Emplacement and Crystallization Histories of Cu-Ni-PGE Sulfide-mineralized Peridotites in the Eagle and Eagle East Intrusions

A THESIS SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL OF THE UNIVERSITY OF MINNESOTA BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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June 2018
Acknowledgments

I would like to thank my adviser, Dr. Jim Miller, for his guidance and patience with me as I worked through this project. His judgement, expertise, and encouragement were essential to the completion of this project.

I would like to thank Lundin Mining Co. for the opportunity to work on this project as well as their financial, material, and experiential support. Additionally, I would like to thank each of the staff at Eagle’s exploration office for their friendship, support, and guidance – especially Bob Mahin, Steve Beach, and Bob Nowak.

I would like to thank Dr. Anette von der Handt of the University of Minnesota Twin Cities Electron Microprobe Laboratory for her expert training and counsel.

Finally, I would like to thank my wife, Adriane, for standing by me and supporting me through all of the time that I spent working on this project – in the end, it was only possible because you were there with me.
Abstract

The Eagle and Eagle East intrusions, located about 40 kilometers northwest of Marquette, MI, are two small, partially exposed, sub-vertical, funnel-shaped mafic/ultramafic intrusions emplaced in Paleoproterozoic black slates. Both intrusions host economic Ni-Cu-(PGE) sulfide deposits, the Eagle intrusion in its main body and the Eagle East intrusion in its feeder at depth. The Eagle deposit has been being mined by the Lundin Mining Corporation since 2014, which is now also expanding its operation to mine the Eagle East deposit.

Transmitted light petrography, scanning electron microscopy, and electron microprobe analyses were performed on samples from six drill cores in the Eagle system, three from Eagle and three from Eagle East. Lundin additionally provided whole-rock geochemistry for five of these cores at ~1.5m intervals.

The concentration of Ni in olivines in the Eagle and Eagle East intrusions were measured by electron microprobe. A bimodal distribution of Ni concentration in olivine - i.e., both enriched and unenriched populations being present - may have been evidence for multiple magma pulses in the Eagle system. However, olivine in both intrusions were determined to be universally Ni-enriched, which means that this line of inquiry was not useful for determining the number of magma pulses.

The cumulate nature of samples were determined by whole-rock geochemistry, wherein incompatible trace elements including Zr, and La were used as proxies for the amount of intercumulus material present in a sample, as well as by visual estimation using transmitted-light petrography. Counter to the conclusions of Ding et el. (2010), variations in incompatible
trace element ratios in various rock types in the Eagle system were satisfactorily explained by the cumulate nature and high sulfide content of the samples, with no need to invoke multiple parental magmas in the explanation.

The intrusive breccia (or “IBRX”) lithology present in both the Eagle and Eagle East intrusions was studied with transmitted light petrography. It was determined to occur in at least two variations. Both variations have a feldspathic lherzolite matrix with subangular clasts, but in one type heavy sulfide mineralization (up to 30% by volume) occurs in the clasts and in the other type the clasts are nearly devoid of sulfides. In both cases the clasts have high pyroxene abundances and are devoid of olivine, but clasts with high sulfide content tend to have more plagioclase and are more heavily altered. In the Eagle East intrusion, sampled clasts were only of the low-sulfide variety. The IBRX clasts may be a slower-cooling version of the PRX lithology also present in the Eagle system. Alternatively, they may be part of an older intrusion that the Eagle system parental magma cannibalized at depth during emplacement.

The main body of the Eagle East intrusion was studied by petrographic examination of a core that profiled its depth. While there was no significant change in cumulate rock type, the core did show modest cryptic variation with depth. Notably, a horizon of increased olivine abundance indicated the potential recharge of the intrusion with the same, homogeneous parental magma. The lithological similarity of the Eagle and Eagle East intrusions indicates that they likely formed from the same parental magma. The main petrographic differences between the two intrusions were the poikilitic nature of clinopyroxene and the lower abundance of plagioclase in the Eagle East intrusion. These differences may be explained by the larger size and thus presumed longer cooling time of the Eagle East intrusion.
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1. Introduction

As defined by Naldrett (2004), magmatic sulfide deposits are metal deposits associated with sulfide minerals that have collected in a mafic to ultramafic magmatic system. Their formation requires both a partitioning of chalcophile elements into liquid immiscible sulfide, and the segregation and concentration of this liquid sulfide. Magmatic sulfide deposits can be divided into two major groups: those with platinum-group elements (PGE) as the main contributor to the deposit’s value, and those with Ni and Cu yielding the greatest value. PGE-type deposits tend to be relatively sulfide-poor (0.5-5% sulfide by weight), while Ni-Cu-type deposits tend to be relatively sulfide-rich (20-90% sulfide by weight).

An economically important sub-type of Ni-Cu deposits are small, high-grade deposits associated with conduits of large igneous provinces. Commonly cited examples of this sub-type include Noril’sk and Voisey’s Bay deposits. The Permian-aged Noril’sk deposit formed in sub-horizontal magma conduits that served as feeders to a flood basalt province (Siberian Traps). The Mesoproterozoic Voisey’s Bay deposit formed in a sub-vertical magma conduit system (Ripley and Li, 2011) that was a feeder to a larger shallow intrusion. Recently, several high-grade Ni-Cu sulfide deposits in conduit-style intrusions have been discovered in association with the Midcontinent Rift (MCR), a 1.1Ga large igneous province exposed in the Lake Superior region. These include the Tamarack Deposit/Intrusion in Minnesota (Goldner, 2011), the Thunder Bay North Deposit/Current Lake Intrusion in Ontario (Goodgame et al., 2010), and, most notably, the Eagle Deposit/Intrusions in Upper Michigan (Ding et al., 2010). While active exploration on these and other high-grade conduit-style Ni-Cu prospects is ongoing in the Lake Superior area, the Eagle deposit is the only deposit currently being mined.
The Eagle Deposit consists of two high-grade Ni-Cu sulfide ore bodies hosted in petrologically similar, but spatially distinct ultramafic-mafic intrusions - the Eagle and Eagle East intrusions. Both are small, sub-vertical, funnel-shaped intrusions emplaced during an early stage of MCR magmatism into Paleoproterozoic black slates (Ding et al., 2010). However, the Eagle intrusion, which was discovered first and is currently being mined by the Lundin Mining Corporation (“Lundin” from here forward), appears to be an erosionally truncated version of the Eagle East intrusion, whose mineralized feeder is about 500 meters deeper than Eagle’s (Mahin and Beach, personal communication, June 2017).

Discovery of the Eagle Deposit began with the identification of small, modestly mineralized, ultramafic exposures in the Yellow Dog Plains north of Marquette, Michigan, which were mapped by the U.S. Geological Survey in the early 1970’s and termed the Yellow Dog Peridotite. The petrography and geochemistry of these exposures were the subject of an M.S. thesis by William Morris in 1977 (Morris, 1977). An exploratory drilling program run by Kennecott Exploration (a subsidiary of Rio Tinto) intersected high-grade Ni-Cu sulfide mineralization in the Eagle intrusion in 2002. Subsequent resource drilling, mine permitting, and mine and mill construction by Kennecott and Lundin, who acquired the property in 2013, culminated with the beginning of underground mining of the Eagle deposit in 2014. At the time that mining began, the probable and proven reserves of the Eagle deposit were 5.3 million tonnes grading 3.1% nickel and 2.5% copper, with by-product platinum, palladium, gold and cobalt (Mahin and Beach, 2013). As of November of 2017, the Michigan Department of Environmental Quality approved the mining of ore at Eagle East (Fitch, 2017). This adds an
additional probable mineral reserve of 1.54 million tonnes at 3.7% Ni and 3.0% Cu to the project (Lundin Mining Co. website, 2018).

The most complete petrological study of the Eagle intrusion to date was conducted by Xin Ding at Indiana University (Ding, 2010; Ding et al., 2010; Ding et al., 2012a; Ding et al., 2012b). This work suggested that the intrusion represented a dynamic plumbing system related to MCR magmatism. The emplacement history for Eagle proposed by Ding et al. (2010) included at least four different pulses of magma, at least two of which were hypothesized as being genetically distinct. Further drilling and enhanced understanding of underground field relations led Lundin geologists to later propose a model with two main phases of emplacement and mineralization. Eagle East was mentioned by Ding et al. (2010), but no significant interpretation was done on its origin or emplacement.

The main objective of this thesis is to compare the feasibility of Lundin’s two-phase emplacement model to the four-phase emplacement model proposed by Ding et al. (2010). A secondary objective of this thesis is gaining a better understanding of the origin of an enigmatic intrusive breccia lithology that was relatively unknown at the time of the study by Ding et al. (2010). An additional objective of this study is making a preliminary evaluation of the emplacement, crystallization, and mineralization history of the Eagle East intrusion and contrasting this history with that interpreted from Eagle. It should be noted that samples included in this study were taken from drilling core acquired before 2016, and as such do not include information on more recent drilling of the mineralized Eagle East conduit.

These objectives will be addressed by acquiring and evaluating petrographic, mineral chemical and lithogeochemical data collected from select core samples profiling the Eagle and
Eagle East intrusions. For the Eagle Intrusion, 35 samples were collected principally from three 
drill cores that intercept areas which are relevant to Lundin’s two-phase emplacement model 
and which include intercepts of the enigmatic intrusive breccia. For the Eagle East intrusions, 66 
samples were collected from three cores that profile the igneous stratigraphy of this larger 
intrusion. Transmitted light petrography was conducted on drill core samples to document the 
lithologic attributes (mineralogy, texture, alteration, mineralization) of the two intrusions. For 
49 select samples, mineral chemical data were collected on olivine and pyroxene by electron 
microprobe and SEM-EDS analyses to document cryptic variation in mg# (= Mg/(Mg+Fe), 
cation%). Also, Ni concentrations in olivine were measured in order to evaluate the relative 
timing of olivine crystallization and sulfide liquation. Finally, whole-rock lithogeochemistry, 
previously acquired by Lundin on both the Eagle and Eagle East cores, were evaluated to further 
understand the parental compositions of the two intrusions and their modes of emplacement 
and crystallization.

1.1 Regional Geologic Setting

The Midcontinent Rift (MCR) is a 1.1 Ga large igneous province in the Lake Superior 
region that is interpreted to have been formed by the initiation and subsequent abortion of an 
intracontinental rift (Hutchinson et al., 1990; Nicholson and Shirey, 1990). Gravity and 
aeromagnetic anomalies associated with the MCR define an arcuate shape that extends from 
exposures in the Lake Superior region to the southwest into Kansas and southeast to the lower 
peninsula of Michigan where rift rocks are buried beneath Phanerozoic strata (Fig. 1).
Figure 1: Bouger gravity anomaly map (A) and aeromagnetic anomaly map (B) of the western arm of the Midcontinent Rift. From Kucks, 1999 and Bankey et al. (2002).

The initiation of rifting in the MCR is thought to have been attended by, if not result from, the impact of a starting mantle plume (Hutchinson et al., 1990; Nicholson and Shirey, 1990; Cannon and Hinze, 1992). Evidence for this includes the large volume and relative homogeneity of igneous material, and the enrichment of MCR-related rocks in incompatible trace elements when compared to a depleted mantle source (Nicholson and Shirey, 1990). Additionally, Hutchinson et al. (1990) calculated inferred mantle temperatures of at least 1500°C to generate the volume of mafic magma inferred by the geophysical attributes of the rift in the Lake Superior area, values which would be consistent with an asthenospheric mantle plume. Cannon (1994) speculated that rifting was halted by compression arising from the Ottawan phase of the Grenville Orogeny.
MCR-related rocks are well exposed in the Lake Superior region (Fig. 2). As described by Miller and Nicholson (2013), these rocks compose three groups: volcanic edifices, intrusions, and post-volcanic sedimentary sequences.

The volcanic edifices associated with the MCR include nine groups of volcanics and/or their associated sedimentary rocks (Miller and Nicholson, 2013). High-precision U-Pb ages from these volcanics indicate that the magmatic activity occurred between 1115-1086 Ma. Subaerial, tholeiitic flood basalts make up the bulk of these volcanic sequences, but intermediate and felsic flows are also represented, as are fluvial interflow sedimentary rocks (Green, 1982). Prior to the acquisition of U-Pb ages, volcanic sequences in the western Lake Superior region were age-
correlated based on a major magnetic polarity reversal from early reversed to late normal. In eastern Lake Superior, at Mamainse Point, an additional reversed and normal magnetic interval were present in the rock record and used for correlation. Based on U-Pb ages, the major magnetic reversal is now constrained to 1105-1102 Ma, while the second reversal occurred around 1101-1100 Ma (Miller and Nicholson, 2013). Volcanic packages associated with the rift have exposed thicknesses ranging from as little as 10m to over 8000m. The thickest sequences are the Porcupine and Portage Lake volcanics in MI, units 6-8 of the Mamainse Point Volcanic Group in ON, and the upper northeast, lower northeast, and upper southwest sequences of the North Shore Volcanic Group in MN (Miller and Nicholson, 2013).

Intrusive rocks associated with the MCR can be split into four categories: large subvolcanic intrusive complexes, isolated alkalic and carbonatitic intrusions, mafic dike and sill swarms, and small ultramafic/mafic intrusions often associated with Ni-Cu-PGE mineralization (Weiblen, 1982; Miller and Nicholson, 2013).

Large subvolcanic intrusive complexes include the Duluth Complex and Beaver Bay complex which are emplaced into the North Shore Volcanic Group and the Mellen Complex which is emplaced into the Powder Mill Volcanic Group (Miller et al., 2002a,b; Fitz, 2011). The Duluth Complex is the largest of the three complexes, with a surface area of over 5,000 km² and an estimated volume of at least 35,000 km³ (Allen et al., 1997; Miller and Nicholson, 2013). The complex contains felsic, gabbroic, anorthositic, and layered intrusions that are dated to 1109-1106 Ma (Miller and Weiblen, 1990; Miller and Ripley, 1996; Miller and Severson, 2002b; Paces and Miller, 1993; Vervoort et al., 2007). These plutonic intrusions were emplaced into the base of the North Shore Volcanic Group edifice (Miller and Weiblen, 1990; Miller and Ripley, 1996; Miller and Severson, 2002b). The Beaver Bay Complex is a set of hypabyssal intrusions emplaced
higher into the North Shore Volcanic Group edifice than the Duluth Complex (Miller and Nicholson, 2013). With an exposed area of about 600 km², it is smaller than the Duluth Complex (Miller and Chandler, 1997; Miller and Green, 2002a). U-Pb age dates indicate emplacement at around 1096 Ma (Paces and Miller, 1993; Hoaglund, 2010). Of the thirteen intrusive units identified in the complex, one is composed of granophyre and the rest are variably evolved lithologies originating from gabbroic to dioritic parental magmas (Miller and Nicholson, 2013). The Mellen Complex, emplaced into the Powder Mill Volcanic Group, is sheet-like and one to five kilometers thick (Miller and Nicholson, 2013). It consists of four main plutonic intrusions: one granitic intrusion, one layered mafic intrusions, and two intrusions grading from olivine gabbroic cumulates to gabbroic anorthositic cumulates to granophyre (Miller and Nicholson, 2013; Olmsted, 1969). The granite is unique in among MCR-related felsic intrusions because of its intergranular texture and abundance of biotite (Miller and Nicholson, 2013). Age dates from one of the graded intrusions and from the granite give dates of 1102 and 1101 Ma, respectively (Zartman et al., 1997).

Several isolated alkalic and carbonatitic intrusions associated with the MCR are emplaced into Archean rocks north of Lake Superior (Miller and Nicholson, 2013). These include multiple small lamprophyric, carbonatitic, and alkaline intrusions, as well as the larger Coldwell and Killala Lake alkaline complexes and the Prairie Lake carbonatite (Sage, 1991). The Trans-Superior Tectonic Zone (TSTZ), a north-northeast trending structure that is interpreted to be a major accommodation zone in the segmentation of the MCR, is spatially associated with and structurally controls most of these intrusions (Klasner et al., 1982; Dickas and Mudrey 1997; Miller and Nicholson, 2013). The Coldwell Complex, which hosts potentially economic Cu-Ni-PGE mineralization, is the largest and most complex of these intrusions with an area of about 580
km² (Good et al., 2010; Miller and Nicholson, 2013). It is dated at 1108 Ma, but other intrusions associated with the TSTZ range in age from 1150 Ma to 1100 Ma (Heaman and Machado, 1992; Heaman et al., 2007; Smyk, 2010).

Mafic dike and sill swarms are common in and around the MCR in the Lake Superior basin, the Lake Nipigon area, the MN-ON border area, and the eastern Mesabi range (Miller and Nicholson, 2013). These dikes have compositions that span the ranges of typical basalts in the MCR (Green et al., 1987; Miller and Nicholson, 2013). Dike swarms that occur in pre-rift basement rocks show as strong positive or negative linear anomalies on high resolution aeromagnetic images, making them easily recognizable (Green et al., 1987; Miller and Nicholson, 2013). Both normal and reversed magnetic polarity dikes are common, often even in the same swarm (Green et al., 1987; Miller and Nicholson, 2013). The strike of the dikes is usually parallel to the trend of the rift (Green et al., 1987; Miller and Nicholson, 2013). While some dikes can be as wide as 500m, most range from 10m to 50m in width (Green et al., 1987; Miller and Nicholson, 2013). Recently, Hollings et al. (2007b, 2010) have begun to produce evidence that there are two different kinds of dikes, a low TiO₂-Gd/Yb group and a high TiO₂-Gd/Yb group.

Small, ultramafic to mafic intrusions associated with the MCR have received special attention in the past decade because they are often associated with Ni-Cu-PGE deposits (Miller and Nicholson, 2013). These intrusions are generally emplaced into Paleoproterozoic metasedimentary rocks (Minnesota and Upper Michigan, four intrusions; Goldner, 2011; Ding et al., 2010; Rossell, 2008; Foley, 2011; Schulz and Nicholson, 2009) or Archean to middle Mesoproterozoic rocks (Thunder Bay and Lake Nipigon areas, eight intrusions; Hart and MacDonald, 2007; Goodgame et al., 2010; Hollings et al., 2007b, 2007c, 2010, 2012). These
intrusions are variable in size and shape – sheet-like, cone-shaped, lopolithic, bowl-shaped, and chonolithic intrusions are all represented, and intrusions range in area from less than 1 km\(^2\) to just over 80 km\(^2\) (Miller and Nicholson, 2013). All intrusions are less than one kilometer thick and those that have been dated have ages between 1115 Ma and 1105 Ma (Miller and Nicholson, 2013). Most of the intrusions include a lower, ultramafic section that is composed of olivine and pyroxene cumulates and an upper, mafic section that is composed of plagioclase, pyroxene, and Fe-Ti oxide (Miller and Nicholson, 2013). However, two of the intrusions, the Eagle and Current Lake intrusions, are composed entirely of Iherzolitic cumulates with 15-40% plagioclase (Ding et al., 2010; Goodgame et al., 2010). At the Eagle intrusion, this lack of a mafic cap may be due to erosion of the upper part of the intrusion (Miller and Nicholson, 2013). At the Current Lake, the narrow, tube-like shape of the intrusion may explain the lack of a mafic cap (Mill and Nicholson, 2011). Another similarity between the intrusions is that most of them seem to have been formed by at least two major magma pulses (Tamarack - Goldner, 2011; BIC - Foley, 2011; Eagle - Ding et al., 2010; Current Lake - Goodgame et al., 2010; Seagull - Heggie, 2005; Hele - Hollings et al., 2007a). While all intrusions contain cumulates of similar minerals, the paragenetic sequence is different between the intrusions (Miller and Nicholson, 2013). Estimation of parental magmas from chill zones in the intrusions suggest similarities to picritic lavas in early reversed MCR lava sequences (Hollings et al., 2007b; Ding, 2010; Goldner, 2011; Foley, 2011). Incompatible trace element patterns are similar to plume-generated (OIB-type) magmas but with a negative Nb-Ta anomaly that may indicate contamination of such a magma with continental crust, subcontinental lithospheric mantle, or recycled crust from Archean subduction (Shirey, 1997; Hollings et al., 2007b, 2010, 2012; Goldner, 2011; Foley, 2011).
Post-volcanic sedimentary sequences associated with the rift occur in two groups. The first group, including the Copper Harbor Conglomerate, the Nonesuch Shale, and the Freda Sandstone (collectively termed the Oronto Group) were formed during the subsidence of rift grabens (Cannon, 1992; Miller and Nicholson, 2013). This subsidence resulted in the accumulation of up to 8 km of sedimentary material (Cannon, 1992). This occurred when volcanic activity in the rift was waning, and the sedimentary material is intercalated with localized volcanic eruptions (Cannon, 1992). The Copper Harbor Conglomerate, with a maximum thickness of 1830m, is interpreted as prograding alluvial fan complex (Daniels, 1982, Miller and Nicholson, 2013). It is composed of a clast-dominated conglomerate that grades upward to a lithic subarkose sandstone (Daniels, 1982). In its upper levels, it interfingers with the Nonesuch Shale, which is interpreted as having formed in a closed lacustrine basin and has a maximum thickness of 215m (Daniels, 1982; Miller and Nicholson, 2013). The Nonesuch Shale is unoxidized and has a high hydrocarbon and sulfur content, which are interpreted to have been important in the formation of stratiform Cu-sulfide deposits in the area (Daniels, 1982; Swenson et al., 2004). It is composed of siltstone, shale, and sandstone (Daniels, 1982). The Freda Sandstone, with a maximum thickness of 3660m, is composed of arkosic to quartzose sandstone and is interpreted to be fluvial in origin (Daniels, 1982).

The second group includes the Bayfield Group and the Jacobsville Sandstone. These formed during the Grenville Orogeny, when compression reversed the rift’s graben-bounding normal faults (Cannon, 1994). With the rift inverted, the Oronto Group sediments were locally reworked and deposited into basins along the margin of the rift (Miller and Nicholson, 2013). Sediments from outside the MCR basin were also deposited in these marginal basins Miller and
Nicholson, 2013). Generally, these groups are composed of feldspathic to quartzose red-bed sandstones (Morey and Ojakangas, 1982; Kalliokoski, 1982).

Miller and Nicholson (2013) has proposed a six-stage tectonomagmatic model for the development of the MCR in the Lake Superior region (Fig. 3). The Initiation Stage (1115Ma – 1110Ma) is marked by a few ultramafic-mafic intrusions, which occur in northwest Ontario (Heaman et al., 2007). The lack of volcanics in this stage may indicate that these intrusions were emplaced during a period of crustal doming or are buried beneath younger volcanics in the core of the rift. The Early Stage (1110Ma – 1106Ma) is characterized by compositionally diverse lavas and intrusions of reversed magnetic polarity. Volcanism in this stage began with primitive mafic compositions but transitioned into variably evolved compositions showing signs of crustal contamination and anatetic melting. This stage saw the emplacement of the Eagle and East Eagle ultramafic intrusions, as well as a number of other small, mineralized, mafic-ultramafic intrusions, including Current Lake and Seagull in northwestern Ontario, BIC in Upper Michigan, and Tamarack in Minnesota (Fig. 2). The gabbroic to alkaline Coldwell Complex of Ontario was also emplaced during this stage. The Hiatus Stage (1105Ma – 1101Ma) is characterized by a cessation of mafic magmatism and minor felsic volcanism. This stage is thought to represent extensive underplating of the crust by mantle-derived magmas, which caused lower crustal melting to produce felsic magmatism and triggered further mafic underplating. The Main Stage (1101Ma – 1094Ma) is associated with the greatest volume of volcanic and intrusive rocks occurring in the MCR. This stage is characterized by normal magnetic polarity, relatively uncontaminated but commonly evolved mafic magma compositions, and minor intermediate and felsic magmatic activity. The majority of large intrusive complexes of Duluth, Beaver Bay, and Mellen were emplaced during this stage. The Late Stage of magmatic activity (1094Ma –
Figure 3: Tectonic stages of the MCR proposed by Miller and Nicholson (2013).
1080 Ma) was dominated by sedimentary deposition, with intermittent felsic and intermediate volcanic activity associated with the waning of magmatism. After magmatic activity ended, detrital sedimentation continued into the Post-magmatic Structural Inversion stage. The uplift of a central horst was brought about by compression attributed to the Ottawan phase of the Grenville Orogeny and led to originally normal graben faults to become re-activated as reverse faults (Cannon, 1994). Detrital sedimentation was concentrated in basins marginal to the horst. Starting at around 1086 Ma and lasting until around 1040 Ma, this stage saw shortening of about 30 km occur in the region (Miller and Nicholson, 2013).

Two major types of magmatic sulfide deposits are associated with the MCR. The more well-known and earliest discovered occurrences are low grade, high volume Cu-Ni(-PGE) sulfide deposits that have Cu:Ni ratios of approximately 3:1 (Miller and Nicholson, 2013). The best and most voluminous of these are the deposits hosted by troctolitic layered intrusions at the base of the Duluth Complex (Fig. 2) that were emplaced during the Main Stage of MCR magmatism at around 1099 Ma (Severson et al., 2002). Examples include the Northmet (Dunka Road) and Mesaba (Babbitt) deposits in the Partridge River Intrusion and the Maturi and Birch Lake deposits in the South Kawishiwi Intrusion (Hauck et al., 1997). Other occurrences of this deposit type in the Lake Superior region include the Great Lakes Nickel deposit of the Crystal Lake Gabbro and the Marathon Deposit of the Coldwell Complex, both occurring in Ontario (Miller and Nicholson, 2013). Exploration of these deposits has been ongoing since the 1950’s and several are at advanced stages of evaluation.

The other type of base metal sulfide deposit associated with the MCR is high grade, low volume Ni-Cu-PGE mineralization associated with small ultramafic intrusions emplaced during
early stage magmatism (noted by orange stars in Fig. 2). The Eagle deposit, the focus of this study, was the first of this deposit type to be discovered (1992) and is the only deposit to go into active production (2014). In contrast to the low-grade, high-volume deposits such as the Duluth Complex, these high-grade, low-volume deposits are distinctly Ni rich with Cu:Ni ratios of 1:2 (Miller and Nicholson, 2013). Two other Ni-Cu-PGE deposits associated with ultramafic intrusions that are at advanced stages of exploration and evaluation include the Tamarack deposit of Minnesota and the Current Lake/Thunder Bay North deposit of Ontario (Miller and Nicholson, 2013).

1.2 Exploration and Development History of the Eagle Deposit

Because of historic occurrences of native copper in the Keweenaw Peninsula and iron deposits near Marquette, mining and minerals exploration has proceeded in Upper Michigan nearly continuously since the 1840’s. Starting at least as early as the 1950’s, there was exploration for copper in and around the city of Marquette (Eagle Mine website, 2017). In the 1970’s, the United States Geological Survey, Michigan Geological Survey, and Michigan Technological University cooperated to produce geologic and mineral maps of Upper Michigan (Klasner et al., 1977). These efforts revealed outcrops of ultramafic rocks in an area known as the Yellow Dog Plains (now known as the Eagle and Eagle East intrusions) about 45 kilometers northwest of Marquette (Fig. 4).

Michigan Tech drilled a 31m core of the Eagle Rock outcrop (which is now recognized as part of the Eagle East body) for the Michigan Geologic Survey in 1976. This core was used in the
first academic study (Morris, 1977) of what was then termed the Yellow Dog Plains Peridotite.

Morris (1977) noted a minor amount of Ni-Cu sulfide mineralization in the surface outcrop and drill core samples and speculated, based on geophysical data, that the peridotite might host significant sulfide mineralization at depth. However, based on the high Ni content of sampled olivines, the conclusion of Morris (1977) was that the hypothetical mineralization was unlikely to be economic.

Figure 4: Generalized bedrock geology in the vicinity of the Yellow Dog Peridotite, later termed the Eagle and Eagle East intrusions. Modified from USDA website (2018).

Between 1991 and 1994, Kennecott Exploration (a subsidiary of Rio Tinto) ran an exploration program for zinc in Upper Michigan. While this program never revealed economic zinc deposits, it did accidentally discover small Ni-Cu sulfide mineralized boulders in a gravel pit.
near Marquette (Mahin and Beach, 2013). Seeking out the source of the boulders, it was eventually concluded that they likely were derived from the Yellow Dog Peridotite. Kennecott began exploration drilling of the area in 1995, initially encountering only disseminated sulfide mineralization (Mahin and Beach, 2013). Early drilling and aeromagnetic data defined two neighboring but seemingly unconnected peridotite bodies (Fig. 5), which Kennecott renamed the Eagle and Eagle East intrusions (Eagle Mine website, 2017). In 2002, drilling intersected high-grade, massive Ni-Cu sulfide mineralization in the Eagle intrusion (Mahin and Beach, 2013). Drilling in the Eagle East body was suspended because no significant mineralization had been found and subsequent drilling focused on defining the resource of the Eagle deposit.

Permitting for a mine began in 2004, and after permits were granted, construction of the mine and processing plant near Champion, Michigan began in 2010. In 2013, just before the mine would have gone into production, Kennecott sold the mine and processing plant to the Lundin Mining Corporation, a mid-sized mining company headquartered in Toronto, Canada. In Quarter 4 of 2014 the mine began initial production.

In 2014, Lundin’s exploration team re-started drilling in the Eagle East body. Although not locating any physical connection to the Eagle intrusion, they did discover that the Eagle East intrusion narrowed into a funnel-shape that steeply plunged to the east, away from the Eagle intrusion (Fig. 5). Following what they believed was a feeder conduit, a zone of massive sulfide mineralization with metal grades higher than those at Eagle was discovered deep in the Eagle East intrusion in June 2015 (Mahin, pers. com., June 2015). Currently, Lundin’s exploration team is conducting delineation drilling to define the indicated and inferred resource of the Eagle East deposit.
1.3 Previous Petrologic and Metallogenic Studies

The first petrologic study of the Eagle/Eagle East intrusions was Morris (1977). The primary objective of this work was to compare the ultramafic rocks exposed at surface and in a short drill core to the Keweenawan diabase dikes (the Marquette-Baraga swarm) which also occur in the area. A rough geologic map of the Eagle Rock outcrop area was produced, primarily to show the extent of exposure and sample locations. The sample suite of Morris (1977) consisted of 40 samples taken from the outcrop of Eagle East and from a 31-meter-long drill
core into the main body of Eagle East (drilling performed by the Michigan Geologic Survey), and from outcrop samples of five Keweenawan diabase dikes from various localities in Upper Michigan. The Eagle intrusion was not sampled because it is poorly exposed and, at that time, was not known to be a separate body than the Eagle East intrusion. Petrographic analysis of the Eagle East outcrop samples and drill core were performed, and the compositions of the olivine, clinopyroxene, and orthopyroxene present were determined by electron microprobe analysis. Additionally, major and trace element whole-rock geochemistry were acquired for the samples.

Morris (1977) concluded that the Yellow Dog Plains Peridotite was not genetically associated with the diabase dikes based on differing REE patterns. The LREE enrichment of the peridotite was interpreted to indicate a parental magma derived from a primitive mantle melt rich in volatiles, similar to a kimberlite. Regular chemical changes with depth in the drill core were also noted, leading Morris (1977) to suggest that the intrusion was cryptically layered. Morris (1977) speculated that there was a massive sulfide body at depth beneath the Eagle East outcrop, based both on the presence of globular sulfides in samples and on data from a then-recent geophysical survey of the area. However, because the olivines in the samples were unusually Ni-rich, it was also speculated that this hypothetical massive sulfide body would be Ni-poor and thus uneconomical to mine.

Other than Morris (1977), all published work on the petrology and metallogenesis of the Eagle and Eagle East intrusions was done by Xin Ding. Ding published three journal articles on the Eagle system in collaboration with Ed Ripley, Chusi Li, and others (Ding et al., 2010; Ding et al., 2012a; Ding et al., 2012b). This work was conducted and published prior to Lundin Mining acquiring the property from Rio Tinto.
Ding et al. (2010) largely focused on petrologic evolution of the intrusion, but also reported a U-Pb crystallization age of 1107.2 +/- 5.7 Ma on baddeleyite from the Eagle intrusion. This confirmed that the Eagle was coeval with the Early Stage of MCR magmatism (Fig. 3). The petrologic study was conducted on three Eagle drill cores and one Eagle East drill core, which were drilled and sampled prior to 2010. Four distinct rock types in the Eagle intrusion were defined: feldspathic peridotite, feldspathic pyroxenite, olivine melagabbro, and melatroctolite. Using petrographic and geochemical evidence, Ding et al. (2010) postulated that the Eagle intrusion had formed from at least two and possibly up to four distinct parental magmas. Ding et al. (2010) also concluded that the massive sulfide unit in the Eagle intrusion cross-cut (and thus postdated) the semi-massive sulfide unit, but a more thorough understanding of the field relations has emerged since underground mining began, and Lundin geologists now believe that the opposite is true (see section 1.4).

Ding et al. (2010)’s petrologic study of Eagle East was on one ~450m drill core. It was noted that the entire ~450m length of the core showed no visible igneous layering or foliation and that the only lithology present was melatroctolite, but made no other significant observations (Ding et al., 2010).

Ding et al. (2012a) evaluated the PGE geochemistry of the sulfide minerals in the Eagle deposit. Different types of sulfide mineralization were distinguished between based on the relative fractionation of IPGE (Os, Ir, Ru, and Rh) or PPGE (Pt and Pd). Within the massive sulfide

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1 A feature of the intrusions that was not studied by Ding et al. (2010) is the intrusive breccia unit, which was not recognized at the time of her study. This unit is composed of a mafic-ultramafic matrix with variably mineralized mafic-ultramafic inclusions. The relation of the breccia unit to the other lithologies in the intrusions had not been evaluated petrographically or geochemically prior to this study.
zone, IPGE-rich, PPGE-rich, and PGE-unfractionated sections were found. Disseminated sulfides and semi-massive sulfides below massive sulfides showed relatively unfractionated PGE patterns. Semi-massive sulfides above massive sulfides showed moderate depletion in IPGE and moderated enrichment in PPGE. Cu-rich sulfide veins in sedimentary country rock are highly fractionated, being strongly depleted in IPGE and enriched in PPGE. R factors for the different types of sulfides were modeled, and it was found that the disseminated sulfides, the unfractionated massive sulfides, and the semi-massive sulfides above the massive sulfides had an R factor of between 200 and 300, the semi-massive sulfides below the massive sulfides had an R factor of <100, and the IPGE-rich and PPGE-rich sections of the massive sulfide had an R factor of about 400.

Ding et al. (2012b) assessed the extent of country-rock contamination within the Eagle intrusion using a combined trace element and Nd-, Os-, O-, and S-isotope study. The trace element, Os, Nd, and O isotope values generally indicated primitive mantle values with bulk contamination of <5%, though O isotopic values in pyroxene suggested local contamination of up to 20% is possible. Sulfur isotope values in disseminated and massive sulfide range between 0.3‰ and 4.6‰ in δ34S and between -0.10‰ and 0.09‰ in Δ33S. These values permit a bulk sulfur contamination of up to 50% by Paleoproterozoic metasedimentary rocks, which host the Eagle deposit. However, sulfur isotopic values in semi-massive sulfides (Δ33S: -0.86‰ to 0.86‰; δ34S: 2.2‰ to 5.3‰) imply that Archean country rocks must also have provided a significant source of sulfur contamination for at least the semi-massive ore.

There has also been some recent work conducted on the Eagle system that was presented in poster presentations by Benjamin Hinks and Andrew Sasso at the 2016 Institute on
Lake Superior Geology held in Duluth. Both are students at Western Michigan University working under the advisement of Dr. Joyashish Thakurta.

Hinks et al. (2016) conducted sulfur isotope analyses on ores from Eagle and Eagle East, as well as on Michigamme Formation and Archean basement rocks. It was reported that the Eagle ores have δ34S values ranging from 0‰ to 5‰, the Michigamme Formation has values between 6‰ to 20‰, and Archean basement rocks have values between -11‰ to 7‰. These values are very much in line with those measured by Ding et al. (2012b). However, Hinks et al. (2016) speculated that the δ34S values of Eagle and Eagle East ores were the result of mantle-sourced sulfur being slightly enriched by interaction and mixing with crustal-sourced sulfur. Hinks et al. (2016) also proposed another mechanism for the range of δ34S values of the Eagle ore bodies in which the two possible crustal sources of sulfur, the Michigamme Formation rocks and the Archean rocks, produced attenuating isotope signals that averaged the range seen within the intrusions to 0‰ to 5‰.

Sasso and Thakurta (2016) compared the geochemistry and petrology of three rock units in Marquette County, MI: (1) the Presque Isle Peridotite (PIP), (2) the Deer Lake Peridotite (DLP), and (3) the Yellow Dog Plains Peridotite (YDPP). Based on geochemical analyses, it was suggested that the DLP was unrelated to the PIP and the YDPP, having formed from shallow melting rather than deep melting. Field relations of the DLP were compared to the Great Lakes Tectonic Zone to interpret that the DLP predates the PIP and YDPP by at least 750 Ma. Based on minor and trace element analyses, it was interpreted that the PIP and YDPP have similar petrogenesis associated with the MCR. Sasso and Thakurta (2016) speculated that the PIP is a good target for hosting a magmatic sulfide deposit because it shares key similarities with the
YDPP: high nickel content, sulfide inclusions in olivine, primary magmatic sulfide assemblage of chalcopyrite and pentlandite, and incompatible element enrichment.

1.4 Current Working Mineralization Models for Eagle and Eagle East

Because the transition in ownership of the Eagle deposit from Rio Tinto to Lundin in 2013 did not involve a significant change in exploration personnel, the nomenclature used to describe the intrusion and its mineralization has been consistent among Eagle geologists since active exploration began in 2001 and mining began in 2014. The main ultramafic lithology of the Eagle intrusion, host to the sulfide mineralization, is generically classified by Eagle geologists as peridotite. The Eagle ore body is subdivided into four classes of mineralization based on the volume of contained sulfide (Table 1).

Table 1: Classification system used by Lundin geologists for subdividing the peridotite unit into mineralization categories (S. Beach, personal communication, 2016).

<table>
<thead>
<tr>
<th>Unit Name</th>
<th>Unit Code</th>
<th>Sulfide (Volume %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peridotite</td>
<td>PER</td>
<td>0-5</td>
</tr>
<tr>
<td>Mineralized Peridotite</td>
<td>MPER</td>
<td>5-25</td>
</tr>
<tr>
<td>Semi-massive sulfide</td>
<td>SMSU</td>
<td>25-75</td>
</tr>
<tr>
<td>Massive sulfide</td>
<td>MSU</td>
<td>75-100</td>
</tr>
</tbody>
</table>

With the additional drilling, core logging, and geochemical assays of the Eagle deposit conducted since the sampling of two representative cores by Ding et al. (2010), Lundin geologists have developed a two-stage working model to explain its emplacement and
mineralization history (S. Beach, personal communication, 2015). In this model, two main magma pulses are recognized. The first was a pulse of sulfide-oversaturated magma that intruded and formed the massive sulfide body, the lower semi-massive sulfide ore, and the disseminated sulfide-bearing peridotite. A second pulse of magma, perhaps initially sulfide undersaturated, intruded along the same path and interacted with the already-formed massive sulfide body, creating the upper semi-massive sulfide body and a marginal semi-massive sulfide body not sampled by Ding et al. (2010). This second metal-rich pulse became sulfide saturated as it interacted with the massive sulfide body, resulting in local upgrading of the metal tenor of all sulfide minerals it encountered. Evidence for this model includes the spatial distribution and grades of mineralized sections of the Eagle intrusion and observations of cross-cutting relationships noted in drill core by Lundin geologists.

This current mineralization model contradicts the interpretation by Ding et al. (2010, 2012a, 2012b) that the massive sulfide body cuts into the semi-massive sulfide units. However, the Lundin model is more consistent with the PGE and sulfur isotope data presented by Ding (2012a, 2012b). Ding et al. (2012a) shows unfractionated PGE signatures in the Mper, SMSU (lower) and some of the MSU units. In contrast, the upper SMSU unit and some areas of the MSU unit show variably fractionated PGE signatures. Sulfur isotopic data presented by Ding et al. (2012b) similarly show different ranges in $\delta^{34}$S and $\Delta^{33}$S between the semi-massive sulfide, massive sulfide and disseminated sulfide ores. Sulfur isotope values in disseminated and massive sulfide range between 0.3 $\%_{o}$ and 4.6$\%_{o}$ in $\delta^{34}$S and between -0.10$\%_{o}$ and 0.09$\%_{o}$ in $\Delta^{33}$S. However, sulfur isotopic values in semi-massive sulfides are much more variable and indicative
of Archean sources ($\Delta^{33}S$: -0.86‰ to 0.86‰; $\delta^{34}S$: 2.2‰ to 5.3‰). More details about the current Lundin model are discussed in chapter four.

While Eagle East was thought of as having low exploration potential at the time of Ding et al. (2010), by the time sampling for this study began in 2014, a feeder dyke for the intrusion had been identified that appeared to be a good exploration target, and drilling was ongoing (Mahin and Beach, personal communication, 2015). In June of 2015, after sampling for this study was over, exploration drilling intercepted a zone of Eagle-like, potentially economic massive sulfide mineralization in the feeder dyke of Eagle East (Mahin and Beach, 2016). Definition drilling continued and as of September of 2017 the zone is being developed to mine after the Eagle body is mined (Eagle Mine website, 2018).

1.5 Objectives of Study

This study has four major objectives.

1) Test whether Lundin’s two-stage emplacement model can be discerned by geochemical distinctions between MSU, SMSU (lower), and Mper and presumably later SMSU (upper and marginal) units. This will be done by evaluating whole rock trace element geochemistry of the various lithologies and by using the Ni content and Ni-Fo ratios in olivines to determine relative timing of olivine crystallization and sulfide liquation which may differ between the two mineralization events.

2) Since the two-stage Lundin model seems to be at odds with Ding et al.’s (2010, 2012a, 2012b) interpretation of multiple magma sources for the Eagle intrusion, the second
objective is to reevaluate Ding’s conclusion which is largely based on interpretations of incompatible trace element ratios. This will be done by investigating whether the variations in trace element chemistry that Ding et al. (2010) interprets to reflect differing parent magma compositions may in fact be reflective of the control of variable mineral-liquid partition coefficients on the trace element compositions of cumulus minerals.

3) A third objective is to better understand the petrogenesis of the intrusive breccia (IBRX) unit. This includes establishing the magmatic relationship between the IBRX, the other mineralized units (MSU, SMSU, MPER), and the likely source of the various inclusions (xenoliths or autoliths) that compose the IBRX unit. This will be accomplished by characterizing the petrographic attributes of the matrix and the inclusions.

4) The final objective of this study is to evaluate the emplacement, crystallization, and mineralization history of the Eagle East intrusion and compare its petrology and mineralization with the Eagle body. This includes an evaluation of both the relatively non-mineralized main body of the intrusion, and the heavily mineralized newly discovered mineralized conduit. Specific questions concerning the petrogenesis of the Eagle East that will be addressed include:

- Is there evidence for multiple magma emplacement and mineralization events in Eagle East, and, if so, how do they compare to those found in Eagle?
- Is there evidence for in situ differentiation in the Eagle East body?
- Do the lithologies and mineralization styles observed in Eagle have petrologic-equivalent analogues in Eagle East?
This will be accomplished by characterizing the petrographic attributes of a drill core that profiles the main body of Eagle East as well as those of three drill cores that intersect the feeder and heavily mineralized sections of Eagle East at depth.

2. Methods

This study was conducted on samples collected from drill core that vertically and horizontally profile the Eagle and Eagle East intrusions. One-hundred and twenty-one samples were collected. Of these, fifty-five samples were collected from three drill holes in the Eagle intrusion, and sixty-six samples were taken from three drill holes from the Eagle East intrusion. Samples were selected to represent major lithologies, define contacts, and delineate areas of interest. All samples were initially made into unpolished thin sections and studied with transmitted light petrography. Of the original one-hundred and twenty-one thin sections, forty-nine were selected for polishing to be analyzed by scanning electron microscope (SEM), electron microprobe, and/or reflected light petrography. All thin section preparation and polishing was done by Quality Thin Sections of Tucson, Arizona.

2.1 Core Sampling

Lundin geologists selected three drill holes from the Eagle intrusion, EAUG0041, EUGX0016, and EUGX0028, which they identified as being most representative of the different lithologies in the intrusion (Fig. 6). Several additional samples were taken from cores EAUG0056, EAUG0063, and EAUG0049. Because this study will gather similar petrographic and mineral chemical data as
the study of Ding et al. (2010), Lundin geologists avoided areas where Ding et al. (2010) had sampled. All three drill holes had previously been logged by Lundin geologists.

Figure 6: Three-dimensional model of the Eagle intrusion (looking south) showing the location of drill cores sampled for this project. Sections A1, A2, and A3 are approximate locations of core sampled by Ding et al. (2010). Red shell is MSU; orange shell is SMSU; other mineralization styles not shown. Scale bar and grid lines in meters. Modified image provided by Lundin Mining Co. (2015).

The full lengths of relevant core (excluding sedimentary lithologies adjacent to the intrusions) were laid out for examination on core logging tables at Lundin’s Marquette exploration office. Core intervals spanning 5cm to 25cm long were chosen that represented a particular lithology, crossed a significant contact, or required a microscopic view to better understand. A Lundin technician cut the intervals of interest into quarter core samples. A total of 52 core samples were collected from Eagle – 11 from hole EAUG0041, 22 from hole
EUGX0016, and 19 from hole EUGX0028 (Fig. 7A). For the 59 quarter core samples collected from Eagle East cores (Fig. 8), 23 were from hole 08EA222D, 13 from hole 14EA331F, and 23 from hole 04EA0085 (Fig. 7B).

Figure 7 A and B: Distribution of samples collected from A) Eagle drill cores EUGX0041, EUGX0016, and EUGX0028 and B) Eagle East drill cores 08EA222D, 14EA331F, and 04EA0085. Colors represent rock types logged by Lundin geologists.
Figure 8: Cross-sections looking north (A) and west (B) of the Eagle East intrusion showing the location of the three primary drill cores sampled for this project, 04EA0085, 08EA222D, and 14EA331F. Grid lines in meters. Modified image provided by Lundin Mining Co. (2015).

Lundin geologists provided six additional samples from miscellaneous drill cores. Three of the additional samples were semi-massive sulfides from Eagle taken from cores EAUG0056, EAUG0063, and EUGX0049 (Fig. 6), and three of the additional samples were semi-massive sulfides from Eagle East collected from holes 14EA331B, 14EA331D, and 14EA331I (Fig. 9). The semi-massive sulfide samples were provided to see whether the SMSU differed petrographically in different areas of the intrusion.
Figure 9: Three-dimensional model of Eagle East showing the location of miscellaneous drill cores 14EA331B, 14EA331D, 14EA331G, 14EA331I, and 08EA214. Modified image provided by Lundin Mining Co. (2015).
2.2 Petrography

In this study, rock types are defined according to the modal rock classification proposed by Miller et al. (2002a). In this system, mafic and ultramafic rocks are subdivided by their modal abundance of plagioclase (Pl) into ultramafic (Pl<30%), mafic (Pl 30%-80/85%), and anorthositic (Pl>80/85%) groups (Fig. 10A). Mafic and ultramafic group rocks are then named based on the relative proportions of olivine (Ol), low-Ca pyroxene (Opx), high-Ca pyroxene (Cpx), and Fe-Ti oxides (FeOx) (Fig. 10B and 10C, respectively).

Figure 10 A-C: Modal classification scheme for mafic and ultramafic rocks proposed by Miller et al. (2002a). (A) General rock groups and subgroups based on proportions of Ol, Pl, and Cpx. (B) Classification for rock types in the ultramafic group (Pl<30%). (C) Classification for rock types in the mafic group (Pl 30%-80/85%).
A cumulate code scheme is used in addition to regular rock classifications. This cumulate code scheme is taken from Miller et al (2002a). In this scheme, rocks are assigned a multi-letter code based on their relative proportions of primary mineral phases with greater than 2% modal abundance. These letters are uppercase or lowercase depending on whether the mineral phase in question has a granular (cumulus) habit or and interstitial (intercumulus) habit, respectively. For example, a rock composed of mainly subhedral granular olivine greater than subprismatic augite and minor subpoikilitic plagioclase would classify as an OCp cumulate. Mineral abbreviations for this scheme are listed in Table 2 below.

Table 2: Mineral codes for cumulate classification scheme proposed by Miller et al. (2002a).

<table>
<thead>
<tr>
<th>Granular/Intergranular Mineral Codes</th>
<th>Mineral</th>
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<tbody>
<tr>
<td>P/p</td>
<td>Plagioclase Feldspar</td>
</tr>
<tr>
<td>F/f</td>
<td>Fe-Ti oxide</td>
</tr>
<tr>
<td>O/o</td>
<td>Olivine</td>
</tr>
<tr>
<td>A/a</td>
<td>Apatite</td>
</tr>
<tr>
<td>C/c</td>
<td>Clinopyroxenite (augite)</td>
</tr>
<tr>
<td>-/b</td>
<td>Biotite</td>
</tr>
<tr>
<td>l/i</td>
<td>Inverted pigeonite</td>
</tr>
<tr>
<td>-/α</td>
<td>Amphibole</td>
</tr>
<tr>
<td>H/h</td>
<td>Hypersthene, bronzite (orthopyroxene)</td>
</tr>
<tr>
<td>-/g</td>
<td>Granophyre</td>
</tr>
</tbody>
</table>

Textural and structural terminology used in this study follows the recommendations of the AGI Glossary of Geology (Bates and Jackson, 1987).

All thin sections were examined with a Leica DM Series petrographic transmitted light microscope. Information recorded for each thin section included: 1) visual estimates of the modes of essential and accessory mineral phases, 2) primary mineral features (habit, exsolution, twinning, zoning, etc., 3) mutual textural relations of the different phases (intergrowth and
overgrowth textures), 4) structural elements (foliation, modal layering), and 5) degree and distribution of secondary alteration. The information obtained from the transmitted light examination was used to determine which thin sections would be selected for polishing and subsequent analysis by SEM and electron microprobe.

Sulfides and Fe-Ti oxides are difficult to distinguish from one another in transmitted light, as both sets of minerals are opaque. While reflected light petrography was not a major part of this study, several slides were examined under a reflected light microscope to qualitatively determine the sulfide and Fe-Ti oxide minerals present, and their approximate proportions. Six samples (three from Eagle and three from Eagle East) were studied with reflected light petrography to determine which minerals were present, and after that all core samples were examined under a hand lens to determine rough proportions of sulfides and Fe-Ti oxides.

2.3 Lithogeochemical Analyses

Rio Tinto and now Lundin has routinely acquired ultra-trace level XRF and ICP-MS lithogeochemical analyses on drill core that shows significant sulfide mineralization. They submit split cores up to 1.5m long to ALS Global Labs of Reno, Nevada. The analyzed cores included in this study are Eagle cores EUGX0016 and EUGX0022 and Eagle East cores 14EA331F and 08EA222D.

The methods for these lithogeochemical analyses are described on the ALS Global website (alsglobal.com, 2017). ALS’s ME-XRF06 and ME-MS81 analytical methods measure 51 major, minor and trace element abundances. The ME-XRF06 method is used to analyze major and minor elemental oxides (Table 3). For this method, a 0.9g sample split of the crushed and
pulverized split core sample is ignited or calcined and added to 9.0g of lithium borate flux. The resultant combination is then mixed well and fused in an auto fluxer at 1050 - 1100°C. The resulting melt is formed into a flat, molten glass disc, which is cooled and then analyzed by x-ray fluorescence (XRF) spectrometry. Trace elements are analyzed by the ME-MS81 method using ICP-MS (Tables 4) and ICP-AES (Table 5). For the ICP-MS method, a 0.2g sample of the material of interest is mixed with 0.9g of lithium metaborate flux and fused in a furnace at 1000°C. After the resulting melt is cooled, it is dissolved in 100 mL of 4%HNO₃ / 2% HCl₃ solution. Inductively coupled plasma – mass spectrometry (ICP-MS) is then used to analyze 40 trace elements in the solution (Table 4). For the elements Ag, As, Cd, Co, Cu, Hg, Mo, Ni, Pb, and Zn, samples are digested with the four-acid method before being analyzed with inductively coupled plasma-atomic emission spectrometry (ICP-AES) (Table 5). In the four-acid digestion, perchloric, nitric, hydrofluoric, and hydrochloric acids are used to digest a 0.25g prepared sample. The residue of the digestion is combined with dilute hydrochloric acid and then analyzed by ICP-AES.

Table 3: Elements and Detection Limits of Method: ME-XRF06 (XRF) Analytical Method

<table>
<thead>
<tr>
<th>Compound</th>
<th>Units</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>BaO</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>CaO</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>K₂O</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>MgO</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>MnO</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>Na₂O</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>SiO₂</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>SrO₂</td>
<td>%</td>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>TiO₂</td>
<td>%</td>
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<td>100</td>
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</table>
Table 4: Elements and Detection Limits of ALS’s ME-MS81 (ICP-MS) Analytical Method

<table>
<thead>
<tr>
<th>Element</th>
<th>Units</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Element</th>
<th>Units</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
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<td>1000</td>
<td>Ni</td>
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<td>10000</td>
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<tr>
<td>Ba</td>
<td>ppm</td>
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<td>10000</td>
<td>Pb</td>
<td>ppm</td>
<td>5</td>
<td>10000</td>
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<tr>
<td>Ce</td>
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<td>10000</td>
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<tr>
<td>Co</td>
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<td>10000</td>
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<tr>
<td>Cr</td>
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<td>10</td>
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<td>Sm</td>
<td>ppm</td>
<td>0.03</td>
<td>1000</td>
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<tr>
<td>Cs</td>
<td>ppm</td>
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<td>10000</td>
<td>Sn</td>
<td>ppm</td>
<td>1</td>
<td>10000</td>
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<tr>
<td>Cu</td>
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<tr>
<td>Dy</td>
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<td>Ta</td>
<td>ppm</td>
<td>0.1</td>
<td>10000</td>
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<tr>
<td>Er</td>
<td>ppm</td>
<td>0.03</td>
<td>1000</td>
<td>Tb</td>
<td>ppm</td>
<td>0.01</td>
<td>1000</td>
</tr>
<tr>
<td>Eu</td>
<td>ppm</td>
<td>0.03</td>
<td>1000</td>
<td>Th</td>
<td>ppm</td>
<td>0.05</td>
<td>1000</td>
</tr>
<tr>
<td>Ga</td>
<td>ppm</td>
<td>0.1</td>
<td>1000</td>
<td>Tl</td>
<td>ppm</td>
<td>0.5</td>
<td>1000</td>
</tr>
<tr>
<td>Gd</td>
<td>ppm</td>
<td>0.05</td>
<td>1000</td>
<td>Tm</td>
<td>ppm</td>
<td>0.01</td>
<td>1000</td>
</tr>
<tr>
<td>Hf</td>
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<td>10000</td>
<td>U</td>
<td>ppm</td>
<td>0.05</td>
<td>1000</td>
</tr>
<tr>
<td>Ho</td>
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<td>ppm</td>
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<td>10000</td>
</tr>
<tr>
<td>La</td>
<td>ppm</td>
<td>0.5</td>
<td>10000</td>
<td>W</td>
<td>ppm</td>
<td>1</td>
<td>10000</td>
</tr>
<tr>
<td>Lu</td>
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<td>1000</td>
<td>Y</td>
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<td>10000</td>
</tr>
<tr>
<td>Mo</td>
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<td>Yb</td>
<td>ppm</td>
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<tr>
<td>Nb</td>
<td>ppm</td>
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<td>10000</td>
<td>Zn</td>
<td>ppm</td>
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<td>10000</td>
</tr>
<tr>
<td>Nd</td>
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<td>Zr</td>
<td>ppm</td>
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Table 5: Elements and Detection Limits of ME-MS81 (ICP-AES) Analytical Method.

<table>
<thead>
<tr>
<th>Element</th>
<th>Units</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>ppm</td>
<td>0.5</td>
<td>100</td>
</tr>
<tr>
<td>As</td>
<td>ppm</td>
<td>5</td>
<td>10000</td>
</tr>
<tr>
<td>Cd</td>
<td>ppm</td>
<td>0.5</td>
<td>10000</td>
</tr>
<tr>
<td>Co</td>
<td>ppm</td>
<td>1</td>
<td>10000</td>
</tr>
<tr>
<td>Cu</td>
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<td>10000</td>
</tr>
<tr>
<td>Pb</td>
<td>ppm</td>
<td>1</td>
<td>10000</td>
</tr>
<tr>
<td>Zn</td>
<td>ppm</td>
<td>2</td>
<td>10000</td>
</tr>
</tbody>
</table>
2.4 Electron Microprobe Analyses of Ni in Olivine

The concentration of Ni in olivine can be a helpful tool for determining the timing of olivine crystallization relative to sulfide liquation (Simkins and Smith, 1970; Li et al., 2007). A total of eight samples from the Eagle intrusion and 11 samples from the Eagle East intrusion were selected for electron microprobe analysis of olivine (Table 6). The main objective of the analyses was to acquire precise measurement of Ni concentrations in olivine. Samples were selected from high-sulfide zones (SMSU or MPER with large sulfide globules), low-sulfide zones adjacent to high-sulfide zones (samples with less than 10% sulfide by volume within one meter of SMSU), and low-sulfide zones distant from high-sulfide zones (samples with less than 10% sulfide by volume meters from SMSU). Only samples with at least several grains of fresh olivine were selected. Based on these criteria, samples selected were the best possible representations of their respective zones.

Table 6: Attributes of samples selected for microprobe analysis of olivine.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Host Rock</th>
<th>Sample Classification</th>
<th>Sulfide %</th>
<th>Proximity to High Sulfide Zone</th>
<th>Alteration of Olivine</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-49.3</td>
<td>MPER-SMSU</td>
<td>SMSU</td>
<td>30</td>
<td>6m</td>
<td>Moderate</td>
</tr>
<tr>
<td>16-62.0</td>
<td>IBRX</td>
<td>IBRX</td>
<td>90</td>
<td>18m</td>
<td>Mild</td>
</tr>
<tr>
<td>16-69.3</td>
<td>IBRX</td>
<td>IBRX</td>
<td>3</td>
<td>25m</td>
<td>Mild</td>
</tr>
<tr>
<td>28-41.8</td>
<td>PER</td>
<td>SMSU</td>
<td>40</td>
<td>1m</td>
<td>Moderate</td>
</tr>
<tr>
<td>28-58.1</td>
<td>PER</td>
<td>PER</td>
<td>&lt;5</td>
<td>18m</td>
<td>Mild</td>
</tr>
<tr>
<td>28-67.3</td>
<td>MPER</td>
<td>MPER</td>
<td>10</td>
<td>27m</td>
<td>Mild</td>
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<tr>
<td>D-787</td>
<td>PER</td>
<td>PER</td>
<td>&lt;5</td>
<td>83m</td>
<td>Mild</td>
</tr>
<tr>
<td>D-871B</td>
<td>IBRX</td>
<td>IBRX</td>
<td>5</td>
<td>1m</td>
<td>Mild-Moderate</td>
</tr>
<tr>
<td>D-931</td>
<td>PER</td>
<td>PER</td>
<td>&lt;5</td>
<td>1m</td>
<td>Mild</td>
</tr>
<tr>
<td>D-933</td>
<td>SMSU</td>
<td>MPER</td>
<td>15</td>
<td>0m</td>
<td>Moderate</td>
</tr>
<tr>
<td>D-936</td>
<td>SMSU</td>
<td>MPER</td>
<td>15</td>
<td>0m</td>
<td>Mild</td>
</tr>
<tr>
<td>F-1078</td>
<td>PER</td>
<td>PER</td>
<td>3</td>
<td>19m</td>
<td>Mild</td>
</tr>
<tr>
<td>F-1107A</td>
<td>IBRX</td>
<td>IBRX</td>
<td>20</td>
<td>0m</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Selected thin sections were polished and analyzed with the JEOL JXA-8900R electron microprobe on the University of Minnesota Twin Cities campus under the direction of Dr. Anette von der Handt. Take-off angle was set at 40 degrees, beam energy was 20 kV, beam current was 80 nA, and beam diameter was 1 micron. Analyzing crystal LiF was used to acquire Mn and Fe composition data, analyzing crystal LiFH was used to acquire Ni composition data, analyzing crystal PETJ was used to acquire Ca composition data, and analyzing crystal TAP was used to acquire Si and Mg composition data. Hornblende standard NMNH 143965 was used for Ca and Si composition data, forsterite standard GRR1017 was used for Mg composition data, fayalite standard GRR391 was used for Fe composition data, Mn-olivine standard GRR392 was used for Mn composition data, and Ni-olivine standard GRR192 was used for Ni composition data. On- and off-peak counting time was 20 seconds for Mg, Si, Mn, and Fe data acquisitions, and 40 seconds for Ca and Ni data acquisitions. Off-peak correction method was linear for all elements. Unknown and standard intensities were corrected for deadtime. Standard intensities were corrected for standard drift over time. Oxygen was calculated by cation stoichiometry and included in the matrix correction. The matrix correction method used was ZAF or Phi-Rho-Z Calculations and the mass absorption coefficients dataset used was FFAST Chantler (NIST v 2.1, 2005). The ZAF or Phi-Rho-Z algorithm utilized was Armstrong/Love Scott (Armstrong, 1988).

For each sample, three to ten olivine grains were analyzed, with three to nine analyses per grain.
2.5 SEM-EDS Analyses

Seven samples from drill core 04EA0085, which vertically profiles the main body of the Eagle East intrusion, were selected for SEM-EDS analysis to document the cryptic variation (regular variation in mineral chemistry with depth that is not observable visually) of mg# (= Mg/(Mg+Fe), cation%) in pyroxene and olivine through the intrusion. A Denton vacuum carbon coater was used to coat the samples with approximately 30 nm of carbon. Spot analyses of pyroxene and olivine were acquired with a JEOL JSM-6490LV scanning electron microscope equipped with an energy dispersive spectrometer system (EDS) housed at the Research Instrumentation Laboratory at the University of Minnesota Duluth. Analyses acquired were standard-less but calibrated to a sample of pure copper. The resulting semi-quantitative analyses (major element compositions of pyroxene and olivine) have standard deviation errors for mg# of 0.5% or less based on multiple analyses of a single spot. The accelerating voltage for the SEM was 20 kV, the spot size was 60 μm, and the count time was 10 seconds. Data were reduced from oxide weight percent to cation percent, and the sums of the cations were checked against their expected stoichiometric values to identify anomalous values.

The SEM-EDS was also used to confirm petrographic observations of primary mineral type and alteration assemblage. This was especially helpful for slides that were slightly thicker than normal, which made it difficult to petrographically distinguish orthopyroxene from clinopyroxene.
3.0 Results

The data acquired from the petrographic study, lithogeochemical analyses, electron microprobe mineral analysis, and scanning electron microscope analysis are reported here. These data are reported in the context of Lundin’s rock type identification scheme (Table 1), which is based largely on the amount of sulfide present in the rocks. The petrographic study will focus on the silicate mineral assemblages in each category of Lundin’s identification scheme.

3.1 Petrographic Attributes of Eagle Lithologic Units

Lundin core logs distinguish fourteen different lithologic units in drill core at Eagle based mainly on the percent of sulfide mineralization, but also on rough macroscopic approximations of olivine, pyroxene and plagioclase abundances and textures, and on the homogeneity of the rock type on a centimeter to meter scale. The rock units distinguished within the Eagle intrusion are massive sulfide (MSU), copper-rich massive sulfide (CMSU), semi-massive sulfide (SMSU), mineralized peridotite (MPER), feldspathic peridotite (FPER), peridotite (PER), intrusive breccia (IBRX), and pyroxenite (PRX). Lithologic units identified in the country rocks around Eagle are gabbro (GAB), mafic intrusive rock (MIRK), siltstone/greywacke (SLST), hornfelsed sedimentary rocks (HFL), felsic intrusive rock (FLS), and mineralized hornfelsed sedimentary rocks (CHFL). Only the intrusion-related lithologies were investigated in this study; the country rocks were not considered. Table 7 below summarizes some the principal modal and textural characteristics of these lithologic units.

The principle objective of this petrographic study is to define the silicate (and oxide) mineralogy and the textural, structural, and alteration attributes of the main Eagle lithologic
units. Although the Eagle lithologic units are distinguished primarily on degree of mineralization and, to a lesser extent, on estimations of silicate mineralogy and other rock characteristics, the unit designations are a well-established and practical macroscopic classification scheme for core logging. As such, the objective here is not to redefine the established units, but rather to provide more details about the range of modal rock types and microscopic attributes that comprise each lithologic unit.

3.1.1 Peridotite Lithologic Units (PER, FPER, MPER)

Lundin geologists describe the silicate mineralogy of all PER-family lithologies as generically “peridotite”, which is mixture of olivine and pyroxene. The three Eagle lithologic units generally logged as peridotite (PER – peridotite, FPER – feldspathic peridotite, and MPER – mineralized peridotite) have very similar petrographic attributes. FPER and MPER are essentially the same as PER, except with slightly higher modal percentages of plagioclase feldspar and sulfides, respectively. Lundin geologists classify PER based largely on macroscopic textural characteristics. These include medium to large grain size, equigranular mineral habit, dark gray color tinged with green, less than 5% by volume sulfide minerals (visual estimate), and/or visible olivine or feldspar crystals. Lundin core logging protocol dictates that if
<table>
<thead>
<tr>
<th>Modal Rock Types</th>
<th>Peridotite (PER, MPER)</th>
<th>Semi-Massive Sulfide (SMSU)</th>
<th>Massive Sulfide (MSU, CMSU)</th>
<th>Intrusive Breccia (IBRX)-Matrix</th>
<th>Intrusive Breccia (IBRX)-Clasts1</th>
<th>Intrusive Breccia (IBRX)-Clasts2</th>
<th>Pyroxenite (PRX)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peridotite</strong></td>
<td>Fld lherzolite, melagabbro-norite</td>
<td>Fld lherzolite, melagabbro-norite</td>
<td>Dunite??</td>
<td>Fld lherzolite, olivine melagabbro-norite</td>
<td>Clinopyroxenite</td>
<td>Websterite</td>
<td>Melaqabbr, oxide melagabbro</td>
</tr>
<tr>
<td><strong>Intrusive Breccia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Intrusive Breccia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cpx:Opx (% Avg/Range)</td>
<td>70:30 / 50-80:50-20</td>
<td>80:20 / 50-90:50-10</td>
<td>N/A</td>
<td>70:30 / 50-85:50-15</td>
<td>100:0 / 100-100-0-0</td>
<td>90:10 / 100-85:0-15</td>
<td>75:25 / 45-90:55-10</td>
</tr>
<tr>
<td>Pl (% Avg/Range)</td>
<td>25% / 10-30</td>
<td>25% / 10-40</td>
<td>N/A</td>
<td>25% / 20-35</td>
<td>5% / 3-15</td>
<td>10% / 5-20</td>
<td>40% / 20-75</td>
</tr>
<tr>
<td>Amph (%) Avg/Range</td>
<td>5% / 1-20</td>
<td>12% / 5-25</td>
<td>N/A</td>
<td>7% / 3-20</td>
<td>3% / 0-5</td>
<td>3% / 0-5</td>
<td>4% / 1-7</td>
</tr>
<tr>
<td>FeOx (%) Avg/Range</td>
<td>2% / Tr-5</td>
<td>4% / Tr-7</td>
<td>N/A</td>
<td>2% / Tr-5</td>
<td>3% / Tr-5</td>
<td>3% / Tr-5</td>
<td>10% / 3-20</td>
</tr>
<tr>
<td>Alteration Intensity</td>
<td>Mild-Mod</td>
<td>Mod</td>
<td>Str</td>
<td>Mild</td>
<td>Mild</td>
<td>Mod-Str</td>
<td>Mod-Str</td>
</tr>
</tbody>
</table>

Table 7: Summary of Modal and Textural Attributes of Major Eagle Lithologies
the core appears to have greater than 10% feldspar by volume (visual estimate based on white-
ish tint of altered plagioclase), it is classified as a feldspathic peridotite (FPER). Lundin core log-
ning protocol also dictates that if the core is visually estimated to have between 5% and 25% sul-
fides by volume, it be classified as a mineralized peridotite (MPER). However, in practice, Lundin 

geologists use the appearance of net-textured sulfides, more than mode, as the main criteria for 
distinguishing SMSU from MPER.

In this study, to keep things simple and unambiguous, all peridotite samples will be classi-

cified on the basis of sulfide modal percentage rather than sulfide texture. As such, PER = 
<5%, MPER = 5-25%, SMSU = 25-75%, and MSU = >75% sulfide. Peridotite matrix samples from 
the intrusive breccia unit of the intrusion will be classified as “IBRX-matrix”. Sections of non-
peridotite material in the intrusive breccia unit will be classified as “IBRX-clast”. Since nearly all 
PER-family lithologies (including SMSU) contain at least 10% plagioclase and classify modally as 
feldspathic peridotite to melagabbronorite (Table 7), Lundin’s FPER designation will not be used 
here.

Nine samples of PER and MPER were collected from the Eagle intrusion; one from core 
EUGX0016 at 46.7 m and eight from core EUGX0028 from the section spanning 53 m to 83 m 
(Fig. 7A). Photographs of drill core and thin section photomicrographs of typical PER are shown 
in Figure 11. The relative modal abundances of Ol, Cpx, and Opx for the PER samples are shown 
in Figure 12 and indicate that the dominant modal ultramafic rock type of PER lithologies is 
lherzolite. With plagioclase typically ranging from 10-30%, the complete modal rock name for 
the majority of PER samples is feldspathic lherzolite. The petrographic attributes of the primary,
Figure 11: Sample 28-51.8 logged as PER in wet hand sample (A), ppl (B), and xpl (C). The sample contains ~95% silicate minerals and ~5% opaque minerals. In decreasing order of abundance, the rock is composed of plagioclase, olivine, Cpx, Opx, opaques, biotite, and amphibole. The opaque minerals display several different habits, including subhedral equant (Cr-chromite?), bladed (ilmenite?), and euhedral cubic (pyrrhotite?). Note that olivine is relatively unaltered. This rock classifies as a feldspathic lherzolite (Fig. 12).
Figure 12: Estimated relative modal proportions of olivine, orthopyroxene, and clinopyroxene abundances in PER and MPER samples from cores EUGX0016 (DDH 46.7m) and EUGX0028 (DDH 53m to 83m) in the Eagle intrusion. General abundance of plagioclase is denoted by symbol type.

Accessory, and secondary minerals comprising PER-family lithologies is described below in order of decreasing abundance.

Olivine is typically the most abundant silicate phase in PER lithologies and occurs as subhedral to euhedral, equant grains that are generally 1.5 mm to 3.5 mm in diameter, though rare grains can range down to 0.5 mm or up to 6.0 mm in diameter. Modal range of olivine is 20-35% of silicate phases (Fig. 12). Some grains occur as chadacrystic phases overgrown by
subpoikilitic pyroxene and plagioclase. Olivine is often partially to completely altered to iddingsite, talc, or serpentine +/- Fe-Ti oxides.

Clinopyroxene (Cpx) occurs as anhedral to subhedral granular to subprismatic grains that are generally 0.5 mm to 1.5 mm in width. Modal range of Cpx is 7-25% of the silicate component. Cpx locally partially to fully encloses olivine indicating that though granular (cumulus) it began to crystallize generally later than olivine. Simple twinning is common in Cpx. Exsolution is rarely observed. Cpx is typically weakly altered by uralitization.

Orthopyroxene occurs as anhedral granular to subpoikilitic grains. Anhedral granular grains are generally 1.0 mm to 2.0 mm in diameter, while subpoikilitic grains can range up to 6.0 mm in diameter and commonly include Ol chadacrysts. Modal range of Opx is 3-15% of silicate phases. Opx exhibits rare simple twinning. Like Cpx, Opx is mostly unaltered but exhibits weak uralitization.

Plagioclase occurs as subhedral to anhedral, lath-shaped grains that range between 0.5 mm and 6.0 mm in width. Modal range of plagioclase is 10-35% of silicate phases. It occurs in the interstices between olivine and the pyroxenes and partially to fully encloses these phases, indicating that it crystallized generally later than mafic silicates. Roughly one third of plagioclase grains exhibit polysynthetic twinning, one third simple twinning, and one third no twinning. Plagioclase grains exhibit gradational core-to-rim zoning and some sector zoning. Oscillatory zoning is absent. Plagioclase can be variably altered to sericite in heavily altered samples.

The Fe-Ti oxide minerals ilmenite and magnetite are present in all peridotite samples, ranging from trace amounts to 5 modal % of the samples. Ilmenite occurs as anhedral grains up
to 2.0mm in diameter or as subhedral, bladed grains up to 1.5mm wide and several millimeters in length. Magnetite occurs as anhedral, equant grains up to 2.0 mm in diameter. Cr-rich spinel is also present as euhedral, equant grains about 1.0 mm in width, usually associated with olivine.

Minor accessory phases in PER lithologies include amphibole, biotite, and apatite. Amphibole occurs as brown, anhedral to subhedral grains generally up to 0.5 mm in diameter. In most samples amphibole makes up 1-7% of silicate phases, but in one sample it makes up 15-20% of the silicate phases. Where amphibole is a significant modal component of the sample, it occurs as subhedral, equant grains up to 1.0 mm in diameter. It exhibits green-brown pleochroism. Amphibole also commonly occurs as overgrowth rims on Cpx and Opx grains. Amphibole grains show weak core-to-rim zoning and splotchy sector zoning. Amphibole is generally unaltered, but in rare cases is replaced by actinolite. Biotite occurs as subhedral, reddish brown to brown grains 0.1 mm to 0.5 mm in width. Modal percent of biotite ranges from trace amounts to 5% of silicate phases. It is strongly pleochroic, with colors changing from very dark, reddish-brown to a nearly clear light brown. It most commonly occurs in association with opaque minerals, especially Fe-Ti oxides. Apatite occurs as very fine, needle-like grains as inclusions in plagioclase or biotite. It occurs in trace amounts in all samples.

Because reflected light petrography was not a major part of this study, the exact proportion of the various sulfide minerals is each sample was not determined. Nevertheless, it is clear from the cursory reflected light microscopy conducted that the sulfide minerals, mostly pyrrhotite, pentlandite, and chalcopyrite, are present in all peridotite samples, comprising at least 2% of the mode. Additionally, sulfides are often clearly visible in hand sample. Sulfide
minerals are anhedral granular to ameboidal to poikilitic in habit and occur as disseminated grains to large blebs interstitial to silicate minerals. Sulfides are not associated with any particular silicate mineral.

Based on their abundance and subhedral granular habit, olivine and clinopyroxene are evidently the dominant cumulus minerals in all PER samples. However, that Cpx locally overgrows olivine indicating that olivine is somewhat paragenetically earlier than Cpx. The cumulus status of Opx is difficult to precisely determine as it is typically low in abundance (<15%), ranges from anhedral granular to subpoikilitic, and locally overgrows both olivine and Cpx, implying that if cumulus, it is paragenetically late to postcumulus.

Plagioclase is a major constituent by volume, ranging from 10-30 modal %, but it occupies an interstitial position relative to the mafic phases and locally overgrows olivine, Cpx, and Opx. As such, plagioclase is interpreted as late cumulus to postcumulus. Fe-Ti oxide, amphibole, biotite and apatite occur in minor to trace amounts and although all are primary, they are entirely postcumulus phases, crystallizing after olivine, Cpx, Opx, and plagioclase. Samples with higher percentages of sulfide minerals have higher proportions of olivine and Cpx relative to the other silicate phases. Using cumulate code terminology, PER and MPER samples range from OCph to OpCh, with interstitial amphibole (hb), Fe-Ti oxide (f) apatite (α) composing significant enough proportions of some samples to be appended to the end of the code.
3.1.2 Semi-Massive Sulfide (SMSU)

SMSU is the designation given by Lundin geologists to any intrusive rock that is visually estimated to have between 25% and 75% sulfides by volume. A key distinction between MPER and SMSU is that SMSU has net-textured sulfide, whereas MPER does not. Lundin geologists describe the silicate portions of this lithology generically as peridotite. Petrographic observations of SMSU samples show that their silicate mineralogy and modal compositions are similar to MPER and PER lithologies described above (Table 7).

Six samples of the SMSU lithology were collected from the Eagle intrusion. Two samples from core EAUG0028 (DDH 41-45m), one from EUGX0016 (DDH 49m), and one each from EAUG0056 (DDH 14m), EAUG0063 (DDH 8m), and EUGX0049 (DDH 13m). A photomicrograph of a typical mineral assemblage is shown in Figure 13. The relative modal abundances of Ol, Cpx, and Opx are shown in Figure 14. These data show that the modal rock types of SMSU sample are, like PER/MPER samples, lherzolites, though an olivine-rich variety. Plagioclase is more variable in abundance, ranging from 5-40%. This indicates that complete modal rock types range from lherzolite to feldspathic lherzolite to olivine melagabbrosomite.

In SMSU samples, olivine is consistently the most abundant silicate phase ranging in mode from 20% to 45% (Fig. 14). In contrast to PER/MPER lithologies, olivine in the SMSU samples is more often euhedral and slightly coarser-grained (1.5 - 4.0 mm). Clinopyroxene in SMSU samples also differ from PER/MPER lithologies by being more commonly subhedral, as opposed to anhedral, coarser grained (1.0 - 2.5 mm), and comprising a slightly lower modal percentage (5-20%) of silicate phases. Orthopyroxene in SMSU samples is typically anhedral granular and has a modal range of 3-15% of silicate phases. Plagioclase is similar in habit to
Figure 13: Sample 28-44.1 logged as SMSU in wet hand sample (A), ppl (B), and xpl (C). The sample contains ~60% silicate minerals and ~40% net-textured sulfide minerals. All silicates show weak to moderate degrees of alteration (Ol – serpentine/iddingsite, Cpx – uralite/chlorite, Pl – sericite/chlorite). This rock classifies as a lherzolite (Fig. 14).
Figure 14: Estimated relative modal abundances of olivine, orthopyroxene, and clinopyroxene abundances in six SMSU samples in the Eagle intrusion (two from EAUG0028 DDH 41-45m, one from EUGX0016 DDH 49m, and one each from EAUG0056 DDH 14m, EAUG0063 DDH 8m, and EUGX0049 DDH 13m). General abundance of plagioclase is denoted by symbol type.

PER/MPER lithologies, being subhedral to anhedral granular laths, but has a slightly higher modal range (5-40%) of silicate phases. A diverse range of Fe-Ti oxide minerals (titanomagnetite, ilmenite, and Cr-spinel) occur in SMSU samples and compose 1-7% of non-sulfide minerals. The accessory phases in the SMSU lithology are similar to those in the PER/MPER lithologies, except that in the SMSU lithology, amphibole is more abundant at 5-25% of silicate phases.

The sulfide minerals pyrrhotite, pentlandite, and chalcopyrite make up 25%-75% by volume of SMSU samples. Sulfide minerals are ameboidal to poikilitic in habit, occurring as
disseminated grains to large globules, always interstitial to silicate minerals. In SMSU samples, sulfide minerals usually form a net-textured network enclosing the silicate minerals in the sample. Larger masses of sulfides often partially to fully enclose large, euhedral olivine grains.

The paragenetic sequence of non-sulfide minerals in SMSU rock types implied by their mode and texture is similar to PER/MPER lithologies: Ol → Cpx → Pl → Opx + Feox → Amph+Bio+Ap. While the Pl:Cpx ratio is slightly higher in the SMSU than the PER/MPER, possibly suggesting paragenetic equivalence, overgrowth relations consistently imply that Cpx is paragenetically earlier than Pl. The most notable difference between PER/MPER and SMSU sample is the increase in relative proportions of olivine to pyroxenes. The Ol:Pyx ratio increases from about 50:50 in PER/MPER lithologies (Fig. 12) to about 75:25 in SMSU samples (Fig. 14). The proportion of Cpx to Opx changes only slightly, from an average of 68:32 in the PER/MPER to an average of 78:22 in the SMSU. The Pl:Cpx ratio increases from 61:39 to 69:31. Additionally, there is an increase in the amount of amphibole present and an increase in the intensity of alteration as compared to the PER/MPER lithologies.

3.1.3 Massive Sulfide (MSU) and Copper-Rich Massive Sulfide (CMSU)

MSU is the designation given by Lundin geologists to any rock that is visually estimated to have more than 75% sulfide by volume. However, generally this lithology is composed of nearly 100% sulfide minerals (Fig. 15). Lundin geologists assume that any non-sulfide portion of
Figure 15: Transition of an MSU section (left) into a SMSU section (right) in sample 16-62.8. While 16-62.8 is actually a sample in the IBRX section of core EUGX0016, it is the most representative sample of massive sulfide collected for this study. Yellowish chalcopyrite (ccp) and brassy pyrrhotite (po) are visible. Notice that in the MSU, silicate minerals do not appear to be present except in the form of serpentine and/or calcite veins. Scale card with centimeter demarcations in foreground.

Copper Massive Sulfide (CMSU). This designation is based on the visual estimation of the this lithology is peridotite. Massive sulfide that is especially rich in chalcopyrite, compared to standard MSU, is referred to as proportion of bright yellow sulfide minerals (chalcopyrite) relative to brassy yellow sulfide minerals (pyrrhotite); core with a yellow:brassy ratio of 50:50 or greater is classified as CMSU. The silicate portions of the two designations are similar and they will be treated here together.
No MSU-only samples were collected, but two samples (16-30.1 and 16-62.8) had significant MSU components (25% of the sample or greater). MSU samples have no primary silicate minerals. Instead, they are composed entirely of sulfide minerals with some minor secondary silicate veining, usually serpentine or calcite. The edges of MSU sections (i.e., their contacts with other lithologies) are marked by a higher than usual amount of alteration in those lithologies.

The sulfide assemblage, as described by Lundin geologists, is pyrrhotite, chalcopyrite, and pentlandite. Pyrrhotite takes on a dull, brassy yellow color in hand sample, and is the most abundant of the phases. Second most abundant in is chalcopyrite, which is more yellow-colored than pyrrhotite. Third in abundance is pentlandite, which cannot be easily distinguished from pyrrhotite in hand sample. See Figure 15 above for examples of pyrrhotite and chalcopyrite in core sample.

3.1.4 Intrusive Breccia (IBRX)

The ‘intrusive breccia unit’, or IBRX, typically occurs in the vicinity of MPER or SMSU lithologies and is similar to them in many respects. Classification of this lithology is based on the chaotic nature of its mineralization, with patches of heavy mineralization and patches with poor mineralization locally intermixed. Lundin geologists classify this lithology primarily based on “clasts” of superficially xenolithic material that appear to be mixed in with the peridotite and the chaotic nature of the mineralization in the core when this occurs. Often, the clasts show significant sulfide mineralization while locally the matrix shows relatively less sulfide
mineralization, but in some cases the clasts are relatively unmineralized while the matrix is more heavily mineralized. Petrographic description of this lithology is divided into three parts: the matrix (Fig. 16), Type 1 clasts (Fig. 16), and Type 2 clasts (Fig. 17). Nine samples of this lithology were collected from the Eagle intrusion, of which five samples contained matrix material, five contained Type 1 clasts, and three samples contained Type 2 clasts.

**Matrix** - The matrix in all IBRX samples is modally and texturally similar to samples classified as PER or MPER (Table 7). Modally, the matrix classifies as feldspathic lherzolite (Fig. 18). Using cumulate code terminology, the matrix of IBRX samples ranges from OCph to OCphf. Compared to the PER/MPER and SMSU lithologies, olivine in the IBRX matrix is finer grained (1.0 - 3.0 mm). Rarely (one or two grains in about every other sample), olivine in the IBRX matrix will occur as ameboidal crystals 3.0 – 6.0 mm in diameter. Modal range of olivine in the IBRX matrix is 20-45% of silicate phases, similar to the PER/MPER and SMSU lithologies. Plagioclase in the IBRX matrix is similar to that in the PER/MPER lithologies except for a lower modal range of 20-35% of silicate phases. Clinopyroxene in the IBRX matrix is very similar to that in the PER/MPER lithologies, but with a slightly larger range of width of 0.5 mm to 2.0 mm and a slightly smaller modal percent range of 10-25% of silicate phases. Orthopyroxene has a size range of 0.5-3.0 mm, which is a slightly larger range than that of the Opx in the PER/MPER lithologies. The Fe-Ti oxide minerals in the IBRX matrix are similar to those in the PER/MPER lithologies (Table 7).
Figure 16: Sample 16-73.1 logged as IBRX in wet hand sample (A), ppl (B), and xpl (C). In this sample, Type 1 IBRX clasts composed of Pl-bearing clinopyroxenite are embedded in IBRX-matrix composed of feldspathic lherzolite. Note that the lherzolitic matrix near the sharp contact with the clinopyroxenite clast contains more plagioclase and shows increased alteration (Ol-talc). The clast section is dominated by Cpx, with small amounts of plagioclase.
Figure 17: Sample 16-54.9 logged as IBRX in wet hand sample (A), ppl (B), and xpl (C). In the core sample, a Type 2 clast, composed of sulfidic (25%), Pl-bearing Cpx-rich websterite, is in contact with a mildly sulfidic feldspathic lherzolite. Thin sections of the clast show them to be composed of sulfide minerals, Cpx, inverted pigeonite, plagioclase, and biotite. The pyroxenes are moderately to heavily uralitized, and the plagioclase is almost completely altered to chlorite.
Figure 18: Estimated relative modal abundances of olivine, orthopyroxene, and clinopyroxene abundances in three types of IBRX samples from core EUGX0016 (DDH 54-89m) in the Eagle intrusion. Nine samples, four of which had two different lithologies in them, yielded thirteen total data points. General abundance of plagioclase is denoted by symbol type.

Accessory minerals in the IBRX matrix is also similar to PER/MPER lithologies. Amphibole is less prevalent in the IBRX matrix than it is in the PER/MPER or SMSU lithologies, generally composing 3-5% of silicate phases. However, in one IBRX matrix sample it does compose 15-20% of silicate phases. Amphibole in the IBRX matrix is subhedral and, with grains of up to 1.0 mm in
diameter, is coarser-grained than PER/MPER amphibole. Biotite in the IBRX matrix is slightly more common at 3-5% of silicate phases. Apatite is similar in mode and texture.

Sulfide minerals in the IBRX matrix are similar to those in the PER/MPER lithologies in habit and other petrographic characteristics, but their modal abundance is lower. They compose from 1% to 5% of all minerals in IBRX matrix samples.

Clasts - The “clasts” in the IBRX unit are dominantly pyroxenites and as such are very distinct from all the “peridotite” lithologies described above for the PER, MPER, SMSU, and IBRX-matrix lithologies. There are two types of pyroxenite clast: those relatively devoid of sulfide minerals (Type 1, “XC1”) and those associated with relatively high concentrations of sulfide minerals (Type 2, “XC2”).

XC1 clasts are composed of weakly altered, plagioclase-bearing clinopyroxenite (Figs. 16 & 18). In terms of cumulate terminology, XC1 clasts classify as CP cumulates. Clinopyroxene is the predominant phase (85-95 vol%) occurring as anhedral, equant grains 0.3 – 0.7 mm in width. Simple twinning is common, and most grains are weakly to moderately uralitized. Minor abundances (3-7%) of plagioclase occur as anhedral grains of highly irregular shape that range from 0.1 – 0.7 mm in diameter, exhibit simple and polysynthetic twinning, and show gradational normal concentric zoning. Most grains are weakly altered to sericite. Fe-Ti oxides, distinguished from sulfides by color in hand sample, likely include magnetite as equant, anhedral grains 0.1-0.2 mm in diameter and ilmenite as bladed, subhedral to anhedral grains 0.1-0.3 mm in width and up to 1.0 mm long. Fe-Ti oxides make up 1-3 modal % of the sample. Up to 3% biotite is present as dark brown, anhedral to subhedral tabular sheafs that are 0.1 – 0.3 mm in width and up to 3.0 mm in length and often partially to fully encloses opaque minerals, presumably Fe-Ti
oxides. A similar abundance of amphibole (1-3%) occurs as brown, anhedral subequant grains (0.1 – 0.3 mm) that displays commonly splotchy sector zoning. Up to 1% sulfide minerals, distinguished from Fe-Ti oxides by color in hand sample, occur as disseminated, anhedral globules. Finally, samples 16-73.1 and 16-78.1 contain semicircular clots of granoblastic calcite which resemble amygdules.

XC2 clasts are composed of moderately altered, sulfidic, Pl-bearing websterite to Opx-bearing, Pl-bearing clinopyroxenite (Figs. 17 & 18). Using cumulate code terminology, XC2 clasts are CPip. Clinopyroxene differs from that in XC1 clasts in that it is less abundant (75-85%), coarser grained, and more subprismatic in habit. Subhedral to anhedral Cpx grains range 0.2 – 0.6 mm in width, 0.3 – 1.5 mm in length. Alteration of Cpx is heavier than in XC1, with moderate to heavy uralitization of most grains. Minor amounts (3-5%) of inverted pigeonite occurs in XC2 clasts as anhedral, roughly equant grains 1.0 – 3.0 mm across with characteristic complex Cpx exsolution bands in an orthopyroxene host. They display mild uralitization. Plagioclase is slightly more abundant in XC2 than in XC1, at 10-15% of silicate phases. It tends to be more altered than that in XC1, sometimes being nearly fully replaced by sericite. Minor abundances of biotite, amphibole, and the Fe-Ti oxides are similar to those in XC1. Unlike XC1, XC2 contains relatively high concentrations of sulfides, at 20-30% of all phases. These sulfides are similar to those in the MPER and SMSU in that they are subpoikilitic to poikilitic, globular, and locally contain white mica.

At the contact between the IBRX clast and matrix, the lherzolitic matrix commonly displays increased plagioclase concentration and shows increased alteration within 5 mm of the
contact (Fig. 17). Locally, the plagioclase in the contact zone appears to be oriented roughly parallel to the contact with the clast.

3.1.5 Pyroxenite (PRX)

Classification of pyroxenite during logging is based on fine grain size, black color, and lack of visible olivine crystals. In sampled cores, PRX occurs stratigraphically below and above the PER lithologies (PER, MPER, SMSU, MSU, IBRX) in core EUGX0016 and below the PER lithologies in core EUGX0028 (Fig. 7a, purple PRX). In core EUGX0016, the upper PRX contacts SLST at its upper and lower contacts, and the lower PRX contacts PER at its upper contact and SLST at its lower contact. In core EUGX0028, the PRX contacts SLST at its upper and lower contacts. In core EUGX0028, a lithology is present stratigraphically above the PER lithologies that was logged as MIRK (“mafic intrusive rock” designation used for unrelated intrusions) but is petrographically similar to PRX samples. This lithology occurs in three pieces, all with SLST contacting their upper and lower contacts. The contacts between PRX and SLST or PER were not directly sampled for this project. Sections of PRX observed in these drill core range in thickness from as little as half a meter to well over 30 m. Sometimes, mafic intrusive rock cross-cutting the ultramafic lithologies of the Eagle intrusion is logged as PRX, but it is unclear whether these are actually related to the PRX lithology.

Six samples of the PRX unit were collected from the Eagle intrusion – two from core EUGX0028 (DDH 81-87m) and four from EUGX0016 (DDH 100-140m). See Figure 19 for a picture and photomicrograph of this lithology. Modally, these samples classify as oxide bearing
Figure 19: Sample 16-103.6 logged as PRX in wet hand sample (A), ppl (B), and xpl (C). In decreasing order of abundance, the sample is composed of plagioclase, clinopyroxene, and opaque minerals. Several small, calcite amygdules are present. Cpx is moderately uralitized. This rock classifies as a melagabbro to feldspathic clinopyroxenite (Fig. 20).
melagabbro to feldspathic clinopyroxenite (Fig. 20). Using cumulate code terminology, they classify as PCf to CPf.

The PRX lithology is in some ways similar to the IBRX-Clast Type 1 lithology. However, there are also major differences between the two lithologies. Clinopyroxene is a major component of both lithologies, but while it makes up nearly 90% of most IBRXC1 samples, it only accounts for 10-35% of silicate phases in the PRX lithology where it occurs as subhedral
euhedral grains 0.25-0.75mm in width. Many pyroxene grains are partially to fully altered to amphibole, and others are moderately uralitized. Compared to plagioclase in IBRXC1, plagioclase in PRX makes up a much larger portion of the sample at 10-40% of silicate phases. While plagioclase in IBRXC1 is anhedral, plagioclase in PRX occurs as subhedral to euhedral lath-shaped grains 0.1 to 0.3 mm in width and up to 2.5 mm in length. Fe-Ti oxides are significantly more abundant in the PRX, making up 3-7% of each sample. They are more euhedral and elongated than those in IBRXC1, ranging in shape from tabular to acicular. Ilmenite occurs as anhedral grains up to 2.0mm in diameter or as subhedral, tabular to needle-like grains up to 1.5mm wide and several millimeters in length. Magnetite occurs as anhedral, equant grains up to 2.0mm in diameter. Biotite is rare in PRX and typically occurs marginal to Fe-Ti oxide. Amphibole is also rare and occurs as anhedral grains 0.10-0.50mm in diameter. Unlike IBRXC1, sulfides are completely absent from PRX samples. Calcite and quartz-filled amygdules are present near this lithology’s upper contacts with other lithologies.

### 3.2 Eagle East Lithologies

The peridotitic lithologies at Eagle East are nearly identical to those at Eagle. However, in drill core 04EA0085, which passes through the core of the Eagle East intrusion (Fig. 8), the feldspathic Iherzolite shows distinctive textural characteristics compared to PER lithologies in other areas of the Eagle East or Eagle intrusions. Most notably, clinopyroxene and orthopyroxene are more commonly poikilitic rather than subhedral granular as found elsewhere. Given this significant textural attribute of the PER unit in the Eagle East intrusion, it is given its own unit designation – Eagle East Core Peridotite (EEC-PER).
3.2.1 Eagle East Core Peridotite (EEC-PER)

In drill core, this lithology is generally a greenish dark gray, non-foliated, coarse-grained, locally feldspathic peridotite. Fourteen samples of EEC-PER were collected in core 04EA0085 (Fig. 7).

In thin section, olivine ranges from 20% to 60% in mode and occurs as subhedral to euhedral, equant grains. In the first 200 m of the core, olivine ranges in diameter from 0.75 mm to 2.5 mm, increasing to a maximum average diameter of 4.0 mm to 6.0 mm at a depth of 318 m, with the remaining ~200m of core containing olivine with an average diameter of 1.5 mm to 3.5 mm (Fig. 21). Olivine is often partially to completely altered to serpentine +/- Fe-Ti oxides.

The most distinctive characteristic of the Eagle East Core Peridotite compared to other PER lithologies is the subpoikilitic to poikilitic habit of the pyroxenes (Fig. 21). Clinopyroxene comprises 10-40% of the EEC peridotite unit (Fig. 22) and is subpoikilitic to poikilitic, commonly enclosing chadacrysts of olivine (Fig. 21). Cpx oikocrysts are generally 1.5 mm to 2.5 mm across but can range up to 5.0 mm.

Orthopyroxene abundance ranges from 5% to 25% (Fig. 22) and is subhedral granular to subpoikilitic (Fig. 21), also commonly enclosing olivine. Subhedral to anhedral grains range from 0.5mm to 2.0mm in diameter, while oikocrysts range from 2.0 mm to 5.0 mm in diameter.

Orthopyroxene and clinopyroxene are commonly found intergrown with one another. In the central 200 meters of EEC-PER unit in the 04EA0085 core, Opx+Cpx abundance is greater than
olivine (Fig. 21), giving rise to olivine websterite, rather than lherzolite, which composes most PER units. Pyroxenes are also more poikilitic in this interval.

Plagioclase occurs as subhedral to anhedral, roughly tabular grains that range in width from 0.25mm to 1.5mm. Modal range is generally 5-10%, but sample A-501 contains about 25% plagioclase (Fig. 21, 22).

Accessory minerals in the EEC-PER unit resemble occurrences in other PER units. Amphibole generally occurs as anhedral grains up to 0.5 mm in diameter and makes up 1-5% of silicate phases. Biotite occurs as subhedral grains 0.1 mm to 0.5 mm in width and makes up 1-3% of silicate phases. Apatite occurs as very fine, needle-like grains, and is often associated with plagioclase. It makes up 1% of silicate phases. Fe-Ti oxides are common, but mostly occur with serpentine as very finely disseminated alteration products of olivine. Less commonly, Fe-Ti oxides occur as fine, needle-like to elongate-tabular grains. Primary Fe-Ti oxides make up 1-5% of each sample. The sulfide minerals pyrrhotite, pentlandite, and chalcopyrite are rare in the EEC-PER unit profiled in 04EA0085, except at the very bottom of the hole (sample A-501), which resembles MPER lithologies seen at Eagle. Serpentine veins occasionally cut samples, in which case many of the minerals nearest to the veins are altered to serpentine. Other common alteration minerals are talc, tremolite, chlorite, and iddingsite.

Using modal nomenclature, the EEC-PER unit ranges from a feldspathic olivine websterite to feldspathic lherzolite (Fig. 22). In terms of cumulate nomenclature, the mineral habits and relative modes of most EEC-PER samples classify them to be olivine cumulates with intercumulus clinopyroxene, orthopyroxene, and plagioclase. However, the local occurrence of
Figure 21: Down-hole variations in texture and mode of mafic minerals in Eagle East Core Peridotite samples from 04EA0085. For grain size, f = fine grained, mf = medium-fine grained, m = medium grained, mc = medium-coarse grained, c = coarse grained. For mineral habit, eu = euhedral, sub = subhedral, an = anhedral, sp = subpoikilitic, and p = poikilitic.
Figure 22: Estimated relative modal proportions of olivine, orthopyroxene, and clinopyroxene abundances in Eagle East Core Peridotite samples from core 04EA0085 (DDH 50-501m). General abundance of plagioclase is denoted by symbol type.

Anhedral to subhedral granular orthopyroxene indicates that it may intermittently achieve cumulus status. Using cumulate code terminology, this lithology is an Ochp to OcHp.

3.2.2 Eagle East PER/MPER Lithologies

Fifteen samples of MPER and PER unit lithologies were collected from Eagle East core; four from core 14EA331F between a depth of 1075m and 1120m, and eleven from core 08EA222D between a depth of 785m and 945m (Fig. 7). The MPER and PER lithologies in the
Eagle East intrusion are generally similar to their equivalents in the Eagle intrusion. The differences will be highlighted below. The relative modal abundances of primary silicate minerals in Eagle East peridotitic lithologies (Fig. 23) indicate that they are generally poorer in Opx and span a broader range of olivine:clinopyroxene proportions and plagioclase concentrations compared to Eagle PER/MPER samples (Fig. 12). Modal rock types include dunite, lherzolite, olivine websterite, feldspathic lherzolite, feldspathic olivine websterite, olivine melagabbro, and augite melatroctolite.

Olivines in the Eagle East PER and MPER lithologies are slightly more anhedral than those in the Eagle Per and MPER. One exception to this is sample D-787, which contains very euhedral olivine grains. Olivine in the Eagle East PER and MPER is slightly coarser than olivine in the Eagle PER and MPER, at 2.0 – 4.5 mm in diameter. Its modal abundance is considerably higher than in the Eagle PER and MPER, at 35 – 45% of silicate phases. As in Eagle peridotite lithologies, both clinopyroxene and orthopyroxene are anhedral to subhedral in the Eagle East PER and MPER units. Clinopyroxene mode is 25-35% of non-sulfide phases and orthopyroxene mode is 3-7%. Cpx grains range from 0.75 mm to 1.5 mm in width and Opx grains range from 0.25-0.75 mm in width. Plagioclase in the EE-PER is anhedral and ranges in modal abundance from 15% to 25% of silicate phases. The modal and textural attributes of sulfide, Fe-Ti oxides, amphibole, biotite, and apatite in Eagle East PER and MPER are similar to those of Eagle.

The alteration intensity, especially serpen tinization, is heavier in the EE-PER samples than in the PER samples.
Figure 23: Estimated relative modal proportions of olivine, orthopyroxene, and clinopyroxene abundances in Eagle East PER and MPER samples from cores 14EA331F (four samples, DDH 1075-1120m) and 08EA222D (eleven samples, DDH 785-945m). General abundance of plagioclase is denoted by symbol type.

3.2.3 Eagle East SMSU Lithologies

Six samples of the semi-massive sulfide unit were collected from the Eagle East intrusion: three from core 08EA222D between a depth of 845m and 940m, and three from core 14EA331F between a depth of 1095m and 1110m (Fig. 7). The relative modal abundances of primary silicate minerals in Eagle East SMSU lithologies (Fig. 24) indicate that they are slightly
poorer in Opx and span a broader range of olivine:clinopyroxene proportions compared to Eagle SMSU samples (Fig. 14). Modal rock types include lherzolite, feldspathic lherzolite, and feldspathic olivine websterite.

Olivine in the EE-SMSU is more modally abundant than that in the Eagle SMSU at 30-60% of silicate phases. It is slightly coarser grained at 1.5-6.0mm in diameter, and it is usually more heavily altered, with serpentine, iddingsite, and Fe-Ti oxides being the most common alteration products. Clinopyroxene is more modally abundant in the EE-SMSU than in the Eagle SMSU, at 20-30% of silicate phases. It is more anhedral than that in the Eagle SMSU, sometimes ranging to sub-poikilitic. Orthopyroxene is less modally abundant in the EE-SMSU than in the Eagle SMSU, at 3-5% of silicate phases. It is more euhedral (subhedral) and finer grained at 0.5-0.75mm in diameter. Plagioclase is less modally abundant in the EE-SMSU than in the Eagle SMSU, generally ranging from 3% to 10% of silicate phases. Amphibole and biotite are less abundant in the EE-SMSU than in the Eagle SMSU, with amphibole making up 5-7% of silicate phases and biotite making up 3-5% of silicate phases. The sulfide minerals, Fe-Ti oxide minerals, and amount and type of alteration are similar between the EE-SMSU and the Eagle SMSU.
Figure 2: Estimated relative modal proportions of olivine, orthopyroxene, and clinopyroxene abundances in SMSU samples from cores 14EA331F (three samples, DDH 1095-1110m) and 08EA222D (three samples, DDH 845-940m) in the Eagle East intrusion. General abundance of plagioclase is denoted by symbol type.

3.2.4 Eagle East IBRX Lithologies

Four samples of Eagle East IBRX Matrix (EEXM) and Eagle East IBRX Clast (EEXC) were collected, all from core 08EA222D between a depth of 870m and 880m. The relative modal abundances of primary silicate minerals in EEXM lithologies (Fig. 25) indicate that they are marginally poorer in OPX compared to Eagle IBRX samples (Fig. 18). The relative modal abundances of primary silicate minerals in EEXC lithologies indicate that they contain more OPX. Modal rock types for EEXM include feldspathic lherzolite and feldspathic wehrlite, while modal rock types for EEXC include websterite and feldspathic websterite.
Figure 25: Estimated relative modal proportions of olivine, orthopyroxene, and clinopyroxene abundances in IBRX Matrix and Clast samples from core 08EA222D (eight samples, DDH 870-880m) in the Eagle East intrusion. General abundance of plagioclase is denoted by symbol type.

Matrix - Olivine in the EEXM is slightly finer grained than that in the Eagle IBRX-matrix at 1.0-2.5mm in diameter. It is also subhedral, which is slightly less well-formed than at Eagle. Clinopyroxene is more abundant in the EEXM at 25-35%. It is less well formed than in the Eagle IBRX-matrix, at anhedral to sub-poikilitic. It is coarser grained, with anhedral grains ranging from 0.5mm to 1.5mm in width and sub-poikilitic grains ranging up to 3.0mm in diameter. Plagioclase in the EEXM is slightly less abundant than in the Eagle XM at 15-25% of silicate phases.
Orthopyroxene is slightly less abundant in the EEXM at 3-7%. It is subhedral, as opposed to anhedral in the Eagle IBRX-matrix, and it is slightly finer grained at 0.5-1.5mm in diameter. The accessory minerals, including amphibole, biotite, and the Fe-Ti oxides are similar between the two units. The sulfide minerals in the EEXM are similar to those in the Eagle IBRX-matrix but with a higher abundance of 7-12%. Alteration is significantly heavier in the EEXM, with serpentinization affecting 20-40% of the mineral grains in each sample.

**Clasts** - Clinopyroxene in the EEXC is less prevalent at 65-80% than that in the XC2. It is slightly finer grained at .25-.75mm in width and .75-1.5mm in length, and it is more euhedral at subhedral to euhedral. While in the XC2 orthopyroxene only occurs associated with inverted pigeonite, in the EEXC it occurs as a primary phase. It is anhedral to subhedral, equant, and .20-.50mm in diameter. It makes up a greater modal percentage of the sample than in the XC2 at 5-10%. Plagioclase in the EEXC is anhedral granular, similar to that of the XC2. Its grain size is slightly larger at .25-.75mm in diameter, and it makes up a greater modal percent at 5-25%. The accessory minerals, including the Fe-Ti oxides, biotite, and amphibole, are similar in the XC2 and the EEXC. The sulfide minerals are significantly less abundant in the EEXC, at 1-5%. Alteration in the EEXC is less pervasive, usually mild to moderate, with serpentine, talc, and/or carbonate replacement of the pyroxenes being the most common style.

### 3.3 Lithogeochemical Data

Lundin Mining Co. provided whole-rock major and trace element geochemistry for two Eagle drill cores used in this study, EUGX0016 and EUGX0028. Additionally, Lundin provided
whole-rock major and trace element geochemistry for Eagle East drill core 08EA222D and drill core series 14EA331A-I, of which 14EA331F was used in this study.

The elements S and Ni were chosen as proxies for sulfide mineralization. Al and Sr (a slightly compatible trace element in plagioclase and apatite) were chosen as proxies for plagioclase. Ti was chosen as a proxy for the Fe-Ti oxides, while Mg was chosen as a general proxy for olivine and the pyroxenes. Ding et al. (2010) used La/Yb and Zr/Y to differentiate the parental magma types to Eagle lithologies. La/Yb is used here for the same purpose, as well as to compare this data with the data of Ding et al. (2010). Here, Zr/Nb is used instead of Zr/Y because Nb, while similar to Y, is not as compatible with clinopyroxene, orthopyroxene, olivine, or, especially, apatite. Down-hole geochemical data is presented in Figures 26-29 below.

In drill core EUGX0028 (Fig. 26), sulfur and Ni correlate very well with the amount of mineralization. While Sr is more erratic than Al, in general they correlate well with each other and generally indicate the variation in plagioclase abundance. Mg correlates well with observed amount of olivine and pyroxenes; for example, the decrease in Mg % from ~75m to ~85m is mirrored by an observed decrease in olivine over the same interval. Of the incompatible element ratios, Zr/Nb shows greater variation between different lithologies than La/Yb. Interestingly, incompatible trace element (ITE) ratios, besides being relatively constant within each lithology in general, remain constant even when modal mineralogy (based on observations and proxies) begins changing in the interval 75-85m.
Figure 26: Downhole plots of selected lithogeochemical data from Eagle drill core EUGX0028 in the context of lithologic units. Triangles denote petrographic samples. A) Downhole variation in S, Ni, and Mg which are controlled by sulfide, olivine and pyroxene concentration. B) Downhole variations in Al, Sr, and Ti which are controlled by plagioclase and Fe-Ti oxide concentration. C) Downhole variation in incompatible element ratios of Zr/Nb and La/Yb.

In drill core EUGX0016 (Fig. 27), Ni and S correlate well with observed sulfide abundances. Note the drop to 0% for both Ni and S in the PRX lithology. Sr and Al correlate well with both each other and observed abundance of plagioclase. Note the slightly higher TiO2 % in the PRX, where the Fe-Ti oxide abundance is higher. MgO% correlates well with observed abundance of olivine and pyroxenes; note the drop in MgO% in the PRX, where olivine is absent.
Figure 27 A-C: Downhole plots of selected lithogeochemical data from Eagle drill core EUGX0016 in the context of lithologic units. Triangles denote petrographic samples. A) Downhole variation in S, Ni, and Mg which are controlled by sulfide, olivine and pyroxene concentration. B) Downhole variations in Al, Sr, and Ti which are controlled by plagioclase and Fe-Ti oxide concentration. C) Downhole variation in incompatible element ratios of Zr/Nb and La/Yb.
ITE ratios are erratic in areas of high sulfide abundance and at the beginning of the core where there are multiple lithologies, but stable through the rest of the core. Note the slight change in all ITE ratios in the PRX lithology.

In drill core 14EA331F (Fig. 28), Ni and S correlate well with observed sulfide abundances. The change in sulfide abundance with depth is more gradual in this core than in EUGX0028 and EUGX0016. Sr and Al correlate well with both each other and observed plagioclase abundances. Mg and Ti correlate well with observed olivine+pyroxenes and Fe-Ti oxide abundances, respectively. ITE ratios are stable except around DDH45m, which is also the

<table>
<thead>
<tr>
<th>14EA331F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
</tr>
<tr>
<td>B.</td>
</tr>
<tr>
<td>C.</td>
</tr>
</tbody>
</table>

Figure 28 A-C: Downhole plots of selected lithogeochemical data from Eagle drill core 14EA331F in the context of lithologic units. Triangles denote petrographic samples. A) Downhole variation in S, Ni, and Mg which are controlled by sulfide, olivine and pyroxene concentration. B) Downhole variations in Al, Sr, and Ti which are controlled by plagioclase and Fe-Ti oxide concentration. C) Downhole variation in incompatible element ratios of Zr/Nb and La/Yb.
site of irregularities in sulfides and plagioclase. While not logged as IBRX, petrographic samples show that this area of the core contains gabbroic clasts similar to the IBRX. The differences in ITE ratios between lithologies are less extreme in this core than in cores EUGX0028 and EUGX0016.

In drill core 08EA222D (Fig. 29), Ni and S correlate moderately well with observed sulfide abundances until DDH100m, and very well with observed sulfide abundances after DDH140m. Sr and Al correlate moderately well with each other, and Al correlates well with observed plagioclase abundances. ITE ratios are very erratic in this core, with slight increases in sulfide abundance correlating with large deviations in ITE ratio. Note especially the erratic and high S concentrations around DDH 50-60m and the corresponding erratic Zr/Nb, and, to a lesser extent, La/Yb.

In general, the geochemical data for these drill cores correspond well with both the log geology and the observed mineralogy of the cores. Interestingly, ITE ratios appear to vary with sulfide abundance. This can be seen by comparing the ITE ratios of the PER, MPER, and SMSU lithologies, which all have similar modal mineralogy but different sulfide abundances. Al2O3, MgO, and TiO2 seem to correlate relatively well with observed abundances of plagioclase, olivine+pyroxene, and Fe-Ti oxides, respectively. High Al2O3 and Sr abundances often correlate with low MgO2 abundances indicating an increase in Pl:Ol+Pyx ratios. This can be seen in core EUGX0028 from DDH75-85m, in core 14EA331F from DDH 45-55m, and in core 08EA222D from DDH 90-100m. Ni correlates strongly with S, but in the peridotitic lithologies it also subtly correlates with MgO. This can be attributed to the importance of olivine as a silicate mineral with which Ni is highly compatible. ITE ratios are fairly constant within peridotite-family samples.
Figure 29 A-C: Downhole plots of selected lithogeochemical data from Eagle drill core 08EA222D in the context of lithologic units. Triangles denote petrographic samples. A) Downhole variation in S, Ni, and Mg which are controlled by sulfide, olivine and pyroxene concentration. B) Downhole variations in Al, Sr, and Ti which are controlled by plagioclase and Fe-Ti oxide concentration. C) Downhole variation in incompatible element ratios of Zr/Nb and La/Yb.
except where sulfide abundance is high. For example, PER samples consistently have a La/Yb of 4-6 in the Eagle intrusion and 5-7 in the Eagle East intrusion. MPER, SMSU, and IBRX samples also follow this trend, though to a lesser extent than PER samples. Additionally, La/Yb is more consistent between samples of a given lithology than is Zr/Nb. ITE ratios tend to shift slightly when entering the PRX lithology, for example in drill core after DDH 100m where La/Yb shifts from ~6 to ~4 and Zr/Nb shifts from ~20 to ~24. ITE ratios also shift strongly in the sedimentary lithologies, which tend to have higher ITE ratios (La/Yb of 5-14 and Zr/Nb of 17-21) than the intrusive lithologies.

### 3.4 Electron microprobe analyses of olivine

Nineteen samples were analyzed for their olivine compositions by electron microprobe, eight from Eagle and eleven from Eagle East. Samples were selected based on sulfide content, on the freshness of olivine grains, and on stratigraphic position in the intrusion. Samples with both high and very low sulfide content were sought out to compare how Ni concentration in olivine varied with sulfide abundance. Three to seven olivine grains were analyzed from each sample, and three to seven spot analyses were conducted on each olivine grain. Average analyses for each sample are listed in Table 8 below. In several cases, serpentinized or iddingsite-altered parts of olivine grains were analyzed by electron microprobe to compare with unaltered portions. This was done to determine whether reliable data could potentially be collected from altered olivine. Specifically, these data were collected to determine whether NiO remained immobile during serpentinization. However, it quickly became clear that NiO values drop to zero once olivine undergoes serpentinization. Olivine altered to iddingsite retains some
NiO, but it is not clear whether these values represent original concentrations. MgO and FeO values also change drastically with alteration, making the altered portions of olivine grains completely unsuitable for data collection. Unaltered portions of olivine grains retain their original compositions, including NiO, even when in close proximity to altered portions of the grain.

Table 8: Average of electron microprobe olivine analyses from nineteen samples. Fo is the forsterite composition of olivine, equal to mg# or Mg/(Mg+Fe) (cation%). NiO Er % is the percent of error in the set of measurements reported by the microprobe software.

3.5 Scanning electron microscope analysis of Eagle East olivine and pyroxene

The scanning electron microscope on the University of Minnesota Duluth’s campus was used for semi-quantitative analysis of olivine, orthopyroxene, and clinopyroxene. Seven samples were selected for SEM-EDS analysis from drill core 04EA0085, which profiles the Core Peridotite unit of the Eagle East intrusion. Between 5 and 15 grains each of olivine, orthopyroxene, and
clinopyroxene were analyzed in each sample. The average mg# (Mg/Mg+Fe, cation %) calculated for each mineral type in each sample are plotted against drill core depth in Figure 30.

As shown in Figure 30, the mg# of each mineral type varies by less than 3 mole % over the entire 501 m stratigraphy of the Eagle East intrusion. All three mafic phases show a slight upward increase in mg# with from the base of the intrusion to the middle of the core (~250 m). This is followed by a slight decreased in mg# from the middle to the top of the core. As the intrusion is open at the surface and its upper portions are possibly eroded away, it is not clear whether the decreasing mg# observed in the upper part of the core continues upward. If the entire intrusion were present, it may be that continued decreasing mg# would have been observed until the upper contact of the intrusion with the country rock.

The trendlines of all three phases are generally parallel except for a notable decrease in the mg# of clinopyroxene at 105 meters. The highest average mg#’s of olivine, orthopyroxene, and clinopyroxene are 80.5, 81.8, and 84.3, respectively. The lowest mg#’s of olivine, orthopyroxene, and clinopyroxene are 78.4, 80.3, and 82.0, respectively.
Figure 30: Cryptic variation of average mg# (=Mg/(Mg+Fe), cation %) for olivine, orthopyroxene, and clinopyroxene in drill core 04EA008S, which profiles the Core Peridotite unit of Eagle East. Error bars refer to the standard deviation of multiple analyses from each sample.

In the Eagle and Eagle East intrusions, clinopyroxene and orthopyroxene can be difficult to distinguish because of similar habit and internal textures. Moreover, distinguishing pyroxene
types by maximum birefringence was complicated by the fact that many of the thin sections used in the study were not standard thickness (30 microns; Fig. 31). Because of these factors, selected pyroxene grains from multiple thin sections were analyzed by SEM-EDS to simply confirm petrographic mineral classification. Full mineral compositions were not calculated for these cursory analyses.

Figure 31: Plane-polarized light (A) and cross-polarized light (B) images of orthopyroxene (left-center, purple to blue in XPL) and clinopyroxene (right-center, yellow to pink in XPL) from the Eagle East intrusion. Pyroxene types in this photomicrograph were confirmed by SEM-EDS. As such, the high interference colors of both phases indicate that the section is too thick.
4. Discussion

The petrologic, geochemical, and mineral composition data presented above can be used to make important inferences about the crystallization and emplacement history of the Eagle and Eagle East intrusions. However, prior to making these inferences, it is necessary to redefine the generalized and sulfide mineralization-based lithologic units identified by Lundin geologists in terms of their proper modal and cumulate rock types based on the non-sulfide component of these units. Moreover, a comparison of Xin Ding’s (2010) lithologic nomenclature and that used here will be discussed.

After this nomenclature discussion, lithogeochemical data will be assessed to determine whether multiple emplacements of compositionally distinct parental magmas were involved in the creation of the Eagle system, as suggested by Ding et al. (2010). Next, olivine composition data, particularly the trace concentration of Ni, will be used to 1) evaluate the relative timing of olivine crystallization compared to sulfide liquation, and 2) test whether the two major episodes of mineralization postulated by Lundin geologists can be discriminated by differences in this timing. After this, petrographic data will be used to determine the petrogenesis of the enigmatic pyroxenite inclusion-bearing intrusive breccia lithology (IBRX) found in the deeper conduits of the Eagle and Eagle East intrusions. Finally, a model for the emplacement and crystallization history of the Eagle East intrusion will be proposed.
4.1 Reassessment of Lithologic Nomenclature for Eagle and Eagle East Rock Types

The nomenclature used by Ding et al. (2010) is dissimilar to the classification system used by Lundin geologists and differs significantly from the nomenclature used in this paper (Table 9). This section will summarize the modal and cumulate rock types applied to the Lundin rock units in this study, compare the nomenclature used in this study with the nomenclature used by Ding et al. (2010), and then reinterpret the lithostratigraphy of the drill core used in this study by integrating petrographic and lithogeochmical data.

Table 9: Comparison of rock type nomenclature used by Ding et al. (2010) and this study for Lundin mineralization/lithology units.

<table>
<thead>
<tr>
<th>Lundin Rock Unit</th>
<th>Ding Modal Rock Types</th>
<th>Dominant Modal Rock Types</th>
<th>Minor Modal Rock Types</th>
<th>Cumulate Codes</th>
<th>Dominant Pyx Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>PER, MPER</td>
<td>Feldspathic peridotite, melatroctolite, Ol melagabbro</td>
<td>Feldspathic lherzolite</td>
<td>Lherzolite, Feldspathic Ol websterite</td>
<td>OCph to OpCh(f,α)</td>
<td>Subhedral granular</td>
</tr>
<tr>
<td>SMSU</td>
<td>Dunite</td>
<td>Feldspathic lherzolite</td>
<td>Lherzolite, melagabbron orite</td>
<td>OCph to OpCh</td>
<td>Subhedral granular</td>
</tr>
<tr>
<td>IBRX matrix</td>
<td>N/A</td>
<td>Feldspathic lherzolite</td>
<td>Lherzolite</td>
<td>OCph to OpChf</td>
<td>Subhedral granular</td>
</tr>
<tr>
<td>IBRX inclusions</td>
<td>N/A</td>
<td>Clinopyroxenite</td>
<td>Feldspathic clinopyroxenite</td>
<td>CP</td>
<td>Subhedral granular</td>
</tr>
<tr>
<td>PRX</td>
<td>Feldspathic pyroxenite</td>
<td>Gabbro</td>
<td>Feldspathic websterite, oxide gabbro</td>
<td>pC to CpF</td>
<td>Subhedral granular</td>
</tr>
<tr>
<td>EEC-PER</td>
<td>Melatroctolite</td>
<td>Feldspathic lherzolite</td>
<td>Lherzolite, olivine websterite, feldspathic olivine websterite</td>
<td>OpCh to chOp</td>
<td>Subpoikilitic</td>
</tr>
</tbody>
</table>
4.1.1 Modal and Cumulate Rock Types for Lundin Rock Units

Because Lundin geologists were focused mostly on characterizing the sulfide mineralization in the Eagle intrusion, they broadly described the non-sulfide components of their rock units as peridotite or pyroxenite. The petrographic observations conducted for this study now allow for these general terms to be better defined in terms of modal and cumulate rock types, which is summarized in Table 9.

The majority of PER and MPER samples observed in this study (24 in total) modally classify as feldspathic lherzolite, with a few (<10%) classifying as lherzolite and several as olivine websterite or feldspathic olivine websterite (Figs. 12 and 24). The textures of both clinopyroxene and orthopyroxene are consistently subhedral to anhedral granular. The cumulate rock types of these rock units are Ol-Cpx-Opx cumulates with intercumulus plagioclase, Fe-Ti oxide, hornblende and biotite. Using cumulate code terminology, PER and MPER samples range from OCpH to OpCH, with α or f occasionally making up enough of the sample (>2 modal %) to be appended to the end of the code.

The majority of SMSU samples observed in this study (12 in total) modally classify as feldspathic lherzolite, with several (30%) falling under lherzolite and one under melagabbronorite (Figs. 13 and 25). The texture of clinopyroxene is generally subhedral to anhedral granular, but in the Eagle East intrusion it is more commonly subpoikilitic. The texture of orthopyroxene is subhedral to anhedral granular in all occurrences. The cumulate rock type of this unit is Ol±Cpx±Opx cumulate with intercumulus plagioclase, Fe-Ti oxide, hornblende, and biotite. Using cumulate code terminology, SMSU samples range from OCph to OCphα. The two
sections of MSU observed in this study did not contain enough silicate minerals to propose a lithology classification except to say that olivine is the predominant silicate.

The majority of IBRX matrix samples observed in this study (9 in total) modally classify as feldspathic lherzolite, with one sample classifying as melagabbronorite. The texture of clinopyroxene is generally anhedral granular, but in the Eagle East intrusion it can range to subpoikilitic. The texture of orthopyroxene is subhedral to anhedral granular. The cumulate rock type of this unit is Ol-(Cpx)-Opx cumulate with intercumulus plagioclase, Fe-Ti oxide, hornblende, and biotite. Using cumulate code terminology, IBRX matrix samples range from OCph to Ocpf.

Half of the IBRX clast samples (12 in total) modally classify as clinopyroxenite to feldspathic clinopyroxenite, while half of the IBRX clast samples modally classify as websterite to feldspathic websterite. The texture of clinopyroxene is generally subhedral to euhedral granular. The texture of orthopyroxene is anhedral granular in the Eagle intrusion, where it only occurs as inverted pigeonite, and in Eagle East the texture of orthopyroxene is anhedral to subhedral granular. The cumulate rock type of this unit is Cpx cumulate with intercumulus plagioclase and Fe-Ti oxide. Using cumulate code terminology, IBRX clast samples are Cp.

The majority of PRX samples observed in this study (6 in total, all from the Eagle intrusion) modally classify as oxide bearing melagabbro to feldspathic clinopyroxenite. The texture of clinopyroxene is anhedral granular and the texture of plagioclase is subhedral. The cumulate rock type of this unit is a Pl+Cpx±FeOx cumulate with intercumulus hornblende. Using cumulate code terminology, PRX samples range from PCF to CPF.
Most EEC-PER samples (14 in total, all from the Eagle East intrusion) modally classify as feldspathic lherzolite to lherzolite, with a subset (~35%) classifying as olivine websterite. The texture of clinopyroxene is subpoikilitic to poikilitic, and the texture of orthopyroxene is subhedral to subpoikilitic. The cumulate rock type of this unit is an Ol±Opx cumulate with intercumulus plagioclase, clinopyroxene, biotite, and hornblende. Using cumulate code terminology, EEC-PER samples range from OcHp to chOp.

4.1.2 Comparison with Rock Nomenclature and Terminology used by Ding (2010)

As described in the introduction, Ding et al. (2010) and related works (Ding et al. 2012a, 2012b) have been the primary scholarly study to evaluate the petrology and mineralization of the Eagle intrusion to date. The petrographic study of the peridotitic rocks of the Eagle intrusion by Ding et al. (2010) distinguished various lithologies by their silicate modal mineralogy. However, the classification scheme used was unorthodox in that it did not take into account textures, did not differentiate between pyroxene types, and used disputed modal mineral boundaries to define its lithologies (Fig. 32).

In the caption for modal classification scheme used by Ding et al. (2010), reproduced in Figure 32, the classification scheme used is identified as being that proposed by Miller et al. (2002). But in fact, the depicted scheme is that proposed by Severson and Hauck (1990) for modally classifying troctolitic rocks of the Duluth Complex. This three-component scheme (Ol-Pl-Px) works fine for Duluth Complex lithologies because pyroxene is dominantly clinopyroxene and Fe-Ti oxide tends to occur in a constant ratio of ~1:3 with Cpx (Miller et al., 2002). However, given the significant abundance of both pyroxene types in Eagle system rocks, merging the
pyroxenes into one component does not accurately represent the rock type. Moreover, as pointed out by Miller et al. (2002) in their critique of other modal classification schemes, the modal boundaries defined by other schemes, especially for plagioclase abundance, did not bracket natural modal abundances determined from empirical and experimental data. As such, Miller et al. (2002) recommended modal boundaries for mafic phases based on simple ratios (1:1 and 3:1) rather than absolute percentages, arguing that ratios could be more easily estimated visually, especially in the field. The modal classification scheme proposed by Miller et al. (2002) and used in this study is shown in Figure 10.

Figure 32: Modal classification system used by Ding et al. (2010) to name peridotitic lithologies studied from Eagle and Eagle East (from their Figure 3).
Ding et al. (2010) included the modal mineralogy ranges used to classify their assigned rock names, and these ranges are reported in Table 10 below. As such, it is possible to translate these rock names into the classification scheme used here. This translation is done in Table 11.

Table 10: Modal mineralogy ranges noted by Ding et al. (2010) for lithologies plotted in their Figure 3 (reproduced in Figure 34).

<table>
<thead>
<tr>
<th>Ding et al. (2010) Lithology Classification</th>
<th>Olivine % Low</th>
<th>Olivine % High</th>
<th>CPX % Low</th>
<th>CPX % High</th>
<th>OPX % Low</th>
<th>OPX % High</th>
<th>Plag % Low</th>
<th>Plag % High</th>
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</thead>
<tbody>
<tr>
<td>Feldspathic peridotite</td>
<td>30</td>
<td>60</td>
<td>5</td>
<td>15</td>
<td>15</td>
<td>40</td>
<td>15</td>
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<td>30</td>
<td>30</td>
<td>45</td>
<td>15</td>
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Table 11: Translation of lithologies classified by Ding et al. (2010) (Figure 34) to lithologies based on the modal classification proposed by Miller et al. (2002) (Figure 10).

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<thead>
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</tr>
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<td>Olivine melagabbroninite</td>
<td>Feldspatic lherzolite, olivine melagabbro</td>
</tr>
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<td>Olivine melagabbroninite, olivine melagabbro</td>
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<tr>
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<td>Feldspatic websterite</td>
<td>N/A</td>
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</tbody>
</table>

4.1.3 Reinterpretation of Modal and Cumulate Lithologies comprising Eagle and Eagle East Drill Core using Lithogeochemical Data

In this section, modal mineralogy data based on petrographic observations will be integrated with lithogeochemical data to interpret downhole changes in modal and cumulate rock types in Eagle and Eagle East drill cores EUGX0016, EUGX0028, 08EA222D, and 14EA331F.
Drill core 04EA0085 is not considered because there is no available geochemical data for that core. The nomenclature defined in the previous section will be used in this section.

The lithogeochemical data used in this study cover sufficiently short and consistent intervals that they can more accurately define changes in cumulate rock type when linked to petrographic observations made of scattered samples for this study. This is done by scaling absolute incompatible trace element (ITE) abundances, specifically Ce and Zr, with estimated amounts of intercumulus minerals. Since ITE are, by definition, incompatible with cumulus minerals, their concentration can serve as general proxies for the amount of intercumulus material in the rock. Conversely, certain compatible elements can be used as proxies for cumulus minerals. In this study, Al abundance is used as a proxy for plagioclase feldspar, Mg abundance is used as a proxy for combined abundances of olivine, clinopyroxene, and orthopyroxene, and Ti abundance is used as a proxy for the Fe-Ti oxides. Additionally, S abundance is included to serve as a proxy for the amount of mineralization, which the Lundin units are based on.

4.1.3.1 EUGX0016 (Eagle)

The downhole lithogeochemical data from core EUGX0016 (Fig. 33) is interpreted below.

From 0-5m, the high Al concentration (15%) and low Mg and Ti concentrations (3% and 0.5%) imply a sedimentary lithology.

From 10-20m, the high Al and Ti concentrations (9% and 3%) imply high abundances of plagioclase and Fe-Ti oxides respectively, while the low Mg concentration (13%) implies low
olivine+pyroxene abundance. Concentrations of S near zero imply little to no mineralization. The one petrographic sample in this interval was classified as the PRX lithology. The lack of olivine

Figure 3: Interpretation of downhole variations in modal lithology and cumulate rock type from integration of major and trace element concentrations (left and center panels) and non-sulfide modal data (right panel) for Eagle drill core EUGX0016.
may explain the low Mg concentration. At DDH ~18m, an SLST inclusion was noted in the core logging that was not geochemically sampled.

From 20-25m, Mg concentration increases to ~14% indicating increased olivine+pyroxene abundance and Al and Ti concentrations decrease to 7% and 1% indicating decreased plagioclase and Fe-Ti oxide abundances respectively. The concentration of S also increases slightly in this interval, indicating weak mineralization. Igneous modal mineralogy was not observed in this section, but the higher Mg could imply the addition of olivine to the mineral assemblage in this interval. This combined with the lower plagioclase and Fe-Ti oxide abundances and the weak sulfide mineralization imply that this is likely the PER lithology. At DDH ~23m, an SLST inclusion was noted in the core logging that was not geochemically sampled.

From 25-45m, the concentration of major elements drops to nearly zero while the concentration of S increases dramatically. This implies a highly mineralized section, MSU, which is confirmed by core logging. The exception to this is a spike in major element concentrations coupled with a dip in S concentration at 30m, which is likely an inclusion of SLST, PER, or PRX in the mineralization.

From 45-50m, Mg and Al concentrations are high (18% and 6%) while Ti concentration is moderate (2%), indicating high olivine+pyroxene and plagioclase abundances and moderate Fe-Ti oxide abundance. Concentration of S is about 2%, indicating weak sulfide mineralization. These mineral abundances imply the PER lithology, but with a slightly higher than normal abundance of plagioclase. The four petrographic samples in this interval were classified as the PER lithology and high plagioclase and amphibole abundances were noted.
From 50-61m, the concentrations of Mg, Al, and Ti all decrease slightly to ~12%, 5%, and 1%, respectively, indicating decreased abundances of olivine+pyroxene, plagioclase, and Fe-Ti oxides. This is coupled with an increase in S concentration to ~14%, implying the PER lithology but with significant sulfide mineralization, i.e. the SMSU or IBRX lithologies. The two petrographic samples in this interval were classified as the IBRX lithology. Plagioclase and especially amphibole were noted as being less abundant in these samples compared to the samples from 45-50m.

At DDH 62m, there is a spike in S concentration and a drop in major element concentrations to nearly zero, indicating a short section of heavy sulfide mineralization. Core logging indicates that this is the MSU lithology.

From 63-88m, Mg concentrations are high but slightly erratic, ranging from 13% to 17%. Concentrations of Al and Ti are moderate and increase over the range, changing from 3% to 6% and 1% to 3%, respectively. Over the same range, S concentration decreases from 9% to 2%. The seven petrographic samples in this interval were classified as the IBRX lithology. The erratic nature of the Mg concentration over this interval may be due to the influence of the pyroxenite clasts characteristic of this lithology, which are devoid of olivine.

From 89-100m, the concentrations of Mg, Al, and Ti are mostly stable at ~15%, 6%, and 2% respectively. These are normal concentrations for a typical PER lithology. Concentration of S range from 2-4%, indicating weak sulfide mineralization, which is also consistent with a typical PER lithology. The one petrographic sample in this interval was classified as the PER lithology.
From 101-118m, Mg concentration drops to ~11% while Al and Ti concentrations rise to ~10% and 3%, respectively. This implies a decrease in olivine+pyroxene abundance and an increase in plagioclase and Fe-Ti oxide abundances. Concentration of S drops to zero in this interval, indicating a lack of sulfide mineralization. The one petrographic sample in this interval was classified as the PRX lithology.

From 119-140m, ITE trends are essentially the same as from 101-118m except that Mg concentration increases to about 14% before decreasing back to 12% over the interval, mirrored by a slight decrease in Al concentration to 8% followed by an increase back to 9%. Observed modal mineralogy indicates an increase in CPX abundance and a slight decrease in plagioclase abundance in this interval. The three petrographic samples in this interval were classified as the PRX lithology. At DDH 137, an anomalous decrease in Mg and Ti concentrations and increase in S concentration correspond to a vein with heavy sulfide mineralization that was observed petrographically and in core logging.

From 0-3m, concentrations of Ce and Zr are high (52-68ppm and 14-17ppm, respectively). Petrographic observations and geochemical proxies indicate that this interval is composed of sedimentary rock (SLST).

From 10-24m, concentrations of Ce and Zr are high (28-41ppm and 15-17ppm, respectively), implying an orthocumulate nature for this interval. Petrographic observations and geochemical proxies indicate low abundances of cumulate phases (olivine+pyroxene) and moderate abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.
From 45-48m, concentrations of Ce and Zr are high (22-26ppm and 10ppm, respectively), implying an orthocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulate phases (olivine+pyroxene) and moderate abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

From 48-63m, concentrations of Ce and Zr are low (7-9ppm and 4ppm, respectively), implying an adcumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulate phases (olivine+pyroxene) and low abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

From 63-75m, concentrations of Ce and Zr are moderate (12-18ppm and 6-9ppm, respectively), implying a mesocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulate phases (olivine+pyroxene) and moderate abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

From 75-140m, concentrations of Ce and Zr are high (20-40ppm and 10-20ppm, respectively), implying an orthocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate to low abundances of cumulate phases (olivine+pyroxene) and moderate to high abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

### 4.1.3.2 EUGX0028 (Eagle)

The downhole lithogeochemical data from core EUGX0028 (Fig. 34) is interpreted below. From 0-15m, the high Al and Ti concentrations (~12% and 3%) imply high abundances of plagioclase and Fe-Ti oxides, while the low Mg concentrations (~8%) imply low olivine +pyroxene
abundance. Concentrations of S are near zero for the first ~13m of the interval but climb to 1% by the end of the interval, implying a lack of sulfide mineralization that gives way to weak sulfide mineralization. The three igneous petrographic samples in this interval were described as intrusive igneous rock composed of plagioclase, clinopyroxene, and Fe-Ti oxide. This interval was core logged as MIRK but also petrographically is similar to the PRX lithology. Intervals of sedimentary rock (SLST) are present in this interval, but they were not sampled for geochemical analysis, so the geochemistry presented is indicative only of the igneous material.

From 15-17m, Mg concentration increases to ~14% and Al and Ti concentrations decrease to ~8% and ~1%, indicating an increase in olivine+pyroxene abundance and a decrease in plagioclase and Fe-Ti oxide abundances. Concentration of S rises sharply to ~10% over the interval, indicating increasing sulfide mineralization. The two petrographic samples in this interval were classified as PER.

From 17-41m, the core is very highly mineralized (MSU lithology) and accurate geochemistry and petrographic data were not collected.

From 41-45m, Mg concentration is moderate (~14%) and Al and Ti concentrations are relatively low (~2% and ~0.5%, respectively). This indicates moderate olivine+pyroxene abundance and low plagioclase and Fe-Ti oxide abundances. Concentration of S is high at ~16%, indicating heavy sulfide mineralization. The two petrographic samples in this interval were classified as SMSU.
Figure 34: Interpretation of downhole variations in modal lithology and cumulate rock type from integration of major and trace element concentrations (left and center panels) and non-sulfide modal data (right panel) for Eagle drill core EUGX0028.

From 45-67m, Mg concentration is high (18-20%) and Al and Ti concentrations are moderate (6% and 2%), indicating high olivine+pyroxene abundances and moderate plagioclase and Fe-Ti oxide abundances. Concentration of S is low at ~0.5%, implying weak sulfide mineralization. The four petrographic samples in this interval were classified as PER. At DDH 51m, anomalously low Mg and Ti concentrations and anomalously high Al concentrations indicate a short section of SLST included in the PER interval. Abundance of plagioclase was noted
as being high immediately downhole of this SLST inclusion and then decreasing in abundance with further depth down hole.

From 67-77m, the concentration of S increases, cycling between 4% and 9% over the interval. Higher S concentrations are accompanied by lower concentrations of Mg, Al, and Ti, indicating sections of high mineralization and lower abundances of silicate minerals. The two petrographic samples in this interval were classified as PER.

From 77-83m, Mg concentration drops from 17% to 14% and Al and Ti concentrations increase from 6% and 2% to 8% and 3%, respectively. This implies a decreasing abundance of olivine+pyroxene and an increasing abundance of plagioclase and Fe-Ti oxide. Concentration of S is moderate at 2%, indicating weak sulfide mineralization. The two petrographic samples in this interval were classified as PER. Olivine and pyroxene were noted to be lower in abundance and plagioclase was noted to be higher in abundance in the downhole sample.

At DDH 83m, very low Mg and Ti concentrations indicate a short section of SLST.

At DDH 84m, Mg concentrations are low at 6%, Ti concentrations are moderate at 2%, and Al concentrations are high at 12%, implying low abundances of olivine+pyroxene, moderate abundance of Fe-Ti oxide, and high abundance of plagioclase. These element concentrations are similar to those of the MIRK lithology at the top of the hole, and the one petrographic sample in this interval was classified as the PRX lithology which has a mineral assemblage similar to the MIRK lithology. Concentration of S at 2% indicates weak sulfide mineralization, which is unusual for the PRX lithology.

At DDH 86m, high Al concentration of ~18% and low Mg and Ti concentrations of 3% and 1% imply the SLST lithology.
From 0-17m, concentrations of Ce and Zr are high (21-54ppm and 10-25ppm, respectively), implying an orthocumulate nature for this interval. Petrographic observations and geochemical proxies indicate low abundances of cumulate phases (olivine+pyroxene) and high abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

From 41-47m, concentrations of Ce and Zr are low (7-11ppm and 3-4ppm, respectively), implying an adcumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulate phases (olivine+pyroxene) and low abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

From 47-66m, concentrations of Ce and Zr are high (21-40ppm and 11-24ppm, respectively), implying an orthocumulate nature for this interval. At DDH 51m, there is an anomalously high Ce concentration of 61ppm that corresponds to a SLST interval indicated by major element geochemistry. Petrographic observations and geochemical proxies over the rest of the interval indicate high abundances of cumulate phases (olivine+pyroxene) and moderate abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

From 66-77m, concentrations of Ce and Zr are low (12-18ppm and 8-13ppm, respectively), implying a mesocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulate phases (olivine+pyroxene) and moderate abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

From 77-83m, concentrations of Ce and Zr are high (22-26ppm and 14-20ppm, respectively), implying an orthocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate to low abundances of cumulate phases (olivine+pyroxene) and moderate abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.
From 83-86m, with the exception of DDH 84m, petrographic observations and geochemical proxies indicate the presence of sedimentary material (SLST). Over this interval, concentrations of Ce and Zr are high (30-67ppm and 17-22ppm, respectively).

At DDH 84m, concentrations of Ce and Zr are high (52ppm and 22ppm, respectively), implying an orthocumulate nature for this interval. Petrographic observations and geochemical proxies indicate low abundances of cumulate phases (olivine+pyroxene) and high abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

4.1.3.3 08EA222D (Eagle East)

The downhole lithogeochemical data from core 08EA222D (Fig. 35) is interpreted below.

Drill core 08EA222D was not geochemically sampled by Lundin between DDH ~100m and ~140m.

From 20-44m, Mg concentration is high, decreasing slightly over the interval from 28% to 25%, Al concentration is moderate to low at ~4%, and Ti concentration is low at ~0.5%. This implies high but slightly decreasing olivine+pyroxene abundances, moderate to low plagioclase abundance, and low Fe-Ti oxide abundance. Concentration of S over this interval increases from 2% to 3%, implying weak sulfide mineralization. The one petrographic sample in this interval was classified as the PER lithology.

From 44-67m, concentrations of Mg are slightly erratic, ranging from 21-25%, concentrations of Al are low at ~3%, and concentrations of Ti are low at ~0.5%. This implies high but ranging abundances of olivine+pyroxene, low abundances of plagioclase, and low abundances of Fe-Ti oxides. Concentration of S is relatively high, ranging from 4% to 7%,
Figure 35: Interpretation of downhole variations in modal lithology and cumulate rock type from integration of major and trace element concentrations (left and center panels) and non-sulfide modal data (right panel) for Eagle drill core 08EA222D.
implying moderate sulfide mineralization. The three petrographic samples in this interval were classified as the MPER lithology.

From 67-84m, concentrations of Mg are high, decreasing slightly from ~25% to 22%, concentrations of Al are low but increase slightly from 3% to 4%, and concentrations of Ti are low at ~0.5%. This implies high but slightly decreasing abundances of olivine+pyroxene, low but slightly increasing abundances of plagioclase, and low abundances of Fe-Ti oxides. Concentration of S over this interval is moderate at 4%, implying moderate sulfide mineralization. The two petrographic samples in this interval were classified as the MPER lithology.

From 84-98m, concentrations of Mg are high to moderate, decreasing from 20% to 11%, concentrations of Al are low to moderate, increasing from 4% to 8%, and concentrations of Ti are low to moderate, increasing from 1% to ~3%. This implies high to moderate olivine+pyroxene abundances and low but increasing abundances of plagioclase and Fe-Ti oxides. Concentration of S over this interval is erratic, ranging from 3% to 9%, implying erratic, moderate to heavy sulfide mineralization. The five petrographic samples in this interval were classified as the IBRX lithology except for the lowermost sample, which was classified as the MPER lithology. Petrographic observation indicates a sharp decrease in olivine abundance, which matches well with the decrease in Mg concentration.

From 143-145m, concentrations of Mg are high at 17-19%, concentrations of Al are moderate at ~6%, and concentrations of Ti are moderate at ~2%, implying high abundances of olivine+pyroxene and moderate abundances of plagioclase and Fe-Ti oxides. Concentration of S over this interval increases from 1% to ~3%, implying weak mineralization. The two petrographic samples in this interval were classified as the PER lithology.
From 145-153m, Mg concentration is moderate at 15%, Al concentration is low, increasing from 2% to 4%, and Ti concentration is low at ~1%, implying moderate olivine+pyroxene abundances, low plagioclase abundances, and low Fe-Ti oxide abundances. Concentration of S is high, decreasing from 12% to 8% over the interval, implying heavy sulfide mineralization. The four petrographic samples in this interval were classified as the SMSU lithology.

From 153-158m, Mg concentration is high at ~18%, Al concentration is moderate at ~6%, and Ti concentration is moderate to high at 2.5%, indicating high olivine+pyroxene abundances, moderate plagioclase abundances, and moderate to high Fe-Ti oxide abundances. Concentration of S is low at ~1%, implying weak sulfide mineralization. The two petrographic samples in this interval were classified as the PER lithology.

From 20-46m, concentrations of Ce and Zr are low (~9ppm and ~5ppm, respectively), implying an adcumulate nature for this interval. Petrographic observations and geochemical proxies indicate high abundances of cumulate phases (olivine+pyroxene) and low abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

From 46-54m, concentrations of Ce and Zr are moderate (12-14ppm and 5-7ppm, respectively), implying a mesocumulate nature for this interval. Petrographic observations and geochemical proxies indicate lower abundances of olivine+pyroxene than in the 20-46m interval, leading to a higher (plagioclase+Fe-Ti oxide):(olivine+pyroxene) ratio and thus a higher intercumulus:cumulus ratio.

From 54-71m, concentrations of Ce and Zr are low (6-11ppm and ~4ppm, respectively), implying an adcumulate nature for this interval. Petrographic observations and geochemical
proxies indicate high abundances of cumulate phases (olivine+pyroxene) and low abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

From 76-95m, concentrations of Ce and Zr are moderate (11-16ppm and 5-7ppm, respectively), implying a mesocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate but decreasing-downhole abundances of cumulate phases (olivine+pyroxene) and low but increasing-downhole abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval, leading to a steadily increasing intercumulus:cumulus ratio.

From 95-98m, concentrations of Ce and Zr are high (21-34ppm and 11-13ppm, respectively), implying an orthocumulate nature for this interval. Petrographic observations and geochemical proxies indicate low abundances of cumulus phases (olivine+pyroxene) and moderate to high abundances of intercumulus phases (plagioclase+Fe-Ti oxides) over this interval.

From 143-145m, concentrations of Ce and Zr are high (21-24ppm and 13-15ppm, respectively), implying an orthocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulus phases (olivine+pyroxene) and moderate to high abundances of intercumulus phases (plagioclase+Fe-Ti oxides) over this interval.

From 146-152m, concentrations of Ce and Zr are moderate (9-16ppm and 6-10ppm, respectively), implying a mesocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulus phases (olivine+pyroxene) and moderate abundances of intercumulus phases (plagioclase+Fe-Ti oxides) over this interval.
From 153-159m, concentrations of Ce and Zr are high (24-26ppm and 15-16ppm, respectively), implying an orthocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulus phases (olivine+pyroxene) and moderate to high abundances of intercumulus phases (plagioclase+Fe-Ti oxides) over this interval.

4.1.3.4 14EA331F (Eagle East)

The downhole lithogeochemical data from core 14EA331F (Fig. 36) is interpreted below.

From 14-23m, Mg concentration is high at ~18%, Al concentration is moderate, decreasing from 9% to 6%, and Ti concentration is moderate at 1.5%, implying moderate olivine+pyroxene abundance, moderate plagioclase abundance, and moderate Fe-Ti oxide abundance. Concentration of S over this interval increases from 1% to 3%, implying weak but increasingly heavy sulfide mineralization. The one petrographic sample in this interval was classified as the PER lithology with moderate abundances of amphibole and plagioclase.

From 23-34m, Mg concentration is moderate to high at ~19%, Al concentration is moderate, decreasing from 6% to 4%, and Ti concentration is moderate at ~1%, implying high olivine+pyroxene abundance, moderate plagioclase abundance, and moderate Fe-Ti oxide abundance. Concentration of S over this interval increases from 3% to 6% over this interval, implying moderate sulfide mineralization. The two petrographic samples in this interval were classified as the MPER lithology.
From 34-46m, Mg concentration remains high at ~18%, Al concentration is moderate to low, decreasing from 4% to 2%, and Ti concentration is moderate at ~1%, implying high olivine+pyroxene abundance, moderate plagioclase abundance, and moderate Fe-Ti oxide abundance. Concentration of S over this interval increases from 6% to 12% over this interval, implying heavy sulfide mineralization. The three petrographic samples in this interval were classified as the SMSU lithology. Amphibole and plagioclase abundances were noted to be lower in these samples than in the samples from 23-34m.

From 46-54m, Mg concentration is high to moderate, decreasing from ~18% to 15%, Al concentration is moderate, increasing from 5% to 7%, and Ti concentration is moderate,
increasing from ~1% to 3%. This implies moderate but decreasing abundances of olivine+pyroxene, moderate and increasing abundance of plagioclase, and moderate and increasing abundance of Fe-Ti oxides. Concentration of S over this interval decreases from 4% to 1%, implying moderate to weak sulfide mineralization. The four petrographic samples in this interval were classified as the MPER lithology. Olivine abundance was noted to decrease with depth down hole from DDH 46m downwards.

From 14-24m, concentrations of Ce and Zr are high (~20-29ppm and ~8-10ppm, respectively), implying an orthocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulate phases (olivine+pyroxene) and moderate to high abundances of intercumulus phases (plagioclase and Fe-Ti oxides) over this interval.

From 24-44m, concentrations of Ce and Zr are moderate (9-19ppm and 4-8ppm, respectively), implying a mesocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate to high abundances of cumulate phases (olivine+pyroxene) and moderate abundances of intercumulus (plagioclase and Fe-Ti oxides) over this interval.

From 44-47m, concentrations of Ce and Zr are low (7-10ppm and 3-4ppm, respectively), implying an adcumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulate phases (olivine+pyroxene) and low abundances of intercumulus (plagioclase and Fe-Ti oxides) over this interval.
From 47-50m, concentrations of Ce and Zr are moderate (15-18ppm and 5-9ppm, respectively), implying a mesocumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate abundances of cumulate phases (olivine+pyroxene) and moderate abundances of intercumulus (plagioclase and Fe-Ti oxides) over this interval.

From 47-55m, concentrations of Ce and Zr are high (22-31ppm and 11-17ppm, respectively), implying an adcumulate nature for this interval. Petrographic observations and geochemical proxies indicate moderate to low abundances of cumulate phases (olivine+pyroxene) and moderate to high abundances of intercumulus (plagioclase and Fe-Ti oxides) over this interval.

4.2 Evaluation of Eagle Parental Magma(s?) from Incompatible Trace Element Ratios

As mentioned in the introduction, Ding et al. (2010) concluded that the Eagle intrusion was formed by two to four chemically distinct parental magmas based on simple interpretations of clustering of incompatible trace element (ITE) ratios. However, several factors concerning trace element abundances in cumulate rocks need to be taken into account when interpreting trace element data for Eagle and Eagle East rocks. First, Eagle and Eagle East rocks range from adcumulates to orthocumulates of olivine, augite, orthopyroxene, and sometimes plagioclase with variable abundances of postcumulus minerals (locally plagioclase, hornblende, apatite, biotite, etc.; Figs. 33-36). Secondly, postcumulus minerals by and large crystallized from a trapped intercumulus liquid that strongly resembles the parental magma in terms of incompatible trace element ratios and approximate composition. And thirdly, cumulus phases
have generally high, but varying degrees of incompatibility with most trace elements,
particularly immobile rare earth elements (REE) and high field strength elements (HSFE), and as
such can acquire ITE ratios that differ from the parental magma.

In mafic magmatic systems, incompatible trace element ratios are commonly used to
differentiate between different types of parental magmas. This is because different degrees of
partial melting of the source material and the different pressures and temperatures that exist
during partial melting act together to produce a variety of ITE ratios, as does the influence of
crustal contamination. After a magma is created, subsequent fractional crystallization does little
to change its ITE ratios because the cumulus phases take in only minute concentrations of these
elements (Bedard, 1994). This means that different magma sources can be distinguished even
when the magma is moderately differentiated. However, because Eagle cumulates are mixtures
of variable proportions of cumulus phases (mostly Ol, Cpx, and Opx) with low ITE concentrations
and postcumulus phases representing an ITE-rich trapped liquid, whole rock ITE ratios can vary
significantly among comagmatic rocks of different cumulate types. As such, caution must be
taken when attempting to interpret the ITE compositions of various types of cumulate rocks in
terms of their parental magma compositions.

Ding et al. (2010) combined their petrographic study with lithogeochemical data provided
by Rio Tinto to speculate about the number of chemically distinct parental magmas in the
system. Specifically, Ding et al. (2010) refer to the Zr/Y and the La/Yb of their samples, which
ranged from 4.75 to 6.01 and from 4.84 to 6.76, respectively (Fig. 37).
Ding et al. (2010) used Zr/Y and La/Yb in combination with olivine and Cpx compositional zoning, contact relations, textural differences, and olivine Fo values to suggest that the feldspathic peridotite, melatroctolite, olivine melagabbro, and semi-massive sulfide lithologies were each a major, distinct pulse of magma. Of these pulses, they further used Zr/Y and La/Yb to speculate that at least the olivine melagabbro and possibly all four pulses originated from distinct magmas. Ding et al. (2010) did not differentiate their samples based on cumulate textures, nor did they reference the amount of sulfide present in their samples.
4.2.1 Evaluating the Relationship of Cumulate Type and Incompatible Trace Element Ratio

The lithogeochemical data used in this study, provided by Lundin Mining Co., shows ranges in Zr/Y and La/Yb in the Eagle intrusion similar to those found by Ding et al. (2010, Fig. 38). However, given the variability of cumulus mineral assemblages in the Eagle intrusion, this study set out to determine whether these ranges in incompatible trace element ratios might be largely related to variable cumulate types (cumulus/intercumulus mineral ratios), rather than variable parent magma compositions as interpreted by Ding et al. (2010).

The cumulate model, first proposed by Wager and Brown (1968) and subsequently critiqued and modified by many authors, posits that the magmatic differentiation evident in most large, slow-cooled mafic layered intrusions is caused by the physical separation (fractionation) of early formed crystals (cumulus or primocryst minerals) from the parental liquid from which those primocrysts crystallized. The mechanism of fractionation that drives the magmatic differentiation is routinely debated. Some, such as Irvine et al. (1998), agree with Wager and Brown (1968) that most differentiation was caused by crystal settling on the margins of a convecting magma body (crystal fractionation). Others, such as McBirney (1995) have proposed that evolved interstitial liquid is expelled from crystal mushes at the static margins of slow-cooling magmas by crystal compaction and density-driven buoyancy, a process called liquid fractionation. Still others, such as Tegner et al. (2009) propose that both fractionation processes are involved.
Figure 38: Down-hole variations in La/Yb and Zr/Y for Eagle drill holes EUGX0016 (A) and EUGX0028 (B).
Whatever mechanism of fractionation is involved, it is clear that most rocks crystallized from slow cooled mafic to ultramafic intrusions display two general stages of crystallization. The early stage produces well-formed (generally subhedral) crystals forming the structural framework of the rock. When more than one phase is involved in this early stage, the relative abundances of the phases tend to approximate their “cotectic” proportions determined from experimental and empirical observations. The generally uniform major element composition (most are solid solution phases) and the very low incompatible element concentrations in these cumulus/primocrystic phases imply that they crystallized in equilibrium with their parent magma. A mineral-liquid partition coefficient, D, is the ratio of the concentration an element between a certain mineral and a coexisting magma when the two are at equilibrium (Bedard, 1994). Partition coefficients for selected elements and minerals are displayed in Table 12 below.

Table 12: Mineral-Liquid partition coefficients of select minor and trace elements for mineral phases observed in Eagle cumulates. Data from Bedard, 2001, except amphibole data which are from Bedard, 1994.

<table>
<thead>
<tr>
<th></th>
<th>Olivine</th>
<th>CPX</th>
<th>OPX</th>
<th>Plagioclase</th>
<th>Apatite</th>
<th>Ilmenite</th>
<th>Amphibole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>0.02</td>
<td>0.34</td>
<td>0.086</td>
<td>0.043</td>
<td>14.0</td>
<td>12.5</td>
<td>1.0</td>
</tr>
<tr>
<td>P</td>
<td>0.008</td>
<td>0.13</td>
<td>0.02</td>
<td>0.075</td>
<td>18.7</td>
<td>0.002</td>
<td>N/A</td>
</tr>
<tr>
<td>Eu</td>
<td>0.02</td>
<td>0.3288</td>
<td>0.059</td>
<td>0.71</td>
<td>13.0</td>
<td>0.0009</td>
<td>0.88</td>
</tr>
<tr>
<td>Zr</td>
<td>0.26</td>
<td>0.021</td>
<td>0.02</td>
<td>0.01</td>
<td>16.0</td>
<td>0.33</td>
<td>0.37</td>
</tr>
<tr>
<td>Y</td>
<td>0.412</td>
<td>0.2</td>
<td>0.033</td>
<td>0.026</td>
<td>17.5</td>
<td>0.0045</td>
<td>0.73</td>
</tr>
<tr>
<td>La</td>
<td>0.0536</td>
<td>0.0019</td>
<td>0.003</td>
<td>0.124</td>
<td>12.0</td>
<td>0.0023</td>
<td>0.17</td>
</tr>
<tr>
<td>Yb</td>
<td>0.43</td>
<td>0.39</td>
<td>0.05</td>
<td>0.0097</td>
<td>13.0</td>
<td>0.057</td>
<td>0.59</td>
</tr>
</tbody>
</table>

The later (postcumulus) stage of crystallization is represented by minerals that fill in the pore spaces between the primocrysts, displaying anhedral to poikilitic habits. These minerals tend to have lower liquidus temperatures, commonly display compositional zoning, and tend to be enriched in incompatible elements. This postcumulus assemblage of interstitial minerals are
interpreted to have formed by in situ fractional crystallization of parental liquid trapped in the pore spaces of the cumulus minerals. Many studies (e.g., Meurer and Meurer, 2006; Tegner et al., 2009) have shown that this entrapment is not complete, but rather traps and crystallizes only some of the interstitial liquid before the rest migrates away due to compaction or density driven buoyancy. Although the postcumulus minerals formed from this partially trapped liquid will not directly reflect the composition of the parental magma, its composition approaches that of the incompatible element enriched parental magma, especially in terms of ITE ratios.

Wager et al. (1960) recognized that cumulate rocks can have variable proportions of these two stages of crystallization that reflect the volume of intercumulus liquid that is forced to crystallize in the cumulus pore space. They defined three grades of cumulates based on the percentage of postcumulus minerals present. Orthocumulates are rocks with greater than 25% postcumulus minerals, mesocumulates are rocks with between 10% and 25% postcumulus minerals, and adcumulates are rocks with less than 10% postcumulus minerals (Fig. 39). Orthocumulates, in which the trapped liquid component in Eagle cumulates is now represented by intercumulus minerals such as amphibole, Fe-Ti oxide, and biotite, should have the highest concentrations of incompatible trace elements and ITE ratios close to their parental magmas. This is because ITEs, which are not incorporated into early-forming phases during their crystallization, are more concentrated in the more evolved portions of a magma. Rocks composed of higher proportions of the more evolved portions of a magma thus have ITE ratios similar to those of the original magma and ITE abundances similar to or higher than the original magma. In contrast, adcumulates are expected to have low whole rock concentrations of
incompatible trace element abundances reflecting the dominance of ITE-poor early-forming cumulus minerals. Adcumulates will have ITE ratios that are generally close to their parent magmas but are modified by the ITE concentrations in the volumetrically dominant cumulus minerals.

Figure 39: Examples of types of plagioclase cumulates based on the percentage of intercumulus minerals: A) orthocumulates >25%, B) mesocumulates 10-25%, and C) adcumulates <10%. Original sketch from Wager et al. (1960).

Petrography and ITE concentrations suggested that the samples investigated in this study range from adcumulate to orthocumulate (Figures 33-36). To test if the range in incompatible trace element ratios observed might be due to variation in cumulate/intercumulus ratios, Zr/Y and La/Yb were plotted against Zr and La, respectively (Fig. 40). Zr and La are elements that can be used as proxies for the relative amount of trapped liquid in a sample because they are strongly incompatible in the cumulus phases of olivine, clinopyroxene, orthopyroxene, and plagioclase, but compatible in phases that tend to be intercumulus in these rocks, such as ilmenite, apatite, and plagioclase.
Assuming ITE concentrations in most Eagle parent magmas are generally similar, data points further to the left (low values of Zr and La) in graphs such as Figure 40 will reflect more adcumulate rock types, while data points plotting further to the right (high values of Zr and La) will correspond to generally more orthocumulate rock types. Of course, if the Eagle parent magmas span a significant range of differentiated compositions, the ITE concentrations will increase, though their ratios will remain fairly constant. As such, differentiation trends will define a sub-horizontal array on the graphs with more differentiated compositions to the right (increasing Zr and La).

One of the more obvious features of the data is that more sulfide-rich samples (MSU, SMSU) tend to be on the strongly adcumulate side of the graphs, while less sulfide-rich samples (MPER, PER, PRX) tend to be on the orthocumulate side. Also, the variation in Zr/Y and La/Yb for MSU rocks is extreme. The more adcumulate nature of sulfide-rich rocks indicate that lower density intercumulus magma was displaced by infiltration of dense sulfide.

To estimate the ITE abundances and ratios in various types of cumulates, the approximate ITE abundances in the parental magma must first be estimated. One way to do this is to plot ITE abundances against the amount of intercumulus minerals observed in those samples (Fig. 41). If there is an approximate linear relationship between the ITE abundance and
Figure 40A-B: A) Zr/Y vs. Zr (ppm) and B) La/Yb vs. La (ppm) for Eagle drill holes EUGX0016 and EUGX0028. Data points are grouped based on Lundin mineralization units. Lesser values of Zr and La (further left on these graphs) are interpreted to generally correspond to rocks being more adcumulate.
Figure 41: ITE abundance plotted against estimated abundance of intercumulus minerals for samples from the Eagle intrusion. The equations of the best fit lines to the data points are shown with the correlation coefficients indicated in Table 13. Table 13 also reports approximate ITE abundances at 100% intercumulus minerals.

percentage of intercumulus minerals, this can be extrapolated to 100% intercumulus minerals and should approximate the ITE abundance average parental magma. Using this method, several approximate ITE abundances for a hypothetical Eagle parental magma are given in Table 13 below. Because plagioclase may be partially cumulus in some samples, amphibole, biotite, and Fe-Ti oxides were used as the intercumulus minerals for this exercise.

This method of estimating the concentration of ITEs in a parental magma is speculative at best. Visual estimates of modal mineralogy can easily be off by several percent or more and are often inconsistent from slide to slide or core to core. Additionally, when assessing cumulus
vs. intercumulus minerals, the amount of postcumulus overgrowth of cumulus phases must also be accounted for, which is nearly impossible to do visually.

Perhaps because of this, while the ITE ratios returned by this exercise are speculative but reasonable, the absolute ITE abundances are higher than reasonable. For example, the most orthocumulate samples in Eagle have Zr abundances of no more than 200 ppm, implying that the parental magma had a Zr concentration of 200 ppm or less. This exercise returned a Zr concentration estimate for the parental magma of 464.3 ppm.

Table 13: Calculated abundances of ITE in a hypothetical Eagle parental magma and their associated ITE ratios.

<table>
<thead>
<tr>
<th>Element</th>
<th>Correlation Coefficient</th>
<th>Calculated ITE Concentrations (ppm) in average Eagle Parental Magma</th>
<th>ITE ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr</td>
<td>0.33</td>
<td>464.3</td>
<td>Eagle Zr/Y: 6.4</td>
</tr>
<tr>
<td>Y</td>
<td>0.38</td>
<td>72.3</td>
<td></td>
</tr>
<tr>
<td>La</td>
<td>0.48</td>
<td>30.3</td>
<td>Eagle La/Yb: 5.8</td>
</tr>
<tr>
<td>Yb</td>
<td>0.34</td>
<td>5.2</td>
<td></td>
</tr>
</tbody>
</table>

Another way to estimate approximate ITE abundances in the parental magma is to find a strongly chilled sample from the margin of the intrusion. Such a sample, by nature of its fast cooling, will have ITE abundances approximating those in the parental magma. To be a good chill candidate, a sample must be fine grained, have a comparatively high abundance of plagioclase, have high ITE abundances, have subprismatic pyroxenes, and be near a contact with country rock. For the PER lithology, three samples matching this description were found: 28-50.6, 28-53.3, and 28-83.2. The compositions of these samples were averaged together to approximate the composition of the parental magma. However, because the PER lithology is thought to have been carrying olivine phenocrysts in it upon emplacement, the compositions of those
phenocrysts must be subtracted out of the samples’ geochemistry to accurately reflect the composition of the parental magma. This was accomplished by visually estimating the amount of olivine in each sample that was phenocrystic and subtracting that amount of olivine out of the sample. For these three samples, which had a total olivine abundance averaging 20-25%, 10% of the olivine was estimated to be phenocrystic. This composition of this 10% was subtracted from the average composition of the three samples to come up with a better estimation of the composition of the parental magma. Most trace elements, including Zr, Y, La, and Yb, are incompatible in olivine. This means that the olivine phenocrysts in the magma essentially act as a diluent, lowering the concentration of each trace element that is not present in olivine. With this in mind, subtracting the compositions of the olivine phenocrysts from the geochemistry of the chill samples actually involves multiplying that geochemistry by a factor related to the abundance of the olivine phenocrysts such that the geochemical abundances are increased to the level that they would have been at had the phenocrysts been absent (Eq. 1).

\[
Zr_{\text{Magma}} = \frac{Zr_{\text{WR}}}{(1 - \text{[abundance of olivine]})} \\
Zr_{\text{Magma}} = 192.0 \text{ ppm}/(1 - 0.1) \\
Zr_{\text{Magma}} = 192.0 \text{ ppm}/(0.9) \\
Zr_{\text{Magma}} = 213.3 \text{ ppm}
\]  

(Equation 1)

The results of this are shown in Table 14 below.

<table>
<thead>
<tr>
<th>PER</th>
<th>28-50.6</th>
<th>28-53.3</th>
<th>28-83.2</th>
<th>Average</th>
<th>Minus 10% Olivine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr</td>
<td>203.0</td>
<td>179.0</td>
<td>194.0</td>
<td>192.0</td>
<td>213.3</td>
</tr>
<tr>
<td>Y</td>
<td>31.9</td>
<td>27.0</td>
<td>30.0</td>
<td>29.6</td>
<td>32.9</td>
</tr>
<tr>
<td>La</td>
<td>15.9</td>
<td>12.2</td>
<td>11.6</td>
<td>13.2</td>
<td>14.7</td>
</tr>
<tr>
<td>Yb</td>
<td>2.4</td>
<td>2.1</td>
<td>2.3</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Zr/Y</td>
<td>6.4</td>
<td>6.6</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>La/Yb</td>
<td>6.6</td>
<td>5.8</td>
<td>5.0</td>
<td>5.9</td>
<td>5.9</td>
</tr>
</tbody>
</table>
This method returns absolute ITE abundances that are much more reasonable for a hypothetical Eagle parental magma than the abundances returned by the best-fit-line exercise attempted above. The ITE ratios for both exercises are very similar to each other and are also reasonable estimates of the ITE ratios of a hypothetical Eagle parental magma.

For the PRX lithology, two samples matching this description was found: 16-14.9 and 16-16.5. Because no phenocrysts were suspected to be present in the magma during the emplacement of the PRX lithology, no phenocrystal correction was necessary as in the PER lithology (Table 15).

Table 15: ITE abundances and ratios of selected PRX samples

<table>
<thead>
<tr>
<th></th>
<th>PRX 16-14.9</th>
<th>16-16.5</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr</td>
<td>153</td>
<td>169</td>
<td>161</td>
</tr>
<tr>
<td>Y</td>
<td>29</td>
<td>30.2</td>
<td>29.6</td>
</tr>
<tr>
<td>La</td>
<td>12.2</td>
<td>12.8</td>
<td>12.5</td>
</tr>
<tr>
<td>Yb</td>
<td>2.38</td>
<td>2.4</td>
<td>2.39</td>
</tr>
<tr>
<td>Zr/Y</td>
<td>5.3</td>
<td>5.6</td>
<td>5.4</td>
</tr>
<tr>
<td>La/Yb</td>
<td>5.1</td>
<td>5.3</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Using these as a starting condition, mineral-liquid partition coefficients reported by Bedard (Table 12) were used to calculate the theoretical Zr/Y and La/Yb of pure cumulate rocks with modal mineralogy ranges that were observed in our petrologic studies (Tables 15 and 16).

The concentration “C” of an element “i” in a mineral “m” can be found if the concentration of that element is known in the parent magma and the mineral liquid partition coefficient, D, is known according to Equation 2:

\[ iC_m = iC_{Liq} \times \frac{m}{Liq} D \]  

(Equation 2)
When solving for the total amount of ITEs in a theoretical pure cumulate sample, this concentration can be weighted by the modal abundance of each mineral, and the results summed to return the total concentration in the pure cumulate. For example, to determine the concentration of Zr in a pure cumulate composed of 50% olivine, 35% CPX, and 15% OPX that crystallized from a parental magma with 150ppm Zr, the following sets of operations are performed:

\[
\begin{align*}
Zr_{\text{Ol}} & = Zr_{\text{Liq}} \times \frac{\text{Ol}}{\text{Liq}} D \\
Zr_{\text{Ol}} & = 150 \text{ ppm} \times 0.26 \\
Zr_{\text{Ol}} & = 39 \text{ ppm} \\
Zr_{\text{CPX}} & = Zr_{\text{Liq}} \times \frac{\text{CPX}}{\text{Liq}} D \\
Zr_{\text{CPX}} & = 150 \text{ ppm} \times 0.021 \\
Zr_{\text{CPX}} & = 3.15 \text{ ppm} \\
Zr_{\text{OPX}} & = Zr_{\text{Liq}} \times \frac{\text{OPX}}{\text{Liq}} D \\
Zr_{\text{OPX}} & = 150 \text{ ppm} \times 0.020 \\
Zr_{\text{OPX}} & = 3.0 \text{ ppm} \\

Zr_{\text{Cumulate}} & = (39 \text{ ppm} \times 0.50) + (3.15 \text{ ppm} \times 0.35) + (3.0 \text{ ppm} \times 0.15) = 21.1 \text{ ppm}
\end{align*}
\]

Using this method, hypothetical ITE ratios for pure cumulates of various mineral modal abundances can be calculated. In Table 16-18 below, ITE ratios for representative and hypothetical end member cumulates for Eagle lithologies based on observed mineral modes are given. Modal abundances were chosen to display the greatest possible variability in ITE ratios while remaining representative of the observed mineralogy. Situations both with and without plagioclase as a cumulus mineral were considered. All modal abundances included 1% cumulus apatite and 1% cumulus Cr-spinel. While ilmenite was not generally regarded as a cumulus phase for the PER lithology, because some samples have significant abundances of Fe-Ti oxides, one hypothetical pure cumulate with 10% cumulus ilmenite was included here.
Table 16: Calculated Zr/Y and La/Yb for pure PER cumulates of various modal mineralogies.

<table>
<thead>
<tr>
<th>PER</th>
<th>OCPH</th>
<th>OPCH</th>
<th>PCOH</th>
<th>OHC</th>
<th>OCH</th>
<th>POCH</th>
<th>OPCFH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cpx</td>
<td>25%</td>
<td>18%</td>
<td>35%</td>
<td>30%</td>
<td>25%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Opx</td>
<td>15%</td>
<td>5%</td>
<td>13%</td>
<td>35%</td>
<td>15%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Plag</td>
<td>25%</td>
<td>20%</td>
<td>35%</td>
<td>0%</td>
<td>0%</td>
<td>45%</td>
<td>30%</td>
</tr>
<tr>
<td>OI</td>
<td>33%</td>
<td>55%</td>
<td>15%</td>
<td>33%</td>
<td>58%</td>
<td>28%</td>
<td>33%</td>
</tr>
<tr>
<td>Ilm</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>Zr/Y</td>
<td>4.7</td>
<td>5.1</td>
<td>4.7</td>
<td>4.3</td>
<td>4.8</td>
<td>5.0</td>
<td>5.8</td>
</tr>
<tr>
<td>La/Yb</td>
<td>3.1</td>
<td>3.6</td>
<td>3.1</td>
<td>2.0</td>
<td>2.4</td>
<td>4.3</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 17: Calculated Zr/Y and La/Yb for pure PRX cumulates of various modal mineralogies.

<table>
<thead>
<tr>
<th>PRX</th>
<th>PCF</th>
<th>CPF</th>
<th>PCF-2</th>
<th>CPF-2</th>
<th>PC</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cpx</td>
<td>20%</td>
<td>50%</td>
<td>40%</td>
<td>50%</td>
<td>30%</td>
<td>50%</td>
</tr>
<tr>
<td>Plag</td>
<td>70%</td>
<td>40%</td>
<td>40%</td>
<td>30%</td>
<td>70%</td>
<td>50%</td>
</tr>
<tr>
<td>Ilm</td>
<td>10%</td>
<td>10%</td>
<td>20%</td>
<td>20%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Zr/Y</td>
<td>5.0</td>
<td>4.2</td>
<td>5.4</td>
<td>5.0</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>La/Yb</td>
<td>5.2</td>
<td>1.8</td>
<td>2.0</td>
<td>1.5</td>
<td>4.0</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 18: Zr/Y and La/Yb for pure PRX cumulates of various modal mineralogies calculated from PER magma

<table>
<thead>
<tr>
<th>PRX</th>
<th>PCF</th>
<th>CPF</th>
<th>PCF-2</th>
<th>CPF-2</th>
<th>PC</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cpx</td>
<td>20%</td>
<td>50%</td>
<td>40%</td>
<td>50%</td>
<td>30%</td>
<td>50%</td>
</tr>
<tr>
<td>Plag</td>
<td>70%</td>
<td>40%</td>
<td>40%</td>
<td>30%</td>
<td>70%</td>
<td>50%</td>
</tr>
<tr>
<td>Ilm</td>
<td>10%</td>
<td>10%</td>
<td>20%</td>
<td>20%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Zr/Y</td>
<td>5.9</td>
<td>5.0</td>
<td>6.4</td>
<td>6.0</td>
<td>3.9</td>
<td>4.0</td>
</tr>
<tr>
<td>La/Yb</td>
<td>5.8</td>
<td>2.0</td>
<td>2.2</td>
<td>1.7</td>
<td>4.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

If these estimated parent magma ITE ratios and those calculated for pure cumulates shown in Table 16 are overlain on the data shown in Figure 40, a polygon can be drawn that outlines the possible range of ITE ratios for various cumulate formed from such a magma composition (Fig. 42 and 43). This polygon outlines the range of ITE ratios in various cumulate rock types that could be generated from a likely Eagle parent magma composition (Fig. 42 and 43).
Figure 42 A-B: Zr/Y vs. Zr (A) and La/Yb vs. La (B) for Eagle PER samples. Zr and La are taken as proxies of intercumulus minerals and give a qualitative measure of the amount of trapped liquid in Ol-Cpx-Opx-(Plag) cumulates. The small triangles on the right side of each figure represent estimated trace element ratios for the parent magmas (based on chilled sample compositions). The labelled boxes on the left side of each figure represent the ITE ratios of hypothetical pure cumulates (Table 16) in equilibrium with such parental magmas based on experimentally determined mineral-liquid partitions.
coefficients (Bedard, 1994). Transparent polygons indicate the range of trace element ratios that might be expected in orthocumulates to adcumulates generated from a single magma composition.

From Figure 42, it can be seen that the expected range in Zr/Y for PER adcumulates corresponds fairly well with the actual range of the data. However, the calculated range in La/Yb for PER adcumulates does not correspond well with the data nearly as well, tending to fall below the range of actual data. In both cases, more orthocumulate samples are more likely to have ITE ratios above the calculated expected range; however, these samples still have ITE ratios that are roughly the same as the estimated parental magma ITE ratio. As the line of expected ITE ratios from estimated parental magma composition to pure cumulate compositions is not necessarily linear as depicted in the figures, orthocumulate samples falling above the polygon are still within the range of expected data. Note also that very high sulfide samples (MSU) appear to be outside the expected data range for both Zr/Y and La/Yb. High sulfide samples have both very low, and, more commonly, very high ITE ratios compared to other peridotite-family samples. PRX samples seem to have consistently lower ITE ratios than peridotite-family samples, and they also appear to have high ITE abundances.
Figure 43: Zr/Y vs. Zr and La/Yb vs. La for Eagle PRX samples. Zr and La are taken as proxies of intercumulus minerals and give a qualitative measure of the amount of trapped liquid in Cpx-Plag-FeTiOx cumulates. The small triangles on the right side of each figure represent estimated trace element ratios for the parent magmas (based on chilled sample compositions). The labelled boxes on the left side of each figure represent the ITE ratios of hypothetical pure cumulates (Table 17) in equilibrium with such parental
magmas based on experimentally determined mineral-liquid partitions coefficients (Bedard, 1994). Transparent polygons indicate the range of trace element ratios that might be expected in orthocumulates to adcumulates generated from a single magma composition.

From Figure 43, it can be seen that the expected range in both Zr/Y and La/Yb for PRX samples corresponds fairly well with the actual range of the data. Several samples with high ITE abundance and high ITE ratios fall outside the calculated data range, but it is possible that contamination from sedimentary material accounts for this discrepancy. For example, sample 28-85.3, which has among the highest ITE abundances and ratios (Zr, Y, La, and Yb of ~219, ~33, ~23, and ~3 ppm, respectively, leading to Zr/Y of 6.5 and La/Yb of 8.5) was observed to contain inclusions of sedimentary material (Fig. 44).

Figure 44: Inclusions of sedimentary material visible in PRX core sample 28-85.3, which has notably high ITE abundances.
A further thought experiment can be attempted. If the PRX and PER lithologies originated from the same parental magma, then it is likely that a range of pure cumulate compositions for rocks with PRX modal mineralogies but calculated with PER estimated parental magma ITE ratios would overlap the observed ITE ratios of the PRX samples. This is shown in Fig. 45 below. As can be seen in the figure, while the La/Yb calculated polygon overlaps the PRX ITE ratios, the Zr/Y calculated polygon does not. This implies that the PRX and PER lithologies did originate from different parental magmas.

In general, these data suggest that it is plausible that the range of ITE ratios observed within the population of PER samples and within the population of PRX samples is due to their varying cumulate nature. However, the high-sulfide samples and the calculated orthocumulate-adcumulate La/Yb range for PER samples must be explained further. Specifically, the questions of whether 1) plagioclase and 2) sulfide have an effect on the ITE ratio will be addressed, as will the question of whether PRX originated from a different parental magma.
Figure 45: Zr/Y vs. Zr and La/Yb vs. La for Eagle PRX samples, but calculated from a PER estimated parental magma. Zr and La are taken as proxies of intercumulus minerals and give a qualitative measure of the amount of trapped liquid in Cpx-Plag-FeTiOx cumulates. The small triangles on the right side of each figure represent estimated trace element ratios for the parent magmas (based on chilled sample compositions).
The labelled boxes on the left side of each figure represent the ITE ratios of hypothetical pure cumulates (Table 18) in equilibrium with PER parental magmas based on experimentally determined mineral-liquid partitions coefficients (Bedard, 1994). Transparent polygons indicate the range of trace element ratios that might be expected in orthocumulates to adcumulates generated from a single magma composition.

4.2.2 Plagioclase Control on ITE Ratios

As seen in Figure 42, hypothetical pure cumulates both with and without cumulate plagioclase seem necessary to explain the range in Zr/Y. The range in La/Yb (Fig. 43) is less well explained by the hypothetical pure cumulates in general, but also, the pure cumulates without plagioclase have ITE ratios that are especially low compared to the observed data, implying that cumulus plagioclase helps to explain this data. Taken together, these imply that plagioclase is, at least in part, cumulus in most PER lithologies. It is worth noting that cumulate processes are a progression rather than a binary system; though plagioclase is generally anhedral in peridotite-family samples, it is still possible that it was a late cumulus phase.

4.2.3 Sulfide Control on LREE/HREE

Incompatible trace elements, particularly the REEs, are lithophile under most conditions (Wood and Kiseeva, 2015). However, recent research suggests that the behavior of incompatible trace element partitioning in systems containing both sulfides and silicates is more complex than previously thought. Zhao and Jiang (2007) directly measured the REE composition of sulfide minerals in multiple systems in the Dachang mining district. They found a wide range of REE compositions in the sulfide minerals, with magmatic deposits tending to have lower absolute
abundances of REEs and hydrothermal deposits tending to have higher absolute abundances of REEs. The LREE/HREE across the different systems ranged from 3.2 to 56.9, with a skew towards the mid-high end of that range. Ekimova et al. (2010) directly measured the REE composition of sulfide minerals in a system that is much more analogous to Eagle: the orthomagmatic sulfides from a gabbro-norite in the Penikat mafic layered intrusion. The study found low absolute abundances of REE but high LREE/HREE in the sulfide minerals; both observations are similar to the massive sulfide sections of Eagle (which are ~100% sulfide minerals). In fact, the range of LREE/HREE in the study was 13 to 25, which largely overlaps with the range of 8 to 21 found in Eagle massive sulfides. Wood and Kiseeva (2015) experimentally studied the partitioning of trace elements, including several key REE, between sulfide melt and silicate melt. The study found that, while most of the trace elements were traditionally considered lithophile, they became chalcophile under certain conditions. Overall, the REE partition into sulfides more strongly than previously thought. Additionally, multiple studies are now reporting that the LREE are more mobile in hydrothermal fluids than has previously been recognized (Li and Zhou, 2015, others). Since the areas near sulfide minerals at Eagle are typically heavily serpentinized through secondary processes, this idea provides another potential explanation for high LREE/HREE near areas of high sulfide concentration.

Ding et al. (2010) attributed the variation in incompatible trace element ratios in the Eagle intrusion to multiple distinct parental magmas. However, as shown above, a simpler explanation for the variation of incompatible trace element ratios may exist if the effects of cumulate mineralogy and sulfide content on incompatible trace element ratios are considered. For sulfide-poor compositions, the variation in Zr/Y and La/Yb ratios can be explain by the
variable proportions of cumulus to intercumulus components and the variability in cumulus mineral assemblages. For sulfide-rich compositions, the lower incompatibility of LREE compared to HREE in sulfide minerals accounts for the significant increase in La/Yb in the SMSU samples. Zr and Y evidently have similar sulfide/magma partition coefficients and its smaller variation in the Eagle samples can be explained simply by variable cumulate mineralogy. In conclusion, neither the variations in LREE/HREE nor Zr/Y of Eagle rocks require multiple distinct parental magmas to explain their variability.

4.3 Test of the Lundin Two-stage Emplacement Model

Concluding that distinct parental magmas compositions are not necessary to explain the geochemical attributes of the Eagle intrusion does not, however, rule out the possibility of multiple injections of the same parental magma. Indeed, multiple intrusions of the same sulfide-contaminated magma seem necessary to explain the high metal tenors of the sulfide, as well as the distribution of mineralization in the intrusion.

Evaluating the spatial distribution and grades of mineralized sections of the Eagle intrusion, Lundin geologists have developed a two-stage emplacement/mineralization model for the intrusion. In this model, an initial pulse of sulfur-oversaturated magma intrudes as a bifurcating vertical conduit into the metasedimentary country rock (Fig. 46A). The liquated, high-density sulfide settles through the semi-crystallized peridotite to form a massive sulfide body near the join of the two arms of the intrusion, leaving progressively lower grade disseminated sulfide mineralization further up in the intrusion (Fig. 46B). Later, a second pulse
of similar parent magma, this one clearly laden with olivine phenocrysts but perhaps sulfide undersaturated, intrudes along the same path as the initial magma. This second pulse of

![Figure 46: Cartoon of the emplacement model for Eagle proposed by Lundin geologists. A) Sulfur-oversaturated intrudes into the country rock. B) Sulfide liquid drains downward to form a massive sulfide body, a transitional net-textured sulfide zone, and disseminated mineralization. C) A second pulse of magma, laden with olivine phenocrysts, intrudes along the same conduit as the original magma. It interacts with the sulfide zone, re-distributing the semi-massive and massive sulfides. Proposed by S. Beach and R. Mahin, personal communication, 2015.](image)

metalliferous magma interacts with the massive sulfide body, re-distributing entrained sulfide into zones of both massive and semi-massive mineralization (Fig. 46c). The metal-rich second pulse serves to enrich the metal tenor of the recycled sulfide liquid from the first emplacement event.
The unique relationship between Ni, olivine, and sulfides made analyzing the Ni compositions of olivine an ideal tool for evaluating the possibility of multiple magma pulses in the Eagle system. This is because if multiple magma pulses did occur, even if they were from the same parental magma, the possibility exists that the timing of sulfide liquation relative to olivine crystallization was different in the different pulses. If some of the olivine in a system is Ni-depleted and some is Ni-undepleted, then at least two magma pulses would have been required to create that system: one where olivine crystallized prior to sulfide liquation, and one where olivine crystallized after sulfide liquation. With an olivine/silicate melt partition coefficient of 3.5 to 5.5 (Matzen et al., 2013), Ni is more compatible in olivine than it is in other early silicate crystallization phases. However, Ni has a sulfide melt/silicate melt partition coefficient of between 1500 and 8000 (Peach and Mathez, 1993), which means that a sulfide liquation event will quickly strip a magma of its Ni content. The effect of this is that olivine acts as an indicator for when a sulfide liquation event has occurred relative to olivine crystallization. Olivine that crystallized prior to sulfide liquation will have an undepleted Ni signature, while olivine that crystallized after sulfide liquation will have a depleted Ni signature.

Because MgO is more compatible in olivine than FeO (Roeder and Emslie, 1970), olivine that fractionally crystallizes steadily from a magma will show a trend of decreasing Fo content with time. And because Ni is compatible in olivine, fractional crystallization of olivine will also deplete Ni in the magma and result in decreasing Ni concentration as Fo decreases. This should produce a positive correlation between Ni and Fo in an evolving system (Trend A in Fig. 47). However, it has been recognized that when olivine is enveloped in liquid sulfide, it can re-equilibrate with sulfide according to the following reaction (Eq. 3):
\[ \text{NiO}^{\text{olivine}} + \text{FeS}^{\text{sulfide}} = \text{NiS}^{\text{sulfide}} + \text{FeO}^{\text{olivine}} \] (Li et al. (2007)) \hspace{1cm} (Equation 3)

This reaction has the exchange partition coefficient, \( K_D \), of:

\[ K_D = \frac{\text{NiS/FeS}^{\text{sulfide}}}{\text{NiO/FeO}^{\text{olivine}}} \] \hspace{1cm} (Li et al. (2007)) \hspace{1cm} (Equation 4)

At constant \( f_{O_2} \) and sulfide liquid composition, \( K_D \) is constant, and the ratio of NiS/FeS is greater than one because the Ni content of the sulfide liquid decreases as NiS decreases (Li et al., 2007). Li et al. (2007) noted that because of this, the \( K_D \) predicts that olivine grains with higher Fo contents will lose more of their Ni than grains with a lower Fo content, resulting in a negative correlation between Ni and Fo (Trend B in Fig. 47).

Figure 47A-B: Ni vs. Fo for olivine samples from Voisey’s Bay, Canada. Olivine that crystallizes with a normal fractional crystallization pattern will produce a positive correlation between Ni and Fo (A). Olivine that later re-equilibrates with sulfide minerals will show a negative correlation between Ni and Fo (B). Note the reversed values on the x-axis. Modified from Li et al. (2007).

The most obvious mechanism for a situation in which two magmas forming the Eagle system would have different timings of olivine crystallization to sulfide liquation is as follows:
Magma pulse one (M1) becomes sulfur-saturated in a deeper staging magma chamber prior to being transported to the site of emplacement and prior to significant olivine crystallization. Olivine that then crystallizes in the sulfide oversaturated magma should be depleted in Ni. If the later magma emplacement event intrudes initially sulfide undersaturated but with early formed olivine phenocrysts, these olivines should be undepleted in Ni.

The Ni content considered normal in olivine is dependent in part on the Fo composition of that olivine – if an olivine grain is more evolved, then it would generally be expected to contain less Ni than a more primitive olivine grain regardless of whether sulfide is involved. Simkin and Smith (1970) analyzed olivines in a wide variety of geologic environments to produce a range of “normal” Ni compositions for olivine at various stages of evolution. The original figure by Simkin and Smith plotted Ni against weight percent Mg instead of mg# (Fo). Because of this, Li et al. (2007) re-plotted the Simkin and Smith data using mg# (Fo) and re-drew the composition field accordingly. The data from our study are plotted against the re-drawn field of Li et al. (2007) in Figure 48.

All samples had their Fo compositions plotted against their Ni content (Fig. 48). Most holes and samples showed a positive correlation between Fo and Ni. In hole 08EA222D, the Fo-Ni trend became less positive with decreasing depth, with the shallowest sample, D-787, showing a negative Fo-Ni trend.
Figure 48: NiO (%) vs Fo (%) for olivine from Eagle and Eagle East. Data points are grain averages. Orange points denote relatively high-sulfide samples; blue points denote relatively low-sulfide samples. Lines are trend lines for grains within the same sample. Red trend line shows only negative trend, which is for sample D-787. Overlain is the field of Simkin and Smith (1970), re-drawn from Li et al. (2007). Eagle and Eagle East olivines are Ni-undepleted to Ni-enriched compared with the field of Simkin and Smith (1970).

Compared to the field of Simkin and Smith (1970), olivine compositions from Eagle and Eagle East are all undepleted in Ni for their Fo contents (Fig. 48). The undepleted Ni signature of olivine in the Eagle and Eagle East intrusions implies that olivine crystallized prior to sulfide liquation in all situations. Unfortunately, since sulfide could have liquated prior to olivine crystallization in either a single magma pulse or in multiple magma pulses, these data cannot be used either for or against the multiple magma emplacement hypothesis.

Additionally, all data from a given sample, except one (D-787), show a positive correlation between Ni and Fo compositions as would be expected from fractional crystallization. This implies that, with the exception of D-787, the olivine grains did not re-equilibrate with the sulfide minerals that they were in contact with. This is somewhat surprising
given the large volume of sulfides present. With olivine enveloped in net-textured sulfide, one would expect the Ni in olivine to be readily re-equilibrated with sulfide minerals.

This lack of re-equilibration between the olivine phenocrysts and the sulfide minerals requires explanation, but a full analysis is outside the scope of this work. Speculative reasons for the lack of re-equilibration include a fast cooling time which did not thermodynamically allow for re-equilibration and/or the presence of volatiles in the magma.

4.4 Petrologic Significance of the Intrusive Breccia Unit

Both Eagle and Eagle East contain an enigmatic lithology termed the igneous or intrusive breccia (IBRX) by Lundin geologists. This lithology was only recognized in Eagle after 2010 and was only recently (2015) discovered in Eagle East.

The unit is similar in both intrusions: it consists of a matrix of sulfide-bearing mafic-ultramafic rock and numerous sub-angular inclusions of one of two types: those that are relatively devoid of sulfide and those that contain 20-30% sulfides (Fig. 49).

As described in the results section, the matrix of the IBRX is composed of sulfide minerals, olivine, clinopyroxene, orthopyroxene, hornblende, and plagioclase. In terms of both modal mineralogy and texture, the matrix is comparable to the SMSU, MPER, or PER lithologies. In other words, the matrix of the IBRX appears to be the same intrusive phase as the peridotite lithology that forms the main body of both Eagle and Eagle East. In contrast to the olivine-bearing rocks of the matrix, the inclusions in the IBRX lithology are fine to medium grained and contain clinopyroxene, plagioclase, orthopyroxene, and Fe-Ti oxides. While the XC1 clasts
contain primarily fine-grained, anhedral clinopyroxene with some anhedral plagioclase, XC2 clasts contain fine to medium grained, anhedral to subhedral clinopyroxene, inverted pigeonite, and plagioclase. EEXC clasts, those found in the Eagle East intrusion, are similar to XC2 clasts but with 3-5% sulfides instead of 20-30% sulfides.

Figure 49: IBRX lithology with clast types 1 (A) and 2 (B) in core samples 16-57.9 and 16-54.9, respectively. Clast type 1 (A) shows subangular inclusions of fine-grained, sparsely mineralized clinopyroxenite in a matrix of medium-grained, well-mineralized lherzolite. Clast type 2 (B) shows subangular inclusions of fine to medium grained, well-mineralized websterite in a matrix of mildly sulfidic feldspathic lherzolite.

No trace element geochemistry has been obtained from the clasts in the IBRX. As such, it cannot be determined whether the clasts are petrogenetically related to the rest of the intrusive material at Eagle or Eagle East. XC2 clasts, which bear inverted pigeonite and also have a higher plagioclase abundance compared to XC1 clasts, may be a more petrogenetically evolved version of the XC1 clasts. The heavy mineralization of the XC2 clasts compared to the XC1 clasts also supports this hypothesis; it is plausible that a sulfide liquation event occurred after the emplacement of the less-evolved XC1 but before or during the emplacement of the XC2. Superficially, the IBRX clasts are somewhat similar to the PRX unit, in that both have large
amounts of pyroxene with no olivine. Since the PRX unit typically occurs at the margin of the Eagle intrusion, it may be a precursor to the mineralized peridotite lithologies which established the conduit that PER lithologies would later intrude. This could be the case regardless of whether the PRX is genetically related to the PER lithologies or not. The IBRX clasts, then, could be xenoliths picked up from the precursor PRX intrusion during the PER intrusive event. However, as noted in the PRX section in Chapter 3, despite sharing a lack of olivine and a fine to medium grain size, the IBRX clasts are mineralogically and texturally quite different from the PRX unit. The most significant differences include: 1) clinopyroxene makes up only 10-35% of silicate phases in the PRX lithology, whereas it composes up to 90% of the silicate portion of the IBRX-C1 clasts, 2) the PRX unit has significant amounts of cumulus plagioclase, while the IBRX clasts generally have little plagioclase, and what plagioclase does exist is anhedral and thus likely intercumulus, and 3) pyroxenes in the PRX are generally subhedral, while those in the IBRX clasts are generally anhedral.

The PRX lithology, with its higher plagioclase abundances, had to have experienced a different geologic history than the IBRX clasts. For example, since the PRX lithology usually occurs at the margin of PER units, in contact with country rock, the abundance of plagioclase in it may be a result of faster cooling at the margins of the intrusion compared with IBRX clasts slowly cooling in the interior of the intrusion. If the clasts are not genetically related to Eagle and Eagle East, another hypothesis is that they may be part of an older intrusion at depth that the Eagle and Eagle East magmas had to interact with on their journey into the crust. If that were the case, then the different types of IBRX clasts may represent different parts of the precursor
PRX intrusion, and the parent magma of the PER lithology picked up different clasts from different parts of the precursor intrusion as it was emplaced.

4.5 Petrogenesis of the Eagle East Intrusion

Because the main body of the Eagle East intrusion was not previously known to host economic sulfide mineralization and is evidently not structurally connected to Eagle, not as much attention had been paid to it. However, because the two intrusions are both dominantly composed of feldspathic lherzolite, it was reasoned at the onset of this study that understanding the Eagle East intrusion will be helpful in determining an accurate genetic model for the Eagle system. In mid-2014, drilling focused on the Eagle East intrusion intercepted economic sulfide mineralization along the base of its eastward-plunging deep feeder. With subsequent drilling proving out a mineable resource, understanding the Eagle East system in and of itself is now important in its own right.

The main body of Eagle East was uniformly classified as peridotite by Lundin geologists based on core logging. Drill hole 04EA0085, which profiles the main body of Eagle East (Fig. 32), was chosen for this study to investigate the litho- and chemo-stratigraphy of this narrow funnel-shaped intrusion.

Figure 22 shows the downhole variation in the modes and textures of olivine, clinopyroxene, and orthopyroxene. At the top and bottom of the core, the pyroxenes compose a greater modal percent of the silicate minerals than olivine does. In the lower-middle sections of the core, from about 200m to about 400m, olivine is more abundant than pyroxene. This modal
mineralogy variation appears to roughly correlate with textural variation in both olivine and clinopyroxene. Olivine is more euhedral in the sections where it makes up a greater modal percent of the silicate minerals, and clinopyroxene is more poikilitic in sections where it is more abundant than olivine.

This section of different modal mineralogy and mineral textures could potentially represent a magma recharge event. These events are often marked by increased olivine abundance, which is certainly seen in this section. Additionally, a later recharge event would have given the magma more time to evolve, which could explain the slightly less poikilitic clinopyroxene observed in this section. However, as shown in Figure 30, the mg# of olivine, clinopyroxene, and orthopyroxene each vary by less than 3.0 mol. % in mg# from the bottom to the top of the entire 451 m core. Most of the variation is accounted for with a slight dip in mg# in upper 150 m of the intrusion. This lack of variation in mg# implies that a recharge event did not take place in the observed core. Additionally, no major structures suggesting a recharge event were noted during core logging.

These observations, taken alone, imply that the main body of Eagle East was intruded as a single, homogenous magma pulse. However, the total volume of the Eagle East body is unknown, as the top of the body is exposed, and material may have eroded away. Magmatic differentiation produces only minor changes in petrologic attributes until near the end of the differentiation process, where changes are exponential. Because of this, the Eagle East body may be either a relatively nondifferentiated body, or it may be the lower portion of a more completely differentiated body. In either case, it is likely that Eagle East was formed by either one or multiple pulses of a compositionally homogenous magma. Multiple pulses of
compositionally distinct parental magmas would be expected to produce significant variations in mg# and perhaps cumulate rock type, neither of which are observed in this body. Multiple pulses of a compositionally homogeneous parental magma could lead to only subtle variation in mg# and rock type. This type of frequent recharge resulting in minimal cryptic mineral variation is similar to that observed in the troctolitic Partridge River and South Kawishiwi intrusions of the Duluth Complex (Severson and Hauck, 1990; Severson, 1994). New recharge events of this type are typically marked by increases in modal olivine, which occurs at ~230m in DDH 04EA0085 (Fig. 22).

Compared to the Eagle intrusion, the Eagle East intrusion appears to be an analogous system with some differences – the main differences being the poikilitic nature of clinopyroxene and the low modal abundance of plagioclase in the main body of the Eagle East intrusion (EEC-PER), compared to subhedral clinopyroxene and significant plagioclase in the Eagle intrusion. There are two ways to explain these differences. The most obvious way is to say that Eagle East is not as evolved as Eagle, explaining both the poikilitic clinopyroxene and the low abundance of plagioclase. However, the very similarity of the two intrusions in other respects renders this approach problematic. A second, perhaps more nuanced explanation involves cooling speed. The Eagle East intrusion is significantly larger than the Eagle intrusion, and as such, it is likely that it cooled more slowly. The quickly-cooling Eagle intrusion would have hit the clinopyroxene liquidus temperature sooner compared to the slowly-cooling Eagle East intrusion, and the result of this would be sub-cumulus clinopyroxene in Eagle compared to poikilitic clinopyroxene in Eagle East. This explanation allows for the two systems – which are extremely similar to each other in most respects – to have been derived from the same parent magma.
5.0 Conclusions

The four major objectives of this study were to test whether Lundin’s two-stage emplacement model can be discerned by geochemical distinctions between units, reevaluate Xian Ding’s conclusion of multiple magma sources for the Eagle intrusion, better understand the petrogenesis of the intrusive breccia (IBRX) unit, and evaluate the emplacement, crystallization, and mineralization history of the Eagle East intrusion and compare its petrology and mineralization with the Eagle body.

Attempting to discern Lundin’s two-stage emplacement model in the geochemical distinctions between units was undertaken by analyzing Ni concentrations in olivine. Olivines in the Eagle and Eagle East intrusions are universally Ni-enriched. If some olivines had been Ni-enriched while others were Ni-depleted, this would have been evidence for multiple injections of the same parental magma. In this case, the olivine would have acted as a timer, with one or more magma pulses occurring before a sulfide liquation event and one or more magma pulses occurring after a sulfide liquation event. The absence of a bimodal distribution of Ni concentration in olivine implies that if multiple magma pulses did occur, they all occurred prior to sulfide liquation. Additionally, olivines in the Eagle and Eagle East intrusions have a positive correlation between Ni and Fo for all PER lithologies. This implies that they did not re-equilibrate with sulfides after crystallization and further implies that the Ni contents of olivines in these intrusions are likely true to their original values at crystallization. That all magma pulses appear to have occurred prior to sulfide liquation does not allow for testing Lundin’s two-phase emplacement model. This means that this study did not find evidence either for or against the model.
Counter to the conclusions of Ding et al. (2010), variations in incompatible trace element ratios in various rock type in the Eagle intrusion can be explained by consideration of the cumulate nature of the samples and the sulfide content of the samples. Because these rocks are cumulates with varying amounts of intercumulus minerals, the whole-rock ITE ratios vary significantly with the cumulate nature of the rocks. Additionally, many of these rocks have extremely high (up to 99% by volume) sulfide abundances, and while most ITEs are traditionally considered lithophile, in certain conditions they can be chalcophile. Sulfide abundances this high significantly impacted ITE ratios. Between these two factors – the cumulate nature of the samples and the high sulfide abundance of the samples – the variation in ITE ratio can be satisfactorily explained without multiple genetically distinct parental magmas. Note that this is only in regard to the mineralization-related rocks, i.e. the peridotite-family rocks. The genetic relationship between the PER lithology and the PRX lithology was cursorily examined by calculating hypothetical pure cumulate ITE ratios with PRX modal mineralogies but starting with a PER parental magma, and this thought experiment suggested that the two lithologies come from two different parental magmas.

The IBRX lithology has a matrix composed of the same feldspathic lherzolite that is common in other parts of the intrusions. In the Eagle intrusion, the IBRX lithology contains clasts of at least two types, one of which contains significant sulfide material (up to 30% by volume) and one of which contains almost no sulfides. Both types are devoid of olivine and rich in pyroxene, but clasts with sulfides present tend to have more plagioclase and heavier alteration. Clasts in the Eagle East intrusion seem to be of only one type analogous to the low-sulfide clasts at Eagle. The PRX lithology may be a version of the IBRX clasts that cooled quickly at the margins.
of the intrusion. Alternatively, the PRX lithology and the different types of IBRX clast may have been part of an older intrusion at depth that the Eagle and Eagle East parental magmas broke through and partially cannibalized during their emplacement.

The main body of the funnel-shaped Eagle East intrusion does show modest cryptic variation, but not significant variation in cumulate rock type. This implies that it experienced some degree of fractional crystallization and may have been periodically recharged by the same primitive parental magma. One horizon of increased olivine abundance in a drill core that profiles the intrusion may represent a recharge event of the same, homogeneous parental magma. The Eagle and Eagle East intrusions are lithologically very similar and likely formed from the same parental magma. The larger Eagle East intrusion likely cooled more slowly than the smaller Eagle intrusion, resulting in the main petrologic differences of poikilitic clinopyroxene and low abundances of plagioclase in Eagle East’s main body.
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