poor minerals are typically found only in weakly/partially serpentinized ultramafic rocks like the East Dover ultramafic body (Chidester 1951, Eckstrand 1975, Frost 1985). Heazlewoodite, a sulfur poor nickel sulfide, occurs only as interstitial grains within the serpentinized matrix in the East Dover ultramafic body and likely formed in the early stages of serpentinization directly from the breakdown of nickel bearing primary olivine (3000-4000 ppm nickel in type 1 olivine).

Smaller ultramafic bodies throughout Vermont are more intensely serpentinized, indicating that the size of the initial dunite body must have been a factor in controlling the percentage of serpentinization (Ratcliffe et. al., 2011). However, in the East Dover meta-dunite, percent serpentinization varies at the outcrop scale, and not on a regional scale. Hoffman and Walker (1978) created a map showing the non-uniform nature of serpentinization, ranging from 5% serpentinization to 100% regardless of position within the meta-dunite body. Previous authors such as Skehan (1961) speculated that the core of the dunite body was shielded from serpentinizing fluids and was therefore pure dunite. However, this study as well as others by Hoffman and Walker (1978), and Coish and Gardner (2004) provide evidence to the contrary, indicating that the core of the dunite body shows as much variation in percent serpentinization as
areas near contacts with surrounding lithologies. For example, some samples from the core of the
dunite body in the Bemis Brook Locality are completely serpentinized (Figure 16c).

The variation in percent serpentinization may also result from multiple episodes of
serpentinization. Although all analyzed serpentine minerals were antigorite, some of the finer
grained mesh serpentine could represent antigorite pseudomorphs after early lizardite. Antigorite
is stable at high pressures and medium temperatures, indicating that the majority of
serpentinization also took place at high pressures, likely in the mantle wedge above a subducting
slab. The range in serpentine morphology (from fine grained aggregates to coarse blades) may
also indicate that multiple generations of serpentinization are preserved in the East Dover meta-
dunite (Figure 17). Most of the serpentine in the East Dover meta-dunite is fine grained, but
coarse antigorite blades and fractures filled with acicular antigorite can be found throughout the
study area. An initial serpentinization event likely occurred in a subduction environment, but
subsequent movement of the ultramafic rocks (either during their obduction to the Laurentian
margin or during later metamorphic events such as the Acadian Orogeny) may have created
fluids that provided additional local serpentinization along fractures within the meta-dunite. The
ubiquitous presence of blackwall zones also indicates metasomatic alteration that likely persisted
after initial serpentinization (Figure 16d)

**Acadian Metamorphism**

Sample HB09, a pelitic garnet bearing schist (map unit CZrs) was chosen for
themobarometric analysis due to its proximity (within 50 meters) to the meta-dunite. As depleted
ultramafic rocks do not contain many minerals that can be used for thermobarometry,
surrounding lithologies were used to constrain the most recent (Acadian) pressure-temperature
evolution of East Dover meta-dunite. Previous studies showed that the dominant foliation and
mineral assemblages for the southeastern Vermont area were Acadian in age (Sutter et. al., 1985, Armstrong and Tracy 2001). Complex $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra on biotite and hornblende east of the Green Mountain Massif at approximately $355 \pm 4.8$ Ma are interpreted as the timing of cooling following Acadian metamorphism (Sutter et. al., 1985). Pressure-temperature estimates for the same region were calculated to be $540 \pm 50$ °C and $8 \pm 1$ kbar using exchange and net transfer thermobarometers (Ratclifffe and Armstrong 1999, Armstrong and Tracy 2000).

Sample HB09 was 10 km east of the samples analyzed by previous authors (Sutter et. al., 1985, Ratclifffe and Armstrong 1999, Armstrong and Tracy 2000) but pressure/temperature estimates for HB09 are within error of those previously reported for the region (Sutter et. al., 1985, Ratclifffe and Armstrong 1999). Ti in biotite measurements provide the most reliable temperature estimates for the sample because they do not rely on mineral equilibrium with other phases such as garnet. Because the biotite cuts across the dominant foliation in sample HB09, it is interpreted to have grown later than the foliation. Furthermore, due to the decussate/cross fabric texture, biotite is interpreted to represent growth at the highest temperatures (and not the highest pressures) reached by the garnet bearing pelitic schist (Map unit CZrs) during Acadian regional metamorphism. Thermal modeling in the region by Armstrong and Tracy (2001) show a similar trend for the region, where peak temperatures near 600 °C were reached following peak pressure conditions associated with Acadian metamorphism.

**Olivine Textural Variation**

The three olivine textural types are interpreted to illustrate different generations of olivine in the East Dover meta-dunite (Figure 9). Type 1 olivine is interpreted as the oldest generation of olivine preserved in the meta-dunite. Type 2 olivine is interpreted as olivine that recrystallized
during serpentinization. Type 3 olivine is interpreted as neoblastic olivine forming directly from the breakdown of serpentine minerals in response to regional metamorphism (Figure 16e).

Type 1 olivine represents primary olivine inherited from the upper mantle. Since type 1 olivine occur as isolated inclusions within the cores of spinel, they represent olivine that was co-crystallizing with the spinel in the upper mantle. This type 1 olivine has the lowest Mg# (92-93) of all olivine that was analyzed in this study. Since these values are still relatively high compared to primitive mantle olivine (Fo86), type 1 olivine is also interpreted to have crystalized after one or many partial melting events in the upper mantle (Deer et. al., 2013). No serpentine was found in contact with type 1 olivine, indicating that these grains were shielded from serpentinizing fluids by the spinel host. Type 2 olivine represents olivine that underwent recrystallization during or after serpentinization. This olivine type is the most abundant in the East Dover meta-dunite and can be strongly serpentinized. Multiple recrystallization textures are recognized in type 2 olivine (Figure 5) including undulose extinction, kink banding, and rare grain boundary area reduction (Hoffman and Walker 1978). Type 3 olivine occurs in veins that cross-cut type 2 olivine and can be highly elongate (Figure 16e). This olivine also generally lacks recrystallization textures (such as undulose extinction), further indicating that type 3 olivine is neoblastic.

**Acadian Mineral Assemblage in Ultramafic Rocks from the East Dover meta-dunite**

Elongate olivine of metamorphic origin is not uncommon in serpentinized ultramafic rocks that are metamorphosed above the stability range of serpentine (>460°C) (Evans and Trommsdorf 1974, Nagaya et. al., 2014). A typical mineral assemblage at this temperature (below 10 kbar) includes olivine, talc, and tremolite, and diopside (Schwartz et. al., 2013). In addition, olivine produced from the dehydration of serpentine will be highly forsteritic (high
Mg#) forming directly from the breakdown of Mg-rich antigorite (Nozaka et. al., 2005, Schwartz et. al., 2013). Previously published pressure/temperature estimates for Acadian metamorphism, as well as those from this study, place the East Dover meta-dunite above the stability range of serpentine (Ratcliffe and Armstrong 1999, Armstrong and Tracy 2000). Some localities along the meta-dunite’s easternmost contact contain the assemblage: olivine, talc, tremolite, serpentine, magnetite, and carbonate minerals. These minerals would be expected to form close to the antigorite out reaction (Spear 1993, Schwartz et. al., 2013). All Type 3 olivine that was found was also collected from localities within 100 meters of the eastern contact with the surrounding Rowe Formation, where the effects of Acadian metamorphism on meta-dunite would presumably have been greatest. Since Type 3 olivine cross-cuts serpentinized olivine, is often highly elongate, and is composed of nearly pure forsterite (Fo95-Fo97, Figure 6), it is interpreted to be metamorphic olivine that likely formed directly from the dehydration of serpentine (antigorite) during the Acadian Orogeny. Figure 10 shows the variation of olivine composition as a function of olivine type, with a trend towards pure forsterite with increasing metamorphism.

Diopside is another mineral that commonly forms neoblasts in polymetamorphosed ultramafic rocks (Nozaka et. al., 2005, Spear 1993). Some bastite pseudomorphs of serpentine after orthopyroxene are replaced again by olivine and diopside (Figure 11e, 11f). This texture is interpreted to represent secondary growth of olivine and metamorphic diopside during the same thermal event that crystalized type 3 olivine (Figure 7). Coish and Gardner (2004) also found rare diopside porphyroblasts in their study of the origin the East Dover meta-dunite.

The Acadian Orogeny produced a relatively static metamorphic overprint in the East Dover area with peak temperature occurring after peak pressure was reached (Armstrong and Tracy 2000). Evidence of static metamorphism (i.e. temperature outlasting deformation) is seen
in the decussate amphibolite lenses of the Rowe Schist (Figure 16f), in the ultramafic rocks where large (>2mm) bladed antigorite can be found (Figure 17), and in quartz microstructures (from the Rowe Formation) that show grain boundary area reduction (120 degree grain boundaries). The coarse bladed antigorite likely formed in the later stages of Acadian orogeny as temperatures cooled into the stability range of serpentine. This is inferred by coarse antigorite cross-cutting neoblastic olivine veins. The dehydration of serpentine during the Acadian orogeny would have produced fluids that contributed to the development of metasomatic talc in the blackwall zones, but it is likely that some of the fluid was not completely consumed and formed new serpentine (coarsely bladed antigorite) after the region began to cool.

**First Documented Arsenide Minerals in Ultramafic Rocks from Vermont**

Ryan et. al., (2011) found elevated concentrations of arsenic (up to 327 μg/L compared to background levels of 2-9 μg/L) in groundwater wells near ultramafic rocks in northern Vermont. They examined over 100 samples consisting of serpentinized ultramafic rocks, talc-carbonate schists, as well as phyllite that hosted the ultramafic rocks. In general, Ryan et. al., (2011) found an average arsenic concentration of 93 ppm throughout their rock samples (with concentrations as high as 1105 ppm in talc-carbonate lithologies). Ryan et. al., (2011) showed that arsenic can substitute for Mg in the crystal structure of serpentine and magnesite and speculated that the dissolution of those minerals was the source of elevated levels of arsenic in groundwater. No arsenic bearing minerals (arsenides or sulfides) were found in the samples of Ryan et. al., (2011). They also speculated that the arsenic came from the fluids that caused serpentinization. Hattori et. al., (2005) also attributed high levels of arsenic in serpentinites to high concentrations (90 ppm) of arsenic in serpentine and speculated that the arsenic was introduced to the mantle wedge via serpentinizing fluids. In the East Dover meta-dunite, whole
rock arsenic concentrations range from 5 ppm in the least serpentinized samples to 100 ppm in the more serpentinized samples (Figure 18). No talc-carbonate samples were analyzed for whole rock geochemistry in this study.

This study presents the first documentation of arsenide minerals from ultramafic rocks in Vermont. Fully serpentinized ultramafic samples contained abundant small grains of orcelite and maucherite, while the least serpentinized samples contained rare grains of nickeline as inclusions within spinel. No arsenic bearing minerals were found in the talc-bearing lithologies, however, arsenic concentrations in the carbonate minerals from talc schists reached as high as 200 ppm. Other ultramafic bodies throughout Vermont likely contain arsenic bearing minerals, however they are nearly indistinguishable from sulfides when examined with a petrographic microscope. A scanning electron microscope (SEM) or an electron microprobe is needed to confirm the presence of arsenide minerals elsewhere. Although the arsenic minerals described in this report are small (<100 μm), they may be contributing to the elevated levels of arsenic in the groundwater.

**Implications of Results**

**Geologic Mapping**

Detailed geologic mapping of the East Dover area was completed by Skehan (1961), Hoffman and Walker (1971), Ratcliffe and Armstrong (1999), and by Ratcliffe et. al., (2011). In this study new outcrops of several lithologies were discovered during geologic mapping. Multiple zones of talc-carbonate rock were mapped (map unit CZuT), some containing veins of pure talc like those reported by Sanford (1982) farther to the north. Outcrops of partially serpentinized dunite east of North Hill indicate that the dunite body is 200 meters wider than
previously estimated. The occurrence of rare podiform chromitite was also discovered in Elwin Meadows, the Rock River, Bemis Brook, and as a float block in Adams Brook. Further analyses of podiform chromitite from other localities in East Dover or throughout Vermont could reveal additional platinum group minerals or arsenic minerals. Nickel laterite (garnierite) occurs in multiple sections within the dunite body especially in the Rock River and near the junction of Adams Brook and Bemis Brook (Figure 16g). These nickel-rich zones are similar to those mined in places such as New Caledonia and Cuba and provide over 50% of the world’s supply of nickel and over 20% of the world’s cobalt (Butt and Cluzel 2013).

In addition to the ultramafic lithologies, new outcrops of locally sheared large garnet schist (map unit CZrgs) were discovered in Adams Brook North, and in Hunter Brook. Local decussate textured amphibolite lenses are common within the garnet schist near the contact with the meta-dunite. These may have formed from residual heat from the mantle protolith, or perhaps during cooling (thermal relaxation) of the region following regional metamorphism associated with the Acadian Orogeny. Samples with a decussate texture also contained quartz that displayed grain boundary area reduction, another indicator of static recrystallization (Passchier and Trouw 2005). Enclosed within the northern portion of the meta-dunite (Elwin Meadows) is a ridge composed of amphibole bearing garnet schist (Map Unit CZras). Locally garnets are pseudomorphed by chlorite. Previous mapping in the region showed these outcrops to be a fault bound continuation of a chlorite schist member of the Rowe Formation (not fully enclosed within the dunite body), however newly explored outcrops of partially serpentinized dunite suggest that this schist is contained within the dunite body. This schist typically contains a strong N-S trending foliation similar to other outcrops of the nearby Rowe Formation. However, decussate-
poikiloblastic amphibolite (hornblende bearing) locally dominates the fabric of this schist with no apparent foliation, similar to amphibolite found near the contact with the meta-dunite.

**Another Arsenic Source**

This study shows that previously undocumented arsenic-bearing minerals may be contributing to elevated levels of arsenic in groundwater in Vermont. Although rare grains of nickeline were found as inclusions in chrome spinel, most of the arsenides were found in the serpentinized matrix. All fully serpentinized samples that were analyzed contained maucherite or orcelite. This finding, together with the whole rock geochemical data, support findings of Ryan et. al., (2011) who argue that most of the arsenic was introduced into the peridotite by fluids associated with serpentinization. XRF analyses of weakly serpentinized rocks contained less than 10 ppm arsenic, while the most serpentinized sample analyzed contained over 100 ppm arsenic. Electron microprobe analyses of serpentine show similar arsenic concentrations to serpentinites analyzed by Hattori et. al., (2005) from the Indus suture zone, northwest Himalaya, which further suggests a slab-fluid source. However, the finding of nickeline and arsenic bearing PGMs within chrome spinel suggest that some arsenic did exist within the mantle prior to serpentinization.

**Future Work**

**Geochronology of Blackwall Zones**

The chlorite schist that separates the ultramafic rocks from surrounding lithologies represents part of a metasomatic alteration zone (blackwall), typical of ultramafic rocks in metamorphic terranes (Sanford 1982). This metasomatic alteration zone may have formed during/after serpentinization or after the ultramafic rocks were obducted to the Laurentian Margin. No geochronologic studies have confirmed the timing of blackwall formation in
Vermont. However, small zircons are abundant in these chlorite schists from several localities in the East Dover meta-dunite including the contact in Adams Brook North and along the eastern contact in the Rock River (Figure 19). A geochronologic study of these zircons may provide key details about the timing of the metasomatic alteration of the ultramafic rocks.

Cathodoluminescence (CL) imaging of the zircons show no zoning, indicating that these zircons formed during the formation of the blackwall rocks via metasomatism. In addition to the zircons, large magnetite porphyroblasts (up to 1 cm in diameter) also occur in the chlorite schists and can be dated using (U-Th)/He geochronology (Cooperdock and Stockli 2016). Together these two minerals could provide a timeline for the formation of blackwall zones in the ultramafic rocks not only in East Dover, but throughout the Vermont Appalachian Mountains.

**Arsenic in Water from the East Dover Area**

The presence of arsenic bearing minerals in the ultramafic rocks from East Dover Vermont warrants an investigation of the groundwater chemistry of the region. The East Dover area was not examined by Ryan et. al., (2011), however whole rock geochemistry indicates that some areas within the ultramafic body (i.e. the fully serpentinized zones) contain similar arsenic concentrations to those analyzed by Ryan et. al., (2011). Over 90 privately owned wells occur within 1 km of the East Dover meta-dunite, and 203 private wells are within 1 km of any ultramafic body in the Dover region (Figure 20). The Dover Elementary School is also located less than 5 km away from the meta-dunite and small lenses of ultramafic rocks occur less than 1 km from the school (Ratcliffe et. al., 2011). The wells in the East Dover area should be tested for arsenic contamination and the public should be notified of the potential for contamination and what they can do to ensure clean drinking water.
**Detailed Spinel Inclusion Investigation**

This report presents the first documentation of platinum group minerals and arsenide minerals as inclusions in spinel from Vermont. Other ultramafic bodies in the Appalachian Mountains with a similar bulk composition and tectonic history may also contain PGM inclusions. All platinum group bearing minerals were found in rare lenses of podiform chromitite from the East Dover meta-dunite, so future investigations should begin by searching for other occurrences of podiform chromitite in partially serpentinized ultramafic bodies. Some ultramafic complexes in the Canadian Appalachian Mountains (i.e. The Thetford Mines Ophiolite in Quebec and the Bay of Islands Ophiolite/Advocate Ophiolite in Newfoundland) along strike with the East Dover meta-dunite were analyzed for platinum group elements and found that podiform chromitites contained the highest concentrations (Naldrett and Cabri 1976, Oshin and Crocket 1982). In addition, platinum group minerals and arsenide minerals, similar to those reported in this study, were found in chromitite from the Advocate Ophiolite Complex in Newfoundland (Escayola et. al., 2011). The presence of arsenic minerals (nickeline) as primary inclusions within chrome spinel also provides information about the concentration/presence of arsenic in the mantle. Mantle derived arsenic minerals are rare, especially those not sourced from ophiolites, but they have been found in mantle xenoliths from the Kamchatka Peninsula in Russia (Ishimaru and Arai 2008). Additional investigation of inclusion suites in chrome spinel and podiform chromitite throughout the Vermont Appalachian Mountains could reveal more PGE and arsenic bearing minerals that could improve our understanding about their conditions of formation in the Earth’s upper mantle.
Conclusions

The East Dover meta-dunite was altered by several key metamorphic events spanning from the Cambrian Period to present day. This report presents mineralogical and textural evidence for 7 key events with varying relative intensity (Figure 16). Partial melting and fluid/melt-rock interaction during the Cambrian Period produced dunite from lherzolite (either during the formation of the Iapetus Ocean or in a supra-subduction zone setting). Most of the pyroxene in the lherzolite was partitioned into the partial melt leaving behind olivine (Figure 16a). This olivine reacted with the surrounding partial melt and became enriched in magnesium. Since iron has a larger atomic radius compared to magnesium, more energy is required to keep iron within the crystalline structure of olivine. Therefore, olivine becomes enriched in magnesium (i.e. the forsterite component) during fluid/melt-rock interaction. Some olivine (Type 1 olivine, Fo92 - Fo94) was trapped in spinel that likely crystalized/recrystallized during this time. The partial melting and fluid/melt-rock interaction was a regional metamorphic event and left behind a depleted mantle restite (dunite). Massive podiform chromitite also formed during this time, likely crystallizing directly from the partial melt. Alloys of platinum group elements and arsenides were trapped as inclusions in the podiform chromitite (Figure 16b).

Shortly after crystallization of the podiform chromitite, subduction zone metamorphism began (Late Cambrian). Water released from the subducting slab reacted with olivine (and rare pyroxene) to form serpentine (Figure 16c). This water was also relatively rich in fluid mobile elements such as arsenic (Hattori et. al., 2005, Evans et. al., 2013). Serpentinization was widespread and regional during the Ordovician Taconic Orogeny. Portions of the fore-arc upper mantle were completely serpentinized by the time they were obducted to the Laurentian Margin. Olivine that was not fully serpentinized likely recrystallized during serpentinization (Hoffman
and Walker 1978). This recrystallized olivine (Type 2, Fo94 - Fo95) was more magnesium rich than Type 1 olivine, because iron was being consumed by the crystallization of magnetite during serpentinization. After, or during serpentinization of the fore-arc mantle, metasomatic reactions between bodies of ultramafic rock and surrounding material in an accretionary mélange, produced ‘blackwall’ zones that surrounded the ultramafic bodies. These blackwall zones can have a complex mineralogy and can continue to form during subsequent metamorphic events (Sanford 1982). Many of the blackwall zones in the East Dover area are composed of talc and amphibole (Figure 16d).

The Devonian Acadian Orogeny was the next major metamorphic event to alter the East Dover meta-dunite. Regional metamorphism reached amphibolite facies conditions leading to the dehydration of serpentine. Locally, veins of metamorphic olivine (Type 3, Fo95 - Fo96) cross-cut regions of serpentinized olivine (Figure 16e). Rare diopside and olivine pseudomorphs after bastite serpentine are also present (Figure 11E, F) and likely formed under the same metamorphic conditions that produced the cross-cutting olivine veins. As the region slowly cooled following Acadian orogenesis, minerals in the ultramafic rocks and their surrounding lithologies experienced static recrystallization. In the meta-dunite, course serpentine (antigorite) formed blades over 2mm. In the surrounding blackwall zones, decussate textured hornblende and quartz showing grain boundary area reduction are common (Figure 16f).

The final process to alter the ultramafic rocks in the East Dover area was near surface chemical weathering to form nickel laterite, saprolite, and silicified serpentinite. Local zones of nickel mineralization can be identified by bright green clay-like minerals that occur in intensely weathered serpentinite (Figure 16g). Druzy quartz filled cavities and bright green veins of quartz are also common in these areas. Further studies on the ultramafic rocks in Vermont should
examine the timing of mineral petrogenesis, the possible role of serpentinized ultramafic rocks in the exhumation of (ultra) high pressure metamorphic rocks (i.e., in the Tillotson Peak Complex of northern Vermont; Gonzalez et. al., 2020), and the societal implications of the presence of arsenide minerals in serpentinite.
**Figure Captions**

**Figure 1:** Generalized bedrock geologic map modified from Ratcliffe et. al., 2011 and Castonguay et. al., 2012. Major lithotectonic zones are labeled as well as the ultramafic rocks labeled in red.

**Figure 2:** Updated Bedrock geology of East Dover, Vermont (modified from Ratcliffe et. al., 2011). White boxes indicate key localities described in the text.

**Figure 3:** Tectonic model for the Taconic Orogeny from Karabinos et. al., (1998). A) shows the development of the Shelburne Falls Arc from eastward dipping subduction below the Moretown Terrane. B) shows the subsequent development of the Bronson Hill Arc from westward dipping subduction after the oceanic lithosphere between Laurentia and the Moretown Terrane was consumed.

**Figure 4:** Field photographs from East Dover, Vermont. (A) photograph of nickel laterite zone near the junction of Adams and Bemis Brook. (B) Photograph showing talc schist (brown) grading into chlorite schist in Adams Brook North. (C) Photograph of magnetite/brecciated spinel boudins from Bemis Brook. (D) Photograph of chromitite pod in dunite from Rock River. (E) Photograph of a faulted magnetite layer in a partially serpentinized dunite boulder from Hunter Brook. (F) Photograph of an amphibolite (with decussate texture) layer in pelitic schist of the Rowe Formation in the Elwin Meadows Locality.

**Figure 5:** Photomicrographs of olivine, serpentine and chrome spinel textures from the East Dover meta-dunite. (A) Photomicrograph in cross-polarized light (XPL) showing a representative texture of the meta-dunite with large relict (recrystallized and fragmented) olivine (Ol) with a large antigorite serpentine (Srp) blade and grains of magnetite (Mag). (B)
Photomicrograph in XPL showing a typical fully serpentinized sample with a folded layer of disseminated magnetite. (C) Photomicrograph in XPL showing a kink band in very weakly serpentinized olivine. Note the large grain size of the olivine crystal. (D) Photomicrograph in XPL showing a mesh texture with weakly serpentinized olivine. (F) Photomicrograph in reflected light showing a zoned chrome spinel (Spl) with a magnetite rim. Dark zone around the spinel is ferritchromite, a chromium rich magnetite. (G) Photomicrograph in reflected light showing a brecciated (fragmented) chrome spinel surrounded by and filled with serpentine minerals.

**Figure 6:** Platinum group minerals (PGM) and their podiform chromitite host from the East Dover meta-dunite. Numbers in the images correspond to specific PGE bearing alloys/minerals. (A) photograph of massive chrome spinel (podiform chromitite, Black) covered in purple Kammererite (chromium rich chlorite) in a matrix of serpentinized olivine. (B) BSE image showing the podiform chromitite which is highly brecciated and altered to ferritchromite/magnetite between grains. (1) shows a long inclusion of a Ru-Os-Ir alloy in chrome spinel, and 2 shows a spherical lead-arsenic sulfosalt inclusion, also in spinel. (C) BSE image of a Ruthenium arsenide inclusion (3) within chrome spinel along a fracture. (D) BSE image of the long inclusion (1) in Figure 10b. (E) BSE image of a Pt-Ru-Os-Ir alloy inclusion (4) near the rim of massive chrome spinel. (F) BSE image showing a fractured chrome spinel with a geversite (PtSb) inclusion (5) located in the interstitial ferritchromite/magnetite.

**Figure 7:** WDS X-Ray intensity maps of partially serpentinized dunite showing a crystal of spinel and surrounding serpentinized olivine. Maps show relative intensity of magnesium, iron, chromium, and aluminum. Spinel core is enriched in magnesium, chromium, and aluminum compared to the rims, which are enriched in iron.
**Figure 8:** Plot of molar Cr# (Cr/Cr+Al) vs Mg# (Mg/Mg+Fe) showing the chemical variation of spinel from talc schist, serpentinized dunite, and podiform chromitite.

**Figure 9:** Photomicrographs of olivine textural types in the East Dover meta-dunite. (A) Type 1 olivine: Olivine grain within a chrome spinel in XPL. Serpentine blades, magnetite, and serpentinized olivine surround the spinel. (B) Type 1 Olivine: Olivine inclusion in a subhedral chrome spinel surrounded by magnetite in a matrix of serpentine in reflected light. (C) Type 2 Olivine: Highly serpentinized olivine in XPL. Wormy interstitial magnetite occurs throughout the sample (D) Type 2 Olivine: Moderately serpentinized olivine adjacent to podiform chromitite and chromium rich chlorite (Chl) in XPL. (E) Type 3 Olivine: A vein of relatively un-serpentinized olivine cross-cutting serpentinized olivine and chlorite in XPL. (F) Olivine vein-like structure cross-cutting serpentinized olivine in XPL. Note the highly elongate olivine grains imparting a ‘comb-like’ structure. Seams of magnetite penetrate the veins and continue along the elongate olivine.

**Figure 10:** Plot of wt.% MgO in olivine vs %Fo in olivine for three olivine textural types. Note the trend toward pure forsterite between relict igneous olivine (Type 1) and metamorphic olivine (Type 3).

**Figure 11:** Photomicrographs and a back-scattered electron image (BSE) of pyroxene from the East Dover meta-dunite. (A) Diopside (Di) crystal with magnetite (Mag) concentrated along cleavage planes in XPL. Olivine and serpentine surround the diopside which appears partially digested by the olivine and serpentine. (B) A vein of calcite within the diopside crystal from 7a in XPL. (C), (D) Photomicrographs in XPL showing a typical bastite pseudomorph texture where magnetite nucleates along cleavage planes in primary pyroxene which is subsequently
serpentinized. (E) Photomicrograph in XPL and (F) BSE image of what appears to be olivine, diopside, and magnetite replacing a previous pyroxene.

**Figure 12:** Representative Raman spectra of an antigorite serpentine blade in Figure 4a (Black) compared to antigorite from the RRUFF database (Red). All serpentine samples analyzed in this study were found to be antigorite.

**Figure 13:** Photomicrographs and BSE images of sulfides and arsenides from the East Dover meta-dunite. (A) Reflected light image showing the abundance of interstitial nickel sulfides (mostly heazlewoodite, Hz) in moderately serpentinized sample. (B) Close up photomicrograph in reflected light of heazlewoodite with olivine and serpentine. (C) BSE image showing a standalone grain of Maucherite (Mau) in a matrix of serpentine. Heazlewoodite and magnetite are close by. (D) BSE image of Orcelite (Orc) with an ameboid shape adjacent to heazlewoodite. (E) BSE image of a relatively large heazlewoodite with orcelite and magnetite. Note the zoned stripes on the lower left of the heazlewoodite, as well as the numerous inclusions of nickel arsenide (tiny bright spots, possibly orcelite) throughout the grain. (F) BSE image of a nickeline grain as an inclusion in chrome spinel.

**Figure 14:** Photomicrographs of lithologies representing the Rowe Formation in East Dover, Vermont. (A) Garnet from Hunter Brook with inclusion trails in XPL. Epidote, ilmenite, plagioclase, apatite, zircon, and quartz occur as inclusions in the garnet but are too small to be labeled at this scale. (B) Photomicrograph in XPL showing the dominant texture of fine grained amphibolite of the Rowe Formation in Hunter Brook. Notice the fine grained epidote and hornblende that define the foliation, which is slightly crenulated. Some large quartz grains occur in veins. (C) Chlorite replacing garnet in pelitic schist of the Rowe Formation from Elwin Meadows in PPL. (D) A large biotite grain from the Rowe Formation in Adams Brook in XPL.
(E and F) photomicrographs in XPL showing decussate and poikiloblastic hornblende from the Rowe Formation in Adams Brook. Notice the development of 120 degree grain boundaries in quartz.

**Figure 15:** WDS X-Ray intensity maps of a garnet bearing schist of the Rowe Formation from the Hunter Brook Locality. Maps show relative intensity of manganese, calcium, magnesium, silicon, iron, and aluminum. Garnet cores are enriched in manganese, and garnet rims are depleted in calcium.

**Figure 16:** Summary figure showing the relative intensity and relative timing of metamorphic events that altered the East Dover meta-dunite. The location of the letters (A-G) indicates the relative intensity and time. See text for discussion of events. (A) A cartoon showing the formation of dunite from lherzolite. At Time 1 (T1) the rock is lherzolite composed of 70% olivine (grey) and 30% pyroxene (grey with cleavage planes). At Time 2 (T2) the rock is composed of dunite (95% olivine, 5% pyroxene) + melt after a partial melting event. (B) WDS X-Ray intensity map of a platinum group mineral hosted by chromite showing relative concentration of Ruthenium (L alpha). (C) Photomicrograph in XPL showing a serpentine pseudomorph after a rounded olivine or pyroxene in a matrix of serpentine and magnetite. (D) Photomicrograph in XPL showing an actinolite crystal in talc-schist from the blackwall zone of the East Dover meta-dunite. (E) Photomicrograph in XPL showing an olivine vein cross-cutting a serpentine dominated matrix. (F) Photomicrograph in XPL showing decussate hornblende crystals and polycrystalline quartz with an equilibrium microstructure composed of crystals with 120 degree intersections in amphibolite from the blackwall zone. (G) Polished epoxy mount containing green hydrous nickel silicate minerals (garnierite) from a nickel rich saprolite zone in the meta-dunite.
**Figure 17:** Photomicrograph in XPL showing both fine grained antigorite serpentine and coarse acicular serpentine. The coarse antigorite (Atg) blade is piercing into a large type 3 olivine (Ol) crystal at extinction.

**Figure 18:** Bivariate plot from Ryan et. al., (2011) of As vs As/Ce ratio for serpentinites and tale-schists from northern Vermont (solid circles) and meta-sedimentary rocks from northern Vermont (diamonds). Also shown are arc volcanics, mid-ocean ridge basalts, oceanic island basalts and serpentinites from the Himalaya (open circles, from Hattori et. al., 2005). Primitive mantle (PM) from McDonough and Sun (1995) is also shown. Stars indicate values for this study.

**Figure 19:** A,B,C,D are BSE images of zircon (Zrc) in a chlorite (Chl) matrix. Some rutile (Rt) is present around the zircon in (C).

**Figure 20:** Map of the Dover, Vermont region showing the locations of ultramafic rocks (green) and private groundwater wells (red) including the well used for the Dover Elementary School. The number of wells that may contain elevated levels of arsenic is also shown. Bedrock Geology (ultramafic rocks) modified from the Bedrock Geologic Map of Vermont (Ratcliffe et. al., 2011).
Table Captions

**Table 1:** X-Ray Fluorescence (XRF) Major element whole-rock geochemical data for 4 samples from the East Dover meta-dunite. Sample AB02 is partially serpentinized and was collected the middle of the meta-dunite body. Sample TB02 is fully serpentinized and was collected along the western-central contact with the Rowe Formation. Sample EDQ04 is partially serpentinized and from the northernmost outcrops of the meta-dunite body. Sample HB03 contains mostly olivine (Type 3) and magnetite, and was collected from the southernmost outcrops of the meta-dunite body.

**Table 2:** X-Ray Fluorescence (XRF) Trace element whole-rock geochemical data for 4 samples from the East Dover meta-dunite. Sample AB02 is partially serpentinized was collected the middle of the meta-dunite. Sample TB02 is fully serpentinized and was collected along the western-central contact with the Rowe Formation. Sample EDQ04 is partially serpentinized and was collected from the northernmost outcrops of the meta-dunite. Sample HB03 is mostly olivine (Type 3) and magnetite and was collected from the southernmost outcrops of the meta-dunite.

**Table 3:** Representative electron microprobe analyses of spinel rims from the East Dover meta-dunite.

**Table 4:** Representative electron microprobe analyses of spinel cores from the East Dover meta-dunite.

**Table 5:** Representative electron microprobe analyses of olivine from the East Dover meta-dunite.

**Table 6:** Representative electron microprobe analyses of nickel sulfide minerals from the East Dover meta-dunite ( - = not analyzed).
Table 7: Representative compositional analyses of arsenide minerals from the East Dover meta-dunite. Variation in totals may reflect trace quantities of elements not analyzed, or the need for longer counting times on certain elements.

Table 8: Representative electron microprobe analyses of platinum group minerals from the East Dover meta-dunite.

Table 9: Representative electron microprobe analyses of nickel sulfide minerals from the East Dover meta-dunite.

Table 9: Representative electron microprobe analyses of muscovite from the Rowe Formation in the Hunter Brook Locality (Map unit CZrs).

Table 10: Representative electron microprobe analyses of biotite from the Rowe Formation in the Hunter Brook Locality (Map unit CZrs).
Figures.

Figure 1

Generalized Geologic Map of Vermont

From the Bedrock Geologic Map of Vermont (Ratcliffe et al. 2011)
Figure 2.

Bedrock Geology of the East Dover Meta-Dunite Locality
Vermont, USA

Bedrock Lithology
Rowe Formation
- CZra - Fine grained epidote amphibolite
- CZras - Coarse grained garnet bearing amphibolite
- CZgs - Large-garnet pelitic schist
- CZrs - Small-garnet pelitic schist and phyllite

Ultramafic Rocks
- CZu - Partially serpentinized meta-dunite
- CZutc - Talc-carbonate schist

Moretown Formation
- Om - Meta-sedimentary schist and gneiss

Map Symbols
- Elwin Meadows Trail
- Key Samples
- Roads
- Rivers

Key Localities
- ABN- Adams Brook North
- ABS- Adams Brook South
- BB- Bemis Brook
- RR- Rock River
- HB- Hunter Brook
- TB-Taft Brook
- EM- Elwin Meadows
Figure 3.

A. Early Ordovician

Laurentia

Accretionary wedge

Shelburne Falls Arc

Neo-lapetus

W

E

B. Late Ordovician

Laurentia

Shelburne Falls Arc

Bronson Hill Arc

Accretionary Wedge

W Taconian Orogen

E
Figure 4.
Figure 5.
Figure 6.
Figure 7.
Figure 8.

Chemical Variation in Spinel from the East Dover Meta-Dunite

Talc Schist
Serpentinized Dunite
Podiform Chromitite
Coish and Gardner 2004
Figure 9.
Figure 10.

**Variation in Olivine Composition**

- **Type 1:** Olivine inclusions in Spinel
- **Type 2:** Serpentinized Olivine
- **Type 3:** Metamorphic Olivine

**Axes:**
- **Percent Forsterite in Olivine**
- **Weight Percent MgO in Olivine**

Data points are categorized into three types based on their composition and associations.
Figure 11.
Figure 12. Antigorite

![Antigorite graph](image_url)
Figure 13.
Figure 14.
Figure 15.
THE EAST DOVER METAMICT-DUNITE

METAMORPHIC EVENTS THAT ALTERED

A. Fluid/Melt-Rock Interaction
B. Formation of Podiform Chromitite
C. Septentrionization with PGM Inclusions
D. Metamorphic Blockemall Formation
E. Azzadian Regional Metamorphism
F. Thermal Relaxation and Static Dehydration or Separating to Form
G. Near Surface Weathering and the Recrystallization of Nickel Laterite Formation of Nickel Laterite.

Figure 16.
Figure 17.
Figure 19.
Figure 20.

Private Wells Within 1 Km Of Ultramafic Rocks Near Dover, Vermont, USA

Number of private wells in the Dover area that may contain elevated levels of arsenic:

- 203 wells within 1 km of ultramafic rocks
- 84 wells within .5 km of ultramafic rocks
- 11 wells drilled directly into ultramafic rocks
- 1 Elementary school within 1 km of ultramafic rocks

*Ultramafic rocks include talc-carbonate schist and partially-serpentinitized dunite
Tables.

Table 1: Major oxide compositional analysis (XRF) from key localities in the East Dover metadunite

<table>
<thead>
<tr>
<th>Sample</th>
<th>AB02</th>
<th>TB02</th>
<th>EDQ04</th>
<th>HB03</th>
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<tr>
<td>$SiO_2$</td>
<td>40.619</td>
<td>40.110</td>
<td>38.453</td>
<td>39.005</td>
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<td>0.013</td>
<td>0.014</td>
<td>0.013</td>
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<td>$Al_2O_3$</td>
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<tr>
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<tr>
<td>$MgO$</td>
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<td>LOI (%)</td>
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<td>$\sum$ Maj + LOI</td>
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<td>99.159</td>
<td>99.595</td>
<td>99.812</td>
</tr>
<tr>
<td>$\sum$ All</td>
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<td>99.765</td>
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Table 2: Trace element concentrations (in parts per million) from key localities in the East Dover meta-dunite

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<th>EDQ04</th>
<th>HB03</th>
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<td><strong>F &gt;=</strong></td>
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<td>0.000</td>
<td>0.001</td>
<td>0.087</td>
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<tr>
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<td>0.560</td>
<td>0.840</td>
<td>0.560</td>
<td>1.260</td>
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</table>
Table 3: Representative electron microprobe analyses of spinel rims from the East Dover metadunite

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<tr>
<th>Sample</th>
<th>EDABF1</th>
<th>EDQ02</th>
<th>ABN_pod</th>
<th>ABNtc1</th>
<th>EDAb02a</th>
<th>EDQ04a</th>
<th>EDQ04a</th>
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<tbody>
<tr>
<td>FeO</td>
<td>16.06</td>
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<td>24.85</td>
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<td>NA</td>
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<td>Cr$_2$O$_3$</td>
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<td>0.24</td>
<td>0.16</td>
<td>0.77</td>
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<tr>
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<td>99.11</td>
<td>99.37</td>
<td>100.03</td>
</tr>
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</table>

<p>| | | | | | | | |</p>
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<tbody>
<tr>
<td>Cr# (Cr/Cr+Al)</td>
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<td>1.00</td>
<td>0.94</td>
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<td>1.00</td>
<td>0.98</td>
</tr>
<tr>
<td>Mg# (Mg/Mg+Fe)</td>
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<td>0.02</td>
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<td>Sample</td>
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<tr>
<td></td>
<td>Sample</td>
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<td>Fe₂O₃</td>
<td>TiO₂</td>
<td>Al₂O₃</td>
<td>Cr₂O₃</td>
<td>MgO</td>
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<tr>
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<td>19.97</td>
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<td>0.01</td>
<td>11.51</td>
</tr>
<tr>
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<td>21.18</td>
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<td>0.05</td>
<td>11.68</td>
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<td>EDA2B</td>
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<td>1.72</td>
<td>0.01</td>
<td>10.11</td>
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</table>

Legend: Cr# = Cr₂O₃; Mg# = MgO; FeO = FeO; Fe₂O₃ = Fe₂O₃; TiO₂ = TiO₂; Al₂O₃ = Al₂O₃; Cr₂O₃ = Cr₂O₃; MgO = MgO; MnO = MnO; NiO = NiO; Total = Total.
Table 5: Representative electron microprobe analyses of olivine from the East Dover meta-dunite.

<table>
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<tr>
<th>Olivine Type</th>
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<th>Type 1</th>
<th>Type 1</th>
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<th>Type 2</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 3</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample</td>
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<td>EDQ04a</td>
<td>HB03</td>
<td>BBF01</td>
<td>EDQ04a</td>
<td>HB03</td>
<td>HB09</td>
<td>EDQ05d</td>
<td>EDQ04a</td>
</tr>
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<td>52.92</td>
<td>52.61</td>
<td>52.09</td>
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<td>54.45</td>
<td>53.78</td>
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<td>41.69</td>
<td>41.13</td>
<td>41.91</td>
<td>41.66</td>
<td>42.57</td>
<td>41.99</td>
<td>40.07</td>
<td>42.29</td>
</tr>
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<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>MnO</td>
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<td>0.19</td>
<td>0.18</td>
<td>0.11</td>
<td>0.21</td>
<td>0.28</td>
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<td>5.14</td>
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<td>3.32</td>
<td>4.61</td>
<td>3.50</td>
</tr>
<tr>
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<td>0.07</td>
<td>0.06</td>
<td>0.00</td>
<td>0.06</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
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</tr>
<tr>
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<td>0.30</td>
<td>0.23</td>
<td>0.27</td>
<td>0.23</td>
<td>0.34</td>
<td>0.28</td>
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<td>Mole% Fo</td>
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<td>94.91</td>
<td>94.80</td>
<td>94.95</td>
<td>96.70</td>
<td>95.47</td>
<td>96.47</td>
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<td>Total</td>
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<td>100.98</td>
<td>100.89</td>
<td>100.33</td>
<td>99.92</td>
<td>100.14</td>
<td>100.31</td>
<td>99.65</td>
<td>100.05</td>
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</table>

Table 6: Representative electron microprobe analyses of nickel sulfide minerals from the East Dover meta-dunite (- = not analyzed).

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<th>Analysis #</th>
<th>1 (Co,Ni)S</th>
<th>2 PbAsS</th>
<th>3 (Fe,Ni)₂S₈</th>
<th>4 (Fe,Ni)₂S₈</th>
<th>5 NiS</th>
<th>6 NiS</th>
<th>7 Ni₃S₂</th>
<th>8 Ni₃S₂</th>
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<tr>
<td><strong>Formula</strong></td>
<td><strong>S</strong></td>
<td><strong>Fe</strong></td>
<td><strong>Ni</strong></td>
<td><strong>As</strong></td>
<td><strong>Pb</strong></td>
<td><strong>Cr</strong></td>
<td><strong>Co</strong></td>
<td><strong>Ag</strong></td>
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<td><strong>S</strong></td>
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<td>33.36</td>
<td>33.23</td>
<td>35.34</td>
<td>35.61</td>
<td>28.00</td>
<td>27.72</td>
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<td><strong>Fe</strong></td>
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<td>-</td>
<td>29.63</td>
<td>29.29</td>
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<td>0.67</td>
<td>0.23</td>
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<tr>
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<td>0.34</td>
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<td>-</td>
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<tr>
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<td>-</td>
<td>-</td>
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<td>-</td>
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</tr>
<tr>
<td><strong>Cr</strong></td>
<td>-</td>
<td>-</td>
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<td>0.11</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td><strong>Co</strong></td>
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<td>3.78</td>
<td>3.72</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
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<td>-</td>
<td>-</td>
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<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td><strong>Total</strong></td>
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<td>101.24</td>
<td>99.37</td>
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<td>100.02</td>
<td>99.76</td>
<td>100.22</td>
<td>99.52</td>
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Table 7: Representative electron microprobe analyses of arsenide minerals from the East Dover meta-dunite.

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<th>Nickeline</th>
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<td>0.05</td>
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</tr>
<tr>
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<td>44.92</td>
<td>57.99</td>
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<tr>
<td>Cr</td>
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<td>0.65</td>
<td>0.95</td>
</tr>
<tr>
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<td>0.00</td>
<td>0.04</td>
</tr>
<tr>
<td>Ru</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
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<tr>
<td>Pt</td>
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<td>0.00</td>
<td>0.06</td>
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<td>Pb</td>
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<td>0.04</td>
<td>0.00</td>
</tr>
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Table 8: Representative electron microprobe analyses of platinum group minerals from the East Dover meta-dunite.

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<th>Alloy 2</th>
<th>PtSb₂</th>
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<td>0.17</td>
<td>0.05</td>
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<td>18.91</td>
<td>0.14</td>
</tr>
<tr>
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<td>46.92</td>
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<tr>
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<td>0.50</td>
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<td>-</td>
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<td>1.09</td>
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<td>100.76</td>
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<td>98.48</td>
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Table 9: Representative electron microprobe analyses of muscovite from the Rowe Formation in the Hunter Brook Locality (Map unit CZrs).

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</table>

Table 10: Representative electron microprobe analyses of biotite from the Rowe Formation in the Hunter Brook Locality (Map unit CZrs)

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<th>Biotite 3</th>
<th>Biotite 4</th>
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<td>SiO₂</td>
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<td>35.87</td>
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<td>FeO</td>
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<td>19.79</td>
<td>19.56</td>
<td>19.72</td>
</tr>
<tr>
<td>Al₂O₃</td>
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<td>17.82</td>
<td>18.13</td>
<td>18.29</td>
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<tr>
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<td>95.39</td>
<td>95.61</td>
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References


Skehan, J., 1961, Green Mountain Anticlinorium in the vicinity of Wilmington and Woodford Vermont, Vermont Geological Survey, Bulletin no. 17


Curriculum Vitae

John Mark Brigham
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Email: jbrigham@syr.edu

Education:
2020- M.Sc. Geology, Syracuse University, Syracuse, NY (in progress)
2013- BA History (minor: Geology), University of Vermont, Burlington, VT

Teaching Experience
2017- Present (TA at Syracuse University for the following courses):

Fall 2017 - Introduction to Earth Sciences
Spring 2018 - Geohazards and Natural Disasters
Fall 2018 - Introduction to Earth Sciences, Petrology
Spring 2019 - Mineralogy
Fall 2019 - Structural Geology
Spring 2020 - Mineralogy

2013 - 2014 - Designed and ran geology based afterschool programs for elementary and middle school students throughout Southern Vermont.

Research Experience
Summer 2017- Spring 2020 M.Sc research:
Studied the petrogenesis of a partially serpentinized dunite in Southern Vermont. Combined field work, geologic mapping, petrographic analysis, and electron microprobe analysis to better understand how ultramafic rocks deform in polymetamorphosed terranes.

Summer 2018 - Research Assistant in the Thermochronology and Tectonics laboratory at Syracuse University. Prepared samples from the Papua New Guinea collection for thin sections, and conducted a petrographic analysis of those samples.

Summer 2019 - Research Assistant in the Thermochronology and Tectonics laboratory at Syracuse University. Prepared samples from the Papua New Guinea collection for advanced mineral separation. Crushed, cleaned, sieved, and separated minerals (apatite, biotite, muscovite, k-feldspar, zircon) for geochronologic analysis using a variety of mineral separation techniques (heavy liquids, magnetic separation).

Awards:
Vermont Geological Society
2019- 2nd place award for best student presentation at the Vermont Geological Society’s spring meeting.
Syracuse University
2020- Earth Science Department Chair’s Award for outstanding service to the department.

2020- Syracuse University Outstanding TA Award for distinguished contributions to teaching at Syracuse University.

2019 - Marjorie Hooker Award for outstanding thesis proposal.

2018 - K. Douglas Nelson Award for outstanding graduate research in geophysics and tectonics.

List of Relevant Courses and Grades:

Community College of Vermont:
2009 - Wildlife Ecology - A+
2013 - Biology of Dinosaurs - A-
2014 - Calculus I - A
2016
 - Calculus II - A
 - Physics I - B
2017 - Physics II - B+

University of Vermont - Graduated BA 2013
2011
 - Earth System Science - A
 - Field Geology - B
2012 - Geomorphology - B
2013 - Petrology - A-
2015
 - Microstructures - B+
 - Geochronology - A-
2016 - Structural Geology - A-

Michigan State University 2013
 - Completed a four course GIS certification program- Classes taken: Intro to GIS, Intro to Geospatial Technologies, Cartography, Remote sensing).

Syracuse University – MS student graduating Spring 2020
2017
 - Applications of Electron Probe - A
 - Practicum in Science Communication - A
 - Fundamentals of GIS - A
2018
 - Serpentinites and their host rocks - A
 - Advanced Petrology - A
 - Advanced GIS - A
 - Geochemistry - A
 - Plate Tectonics - A