Geology and Petrology of the Wilder Lake Intrusion, Duluth Complex, Northeastern Minnesota

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Abstract

The Wilder Lake Intrusion (WLI) is a well differentiated, northward-dipping, sheet-like mafic layered intrusion that is part of the 1.1 Ga Duluth Complex exposed in northeastern Minnesota. While several reconnaissance studies of the well exposed western quarter of the WLI have shown it to have several distinctive petrologic characteristics compared to other layered intrusions in the Duluth Complex, its relative inaccessibility within the Boundary Waters Canoes Area Wilderness precluded a detailed study of its field and petrologic attributes along its entire 10 km strike length. This changed in the Fall of 2011 when an intense forest fire (the Pagami Creek Burn) created easy access to excellent exposure of the WLI.

Through field mapping, petrographic observations, and geochemical analysis, this study sought to document the igneous stratigraphy of the WLI along its entire strike-length with the goal of better understanding the petrogenesis of its unique petrologic attributes. These attributes, noted by others and confirmed here, include the up-section stratigraphic changes characterized by 1) a cumulus reversal from a olivine oxide gabbroic cumulate of Pl+Cpx+Ox+Ol to a troctolitic (Pl+Ol) cumulate; 2) a reversed cryptic variation of Fo in olivine and En' in clinopyroxene; and 3) the cumulus arrival of Fe-Ti oxide before augite (Miller and Ripley, 1996).

Detailed mapping conducted in 2012 and 2013 revealed that most cumulate units of the WLI can be followed along its entire strike length, but with some notable exceptions. Remapping in the western part of the WLI has confirmed that the 2 km-thick igneous stratigraphy exposed here starts with a basal unit of heterogeneous, intergranular olivine oxide gabbro that is in sharp contact with Anorthositic Series rocks. This marginal gabbro is overlain by a troctolitic unit of Pl+Ol cumulates, which can be subdivided into a heterogeneous subunit, a layered subunit and an anorthosite inclusion-rich subunit. The troctolite unit is overlain by a thin (20-100 m thick) oxide troctolite unit of Pl+Ol+ Ox cumulates that abruptly gives way to an olivine oxide gabbro unit of Pl+Cpx+Ox+Ol cumulates. This four-phase cumulate is abruptly overlain by another troctolitic cumulate unit demarking a cumulus reversal back to Pl+Ol cumulates. Mapping of the excellent exposures created by the Pagami Creek Burn reveal that the upper troctolite unit cross-cuts and locally scoured out the four-phase gabbro and part of the oxide troctolite unit. Thus it is interpreted as a

recharge of more primitive magma into the upper part of the WLI chamber rather than a downward crystallizing roof zone unit as speculated by Miller (1986).

Detailed mapping by overland traverses in the central and eastern extents of the WLI show it to thin from 700 m in the west to 500 m in the east. Moreover, several units pinch out in the eastern section of the intrusion. The oxide troctolite pinches out just east of center, but swells back to about 20 meters in stratigraphic thickness before pinching out again farther east. The lower gabbro also pinches out around the same place and is replaced by a taxitic unit that dominates at the eastern margin; a similar heterogeneous unit also can be found at the western margin.

Petrographic study of 223 thin sections collected along three profiles across the WLI at its western, east-central and eastern extents helped to confirm and refine the stratigraphic variations in mineralogy and texture noted from field observations. In addition, olivine and pyroxene from many of the samples were analyzed by University of Minnesota Duluth's SEM/EDS (Scanning Electron Microscope/Energy Dispersive X-Ray Spectroscopy) to document cryptic variation of mg# (=Mg/(Mg+Fe), cation %). This mineral chemical data was acquired to verify the reversed cryptic variation previously documented in the west and to determine if this variation persists along strike to the east. Reversed cryptic variation of upwardly increasing magnesium number (mg# =MgO/(MgO+FeO), mol %) in olivine (Fo) and pyroxene (En') was confirmed in the west and shown to persist in the eastern profiles. However, the data also reveal that the mg# tends to decrease at a particular stratigraphic horizon from west to east. The reversed cryptic variation up-section is interpreted to reflect a trapped liquid shift within the oxide troctolite and olivine oxide gabbro units. Trapped liquid shift occurs where high mg# cumulus olivine re-equilibrates with low mg# intercumulus liquid. As evidenced by their strong foliation and the low abundance of augite in the oxide troctolite unit, these rocks are clearly adcumulates with very little postcumulus minerals (i.e., representing the trapped liquid component) and thus retain their high-mg#. The lateral decrease in mg# to the east, as well as the disappearance of the oxide troctolite unit, is thought to be caused by the thinning of the intrusion which in turn would result in the eastern portion of the intrusion to cool more rapidly than the west. This more rapid cooling would have trapped intercumulus liquid (and thus a stronger trapped liquid shift) and promoted oxide and pyroxene to crystallize more synchronously since their liquidus temperatures are not very different.

Finally, whole rock geochemical analyses of the basal intergranular gabbro samples were evaluated to determine if they may be representative of a parental liquid composition. One piece of evidence that this is the case is that the WLI marginal gabbro composition is comparable to other tholeiitic magma compositions occurring in the North Shore Volcanic Group (NSVG). Another method used to evaluate the parental composition of the marginal gabbro is to apply its composition to a MELTS-based phase equilibrium program, Pele (Boudreau, 2006). This modelling indicates that the phases in equilibrium with the fractional crystallization of the marginal gabbro compositions can replicate the cumulate stratigraphy observed in the WLI with normal to reduced fO_2 conditions (between QFM and 3 log units below QFM). These modeling results indicate that the cause of early oxide crystallization relative to augite was largely the result of an Fe-Ti enriched parental magma composition, and not elevated oxygen fugacity.

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1. Introduction

In a massive forest fire in the autumn of 2011, 160 square miles of dense forest in the Boundary Waters Canoe Area Wilderness (BWCAW) was intensely burned. Underlying what was termed the Pagami Creek burn area are mafic intrusive rocks of the 1.1 Ga Duluth Complex (Fig. 1.1) - a large, arcuate-shaped, multiple intrusive igneous complex that underlies most of northeastern Minnesota and that constitutes the largest exposed plutonic component of the 1.1 Ga Midcontinent Rift. Located in the central part of the burn area is the Wilder Lake Intrusion (Fig. 1.1) which previous reconnaissance mapping (Phinney, 1972; Miller, 1986; Turnbull and Miller, 2004) had shown to be one of the most distinctive mafic layered intrusions in the Duluth Complex.

Because the Wilder Lake Intrusion (WLI) occurs completely within BWCAW, access is largely limited to canoeing into a series of lakes in the western part of the intrusion and by foot via the Pow-Wow hiking trail in the central and western parts of the intrusion (Fig. 1.2). Like other areas of the BWCAW, outcrops in the thick forest of this area are difficult to map due to their cover with thick mats of moss and decades of deadfall. Accessing exposures away from shorelines or the hiking trail was made all the more difficult by an intense storm that impacted the area in 1999, in which straightline winds from this storm caused major tree blowdowns across the BWCAW and made the woods around Wilder Lake virtually impenetrable.

The intense burn of the Pagami Creek fire (Fig. 1.2) changed all that in an instant. The fire provided a unique opportunity to access unmapped inland exposures of the WLI, especially in the previously inaccessible central area. Not only did the burn provide open access to previously dense forest with abundant deadfall, but it unveiled countless fresh outcrops previously covered by moss or organic soils (Fig. 1.3). This logistic and geologic access to the full extent of the WLI allowed for detailed mapping of its igneous stratigraphy along its entire strike length. It also allowed for confirmation of its petrologic attributes previously recognized mostly from shoreline exposures at its west end.

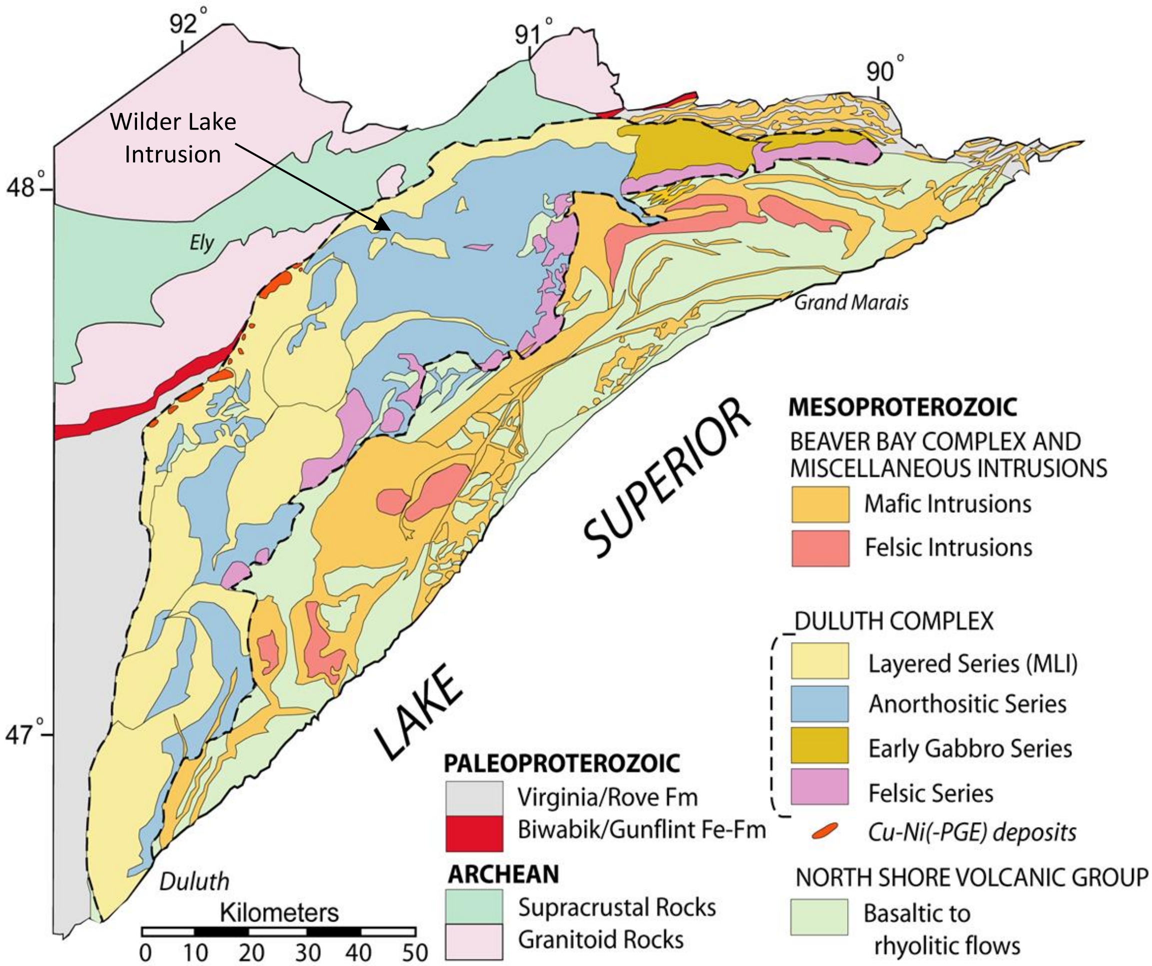


Figure 1.1: Geology of northeastern Minnesota showing the main magmatic series of the Duluth Complex and related rocks. The location of the Wilder Lake Intrusion is noted.

Funding for the mapping phase of this study was provided by the U.S. Geological Survey's EDMAP program which supports mapping projects by students. This study also dovetailed with the Minnesota Geological Survey's 2012-13 STATEMAP project which sought to do reconnaissance mapping of the burn area peripheral to the WLI. Support for this study was also provided by a research assistantship and grant from the Precambrian Research Center and research grants from the Department of Geological Sciences at UMD.

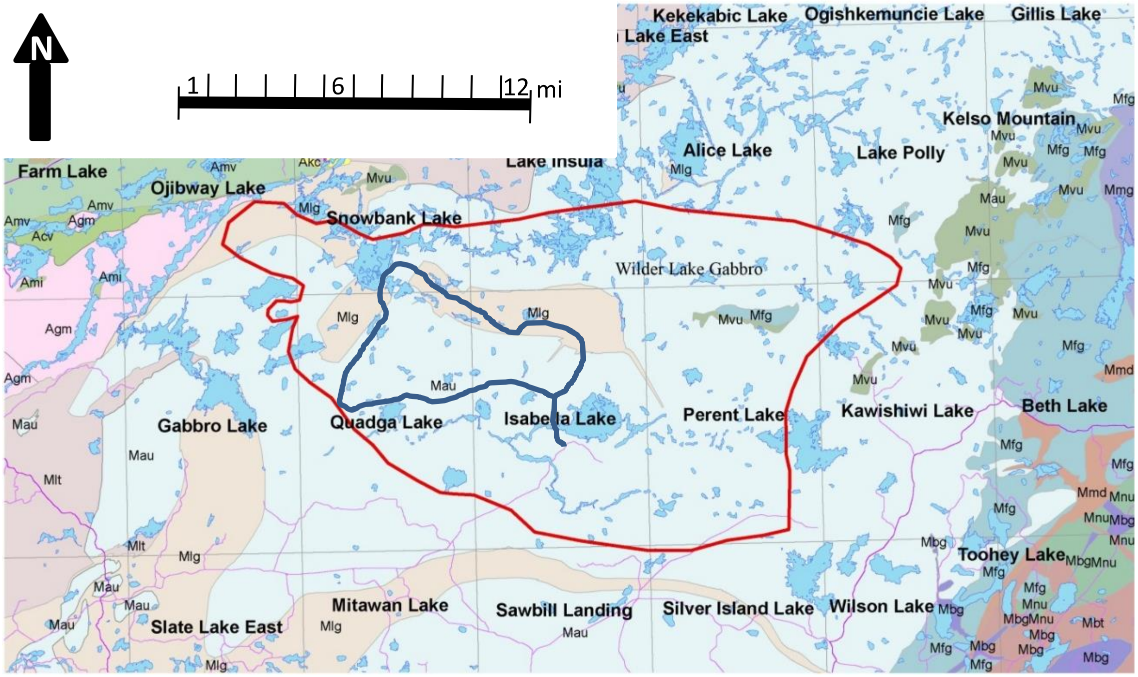


Figure 1.2 Generalized geology of the area affected by the 2011 Pagami Creek fire. Major Duluth Complex units shown on the map that are focus of this study are Mlg – Layered Series intrusions and Mau – Anorthositic Series undifferentiated. Note the position of the Wilder Lake intrusion within the burn area (red outline) and the path of the Pow Wow Trail (blue line). Named purple rectangles are 7.5' quadrangles. Figure created by T. Boerboom (Minnesota Geological Survey, 2012)

Prior to this study, the geology of the Wilder Lake intrusion was only known from shoreline mapping conducted at its western end around North Wilder Lake, South Wilder Lake, Harbor Lake, and Brewis Lake (Miller, 1986; Turnbull and Miller, 2004) and at its eastern end from reconnaissance mapping along pre-BWCAW logging roads (Phinney, 1972). As summarized by Miller and Ripley (1996), these studies nevertheless showed the WLI to be one of the most distinctive intrusions of the Duluth Complex on several accounts: 1) in contrast to the riftward (SE) dip of most layered intrusions in the Duluth Complex, the WLI dips to the north; 2) whereas most layered intrusions were emplaced between pre-rift basement and anorthositic rocks of the complex, the WLI was emplaced entirely within the Anorthositic Series; 3) whereas most well-differentiated layered mafic intrusions show a normal cryptic variation correlating with cumulate phase layering (e.g., Duluth Layered Series, Miller and Ripley, 1996; Greenwood Lake Intrusion, Miller, 2004), the WLI appears to have a reversed cryptic variation relative to its normal cumulate stratigraphy; and 4) whereas all other differentiated intrusions showed a cumulate paragenesis where cumulus augite appears before or simultaneously with cumulus Fe-Ti oxide, cumulus oxide appears well before pyroxene in the WLI.

This study aims to verify and evaluate the origin of some of the enigmatic features of the WLI by conducting detailed field mapping and sampling of its entire strike length, and by acquiring petrographic, mineral chemical, and lithogeochemical analyses of those samples.

Figure 1.3 Panoramic photo of the Pagami Creek burn in an area between Harbor Lake and North Wilder Lake in August of 2012 (photo by J. Miller)

1.1 Geological Setting

The WLI and other mafic igneous rocks of northeastern Minnesota were formed during an intracontinental rifting event about 1.1.Ga. The Midcontinent Rift (MCR) is one of the best preserved large igneous provinces of Precambrian age and is well exposed in the Lake Superior region (Miller, 2007). Gravity and magnetic anomalies easily trace the 2500 km length of the arcuate MCR (Fig. 1.4). Two arms project southwest and southeast from exposures in the Lake Superior region and form one of the most distinctive geophysical features in North America (King and Zietz, 1971; Hinze et al., 1992). The southwest arm extends from the Lake Superior region, where it cuts across Archean (2.8-2.6 Ga) granite-greenstone terrains, into Kansas, crossing several Proterozoic orogenic terrains along the way (Penokean - 1.85 Ga; Yavapai - 1.7 Ga; Mazatzal - 1.6 Ga). The southeastern arm of the MCR is deeply buried under Paleozoic rocks of the Michigan basin and is rarely seen, except in a few deep drill holes (Brown et al., 1982). At nearly a right angle the MCR geophysical anomaly ends in southeastern Michigan at the Grenville Front - a tectonic boundary produced by the Elzevirian (1240-1160 Ma) and Ottawan (1090-1025 Ma) orogenies (Easton, 1992). Interestingly, these Grenvillian orogenies bracket the period of rifting and igneous activity of the MCR (1115-1086 Ma; Heaman et al., 2007).

It is generally agreed that the far-field effects of the Ottawan orogeny were responsible for preventing the MCR from fully developing into an oceanic rift and actually resulting in its structural inversion (Cannon, 1994), but it is less clear what role the Grenville event may have played in the rifting event itself. As discussed in more detail below, most workers on the MCR ascribe to the idea that the MCR was generated or at least strongly influenced by the impact of a starting plume around 1100 Ma.

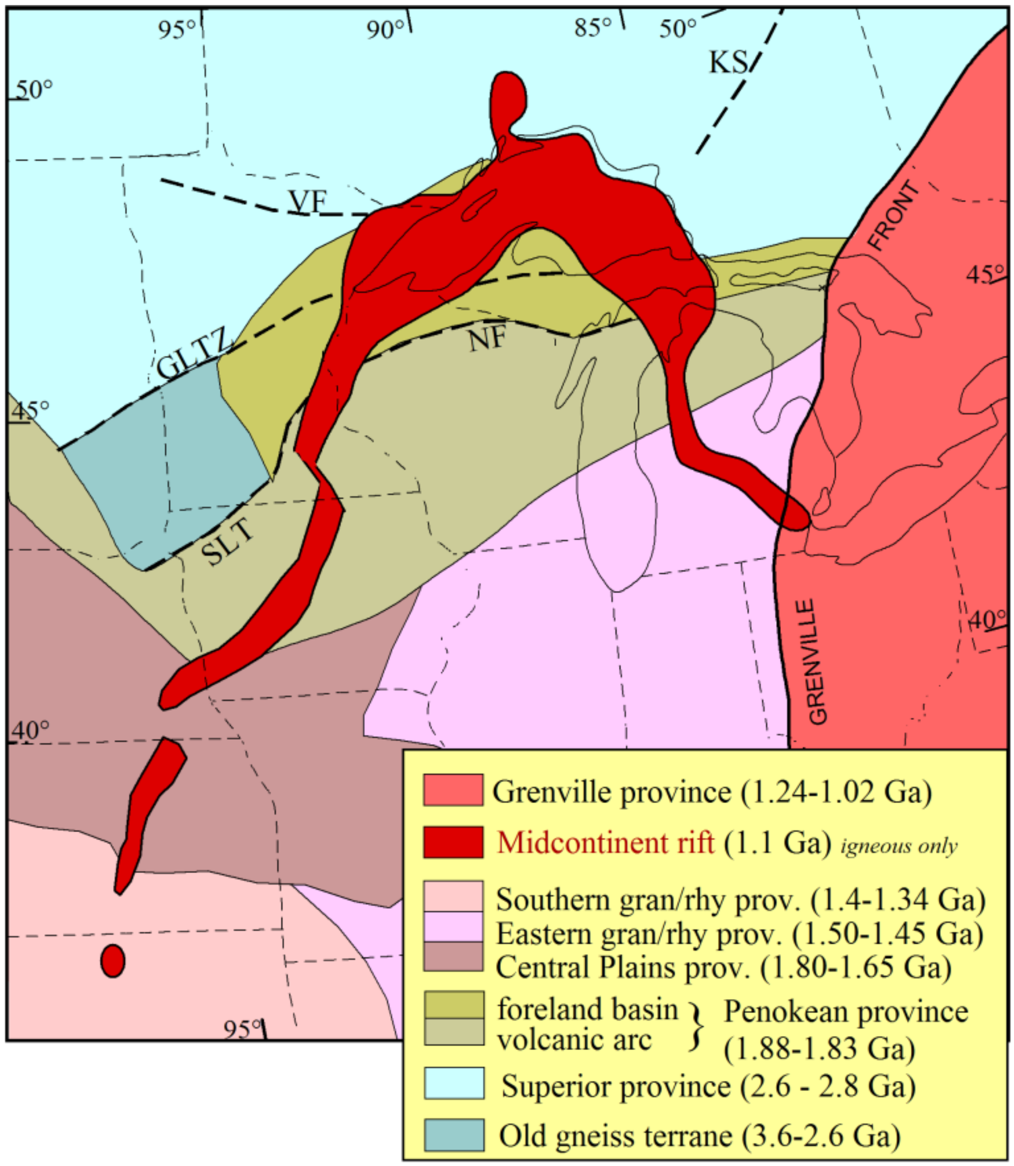


Figure 1.4 Extent of the Midcontinent Rift relative to other Precambrian terranes. Modified from Van Schmus (1992).

Extensive bedrock mapping in the Lake Superior basin has shown that the MCR is composed of three major lithologic components: 1) subaerial lava flows, 2) plutonic hypabyssal intrusive rocks, and 3) overlapping sedimentary rocks (Fig. 1.5). Cannon (1992) estimated a preserved volume of mafic rock in the Lake Superior region to be $2x10^6$ km^3, which puts it on par with other large igneous provinces considered to be generated by plumes (Ernst and Buchans, 2001). Major reverse faults commonly juxtapose the volcanic and sedimentary rocks (Fig. 1.5), however seismic data indicate that many of these faults (e.g. Kf, Df, IRf in Fig. 1.5) originally developed as graben-bounding normal faults whose displacement were reversed during late Grenvillian compression (Cannon et al., 1989; Cannon, 1992, 1994). Geophysical models also imply that grabens developed as asymmetric, en echelon basins separated by subtle- to well-defined accommodation zones (Chandler et al., 1989; Cannon et al., 1989; Dickas and Mudrey, 1997; Anderson, 1997; Berendsen, 1997). Because older volcanic rocks with reversed polarity generally occur outside the main graben faults, whereas younger, normal polarity volcanics are confined to within the grabens, graben development most likely began after the initiation of volcanic activity (Cannon et al., 1989). Further complicating the rift structure in western Lake Superior are the effects of large, crustal blocks (Fig. 1.5). The Grand Marias block and White's Ridge are isolated within the volcanic basins, but the Schroeder-Forest Center ridge (SFC) divides the Duluth Complex and the North Shore Volcanics into two "basins of accumulation" (Miller and Chandler, 1997; Miller and Severson, 2002).

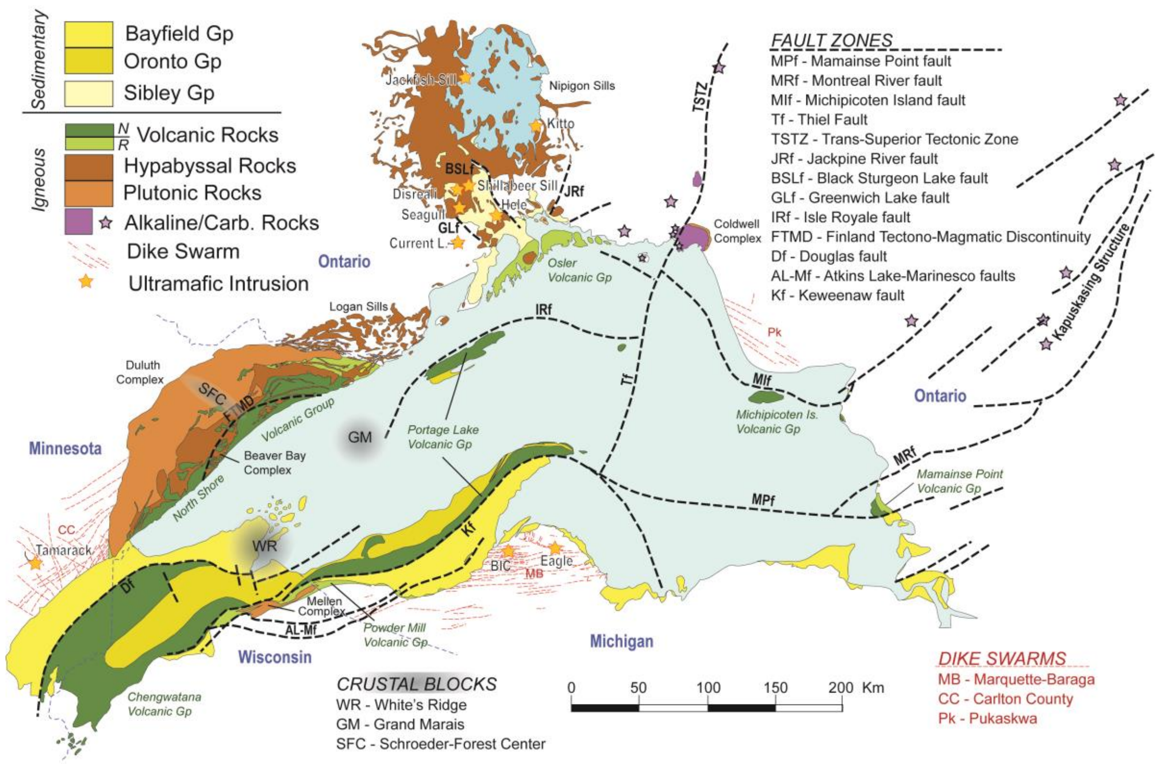


Figure 1.5 Geology of the Midcontinent Rift in the Lake Superior region (from Miller and Nicholson, 2013)

Geochronological, geophysical, and lithogeochemical data imply that the magmatic components of the MCR formed in several distinct stages (Miller and Vervoot, 1996; Nicholson et al., 1997; Davis and Green, 1997; Miller and Severson, 2002; Vervoort et al., 2007; and Heaman et al., 2007). Most recently, Miller and Nicholson (2013) proposed a six-stage model for the tectono-magmatic evolution of the rift that is based on the influence of a starting mantle plume and extensive crustal underplating (Fig. 1.6). Although the role and very existence of mantle plumes is questioned (Foulger and Jurdy, 2007), the majority of studies of the MCR argue that the arrival of an anomalously hot starting mantle plume at the base of the lithosphere at about 1115 Ma best explains the geologic, geochemical, geophysical, and geochronological data associated with the MCR in the Lake Superior region (Hutchinson et al., 1990; Nicholson and Shirley, 1990; Cannon and Hinze, 1992; Shirey et al., 1994; Miller et al., 1995; Miller and Vervoort, 1996; White, 1997; Hinze et al., 1997; Davis and Green, 1997; Shirey, 1997; Nicholson et al., 1997; Wirth et al., 1997; Vervoort and Green, 1997; Hollings et al., 2007b; Heaman et al., 2007; Vervoort et al., 2007; Hollings et al., 2010). The minimum volume of mafic rock estimated by Cannon (1992) of over two million km^3

requires an anomalously hot mantle source that would be expected from a mantle plume (Hutchinson et al., 1990). Others have argued that a starting mantle plume involved in the rifting process from the onset could have provided the tensional forces and thermal energy that drove extension and thinning of the lithosphere (Cannon and Hinze, 1992; Nicholson et al., 1997). In order to explain the anomalously long 30 m.y. duration of the magmatism, Hollings et al. (2012) suggested a mantle plume cluster. Alternatively, Campbell (2001) stated that strength of the lithosphere prior to mantle plume arrival and magnitude of subduction-related forces acting on the plate could extend the time difference between onset of volcanism and runaway extension (Hill, 1991). If by the end of main stage magmatism in the plume began to wane, a less problematic duration of 20 m.y. is achievable.

This study focuses on intrusive igneous rocks of the MCR, collectively referred to as the Midcontinent Rift Intrusive Supersuite (Miller et al., 2002). Weiblen (1982) identified three general categories of intrusive igneous rocks: 1) large subvolcanic intrusive complexes, 2) isolated alkali and carbonatitic intrusions, and 3) mafic sill and dike swarms (Fig. 1.5). A fourth category of small ultramafic/mafic intrusions commonly hosting Ni-Cu-PGE mineralization has been recently recognized (Fig. 1.5; Miller and Nicholson, 2013). Of particular interest to this study are the subvolcanic intrusive complexes, particularly the Duluth Complex (Figs. 1.5 and 1.1), which was emplaced into the lower part of the volcanic edifice that is the North Shore Volcanic Group (NSVG) exposed along Minnesota's shoreline (Miller et al., 2002).

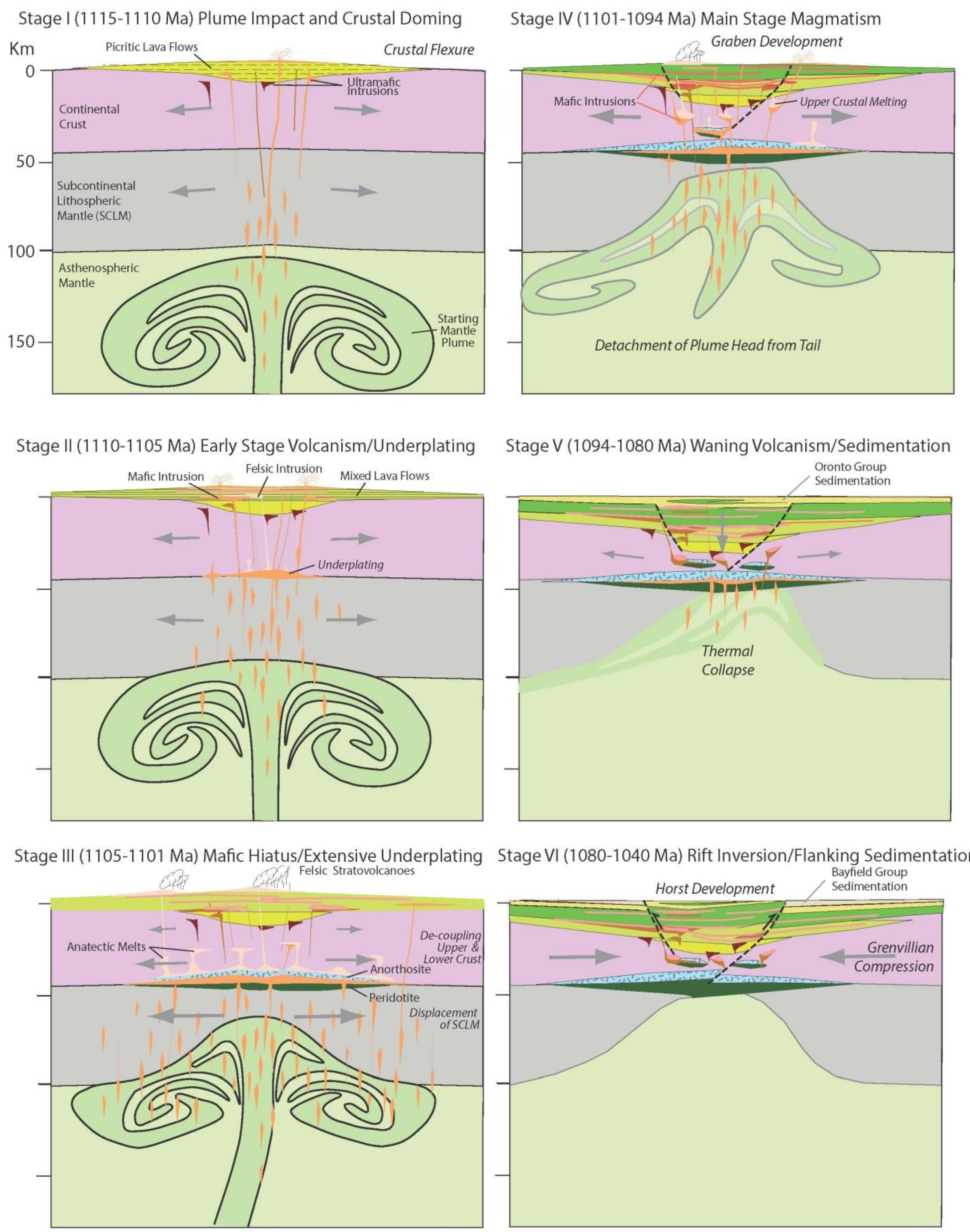


Figure 1.6 Six stage model for the tectono-magmatic evolution of the Midcontinent Rift (from Miller and Nicholson, 2013).

The Duluth Complex, which was emplaced into the base of the NSVG during the early and main stages of magmatism in the MCR (Fig. 1.6), is an arcuate intrusive complex of mafic to felsic rocks extending from Duluth, Minnesota nearly to the Canadian border (Fig. 1.1). With its exposure being some 270 km long, up to 40 km wide, and geophysical modeling of its gravity signature indicating a root up to 13 km thick (Allen et al., 1997), it is estimated to be the second largest mafic intrusive complex on earth in terms of volume (Miller and Severson, 2002). The Duluth Complex is composed of multiple sheet-like intrusions that are commonly grouped into four intrusive series on the basis of lithology, age and internal structure (Miller and Severson, 2002). In order of emplacement, the four series are: 1) the Felsic Series, composed of granophyre intrusions concentrated in the roof zone of the complex, 2) the Early Gabbroic Series, composed of oxide-rich gabbroic intrusions along the northern part of the complex, 3) the Anorthositic Series, composed of structurally complex plagioclase cumulates occurring in the medial to upper reaches of the complex, and 4) the Layered Series, composed of over a dozen discrete mafic layered intrusions that display varied degrees of internal differentiation (Fig. 1.1). These intrusions were emplaced between a footwall composed of Paleoproterozoic metasedimentary rocks and Archean granite-greenstone terrane rocks and a hanging wall of mixed volcanics that was 3 to 5 kilometers thick (Miller et al., 2002).

Emplaced during early stage magmatism along the eastern and central roof zone of the complex, the Felsic Series intrusions consist mostly of massive granite (granophyre) with lesser intermediate rocks. Vervoort et al. (2007) concluded from radiogenic isotopic data collected on Felsic Series intrusions that the granitic magmas were likely generated by partial melting of Paleoproterozoic rocks in the lower crust. Zircon U-Pb ages from the granophyric rocks range from 1109-1106 Ma (Vervoort et al., 2007). The early gabbroic series was also emplaced at this time (~1108 Ma, Paces and Miller, 1993) along the northeastern contact of the complex as layered mafic cumulates. The gabbros are thought to have been emplaced beneath the granophyre bodies, which caused melting and assimilation of the granophyre and gave rise to gradational contact relationships marked by intermediate rocks. Miller and Severson (2002) speculated that the felsic series may have acted as a rheologic and density barrier for the early gabbroic magmas.

The Anorthositic and Layered series were both emplaced during main stage magmatism (Stage IV, Fig. 1.6) and consistently give zircon U-Pb ages around 1099 Ma (Paces and Miller, 1993; Hoaglund, 2010). The Anorthositic Series consists of plagioclase-rich, gabbroic cumulates found throughout the complex (Fig. 1.1). Based on structural complexity indicated by ubiquitous plagioclase foliation and other attributes, Miller and Weiblen (1980) interpreted the anorthositic series to have been formed by multiple intrusions of plagioclase crystal mush – mafic magma carrying up to 60% intratelluric plagioclase. These mushes are thought to have been generated by flotation of plagioclase in lower crustal magma chambers where plagioclase would be buoyant in a mafic magma under high pressure. The Layered Series is made up of numerous, variably differentiated mafic layered intrusions composed of stratiform troctolitic to ferrogabbroic cumulates that were emplaced beneath or into the Anorthositic Series at the base of the complex. The Layered Series is commonly found intruding the anorthositic series and contains inclusions of the plagioclase-rich rocks even though their U-Pb ages are irresolvable (Paces and Miller, 1993; Hoaglund, 2010). Miller and Severson (2002) suggested that both magma series were derived from a deep crustal magma chamber, but after the plagioclase-rich component was extracted from the source, subsequent intrusions were depleted in suspended plagioclase, underplated the Anorthositic Series cumulates, and fractionally crystallized to form the Layered Series intrusions.

The Layered Series can be broken up into at least eleven discrete bodies showing varying degrees of internal differentiation. The majority of these intrusions dip east and southeast toward the MCR rift axis and are 1-4 km-thick sheet-like bodies. Exceptions to this include the funnel-shaped Bald Eagle intrusion, the plug-like Osier Lake intrusion, and the north-dipping WLI. All Layered Series intrusions display some degree of fractional crystallization-driven differentiation with individual differences attributed to recharge and eruption events, country rock assimilation, parental magma composition and, crystallization conditions (Miller and Ripley, 1996). Although a relatively small intrusion, the Wilder Lake intrusion has many petrologic and structural attributes that are distinctive compared to other Layered Series intrusions and, up until this study, are poorly understood.

1.2 Previous Studies of the Wilder Lake Intrusion

The well-layered troctolitic to gabbroic rocks that have come to be called the Wilder Lake intrusion were first recognized during reconnaissance mapping by William C. Phinney in the summers of 1969 and 1970. Phinney's mapping was part of a larger mapping program conducted from 1965 to 1971 throughout northeastern Minnesota funded by the MGS (Miller, et al., 2002). With the Boundary Waters Canoe Area Wilderness (BWCAW) not established until 1978, much of the mapping by Phinney in the northwestern part of the Duluth Complex was accomplished by float plane support by the U.S. Forest Service. His mapping of the lake-poor area of the WLI was accessed by logging roads; logging was a prevalent activity at the time. Phinney's mapping of the Duluth Complex in over six 7.5' quadrangles was never published. Rather, he summarized his mapping observations in the MGS's Centennial Volume on the Geology of Minnesota (Phinney, 1972). In his paper on the northwestern part of the Duluth Complex, he included a figure of his map areas (Fig. 1.7) that showed an area of north-dipping layered gabbros and troctolites that extend south of the main marginal troctolites at the base of the complex and then open up into an east-west area from North Wilder Lake on the west and to Arrow Lake to the east, a strike-length of

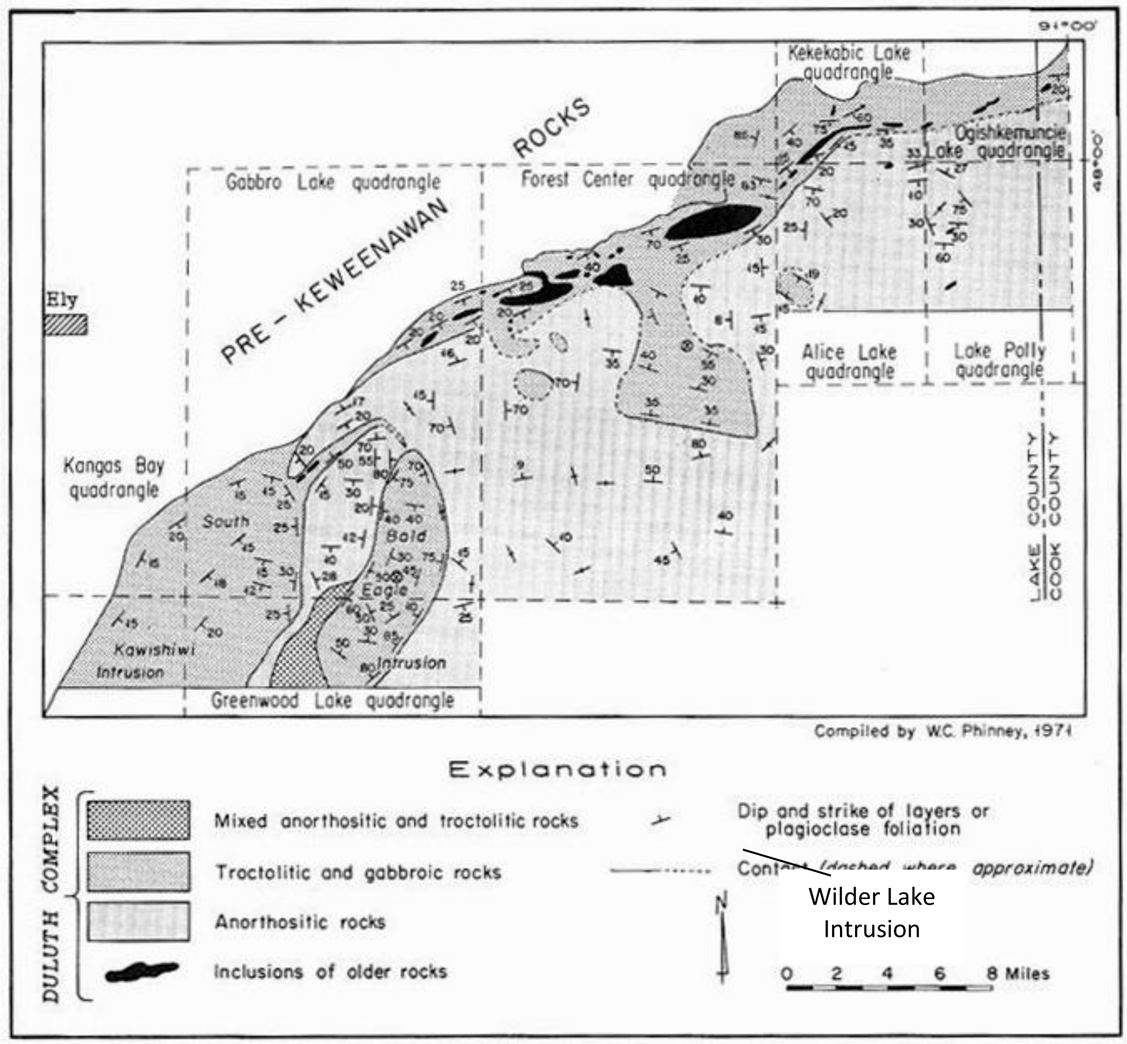


Figure 1.7: Generalized geology of the northwestern Duluth Complex mapped by W.C. Phinney from 1961-1971 (adapted from Phinney, 1972). What is now recognized as the Wilder Lake Intrusion is noted.

about 10 kilometers (Fig.1.7). Phinney (1972) noted that internal layering and foliation dips to the north-northeast between 15° and 35°, which contrasts with the southerly to easterly (riftward) dip of most layered gabbros of the Duluth Complex.

In 1981, J. Miller conducted mapping in the Duluth Complex to the west of the WLI. From reconnaissance level mapping and collecting a suite of 15 samples across its igneous stratigraphy, Miller (1986) quickly recognized the unique attributes of the WLI, described more completely in a later paper by

Miller and Ripley (1996) on layered intrusions of the Duluth Complex. They noted the distinct structural setting of the WLI contained entirely within Anorthositic Series rocks and dipping to the N-NE, its distinctive cumulate stratigraphy with oxide arriving before augite, and its reversed cryptic layering in olivine and pyroxene. They attributed its N-NE dip to its sloping off an Archean granitic structural ridge under the Duluth Complex. The WLI's unique orientation, higher structural emplacement in the Duluth Complex package, and the presence of a chilled margin was taken to indicate that it may be younger than other Layered Series intrusions emplaced beneath the Anorthositic Series along the base of the Duluth Complex. They suggested two possible explanations for the reversal to a troctolitic composition above the four-phase gabbro: 1) multiple recharge events of a primitive magma and 2) the merger of the upper border series with the main layered series, similar to the Sandwich Horizon in the Skaergaard intrusion (Wager and Brown, 1967). Miller (1986) noted curious features of the WLI wherein mineral chemical analyses through the cumulate stratigraphy showed a reversed cryptic variation in the mg# of olivine and pyroxene (Fig. 1.8). Surprisingly, the highest Fo content in olivine occurred in the most mineralogically evolved 4-phase cumulates of Pl-Cpx-FeOx-Ol. With the upper oxide troctolite and olivine oxide gabbro cumulates being well foliated adcumulates, Miller and Ripley (1996) suggested that the reversed cryptic variation could be explained by progressively less trapped liquid in the upper cumulates resulting in a less extreme liquid shift.

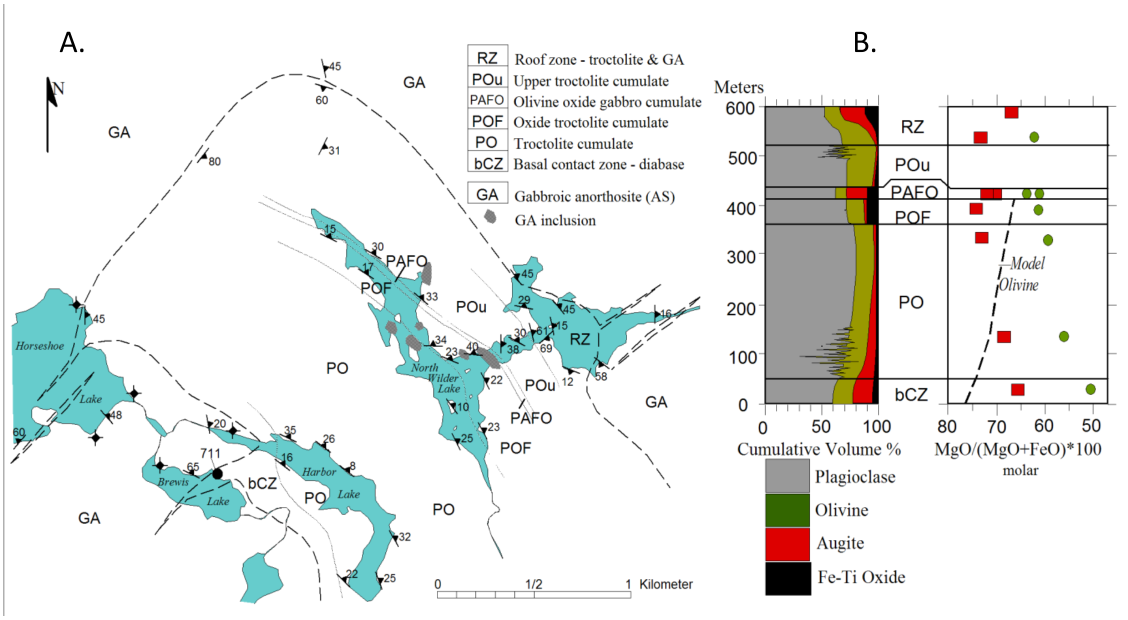


Figure 1.8: A) Cumulate units of the western end of the Wilder Lake Intrusion. B. Stratigraphic variations in modal mineralogy and mg# of augite and olivine. Model olivine line is the calculated cryptic variation in Fo content of olivine expected from fractional crystallization of a chilled gabbro composition from the bCZ unit. (modified from Miller and Ripley, 1996).

In 2002, Joy Turnbull embarked on a study the WLI geology and petrology in greater detail for her MS thesis at the University of Minnesota Duluth. The principal objectives of this study were to extend the mapping away from the lakeshores mapped by Miller (1986) and to verify and evaluate the origin of some of its enigmatic features highlighted by Miller and Ripley (1996; N-dip, unique cumulate stratigraphy, reversed cryptic variation). This was to be accomplished by conducting detailed field mapping, sampling, petrographic study, mineral chemical analysis, and lithogeochemical analysis. An EDMAP award was granted for the 2003-04 academic year to support three weeks of mapping in the western part of the WLI. However, because of extremely dense woods and abundant downed trees from the 1999 wind storm, the amount of map coverage was not as extensive as originally planned. Nevertheless, Turnbull did delineate new details about the igneous stratigraphy of the WLI. One notable discovery was the occurrence of a lower oxide olivine gabbro unit that is not evident everywhere along strike. This and other improvements on previous mapping were integrated into an unpublished 1:24,000 scale geologic map provided to the USGS for the EDMAP project (Turnbull and Miller, 2004) and in a compilation map (M-148) of the Ely and Basswood 30' x 60' sheets published the same year by the MGS (Fig. 1.9; Jirsa and Miller, 2004). In order to create a new Ely-Basswood map, Miller extended the stratigraphy of the intrusion to Arrow Lake in the early 2000's. This was accomplished through the use of Phinney's unpublished data because most of the eastern portion of the intrusion is land-locked and difficult to access.

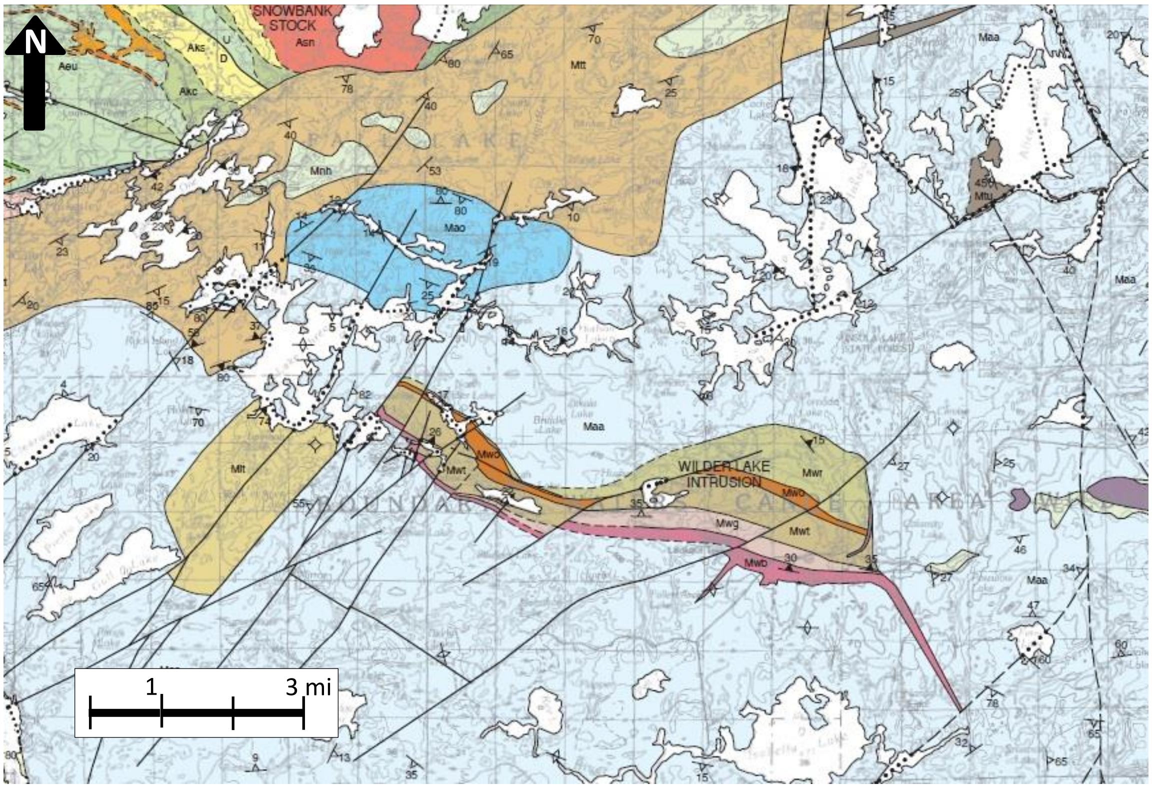


Figure 1.9 Part of the geologic map for the Ely-Basswood 30'x 60' sheet (Jirsa and Miller, 2004) that shows the geology of the Wilder Lake Intrusion as interpreted by the mapping by Turnbull and Miller (2004) on the west end and by Phinney (unpublished mapping, 1969, 1970) on the east end. The five units delineated within the intrusion are: Mwb - olivine gabbro; Mwg - olivine gabbro cumulate; Mwt - troctolite cumulate; Mwo - oxide troctolite to olivine oxide gabbro cumulate; and Mwr - roof zone troctolite.

In addition to the map compilation, Turnbull conducted petrographic studies of samples collected during field work. She acquired mineral chemical analyses from over 40 thin sections through the WLI stratigraphy that sought to verify the reversed cryptic variation reported by Miller (1986; Miller and Ripley, 1996), and she obtained 27 whole rock geochemical analyses through the WLI stratigraphy. With her cooperation and encouragement, Turnbull's unpublished field, petrographic and geochemical data are integrated into this study.

2. Goals and Objectives

The overall goal of this study is to establish the emplacement and crystallization history and the parental magma composition(s) that produced the unique petrologic attributes of the Wilder Lake Intrusion along its entire strike-length. These attributes, noted by others and confirmed here, include 1) its unique cumulate stratigraphy where Fe-Ti oxide becomes a cumulus phase before augite; 2) the cumulus reversal indicated by the change from a four-phase cumulate of Pl+Cpx+Ox+Ol abruptly giving way up-section to a troctolitic (Pl+Ol) cumulate; and 3) its reversed cryptic variation of Fo in olivine and En' in clinopyroxene. From these variations, I hope to show a crystallization history that relates to parent magma evolution during emplacement. The 2011 Pagami Creek forest fire opened up a perfect opportunity to confirm and document the first and second attributes with exceptional and dramatic field exposures along the entire lateral extent of the WLI.

The specific objectives of this study to be pursued to accomplish these goals are:

1. Document the igneous stratigraphy and internal structure of the WLI and the contact relationships with the enclosing Anorthositic Series with detailed field mapping along its entire breadth and width.
2. Document the petrographic attributes of samples collected in order to verify observations made in the field that establish its cumulate stratigraphy and thus discern more about the WLI's crystallization history
3. Measure the compositions of olivine and pyroxene in samples collected along several stratigraphic transects of the WLI to establish its cryptic layering along its vertical and lateral extent
4. Acquire whole-rock chemical compositions of samples from the marginal gabbro unit to evaluate if they may serve as an approximation of the WLI's parental liquid composition and determine what conditions of crystallization, pressure, and oxygen fugacity affecting this composition may explain the cumulate paragenesis of the WLI.

3. Methods of Investigation

In order to accomplish the goals of this study, several different methods of study were employed. Primary to the study was extensive field mapping of the entire WLI, which was conducted from the summer 2012 to the autumn of 2013. Samples collected from the field study were then used for 1) petrographic observations to better characterize primary and secondary mineralogies and textures; 2) mineral chemical analyses to document the cryptic variation and verify its previously identified reversed trend; and 3) whole-rock geochemical analysis to gain insight into the parental magma composition and its crystallization history. The details on how these investigative methods were conducted are presented below.

3.1 Field Mapping

This project included five weeks of field mapping extending over two summers. Building from the previous shoreline mapping in the western extent of the WLI in the Harbor Lake and North Wilder Lake area by Miller (1986) and Turnbull (2003), this mapping project was launched the week of August 5-11, 2012 as part of UMD's Precambrian Field Camp capstone project. The Wilder Lake capstone mapping project involved field camp students Lionnel Djon, Emily LaPietra, Zach Martin, and Ricardo Martinez. I served as teaching assistant for the camp and Dr. Miller was the lead instructor. Anchored at a base camp on Lake Three (Camp A, Fig. 3.1), five days of mapping were conducted by three field parties of two people. Most of the work focused on mapping the newly exposed outcrops in the areas between the lakes that were previously mapped. The results of this work were published as a geologic map by the Precambrian Research Center (LaPietra et al., 2012).

Following this introduction to the WLI in its now well mapped western end, subsequent mapping shifted to the east and central parts of the intrusion. With the assistance of Spencer Young, I conducted mapping during the autumn of 2012. We worked from a base camp on the eastern shore of Brewis Lake (Camp B, Fig. 3.1). From these, mapping transects were made north, south and just west of South Wilder Lake in order to fill in the final details of the western portion of the intrusion, focusing on the land-locked portions of the area. From there, the eastern half of the WLI was accessed via the Pow-Wow Trail (an old logging road) from a base camp set up on the western edge of Isabella Lake (Camp C, Fig. 3.1). Final mapping in2012 in the eastern part of the intrusion was completed by myself, Young, Miller, and Matt

Aldag, divided into two teams in order to complete mapping transects. Because of the distance required to simply reach the central part of the intrusion, however, a sizable gap still remained between the western and eastern mapped regions.

Central parts of the WLI were mapped in 2013 as part of UMD's PRC capstone project, accompanied in the field by John Smith, in the area east of South Wilder Lake (Camp D, Fig 3.1; Smith and Leu, 2013).

Figure 3.1 Locations of base camps A) Lake Three – August 05-10, 2012; B) Brewis Lake – September 14–22, 2012; C) Isabella Lake - September 27- October 02, October 11-14, 2012, May18-22, 2013; and D) South Wilder Lake – August 4-9, 2013. (modified from USDA Forestry Service GIS data)

During the field mapping excursions, samples were collected along transects perpendicular to strike at various locations along the lateral extent of the intrusion (Fig. 3.2). With follow-up petrographic and geochemical analysis of these samples, the lateral changes in lithostratigraphy and chemostratigraphy could be documented. In the field, detailed notes were taken at each outcrop including information on UTM location, type of outcrop, quality of exposure, major and minor lithologies observed, presence and orientation of structural features, descriptions of any photos and samples taken and burn conditions. In addition, outcrop locations, station ID, traverse lines, structural measurements, and sample locations where plotted on mylar overlays of 1:10,000 scale LiDAR base maps.

The nomenclature and terminology used to classify mafic rocks in the field followed the conventions recommended by Miller et al. (2002) where modal rock classification is in line with natural modal populations of essential minerals (olivine, plagioclase, pyroxene, and Fe-Ti oxides) as shown in Table 3.1. This classification scheme was particularly easy to use during field mapping because it is based on relative ratios of major mafic phases, and is subsequently revised during optical petrography. Bulk textures of the mafic rocks are defined by pyroxene texture (ophitic, subophitic, or intergranular). The planar alignment of elongate minerals (foliation), typically defined by plagioclase and locally clinopyroxene, was qualitatively noted as being poorly, moderately, well, or very well developed (or not developed – random) and the orientation of the foliation was commonly measured. Modal and, less commonly, textural layering was commonly developed in some units, particularly in the lower sections of the WLI. The frequency, modal contrast, planarity, lateral continuity, and scale of layering was routinely noted and the orientation of layering was measured during the mapping.

Another rock classification convention that was commonly used in describing the mafic cumulates in the field is a short-hand notation of texture and mode developed by Miller et al. (2002). As summarized in Table 1, mineral abbreviations are used for each common mineral with upper case letters used for minerals with granular (cumulus) habits, and lower case letter used for minerals with interstitial (intercumulus) habits. Any phase greater than 2% is listed in decreasing order of abundance regardless of habit. Some additional features to the code recommended by Miller et al. (2002) include: 1) prefacing the code with grain size abbreviation (vf- very fine, f- fine, mf- medium fine, m- medium, mc- medium coarse, c- coarse); 2) denoting poikilitic and subpoikilitic textures with an accent mark and carrot mark, respectively, over the mineral (e.g., ĉ and ć, for ophitic and subophitic augite, respectively); 3) drawing one or two lines over minerals that display moderate to well-developed foliation, respectively; and 4) enclosing noteworthy minerals with abundance under 2% in parentheses. Examples of the code applied to common rock types observed in the WLI are shown in Table 3.1.

Following field work, field maps were digitally scanned, imported into ArcGIS™ and georeferenced to USGS digital raster graphic images of 7.5' topographic quadrangles and LiDAR images. The outcrops, samples, transects, and structural measurements were then digitally traced from these georeferenced field maps as polygon, line and point shape files and were then attributed. Geological interpretations of map units (described in the results section below) were defined based on general cumulate mineralogy and other attributes (homogeneity of texture and mode, frequency of layering, anorthositic inclusions, etc.). Faults were inferred from topographic lineaments and apparent offset of geologic units, and geologic contacts were inferred from outcrop data, structural measurements of layering and foliation, and topographic features. Subsequently, these data were exported as .eps files and a final map (Plate 1) was produced in Adobe Illustrator™. Included on the geological map are map unit descriptions, cross-sections, geophysical images, a correlation diagram, map symbol legend, references, and a brief description of the regional geologic setting.

Table 3.1: Abbreviated modal and textural Code (Miller et al., 2002) commonly used in this study.

Cumulus/Intercumulus Mineral Codes

PP*/Pp**/P	–	plagioclase	F/f	-	Fe/Ti oxide
O/o	-	olivine	I/I	-	inverted pigeonite
C/c	-	clinopyroxene	b	-	biotite

*designates anorthositic rocks (Plagioclase > 85%)

**designates plagioclase rich (leuco-) rocks (Plagioclase 78-85%)

Cumulate code translation of common rock types in the Wilder Lake Intrusion

Medium-grained ophitic augite troctolite	$\mathrm{mPO\hat{c}f}$
Medium coarse-grained, foliated, subophitic oxide troctolite	$\mathrm{mc\overline{P}OF(\acute{c})}$
Medium fine-grained, well foliated, intergranlar olivine oxide gabbro	$\mathrm{mf\overline{\overline{PC}}FO}$
Coarse-grained, foliated, poikilitic olivine-bearing, anorthosite	$\mathrm{c\overline{PP}\hat{o}}$

3.2 Petrographic Study

Petrographic observations using a transmitted light microscope were made on about 200 thin sections, including samples collected by Turnbull and Miller during their previous investigations in the WLI. Petrographic observations aimed to characterize the mineralogical and textural attributes of the main rock types so as to confirm observations made in the field and to give insight into the cumulus paragenesis of the primary minerals. Whole rock attributes noted included modal mineralogy (visually estimated), absolute and relative grain size, development of foliation (all section were cut perpendicular to foliation), bulk texture (defined by pyroxene habit), and type and intensity of alteration. Noted attributes of individual minerals include habit, compositional zoning, exsolution, overgrowths, and twinning.

Photomicrographs of textures, mineral assemblages, and alteration features were taken to illustrate the textural and mineral characteristics that document and give insight into the formation of these rocks. Representative photomicrographs from each unit in the WLI were used to generalize and illustrate any differences that occurred within and between the sections.

3.3 Mineral Chemical Analysis

In order to confirm the reversed cryptic variation in olivine and pyroxene noted by Miller (1986) and confirmed by unpublished data of Turnbull, a major focus of this project was to further confirm this puzzling attribute in the western WLI and to determine if this upward trend of increasing mg# (Fo in olivine, En' in pyroxene) persists along strike to the east. Therefore, a suite of 32 polished thin sections from three transects crossing the WLI were analyzed for their olivine and pyroxene compositions (Fig 3.2). Plagioclase was excluded from analysis because its significant and variable zoning would require many analyses to determine statistically-valid mean compositions.

Mineral analyses were conducted using a JEOL JSM-6490LV scanning electron microscope (SEM) and Oxford Inca 250 energy dispersive x-ray spectrometer (EDS) at the University of Minnesota-Duluth (UMD). Thin sections were coated with ~ 15 nm carbon film to prevent charging. Between 30 and 60 analyses per phase per sample were taken from the interior of the grains (avoiding rims). In each sample an equal amount of data were gathered, except for phases with very low abundances making it difficult to acquire a similar number of analyses. When analyzing augite, care was taken to avoid pinpointing orthopyroxene exsolution lamellae which could be easily detected (visually) during the analyses. Data from the SEM-EDS were output as atomic/mole percent and these data were input directly to spreadsheet software for analysis.

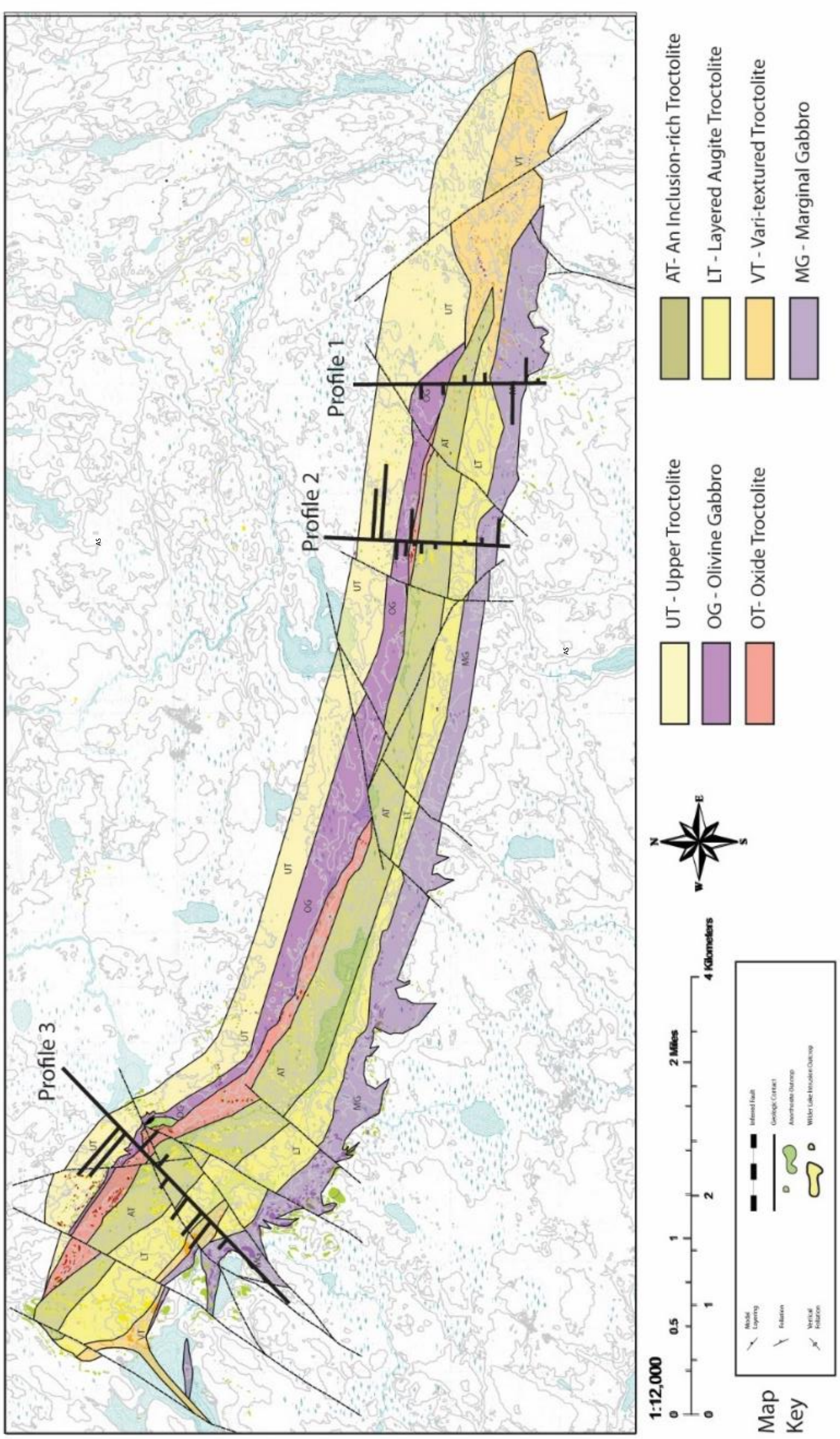


Figure 3.2: Geological map of the WLI, showing transect profile lines with sample locations projected to the profile. These profiles contained 32 samples for an average of 11 samples per profile.

3.4 Lithogeochemical Analysis of Contact Zone Samples

A suite of eleven samples was all chosen from the marginal gabbro at the base of the intrusion as a possible representations of the WLI's parental magma composition. They are all fine- to medium-grained, granular gabbros composed of plagioclase, augite, olivine, and Fe-oxides (listed in decreasing order of abundance). They show no cumulate textures in hand sample or thin section and are located within fifty meters from contacts with anorthositic series country rock.

These eleven contact zone samples were submitted to Acme Laboratories of Vancouver, BC for bulk rock geochemistry using ICP-ES/ICP-MS. Samples were prepared by mild steel crushing and pulverization to 80% passing size - 10 mesh, split 200g and pulverized to 85% passing a 200 mesh. A basic suite of whole rock major and trace element analyses (R200-250 were performed on >10g samples.

To evaluate the appropriateness of these samples as representative of the WLI's parent magma, their major, minor, and trace element compositions will first be compared to similar-aged MCR volcanic data to evaluate their efficacy as magma compositions. Compositions that represent plausible approximations of magmas will then be applied to PELE geochemical modeling program (Boudreau, 1999) to determine whether they could have generated the sequence and mass proportions of cumulus mineral crystallization observed in the WLI. PELE allows for changes in the type of crystallization (equilibrium vs fractional), pressure, and oxygen fugacity.

4. Results

Geologic and petrographic features of the WLI (Plate 1) are first interpreted from field and petrographic observations of the mineralogy, textures, structures and inclusions of the various rocks comprising the WLI. The map units thus defined are used as a framework for reporting on the vertical and lateral changes in petrographic, mineral chemical and lithogeochemical attributes of the WLI.

4.1 Geologic Map of the Wilder Lake Intrusion

A geological map integrating and interpreting the field mapping and petrographic studies of field samples conducted for this and previous studies is presented in Plate 1. A condensed version of this map is shown in Figure 4.1. The map shows that the WLI is a thin tabular mafic intrusive body with a 10 km strike length and a variable stratigraphic thickness between one and two kilometers (Fig. 4.2 A-C). The internal structure of the WLI (foliation and layering) dips gently to the north-northeast between 20-50° with an average ~35° and strikes between 285-320°. In profile, the exposed thickness of the WLI is approximately constant at ~2000 meters (Fig. 4.1).

The WLI is bounded on all sides by the leucogabbroic to anorthositic rocks of the Anorthositic Series. The basal contact along its southwest margin is sharp and is locally marked by dikes of fine- to medium grained olivine oxide gabbro projecting into Anothositic Series rocks. The hanging wall contact is more complex with troctolitic rocks of the upper WLI intruding into and hosting large inclusions of Anorthositic Series rocks.

Within the WLI, seven map strataform units were defined based mostly on cumulus mineralogy (Fig. 4.1). The common occurrence of modal layering or anorthositic inclusions also was used to subdivide a thick lower troctolite zone (LT and AT units, respectively, Fig. 4.1). The main cumulate and modal rock types, stratigraphic thicknesses, and distinctive features of the WLI units are summarized in Table 4.1 and described in more detail in the next section.

Across the strike length of the WLI the units remain fairly consistent in their mineralogy, texture, and are petrographically consistent. Generally, the units decrease in stratigraphic thickness away from the western edge of the intrusion before pinching out approximately 2-3 kilometers from the eastern extent. With more outcrop mapping in the far eastern portion of the intrusion it is possible that more delineations of the various units could be made, which may extend the LT, AT, OT, and OG units closer to the intrusion's eastern extent. That notwithstanding, there is some pinch and swell that occurs in all of these units and the OT and OG pinch out entirely in some places.

The contacts on the eastern and western edges of the intrusion with the surrounding Anorthositic Series has changed since Turnbull and Miller proposed faulted contacts at both sides. In the west there is a notable change in strike orientation indicates a direct igneous contact with the Anorthositic Series rocks. In the East the contact was never seen, but there is a notable disruption of foliation toward the perceived contact indicating that it, also, is a direct igneous contact. This contact was further verified by mapping completed by Mark Jirsa of the Minnesota Geological Survey.

Table 4.1: Main Attributes of WLI Map Units (listed in stratigraphic order)

Map Unit	Cumulate Types	Modal Rock Types	Strat Thick	Other Features
UT	PO, POcf	Troctolite, augite troctolite	130-170m	AS inclusions, crosscuts OG and OT units
OG	PCFO	Olivine oxide gabbro	40-100m	Very well foliated
OT	POF, POFc	Oxide troctolite	0-50m	Pinches and swells
AT	PO, POcf (w/ PPocf)	Troctolite, augite troctolite	140-200m	AS inclusions very common
LT	PO, POcf	Troctolite, augite troctolite	90-115m	Modally layered cm- to m-scale
VT	PPO, PO, POcf, POCf, POFc, POCF, POc, POF	Vari-textured troctolite, taxitic troctolite	0-70m	Variable texture and composition locally
MG	n/a	Olivine oxide gabbro	60-360m	Granular marginal gabbro, no cumulus minerals

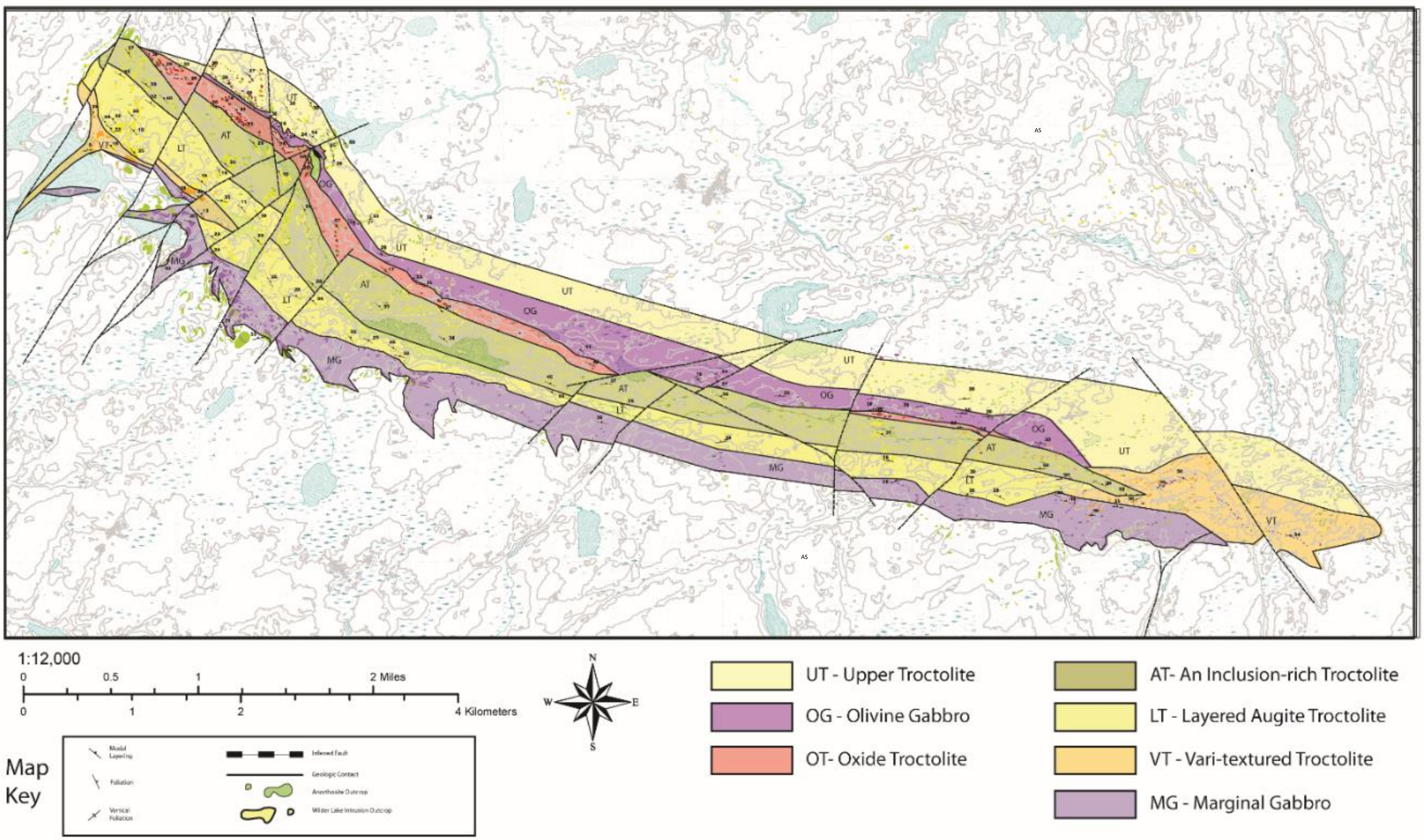


Figure 4.1: Simplified map of the WLI showing units, inferred faults, and internal structure on a LIDAR topographic base. Uncolored part of map is composed dominantly of Anorthositic Series rocks. Based on the 1:12,000 scale geologic map shown in Plate 1.

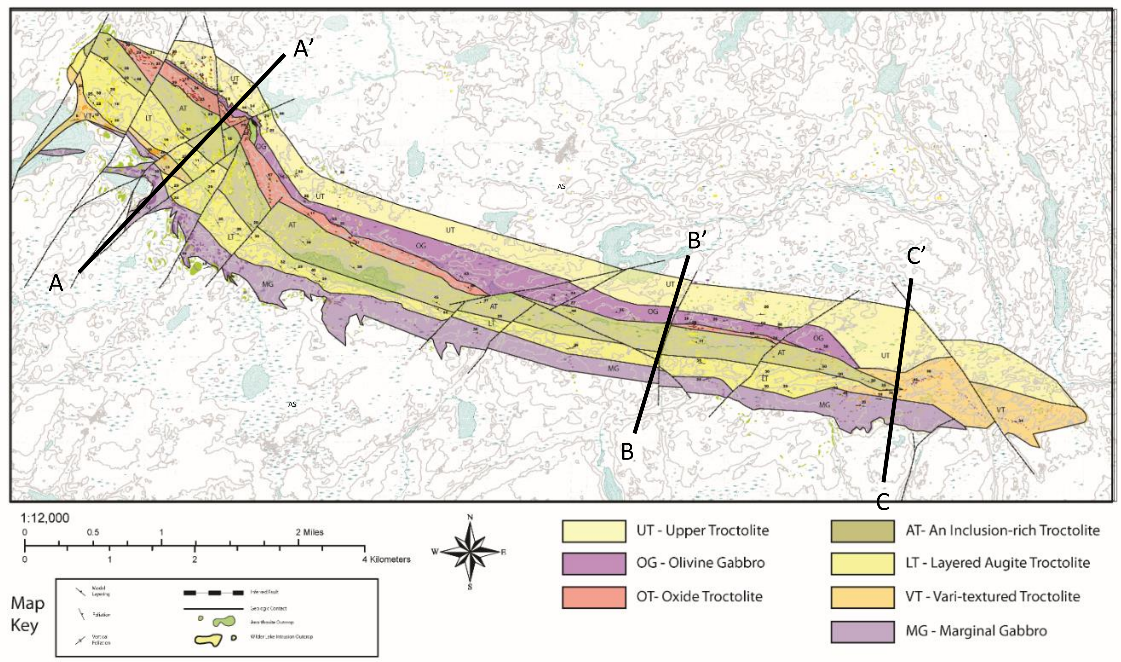


Figure 4.2A: WLI geologic map showing the locations of cross section profiles – A-A’, B-B’, and C-C’.

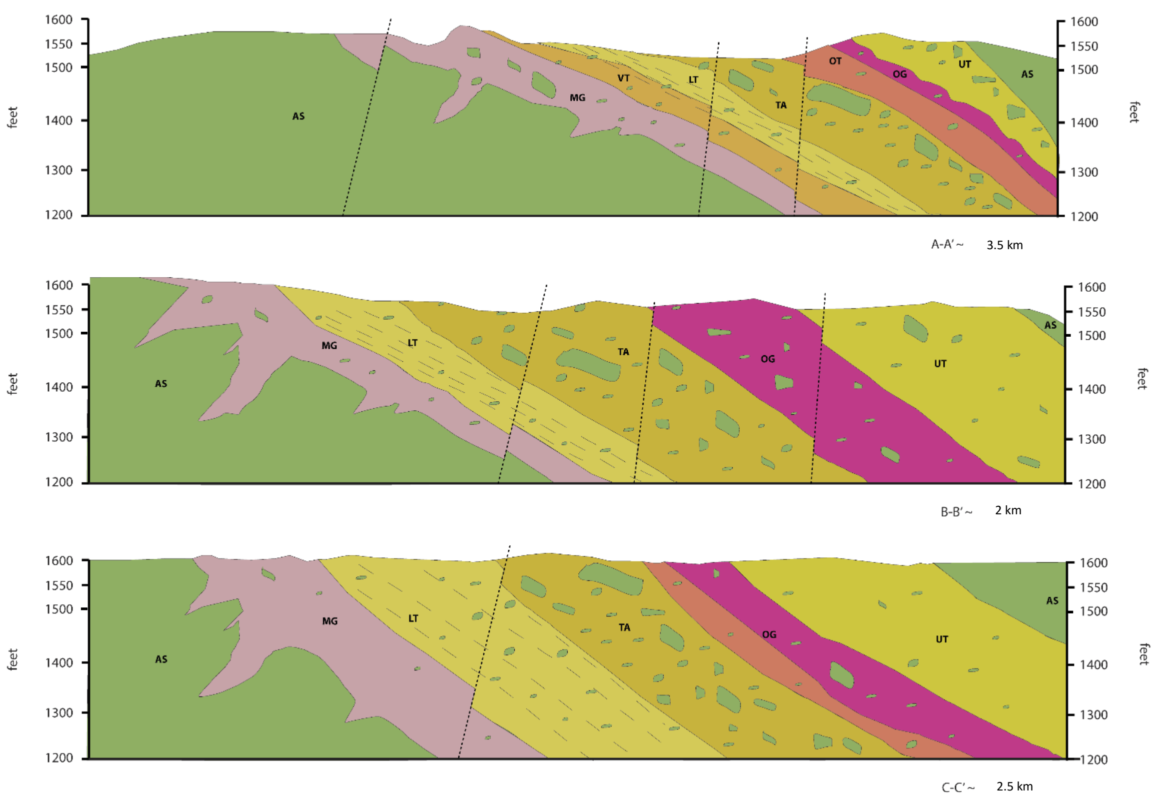


Figure 4.2B: Schematic cross sections profiling the western (A-A’), central (B-B’), and eastern (C-C’) segments of the WLI shown in Fig. 4.2A.

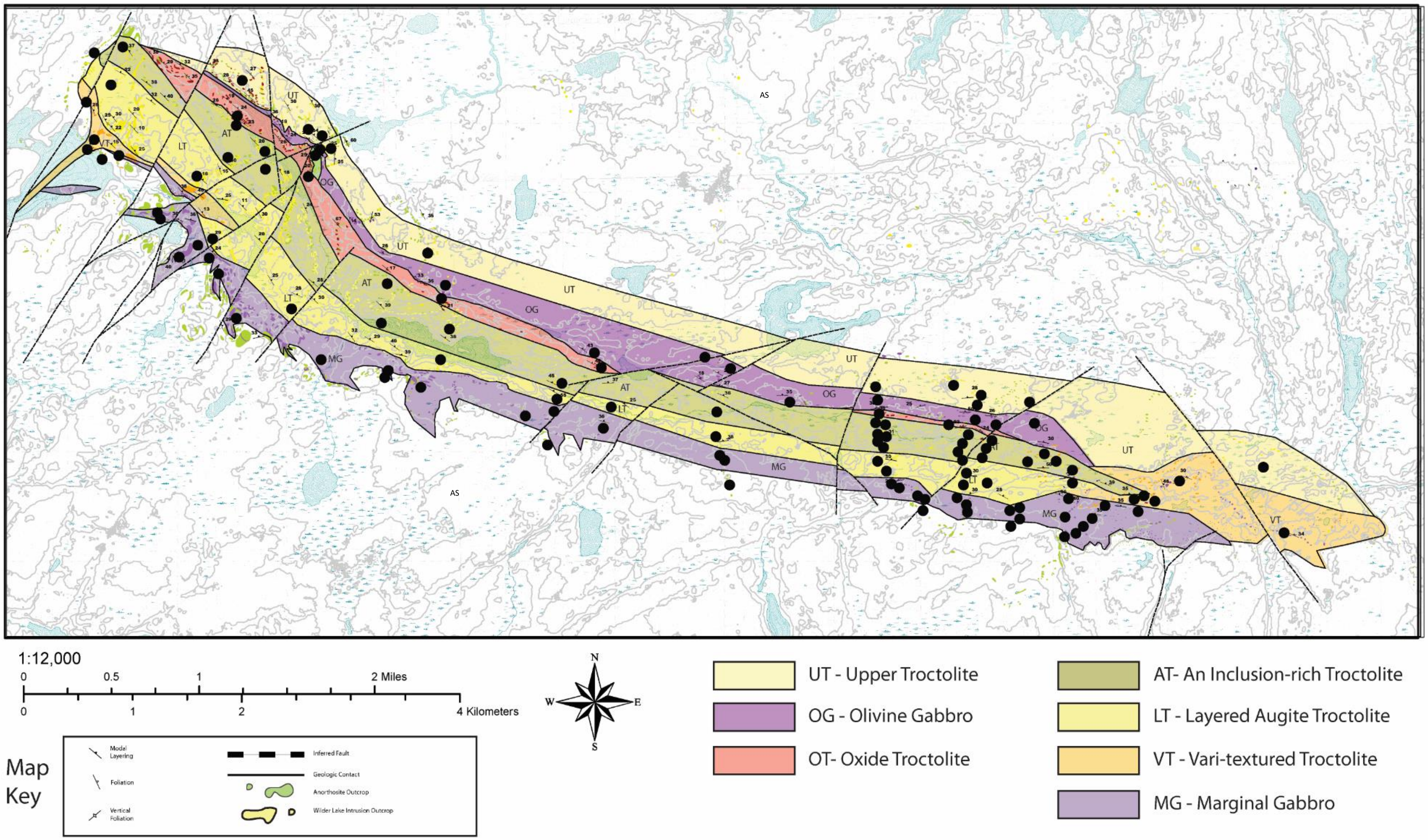


Figure 4.3: WLI geologic map showing sample locations collected for this study (marked by the black circles).

4.2 Field and Petrographic Attributes of the WLI Units

The following is a detailed description of the WLI units both from field observations and petrographic analysis from the stratigraphic bottom to the top. Full petrographic results of individual samples and their UTM locations can be found in Appendix A.

4.2.1 Anorthositic Series (AS) – The country rock surrounding the WLI is composed entirely of Anorthositic Series rocks. As found elsewhere in the Duluth Complex, the AS is composed of a range of plagioclase-rich (75-95%) mafic rock types including nearly pure anorthosite (Figs. 4.4A & 4.5), olivine anorthosite, leucotroctolite, olivine gabbroic anorthosite (Fig. 4.4B), and gabbroic anorthosite (Miller and Weiblen, 1990), though most AS rock types marginal to the WLI tend to be very plagioclase rich (Pl > 90%; e.g., Fig. 4.4A-4.5). Most lithologies tend to be coarse-grained, but range from medium-grained to very coarse-grained and are locally pegmatitic. Most occurrences display moderate to well-developed plagioclase foliation, which tend to be quite variable in orientation. Olivine abundance and habit are the most variable aspect of this series of rocks ranging up to 15% in mode and can be seen texturally as mm-sized anhedral granular crystals to poikilitic oikocrysts up to 10 cm in diameter (Fig 4.4B). Anorthositic Series rocks occur as the main country rock type as well as the main inclusion type throughout the WLI. Contacts with the WLI rocks range from angular to curvilinear and are typically sharp, though only the marginal gabbro unit and, locally, the varitextured troctolite unit show significant chilling effects.

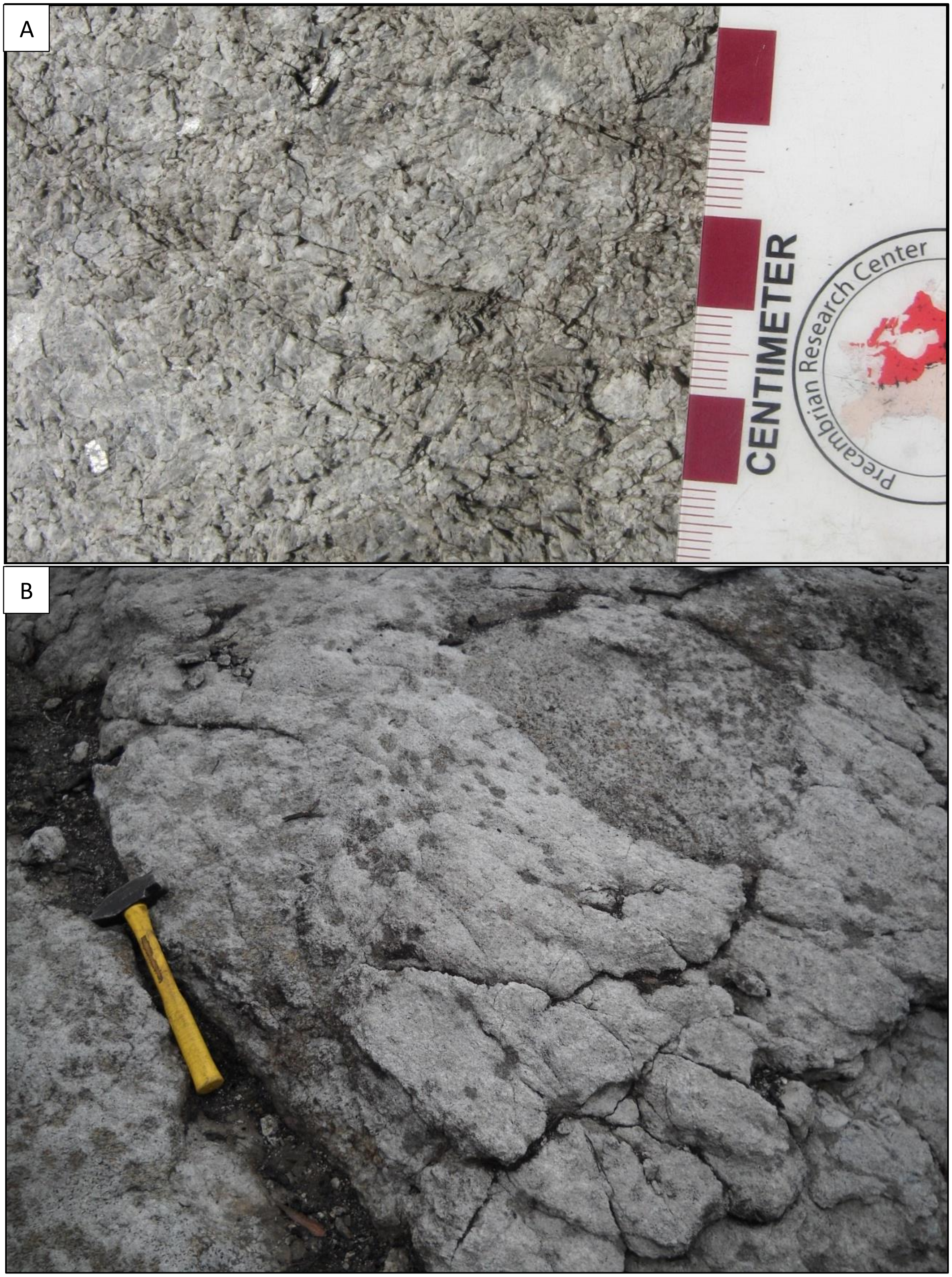

A
CENTIMETER
Precambrian Research Center
B

Figure 4.4: Field photos of Anorthositic Series exposures. A) outcrop composed of >95% plagioclase near Brewis Lake; B) poikilitic olivine gabbroic anorthosite with irregular distribution of 1-4 cm olivine oikocrysts near Horseshoe Lake. Photo (A) by A. Leu and photo (B) by J. Miller.

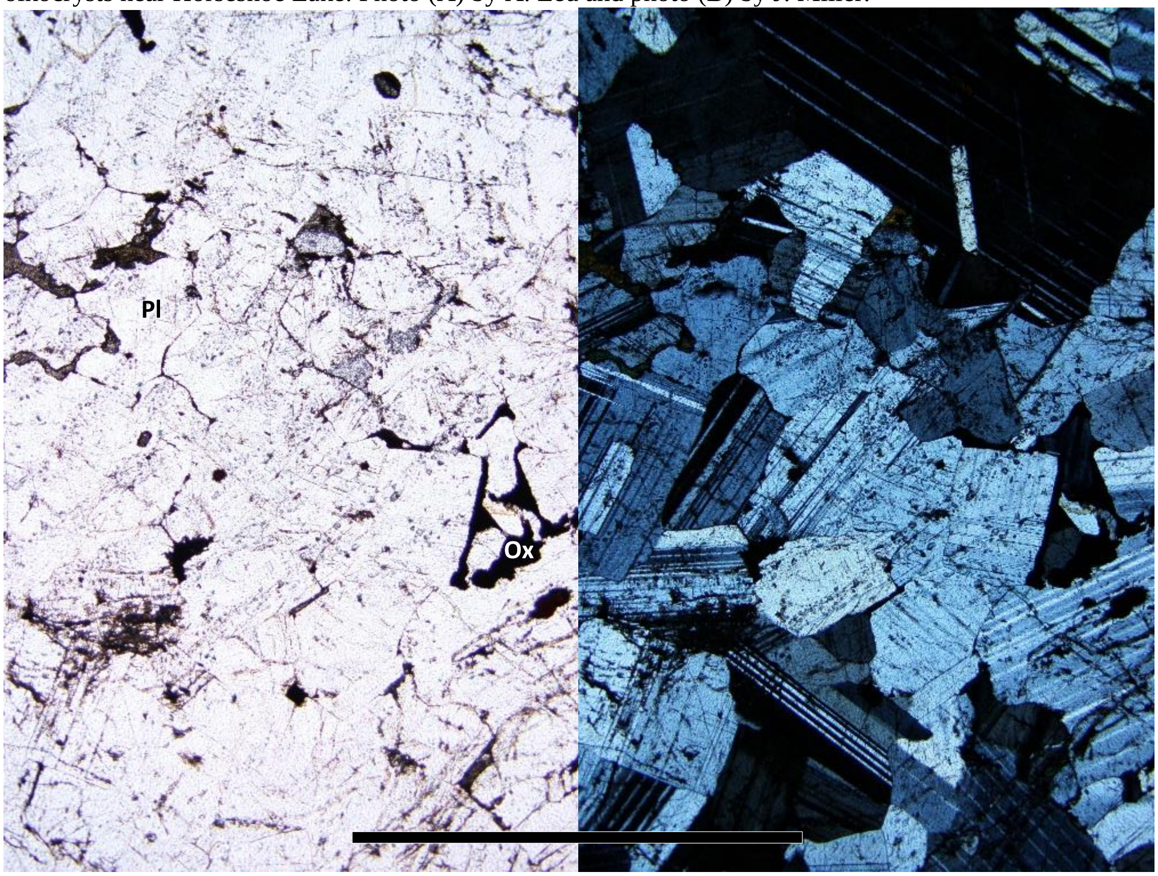


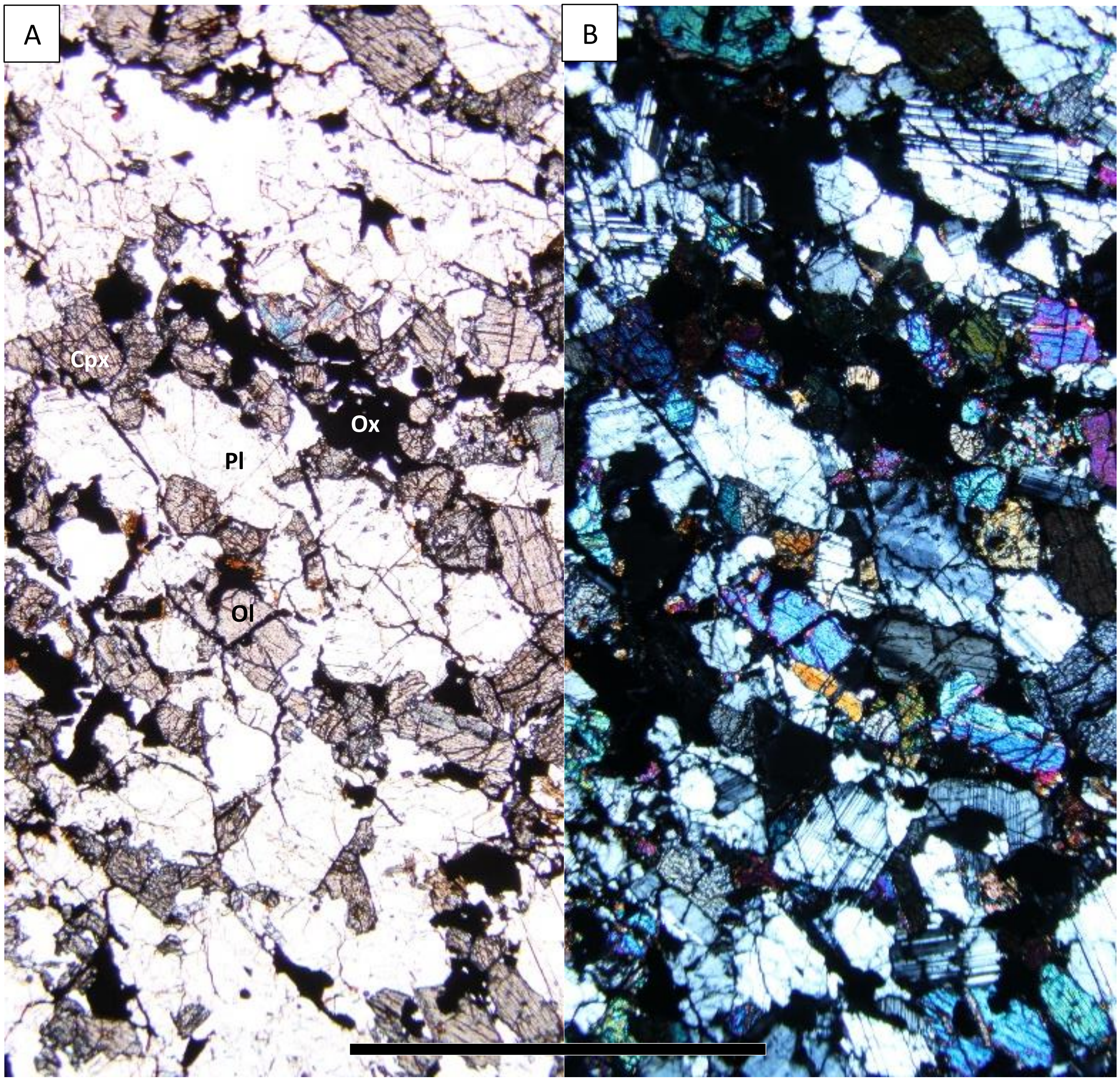
Figure 4.5: Photomicrograph (PPL on the left and XPL on the right) showing the plagioclase-rich mode typical of Anorthositic Series country rock. (Sample AS52; scale bar = 5 mm).

4.2.2 Marginal Gabbro Unit (MG) – Occurring along the irregular basal contact of the WLI with the Anorthositic Series rocks is a homogeneous to locally vari-textured, fine- to medium-grained, locally layered, nonfoliated to poorly foliated, intergranular to subophitic olivine oxide gabbro to ophitic augite troctolite. The marginal gabbro unit forms a basal contact zone for the WLI that is generally a tabular interval that ranges from 0 m to 120 m thick, but also projets into the AS footwall as a complex dike network (Fig. 4.1). At sharp contacts with the Anorthositic Series, the gabbro is consistently fine grained and contains scattered, variably-sized inclusions of Anorthositic Series rocks. Modal layering is commonly well developed in the lower part of the unit and consists of plagioclase-rich and mafic-rich (pyroxene and oxide) layers. The gabbro coarsens to medium grained inboard of the contact. At the contact, the gabbro displays an intergranular texture (Fig. 4.6A) that grades upward to a subophitic texture (Fig. 4.6B). The upper contact of this unit is gradational over several meters into either vari-textured troctolite on the intrusion flanks or with the layered troctolites across the interior of the intrusion (Fig. 4.1).

Figure 4.6: Field photos of the Marginal Gabbro Unit A) fine-grained intergranular texture of this unit near the contact with the Anorthositic Series rocks. B) medium-grained subophitic texture found near the contact zone with the overlying layered troctolite. Photos taken near the center of the WLI southwest of Pose Lake near the Pow Wow Trail less than 100 m apart.

Modal percents in this unit range from 35-65% plagioclase, 5-35% olivine, 5-40% pyroxene, and 5-20% opaques (oxides). This unit coarsens gradationally from a nonfoliated medium-fine-grained granular gabbro to a poorly foliated medium-grained ophitic augite troctolite. Cpx is granular at the lower contact and becomes subophitic to ophititc at the upper contact (Fig 4.7). Plagioclase exhibits simple twining and is the only mode with twins.

Alteration of this unit is weak to moderate, but shows the highest level of alteration in the intrusion. Biotitic mantling of the Fe-Ti oxides is common as is the alteration mineral iddingsite which typically follows internal fractures, particularly in olivine. Clinopyroxenes exhibit thin, pervasive oxide and/or orthopyroxene lamellae. Overgrowths are rare; the intrusion as a whole appears remarkably fresh, exhibiting little alteration.


A
B
Cpx
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Pl
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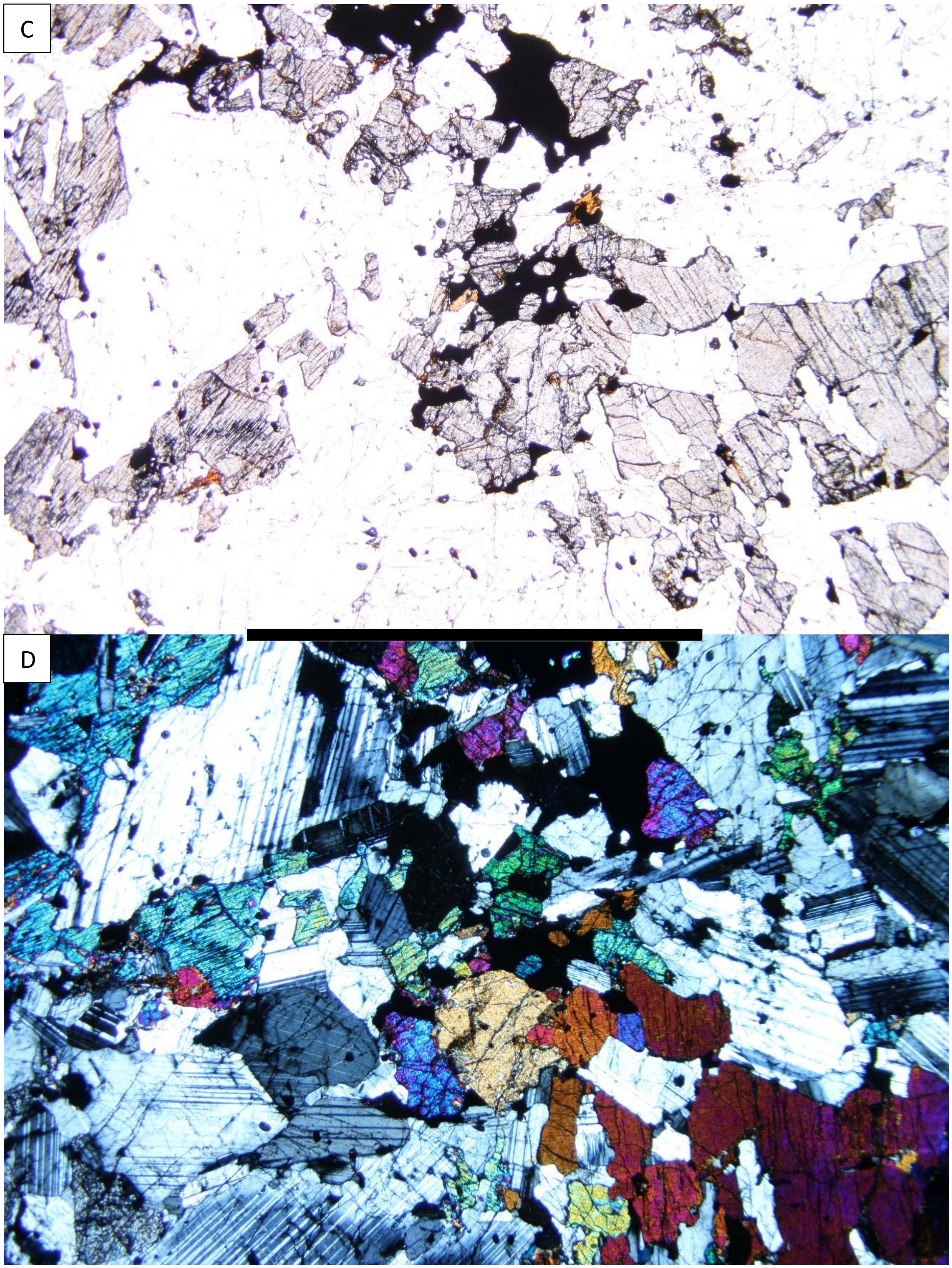

Figure 4.7: Photomicrographs of Marginal Gabbro Unit lithologies. A/B) Fine-grained, intergranular olivine oxide gabbro close to the unit's lower contact (Sample JM039). C/D) Medium-grained, subophitic olivine oxide gabbro close to the unit's upper contact (Sample JA012A). Scale bar = 5 mm; A & C – plane polarized light; B & D – cross-polarized light.

4.2.3 Lower Troctolite Units (VT, LT, AT) - Above the basal gabbro, a sequence of troctolitic (Pl+Ol) cumulates that can be subdivided into three subunits: a vari-textured troctolite (VT), modally layered troctolite (LT), and an anorthosite inclusion-rich troctolite (AT; Plate 1 and Fig. 4.1). The vari-textured troctolite is only found at the eastern and western extents of the WLI. The LT and the AT, however extend from the western edge of the intrusion, generally uniformly, to approximately 2.25 kilometers from the eastern extent of the WLI. Here, the LT and AT, as well as the overlying OT and OG pinch out and give way to a large swath of VT. The layered troctolite subunit overlies the vari-textured troctolite at the east and west ends, but directly overlies the marginal gabbro through most of the intrusion. The anorthosite inclusion-rich troctolite subunit in turn overlies the layered troctolite. Contacts among all three troctolitic subunits are gradational on a meter to decameter scale.

The vari-textured troctolite (VT) subunit is a texturally heterogeneous, medium fine- to coarse-grained, locally layered, variably plagioclase porphyritic, poorly to well foliated, troctolite to ophitic augite troctolite to subophitic olivine gabbro. Extreme variations in grain size occurs randomly on an outcrop scale. As shown in Fig. 4.8, the most common style of textural heterogeneity is the occurrence of clots, stringers, and irregular pockets of coarse-grained to pegmatic olivine, plagioclase, augite, and oxide in a matrix of medium-grained troctolites to augite bearing troctolites. Variable abundances (2-15%) of plagioclase phenocrysts (2-3cm, Fig. 4.9A-B) also contribute to the heterogeneous texture of the unit, as do meter-scale anorthositic series inclusions that range between 5 and 20% of the unit volume. Although the 50-60 m-thick unit is in gradational contact with the overlying layered troctolites, grain sizes are typically medium-grained in both units near the contact. The contact with the underlying marginal olivine gabbro is more significantly heterogeneous ranging in compositions from intergranular to ophitic augite troctolite to troctolite with large olivine oikocrysts. This contact is abrupt, but difficult to trace out laterally due to the m-scale variation in texture and mode. The upper contact is gradational with the overlying layered troctolite unit with the contact being defined by an increase in textural homogeneity, a sharp increase in the occurrence of modal layering, and a decrease in ophitic augite abundance moving into the layered troctolite unit.

Figure 4.8: Field photo of the variable texture and mineralogy of the vari-textured subunit. This photo was taken near the western extent of the intrusion near the contact with the marginal gabbro.

The vari-textured troctolite subunit is difficult to characterize petrographically because of the scale of variability relative to the area of a thin section. Modal estimates range from 45-70% plagioclase, 5-35% olivine, 10-35% pyroxene and 5-15% oxides. In general, the rocks are poorly foliated medium fine- to medium coarse-grained and, locally can be pegmatitic. They display intergranular (e.g., Fig. 4.9C-D) to ophitic pyroxene textures.

Alteration in the vari-textured unit is weak to moderate, showing a similar degree of alteration as the underlying marginal gabbro. Biotitic mantling rims oxides and iddingsite can be found throughout the fractures of olivine. Clinopyroxene, again, shows exsolution lamellae composed of either orthopyroxene or oxides or both. Due to the minimal alteration of the unit overgrowth are rare.

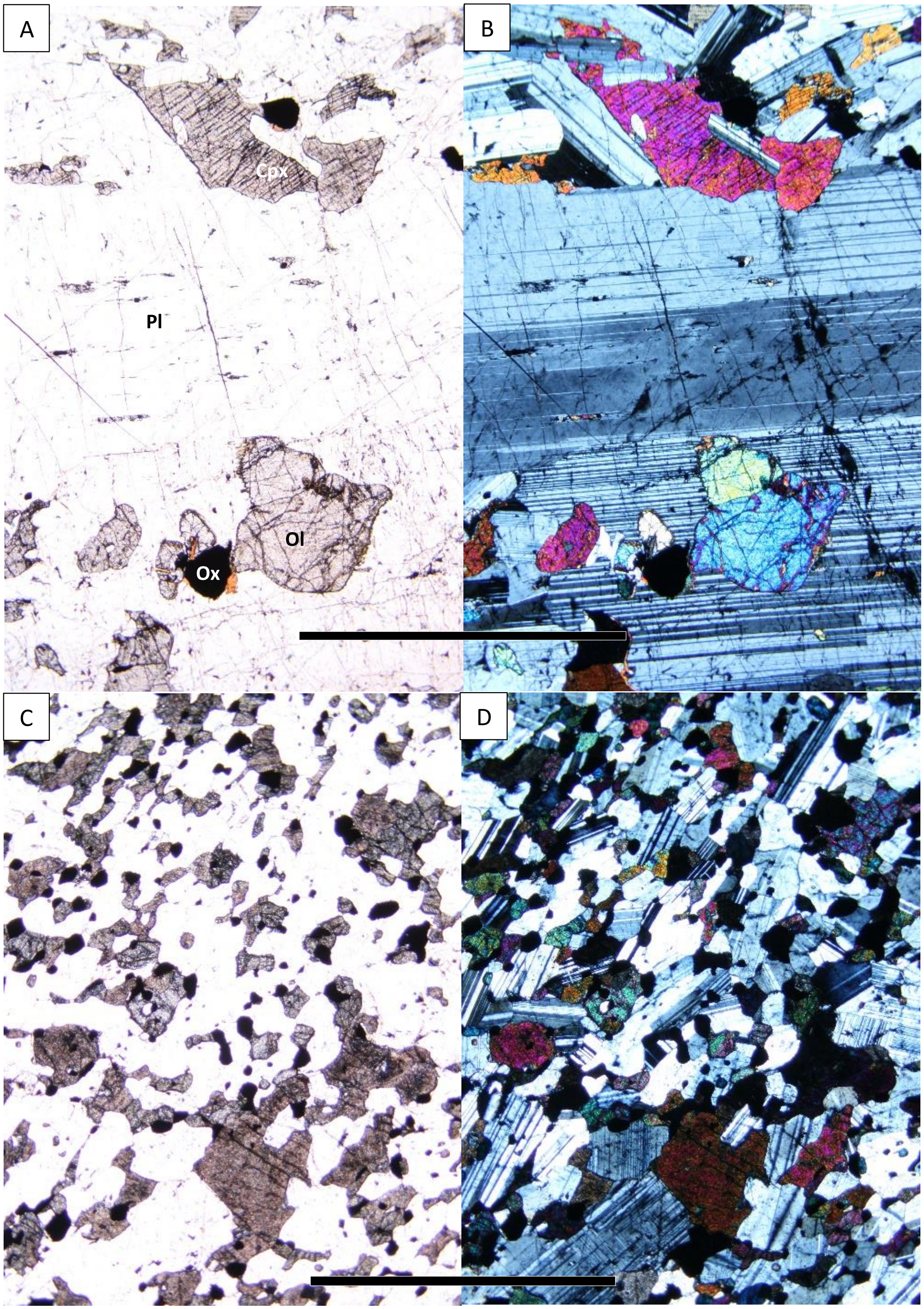
A
B
Cpx
Pl
Ol
Ox
C
D

Figure 4.9: Photomicrographs showing textural variability in the vari-textured troctolite subunit. A/B) large plagioclase phenocrysts and variable grain size (WLA008.1). C/D) granular oxides and anhedral granular to subophitic pyroxenes (WLB009). Scale bar = 5 mm; A & C – PPL; B & D - XPL.

Overlying the vari-textured troctolite and marginal gabbro is the layered troctolite subunit, which is generally a medium-grained, poorly to moderately foliated, ophitic augite troctolite to troctolite that regularly displays modal layering manifest by centimeter scale, stratiform enrichment in olivine to form melatroctolite to feldspathic dunite (Fig. 4.10). Ophitic augite and subpoikilitic Fe-Ti oxides are locally common, especially near the base of the unit, where they comprise up to 20% and 3% of the rock, respectively. Augite oikocrysts can reach up to 5 centimeters in diameter. Layering is defined by subtle to sharply isomodal variations in granular olivine abundances relative to plagioclase. A variety of layering types are recognized including graded olivine layering, cross-stratified layering, rhythmic cm-scale layering, and wispy layering (Fig. 4.10). The lower part of the 70-100m-thick unit displays the most frequent occurrence of layering. Anorthositic Series inclusions are relatively uncommon making up less than <2% of the unit volume.

The layered troctolite subunit is in gradational contact with the underlying vari-textured troctolite unit at the eastern and western margins of the WLI. The contact is defined by an increase in textural homogeneity moving into the layered subunit, a sharp increase in the occurrence of modal layering, and a decrease in ophitic augite abundance. The contact of the LT subunit with the basal MG unit in the southern part of the WLI is characterized by a gradual shift in to an ophitic augite troctolite with abundant modal layers. The ophitic pyroxene and the modal layers are what define this subunit.

Petrographic observations indicate that the layered troctolite unit is generally composed of 60-65% plagioclase, 23-28% olivine, 8-13% clinopyroxene and 2-6% oxides (Fig. 11). In the melatroctolitic modal layers plagioclase ranges from 10-20% and olivine ranges from 80-90% abundance; in the leucocratic modal layers plagioclase ranges from 85-95% and olivine ranges from 5-12%. The LT unit can clearly be interpreted to be an olivine-plagioclase cumulate - the lowermost cumulate stratigraphy of the WLI. Modal layering and plagioclase foliation, which is typically poor to moderate, implies cumulus processes wherein early primocrysts of plagioclase and olivine segregated from the main magma and accumulated at the base of the intrusion. Subophitic to ophitic clinopyroxene and subpoikilitic Fe-Ti oxide occupy interstitial (intercumulus) spaces between subhedral to anhedral granular (cumulus) olivine and plagioclase.

SEM-EDS imaging and analyses indicate that most of the opaque minerals are ilmenite with minor amounts of titanomagnetite as rimming phases. Alteration is typically weak to moderate and takes the form of iddingsite after olivine, sericite after plagioclase, and uralite after augite. Minor biotite commonly rims oxide and rarely plagioclase/oxide symplectites occur. Symplectites are fine-grained vermicular intergrowths of two or more mineral phases. They can be formed as the breakdown product of primary phases. Clinopyroxene exhibits thin, pervasive oxide and/or orthopyroxene exsolution lamellae.


A
Top

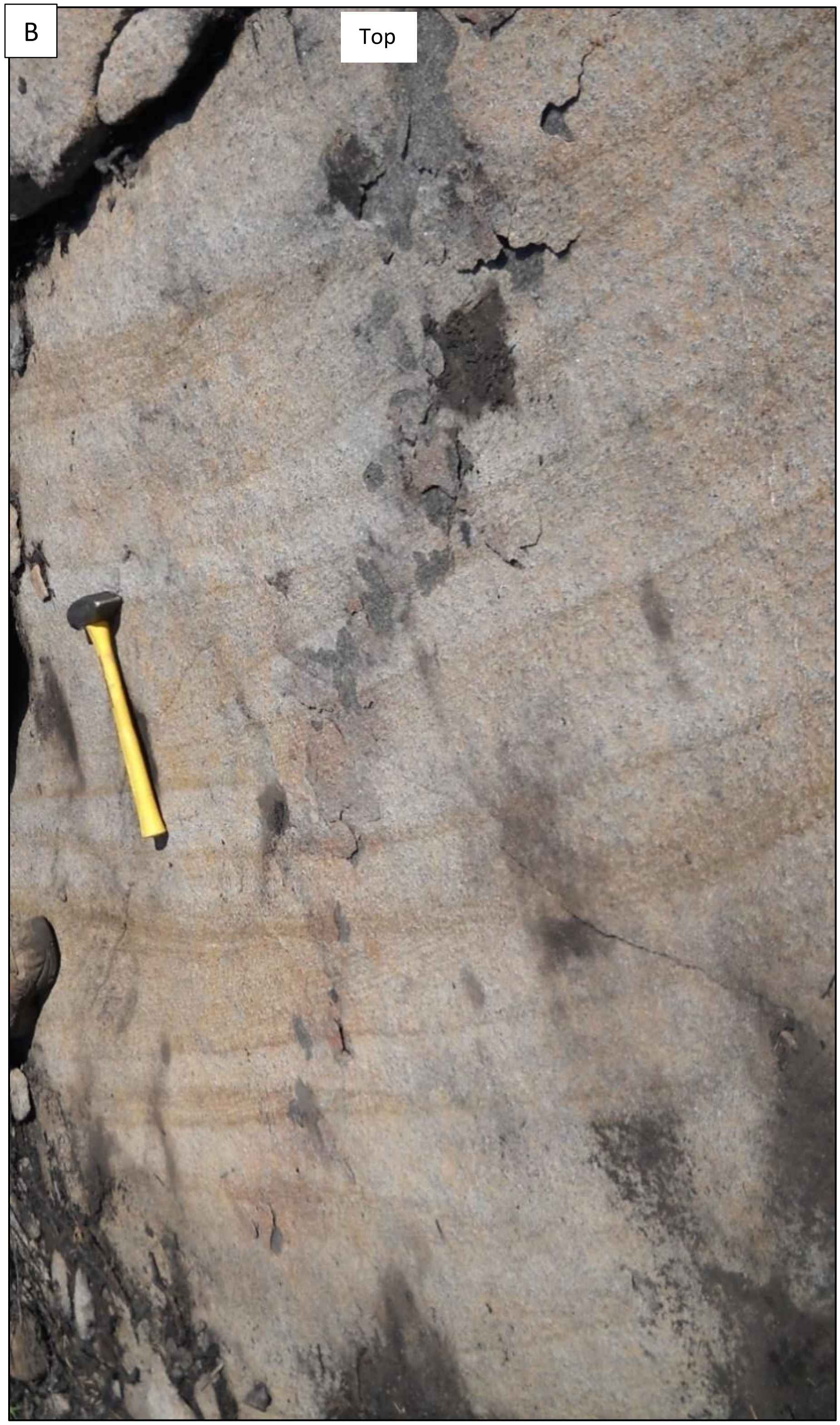
B
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Figure 4.10: Field photos of well layered exposures of the layered troctolite subunit. A) Layering types include olivine isomodal layers, rhythmic centimeter-scale layering, and cross-bedded layering. B) Similar types of olivine layering as well as graded bedding. Photos taken by J. Miller in the western WLI.

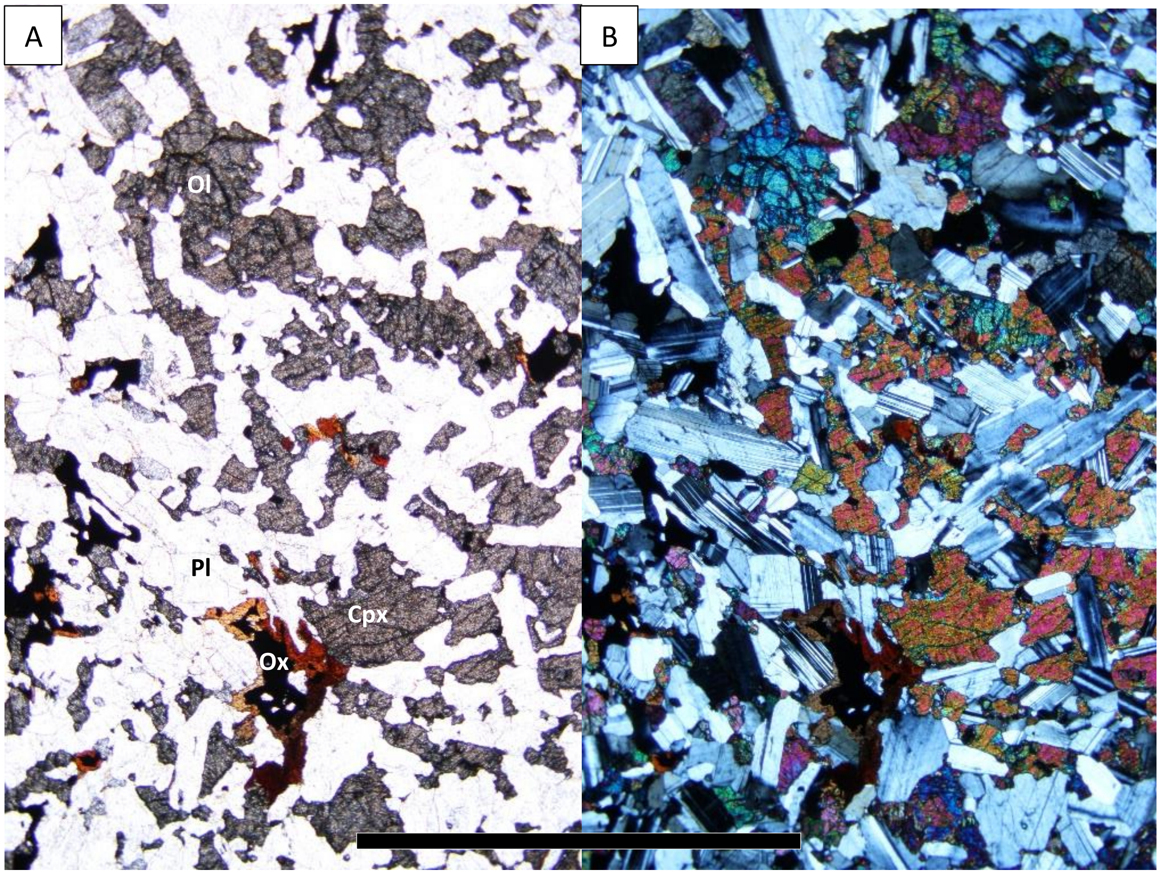


Figure 4.11: Photomicrographs showing ophitic pyroxenes (orange and red birefringence colors in XPL) typical of the lower LT unit. Note the weak foliation of plagioclase and the ameboidal nature of the Fe-Ti oxides. (Sample SA015); Scale bar = 5 mm; A – PPL; B – XPL.

The anorthosite inclusion-rich troctolite subunit (AT) is generally a medium-grained, poorly to moderately foliated, locally plagioclase porphyritic, ophitic augite-bearing troctolite to, less commonly, augite troctolites that characteristically hosts abundant and large inclusions of Anorthositic Series rocks (Fig. 4.12). Intermittent olivine layering is locally observed and locally is oriented at disconformable angles relative to the margins of the inclusions. In some areas, the volume of anorthosite inclusions (up to 30m across) to troctolitic host rock exceeds a 3:2 ratio. The AT unit's contact with the underlying layered troctolites is very gradational and defined by a decrease in anorthositic inclusion to less than 10% and the increased occurance of olivine layering. The AT unit grades into the overlying oxide troctolite with a distinct increase in foliation and the appearance of granular oxides. This contact is easily missed as it occurs over only a few meters. The stratigraphic thickness of the subunit is approximately 220 meters across the entire strike length of the intrusion, until it begins to pinch out near the eastern edge of the WLI.

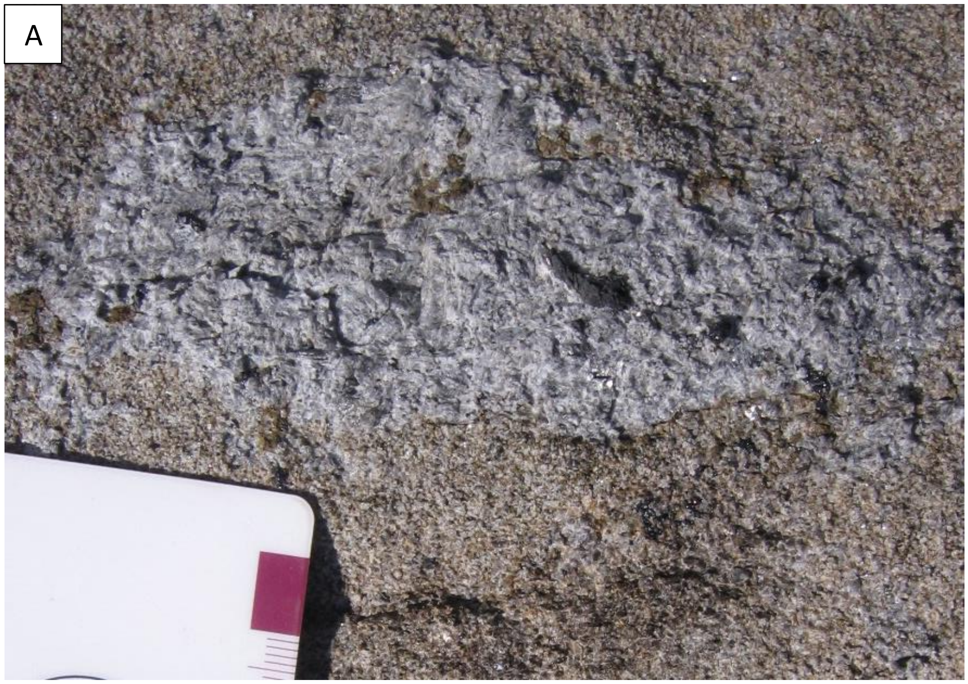


Figure 4.12: Field photos of anorthosite inclusion-rich troctolite illustrating inclusions of Anorthositic Series rocks with angular edges and no textural zoning indicative of chilling. Both photos taken from outcrops of AT in the western portion of the WLI. A - Photo by E. LaPietra; B - Photo by L. Djon.

Petrographic observations show the anorthosite inclusion-rich troctolite subunit matrix to be composed of 65-75% lath-shaped plagioclase, 15-25% granular olivine, 2-15% ophitic to subophitic augite, and 1-5% subpoikilitic Fe-Ti oxide (Fig. 4.13). Like the underlying LT subunit, the AT unit is interpreted to be an olivine-plagioclase cumulate. Augite oikocrysts up to 3 centimeters across occur and commonly display exsolution lamellae of orthopyroxene and Fe-Ti oxide. Late magmatic features locally observed include orthopyroxene peritectic rims on olivine, olivine and plagioclase symplectite, and biotite rims on Fe-Ti oxide.

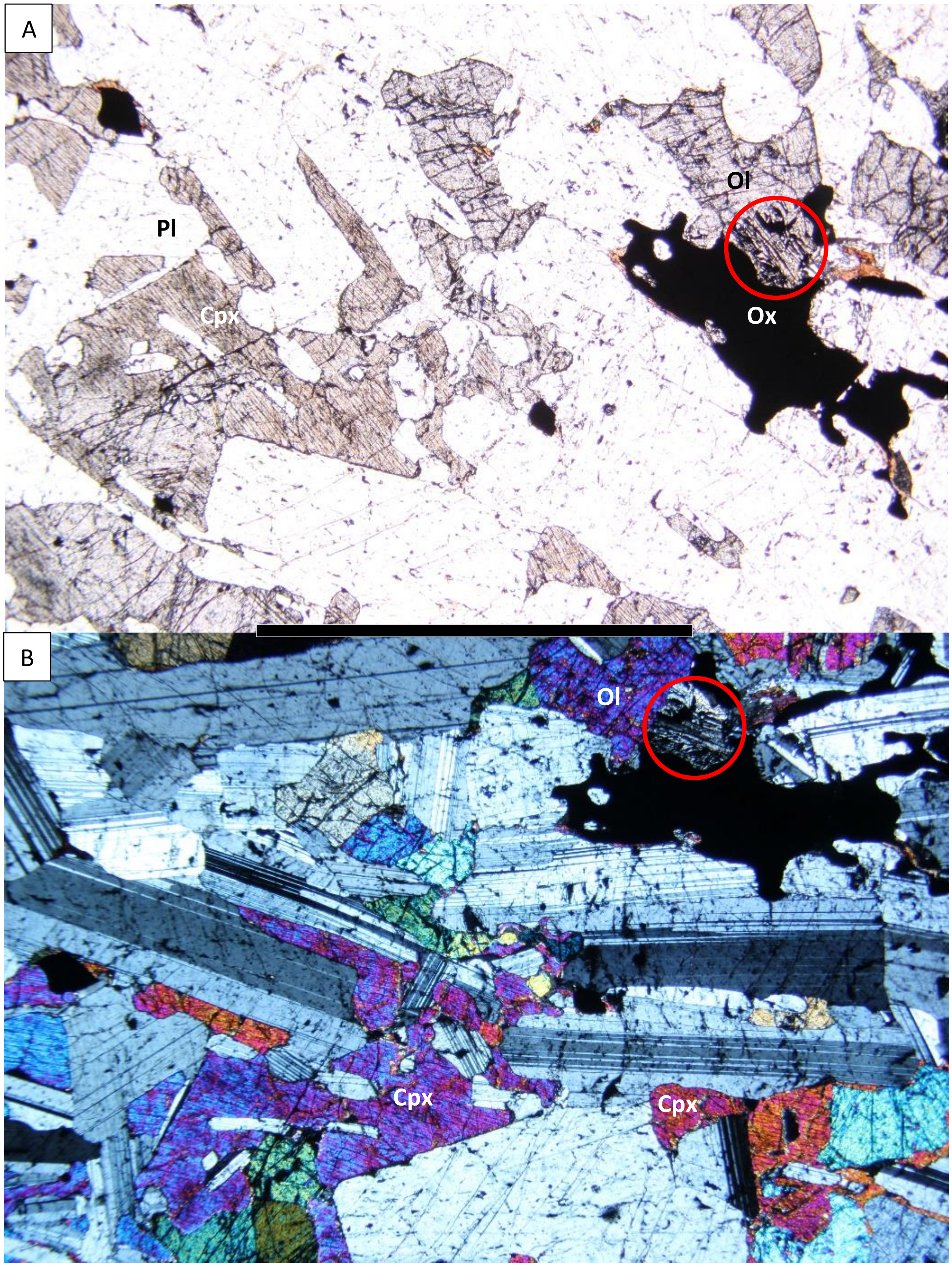


Figure 4.13: Photomicrographs showing Pl-Ol symplectites (circled in red) and ophitic augite (blue-purple birefringence colored mineral with exsolution lamellae in bottom left in B) in the inclusion-rich troctolite. Sample WLA012; scale bar = 5 mm; A – PPL; B - XPL.

4.2.4 Oxide Troctolite Unit (OT) – Overlying the anorthosite inclusion-rich troctolite in the western third of the WLI (Fig. 4.1) is a medium-grained, moderately to well foliated, commonly plagioclase-porphyritic, locally augite-bearing, oxide troctolite. Figure 4.14 shows the Fe-Ti oxides “peppering” the rocks of the OT unit and an obvious increase in foliation compared with the underlying troctolite subunits. Modal layering is rarely developed, however meter- to decameter-sized inclusions of Anorthositic Series rocks are still commonly observed. This unit pinches and swells in thickness, being up to 85 meters thick in the North Wilder Lake area in the western WLI, but is absent from the central portion of the intrusion only to swell back up to 1-15 meters further east and then pinch out approximately 2.5 kilometers from the WLI’s eastern extent (map Plate 1, Fig. 4.1). The upper contact of the OT unit is cyclically gradational into the overlying olivine oxide gabbro which is distinguished by the appearance of cumulate prismatic pyroxene. This contact also contains a distinct lithologic boundary where pyroxene becomes more frequent than olivine for the first time in the cumulate paragenesis.

Petrographic observations show that the oxide troctolite unit is composed of 5-15% plagioclase phenocrysts (2-3cm), 60-70% well aligned, lath-shaped plagioclase; 15-25% anhedral granular olivine; 7-12% subhedral granular Fe-Ti oxide and 0-8% subophitic to ophitic augite (Fig. 4.15). This unit marks an increase in abundance of Fe-Ti oxides, and a change from its subpoikilitic habit in the lower troctolite units to anhedral to subhedral granular habit. These changes indicate that oxide has reached cumulus status along with olivine and plagioclase and would be termed a POF cumulate. Coincident with the cumulus arrival of Fe-Ti oxide is an increase in the strong development of plagioclase foliation.

Alteration in this unit is weak, with the main alteration phases appearing as rims or in fractures. Oxides continue to have biotite rims and iddingsite continues to pervade the internal fractures of olivine. Clinopyroxene is still ophitic to subophitic, comprising less than 8% of interstitial space. It shows exsolution lamellae consistent with the underlying troctolitic subunits. The OT unit also has a notable occurrence of apatite (<1%).

Figure 4.14: Field photo of OT showing a marked increase in both foliation and Fe-Ti oxides. Note the scattered plagioclase phenocrysts and the "peppery" nature of the Fe-Ti oxides. Photo taken in the central portion of the intrusion.

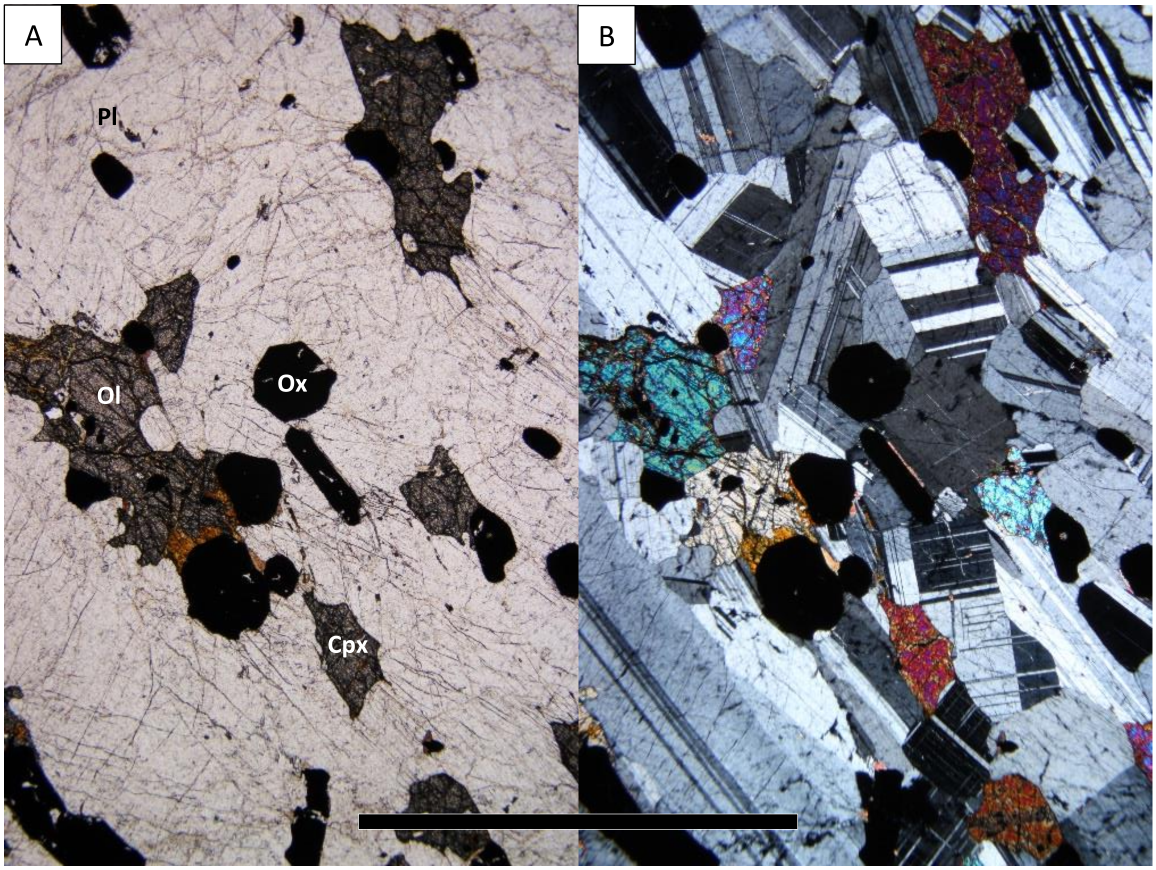


Figure 4.15: Photomicrograph illustrating the increase in foliation development coinciding with the cumulus arrival of Fe-Ti oxide. Sample WC025; scale bar = 5 mm; A – PPL; B - XPL.

4.2.5 Olivine Oxide Gabbro Unit (OG) – This unit is generally composed of a medium-grained, locally layered, well foliated, intergranular olivine oxide gabbro (Fig. 4.16). The increase in abundance in augite and change in its habit to prismatic granular (Fig. 4.17) clearly indicates its cumulus arrival to produce a 4-phase PCOF cumulate. This unit locally contains meter- to decameter-sized inclusions of anorthositic series rocks. The upper contact with the upper troctolite is typically sharp, and varies from concordant to discordant. Contact with the underlying oxide troctolite unit is gradational and cyclic, commonly marked by alternating intervals of PCFO, PCOF, POCF, and POF cumulate types. The OG unit is about 50 meters thick on the central portion of the intrusion but becomes thin and eventually pinches out in the east and northwest. The cumulus appearance of granular augite defines the four phase (PCFO) cumulate, which in terms of cumulus phase relationships, represents the most evolved cumulate in the WLI.

Petrographic observations of samples from this unit show it to be composed of subhedral granular to subprismatic minerals consisting of plagioclase (40-50%), augite (20-30%), Fe-Ti oxide (10-15%) and olivine (5-10%). It is distinguished from the underlying oxide troctolite by the abrupt, but cyclical increase in abundance, size, and texture of clinopyroxene as it joins the other phases as a cumulus mineral. Clinopyroxene becomes granular and the second most abundant mineral, behind plagioclase. The abundance of olivine decreases to become the least abundant cumulus phase. Like the underlying oxide troctolite unit, the olivine oxide gabbro unit is very well foliated but consistently displays the best developed foliation of all WLI units (Figs. 4.16 and 4.17).

Alteration in this unit is generally weak and occurs mostly along crystal rims and in internal fractures. Biotite continues to mantle oxides and iddingsite can be found in the fractures of olivine. As throughout the intrusion, clinopyroxene exsolution lamellae are composed of Fe-Ti oxide and/or pyroxene. Low abundances of apatite are also evident in this unit (~1%).

Figure 4.16: Field photos of olivine oxide gabbro unit showing a close-up (A) and (B) image of the mineralogy and texture. Note the well-developed foliation of prismatic pyroxenes and lath-shaped plagioclase in both photos. Photos taken in the North Wilder Lake area.

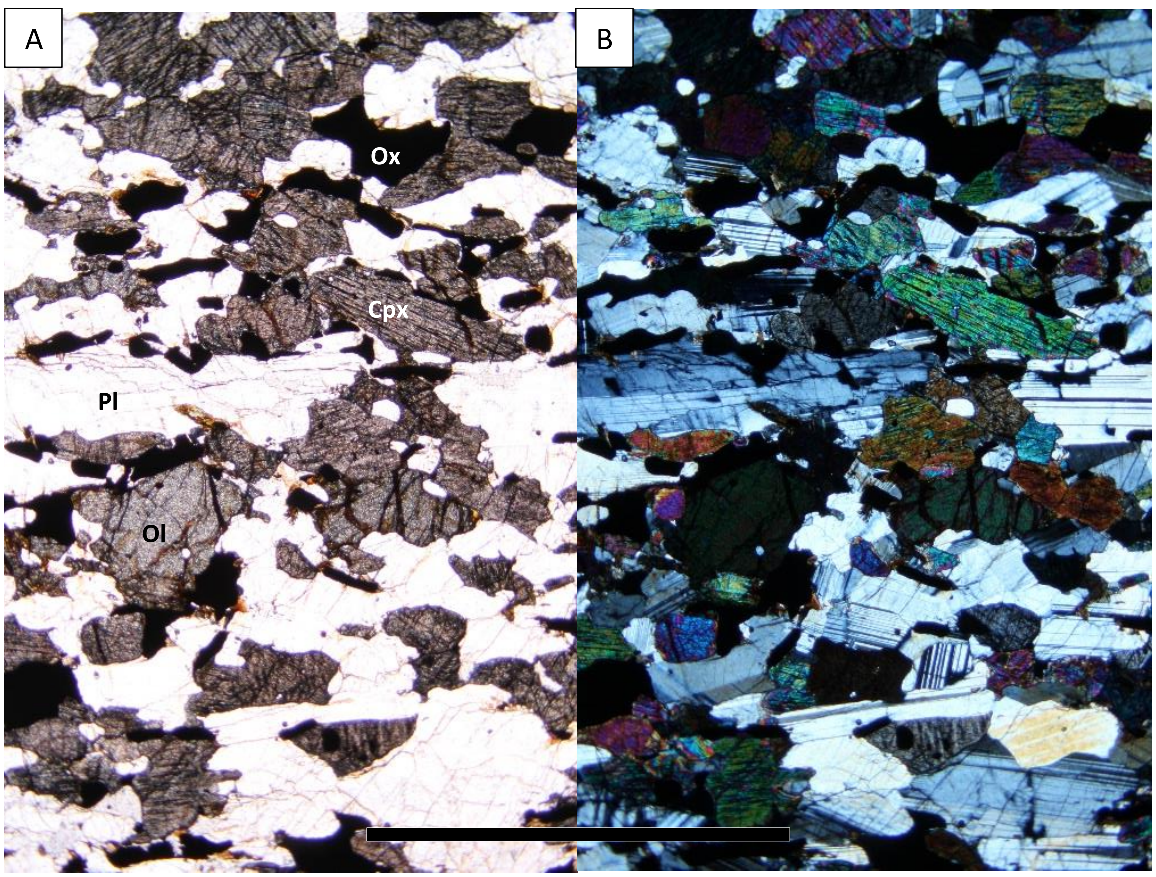


Figure 4.17: Photomicrograph of well foliated, intergranular olivine oxide gabbro (PCFO). Clinopyroxene displays extensive exsolution lamellae and is very abundant in this unit. Sample SA008; scale bar = 5 mm; A – PPL; B - XPL.

4.2.6 Upper Troctolite (UT) – Above the gabbro, another troctolitic unit is present that complexly intrudes the overlying Anorthositic Series hanging wall and cuts down into the underlying olivine oxide gabbro and oxide troctolite units (Fig. 4.1). With the proportion of anorthositic to troctolitic rock types increasing up-section through the UT unit from 25% to more than 75%, and the lower contact of the troctolite scouring down into the OG and in places down into the OT unit, it is difficult to estimate the thickness of the unit. Over the strike length of the entire WLI, the UT unit averages about 120 meters in thickness. (Evidence and implication for the UT unit scouring down into the OG and OT units will be given in the discussion).

Exclusive of the anorthositic inclusions, the upper troctolite unit is composed of medium-grained poorly to moderately laminated troctolite to ophitic augite troctolite (Fig. 4.18A). Phenocrysts of 2-3 centimeter tabular plagioclase (5-15%) stand out against medium-grained, lath shaped matrix plagioclase that range in mode from 40-65%. Olivine ranges in mode from 15-30% and in habit from anhedral granular to ameboidal to subpoikilitic. The mode of subophitic to ophitic augite ranges from 2-15% and averages around 5%. Fe-Ti oxide ranges between 3-7% in mode and typically occur as subpoikilitic clots up to 5 millimeters across (Fig. 4.19). Contacts between anorthositic inclusions and troctolitic host rocks are typically sharp to irregular, but rarely show signs of chilling (Fig. 4.18B)

Alteration in the upper troctolite unit it typically weak, but zones of moderate alteration are not uncommon. Locally orthopyroxene rims can be found around olivine (Fig. 4.19). Symplectites are common between olivine and plagioclase and the oxides (Fig. 4.19). Oxides again exhibit biotite mantling. Iddingsite alteration is commonly quite strong and continues to follow olivine fracture patterns, but can also be found to a lesser degree in fractures through pyroxene and plagioclase.

A

B

Figure 4.18: Field photos of the upper troctolite unit. A) Medium-grained, moderately foliated troctolite, with subpoikilitic olivine. B) Semi-assimilated inclusion of Anorthositic Series rocks within the UT unit. Photos from the eastern portion of the WLI.

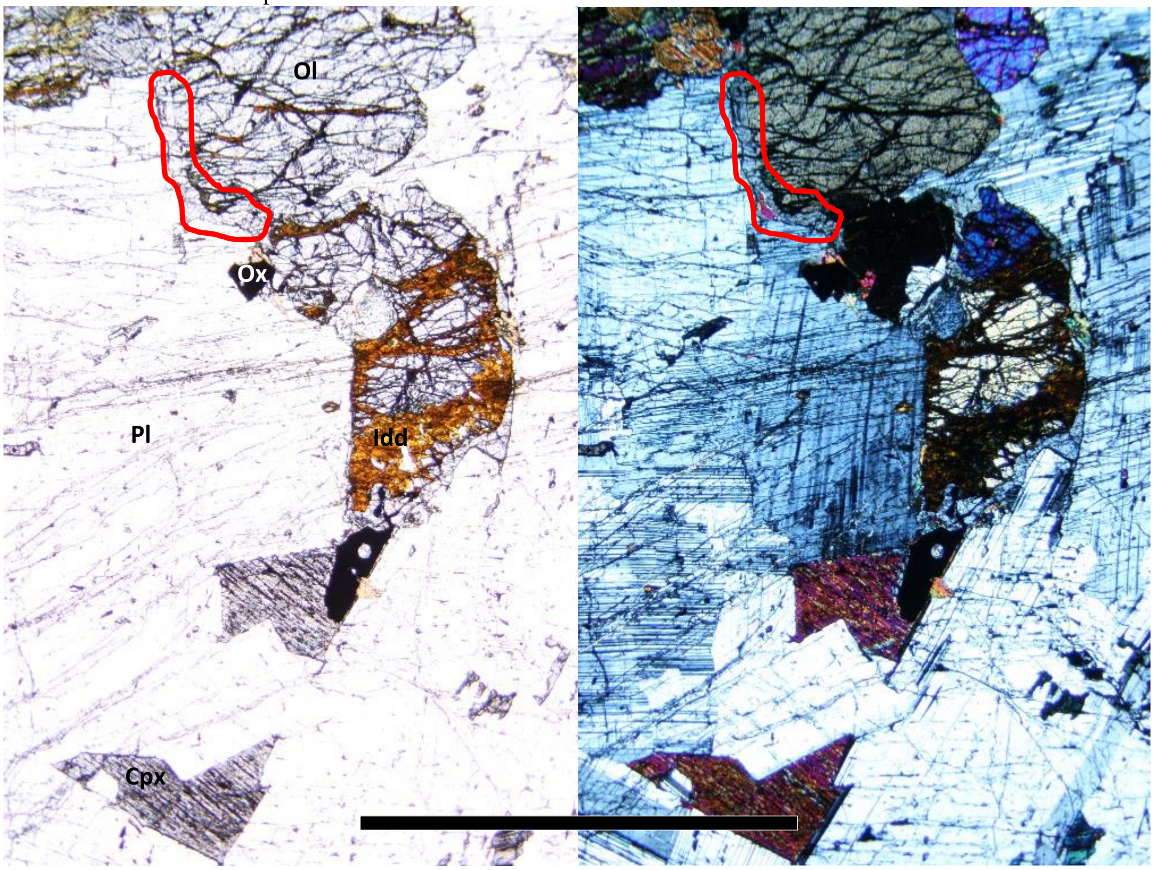


Figure 4.19: Photomicrographs of troctolite from the upper troctolite unit. Plagioclase and olivine are anhedral granular (cumulus) whereas augite (Cpx) with Opx and FeOx exsolution is subophitic (intercumulus). Iddinsite (Idd) after olivine is evident in the center of the picture. Orthopyroxene (circled in red) occurs as a peritectic rim on the olivine. Sample SA031.2; scale bar = 5mm; A – PPL; B - XPL.

4.2.7 Summary Lithostratigraphy of the WLI - The WLI shows some key stratigraphic trends in its modal mineralogy and textures that can be interpreted in terms of cumulate stratigraphy (Fig. 4.20). The surrounding Anorthositic Series rocks are composed almost exclusively of cumulus plagioclase with intercumulus olivine, augite and Fe-Ti oxide (Fig. 4.4). In the marginal gabbro unit rocks have four subhedral to anhedral granular phases (plagioclase, olivine, pyroxene, and Fe-Ti oxides), but a general lack of foliation and modal layering and their medium fine grain size near the contact suggests that most of these rocks are not cumulates, but rather experienced little separation of liquid from crystals. The overlying troctolitic units, despite their unique attributes of variable texture (VT), modal layering (LT), and abundant anorthositic inclusions, are fundamentally composed of primocrystic (cumulus) plagioclase and olivine with subpoikilitic to poikilitic (intercumulus) pyroxene and Fe-Ti oxide. The rocks form PO to POcf cumulates. In the oxide troctolite unit, Fe-Ti oxides join plagioclase and olivine as cumulus phases while pyroxene remains ophitic/intercumulus and thus forms a POFc cumulate. In the olivine oxide gabbro unit pyroxene arrives as a cumulus phase to join the other cumulus minerals to form a four-phase cumulate (PCFO). Foliation increases through the whole intrusion up through this unit where it is well-foliated. The UT marks an important regression in cumulus mineralogy to a two-phase troctolite (PO) cumulate (Fig. 4.20).

4.3 Mineral Chemistry

Previous studies of the WLI showed an up-section increase in mg# (Mg/Mg+Fe*100, cation %) in both clinopyroxene and olivine, which is the reverse of that seen in other mafic layered intrusions within the Duluth Complex (Miller and Ripley, 1996). The mineral chemical data collected for this study along three profiles across the WLI (Fig. 3.2) show a similar increase in magnesium relative to iron up-section in the intrusion. Figure 4.21 illustrates the mg# values in Ol and Cpx along the three profiles, each showing varying degrees of reversed cryptic variation up-section.

The western profile (Fig 4.21A) shows the least total variation in both Cpx and Ol. There is a steady increase in mg# moving up-section except for a small positive trend between the OG unit and the UT unit and positive trend near the VT and LT unit’s contact. In Cpx mg# values range from 69 in the MG unit to nearly 74 in the OG unit. In olivine mg# values range from 54 in the MG unit up to 64 in the OT unit. This data also reaffirms the previous data collected by Miller and Ripley (1996) and Turnbull (2003), shown as red squares in Figure 4.21A.

The central profile (Fig. 4.21B) shows general increase in mg# from the base of the intrusion through the UT unit. There are two data points, one in the MG unit (En , Fo) and one in the LT unit (En 63, Fo 41) which is an outlier from the trend. In cpx mg# values range from 55 in the MG unit up to 73 in the UT unit. In olivine mg# values range from 33 in the MG unit up to 64 in the AT unit.

The eastern profile (Fig. 4.21C) shows the most variation of the three profiles, and the mg# increases rapidly across the MG and LT units then leveling out in the upper units. Both ol and cpx exhibit a sharp increase in mg# moving from the MG-LT unit into the lower AT unit. The trend flattens out through the

OG unit (En 66, Fo 55) with a slight decrease in values in the UT unit (En 63, Fo 53). In cpx mg# values range from 45 in the MG unit up to 70 in the AT unit. Another key feature of these data is the lateral variability along the intrusion. In the east, compositions at the base of the intrusion are far more iron-rich (En 45-70, Fo 22-56) than the western sections (En 60-75, Fo 55-68).

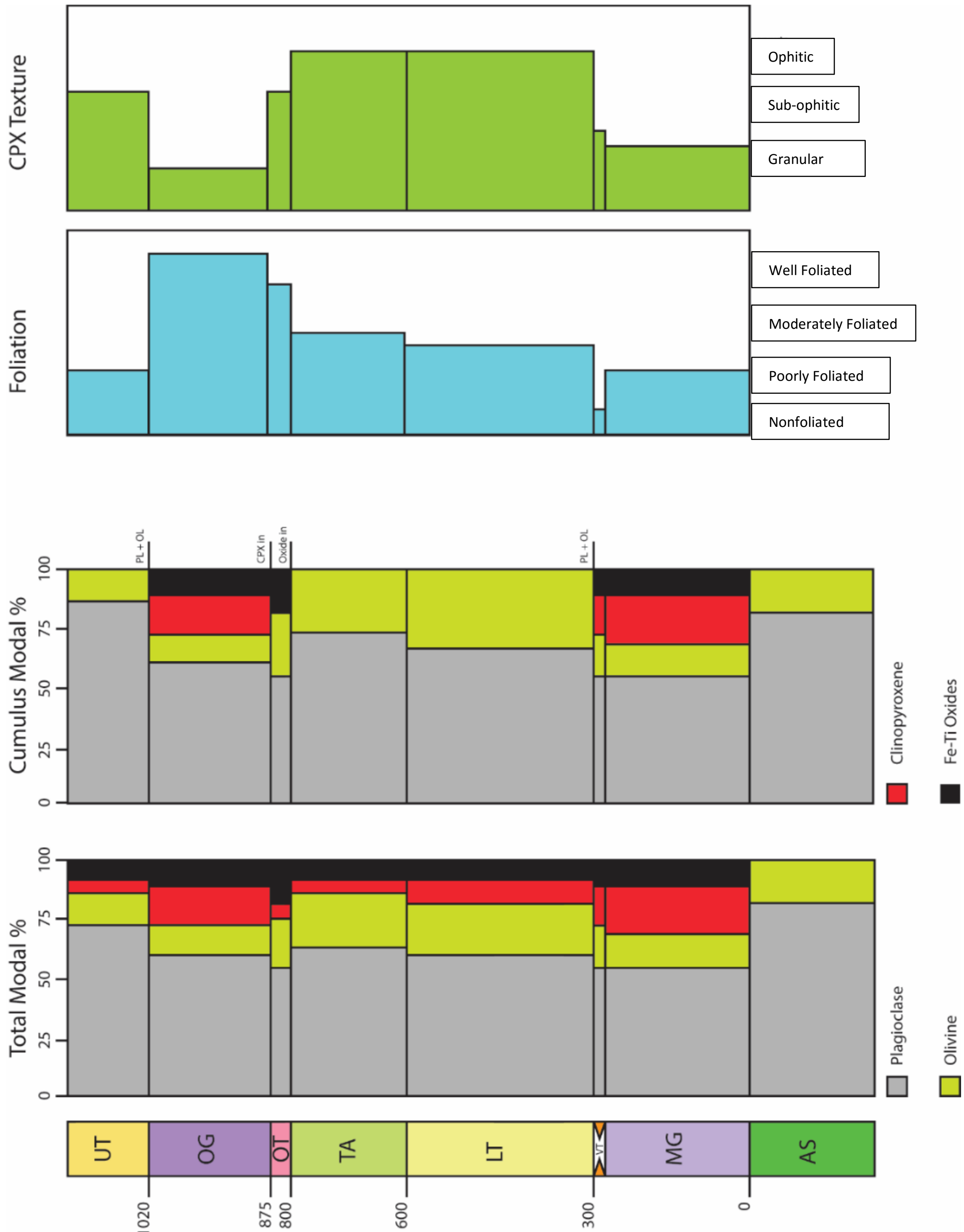


Figure 4.20: Petrographic summary of average cumulative modal percent of essential phases, cumulative modal percent of cumulus minerals, degree of foliation development, and Cpx habit for the major WLI map units plotted relative to an idealized stratigraphic column.

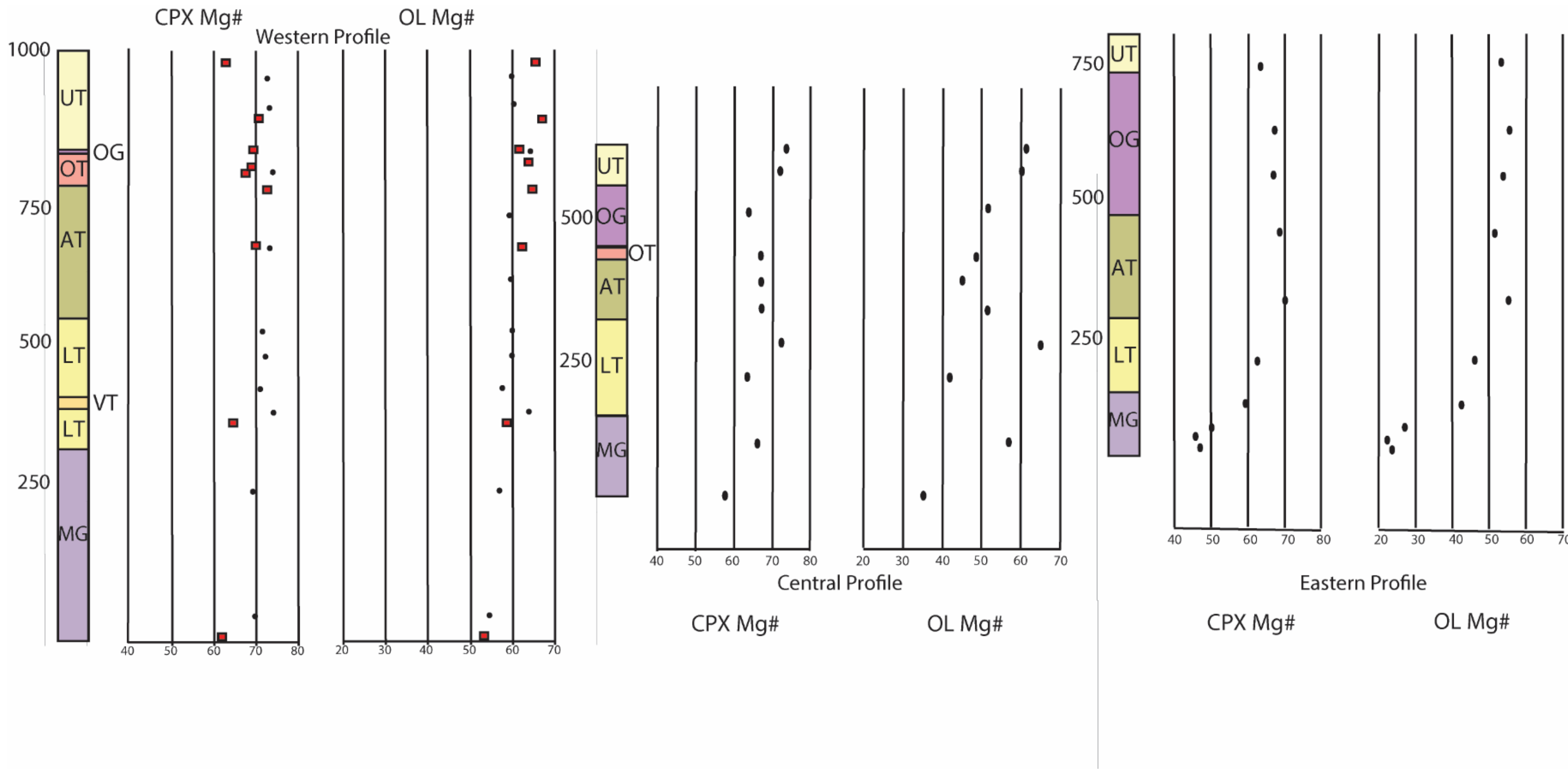


Figure 4.21: Cryptic variation in the mg# in olivine and augite plotted against stratigraphic height in the three sample profiles (Fig. 3.2). Filled circles indicate data from this study, red squares indicate previously gathered data from Miller and Turnbull.

4.4 Lithogeochemistry of the Marginal Gabbro

The whole rock lithogeochemistry of 10 samples collected from the marginal gabbro (fig. 4.22) were analyzed to determine whether they might approximate the compostions of the WLI parental magma. These samples show elevated values of iron and titanium, and have low values of silicon when compared to the transitional tholeiitic basalts of the North Shore Volcanic Group. Figure 4.22 shows the locations of the samples in the WLI. Sample S2 is the closest match to the NSVG basalt compositions, and has the lowest iron and titanium values and the highest silicon value of the WLI samples. Because of its similar composition and its proximity to the edge of the WLI, S2 was chosen as the best match to a potential source composition. All subsequent data regarding the analysis of the lithogeochemical data is sourced from sample S2.

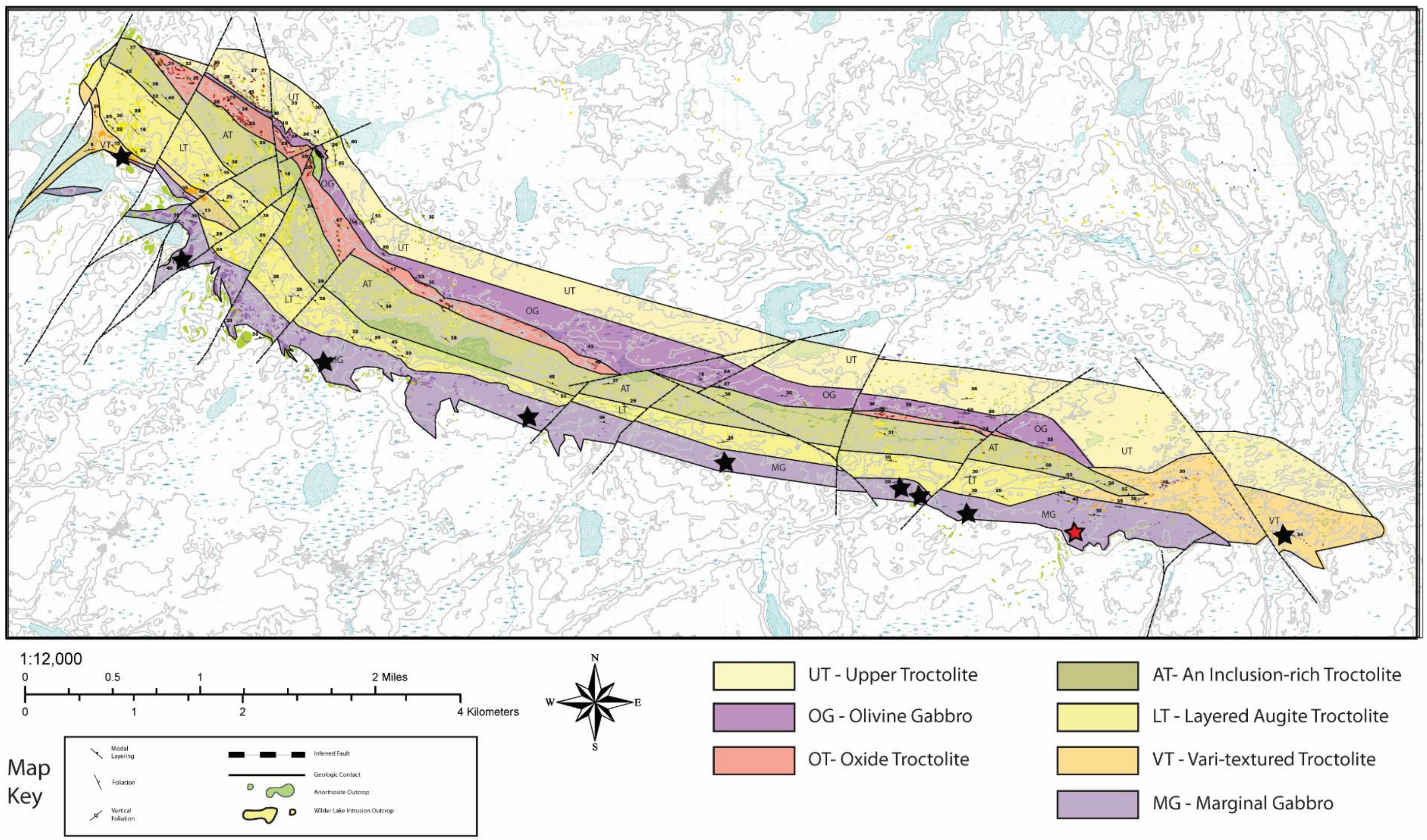
Table 4.2: Major and minor element compositions from nine samples of fine- to medium fine-grained intergranular to subophitic olivine oxide gabbro from the MG unit. At the bottom an average compositions from 47 samples in the North Shore Volcanic Group (NSVG) (Brannon, 1984). Data are all in weight percents.

Sample	SiO2	TiO2	Al2O3	Cr2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5
JM004	40.06	5.42	10.34	0.00	22.12	0.30	6.10	9.61	2.19	0.29	1.42
JM039	40.99	5.69	11.74	<0.002	19.35	0.24	5.30	10.57	2.30	0.30	1.09
JM040	39.21	4.79	11.84	<0.002	22.31	0.32	3.81	9.86	2.53	0.31	2.31
LD009	40.02	5.85	11.48	<0.002	21.84	0.28	5.16	9.30	2.30	0.31	0.80
S2	45.14	3.43	16.97	0.02	13.56	0.17	8.42	8.34	2.88	0.30	0.02
SA004	42.38	5.64	13.69	<0.002	16.76	0.19	6.71	10.48	2.34	0.23	0.02
SA016.1	44.09	5.38	15.17	0.01	15.41	0.21	5.27	9.01	2.98	0.41	0.57
SA043	43.45	5.28	12.77	0.00	17.72	0.24	5.00	9.26	2.76	0.41	0.61
WLA13b	42.32	6.91	15.05	0.01	15.67	0.19	7.05	8.32	2.69	0.28	0.02
WLB009	43.45	4.85	15.26	0.02	15.53	0.19	6.94	9.63	2.66	0.17	0.01
WLI AVG	42.11	5.32	13.43	0.01	18.03	0.23	5.98	9.44	2.56	0.30	0.69
NSVG AVG	46.84	2.06	14.75	0.02	14.45	0.20	6.30	8.52	2.85	0.93	0.23

Table 4.3: Minor and trace element compositions from nine Marginal Gabbro samples. These data are given in parts per million (ppm).

Sample	JM004	JM039	JM040	LD009	S2	SA004	SA016.1	SA043	WLA13b	WLB009
Ni	<20	<20	<20	<20	153	24	27	<20	46	118
Sc	50	53	45	49	21	52	36	45	31	35
Ba	300	262	348	755	131	123	379	279	127	103
Co	50.7	61.4	41.5	57.9	70.1	67.1	48.7	49.5	66	66.6
Ga	17.6	20.1	20.2	20.6	17.6	19.1	19.6	20.2	17	18.5
Hf	2.6	2.4	1	2.3	0.4	0.9	3.2	1.6	1.1	0.1

Sample	JM004	JM039	JM040	LD009	S2	SA004	SA016.1	SA043	WLA13b	WLB009
Nb	22.5	13.8	18.7	19.1	5.4	4.5	21.2	17.7	12.1	2.2
Rb	5.1	4.8	4.5	3.3	0.7	0.9	5	10.3	<0.1	<0.1
Sr	291	275.7	346.8	285.5	299.8	251.8	382.4	313.9	324.6	297.9
Ta	1.3	0.9	1.1	1.5	0.7	0.5	1.2	1.1	0.9	0.3
Th	0.4	0.3	<0.2	0.4	<0.2	<0.2	0.3	0.4	<0.2	<0.2
U	0.2	0.1	0.2	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1
V	526	624	71	509	213	834	405	433	499	468
W	<0.5	<0.5	<0.5	0.6	2.9	<0.5	<0.5	<0.5	<0.5	<0.5
Zr	110.6	83.3	44.3	88.1	20.6	26	125.1	35.2	26.1	3
Y	42.2	30.5	46.9	27.5	3.4	7	28.3	24.7	3.4	2.1
La	29.2	18.7	33.7	14.6	2	1.1	17.2	9.1	0.9	0.2
Ce	69.4	45.3	88.6	39.6	3.7	3.9	42.1	23.5	1.6	0.4
Pr	9.84	6.42	12.85	5.52	0.47	0.63	6.09	3.7	0.23	0.05
Nd	47.3	32	63.4	24.3	2.9	3	30	21.2	1.6	0.3
Sm	10.48	7.11	13.53	6.55	0.62	1.22	7.5	5.31	0.41	0.17
Eu	2.89	2.69	4.26	2.58	0.93	0.87	2.61	2.79	0.95	0.71
Gd	10.81	7.89	14.36	6.87	0.69	1.36	7.11	5.87	0.7	0.48
Tb	1.56	1.13	1.91	1.06	0.12	0.27	1.11	0.87	0.11	0.08
Dy	8.61	5.61	9.63	5.86	0.68	1.51	5.65	4.73	0.42	0.55
Ho	1.48	1.09	1.79	0.99	0.11	0.26	1.12	0.8	0.16	0.05
Er	3.94	2.78	4.24	2.71	0.3	0.94	3.14	2.45	0.35	0.25
Tm	0.55	0.34	0.55	0.33	0.07	0.11	0.35	0.3	0.05	0.01
Yb	3.31	2.12	3.2	2.39	0.37	0.69	2.76	1.78	0.37	0.17
Lu	0.51	0.37	0.42	0.37	0.06	0.13	0.37	0.31	0.06	0.03
Mo	0.7	0.5	1.2	1.2	<0.1	0.1	0.2	0.5	<0.1	<0.1
Cu	48.6	100.5	74.5	95.4	229.8	368.1	120.8	143.3	267.7	298.7
Pb	0.4	0.3	0.2	1	0.2	0.4	0.4	0.7	0.2	<0.1
Zn	115	87	139	117	63	47	73	97	59	57
Ni	16.8	4.4	1	3.7	147.5	22.3	25.3	16.4	45.2	93
Au	7.9	1.8	<0.5	44.2	3.5	3.2	<0.5	<0.5	<0.5	1.5
mg#	38.8	38.6	28.2	35.2	58.8	47.9	44	39.3	50.8	50.7
LOI	-0.6	0.0	0.0	-0.1	-1.0	-0.6	-0.5	0.3	-0.5	-0.7



1:12,000
0
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4 Kilometers
N
S
E
W
Map Key
Modal Layering
Foliation
Vertical Foliation
Inferred Fault
Geologic Contact
Anorthosite Outcrop
Wilder Lake Intrusion Outcrop
UT - Upper Troctolite
OG - Olivine Gabbro
OT- Oxide Troctolite
AT- An Inclusion-rich Troctolite
LT - Layered Augite Troctolite
VT - Vari-textured Troctolite
MG - Marginal Gabbro

Figure 4.22: Map of WLI showing sample locations of the 9 Marginal Gabbro samples. S2 shown in red.

5. Discussion

Based on the data gathered in this and previous studies, the WLI can be defined as a tabular mafic layered intrusion with a 1.2-0.7 km stratigraphic height and an approximately 10 km strike length dipping gently to the north-northeast. It is located in the northwest edge of the Duluth Complex and is completely enclosed within the Anorthositic Series rocks. The WLI has been studied through several different methods including field mapping, petrographic observations, geochemical analyses, and the review of previous work on the intrusion. From the field mapping and petrographic study, a detailed 1:12,000 scale map (Plate 1) was produced and submitted to the USGS EdMap program as a fulfillment of their funding.

The field, petrographic, and geochemical data collected for this study allows for interpretation of the many unique petrologic features of the WLI. Interpreting the petrogenesis of these unique features will be the main topic of discussion in the following section and they include: 1) the cumulate reversal at the top of the intrusion from a four-phase (PCFO) olivine oxide gabbro cumulate (OG unit) to a two-phased troctolite cumulate, 2) the reversed cryptic variation showing an increase in mg# of olivine and augite up-section, and 3) the cumulus arrival of Fe-Ti oxides before clinopyroxene.

5.1 <u>Origin of the Cumulate Reversal in the upper WLI</u>

One of the many enigmatic features of the WLI is the cumulate reversal in the upper part of the intrusion where an evolved PCFO cumulus assemblage gives way up-section to a more primitive PO cumulate. In the western portion of the intrusion, just north of North Wilder Lake, the contact between the olivine oxide gabbro unit and the upper troctolite unit is well exposed in several locations and shows considerable evidence for this cumulate reversal being the result of a later pulse of more primitive magma that overplated and partially to completely scoured out the olivine oxide gabbro unit.

Thanks to a fresh exposure produced by the burn in the Northern Wilder Lake area, well foliated olivine oxide gabbro is clearly observed to be discordantly cut by upper troctolite along a sharp but unchilled contact (Fig. 5.1; Fig. 5.2, Area A). The contact is curved and is distinctly not conformable to the strong constant foliation in the PCFO cumulates of the olivine oxide gabbro unit (Fig. 5.1B). In contrast, the POcf cumulates of the upper troctolite unit display a poor to moderate foliation that is semiconformable with the irregular contact. This implies that the troctolite cross-cuts the olivine oxide gabbro. In fact, on a regional scale in the North Wilder Lake area, the olivine oxide gabbro is completely cut out by the upper troctolite toward the western end of the WLI, such that the troctolite rests directly on the oxide troctolite unit (Fig. 5.2, Area B).

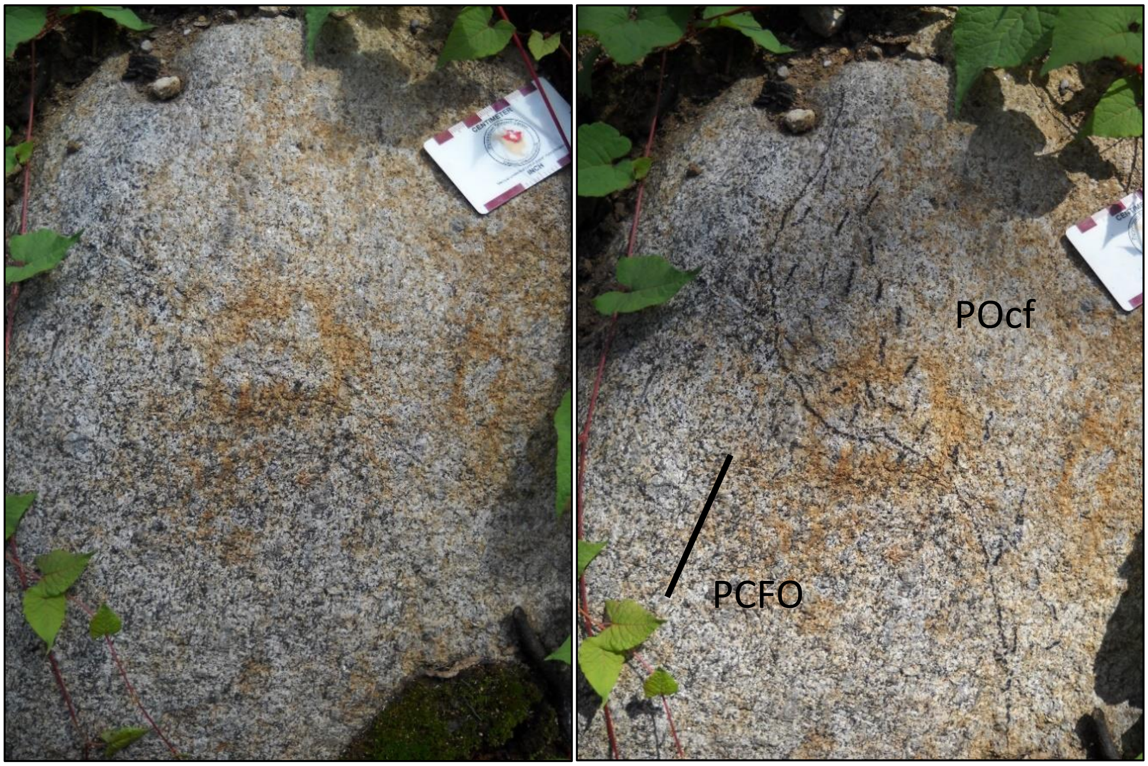


Figure 5.1: Field photos of a sharp contact between PCFO cumulate of the olivine oxide gabbro unit and a POcf cumulate of the upper troctolite unit exposed in Area A of Figure 5.2. A) Unembellished outcrop with troctolite in upper right and olivine oxide gabbro in lower left (note dark augite and oxide phases) B) Orientation of plagioclase in the troctolite is marked on the outcrop and is subparallel to the contact with the PCFO unit indicated by drawn solid black line. The plagioclase foliation in the PCFO cumulate is constantly oriented parallel to the thick black line and is discordant to the contact with the troctolite. Photo by J. Miller.

Usually, where significant phase reversals occur due to the introduction of a more primitive magma, one would expect to also observe a significant shift in mg# of mafic phases (and the An content of plagioclase). However, the change in mg# in olivine and pyroxene in the three sample profiles across this contact (Fig. 4.23) is subtle and variable. In the western profile, the shift is minimal. In the east central profile, an increase of about 10% mg# is observed from the gabbro into the upper troctolite, as would be expected. However, in the far eastern profile, a decrease of about 5% in mg# is observed, which is the reversed of what recharge of the more primitive troctolite unit would be expected to show.

As will be discussed in the next section, some of this inconsistency in the mg# shift across this strong phase reversal may have to do with the orthocumulate troctolite experiencing variable degrees of trapped liquid shift, whereas the adcumulate olivine oxide gabbros experience little to no such shift in mg#. Nevertheless, it is remarkable that despite the lower WLI sequence evolving into a 4-phase cumulate, chemically, it was not much more evolved than the troctolite. In a fully differentiated sequence of a tholeiitic intrusion olivine tends to disappear soon after oxide becomes a cumulus phase (e.g. Middle Zone of Skaergaard, Wager and Brown (1967) and the SLFG unit of Sonju Lake, Miller and Ripley (1997)). Further differentiation leads to the reappearance of the Fe-rich olivine and the cumulus arrival of apatite (Upper Zone of Skaergaard and SLAD unit of Sonju Lake). Yet, Fo and En contents in the PCFO unit are in the 48-65 and 62-75 range, respectively, compared to values as low as Fo_5 in the upper cumulate units of the Sonju Lake Intrusion (Miller and Ripley, 1997). This begs the question whether the lower sequence of the WLI fractionated more extensively only to be cut out by the emplacement of the upper troctolite. The lack of xenoliths of more evolved cumulates in the upper troctolite unit suggests that this did not occur and that the lower sequence of the WLI had only moderately differentiated to the point where oxide and augite were on the liquidus before the upper troctolite was emplaced. This level of differentiation would have corresponded to the lower zone C of the Skaergaard intrusion, at which it was only about 30-35% crystallized (Wager and Brown, 1968).

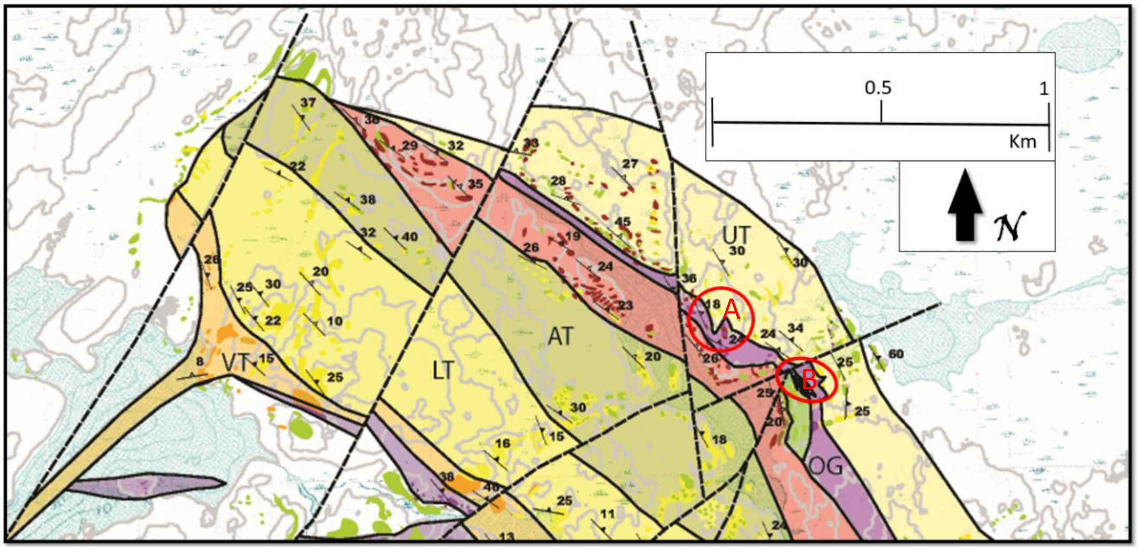


Figure 5.2: Enlarged view of the far western edge of the intrusion showing the complete scouring (Area A) and partial scouring (Area B) out of the gabbro by the upper troctolite.

5.2 Origin of Reversed Cryptic Layering

The cryptic variation of solid solution mineral chemistry upward through the cumulate stratigraphy of tholeiitic layered intrusions commonly show a systematic decrease in magnesium relative to iron in olivine and augite (Wager and Brown, 1968). The shift to more iron-rich mineral compositions is attributed to fractional crystallization of olivine and pyroxenes which, because of their preference for the Mg component (Fig. 5.3), depletes the residual magma in magnesium relative to iron. This decrease in magmatic Mg/Fe ratio is inherited by the crystallizing mafic phases to create a cryptic variation in their mg# (Mg/(Mg+Fe), cation %). In contrast, the WLI shows upward enrichment in mg content (Figure 4.21). The origin of this reversed pattern is explained below.

The cumulate rocks of the WLI range from orthocumulates in the troctolitic units to adcumulates in the OG unit. This implies that there is an upward decrease in the amount of intercumulus. An orthocumulate consists of 50-75% cumulus crystals, a mesocumulate have 75-93% cumulus crystals, and an adcumulate has 93-100% cumulus crystals (Irvine, 1982). According to the classic cumulus theory (Wager and Brown, 1968), primocrystic crystals begin to accumulate and create a framework of touching mineral grains that begin to trap the liquid in the pore space (intercumulus liquid) between the primocrystic phases (cumulus mineralogy). As shown in Figure 5.3 for olivine solid-solution crystallization, cumulus phases which crystallized from an unlimited reservoir of the magma before accumulating at the chamber floor will have homogeneous solidus composition much more Fo-rich than the parental liquid. In contrast, the intercumulus liquid, if not allowed to re-equilibrate with the main magma reservoir (i.e becomes trapped), will equilibrium crystallize postcumulus olivine overgrowths that average to the lower mg# of the liquidus composition for a given temperature. During slow subsolidus cooling, the initial zoning of mg# through the olivine (Fig. 5.4) is known to readily equilibrate by diffusion of Fe and Mg. As illustrated in Figure 5.3, olivine with 50% cumulus olivine and 50% postcumulus olivine will re-equilibrate to an Fo composition that can be more than 10% less than the original cumulus composition. This process of re-equilibrating primocrystic minerals with later, more iron-rich post cumulus mafic phases is called the "trapped liquid shift", as was first explained by Barnes (1986).

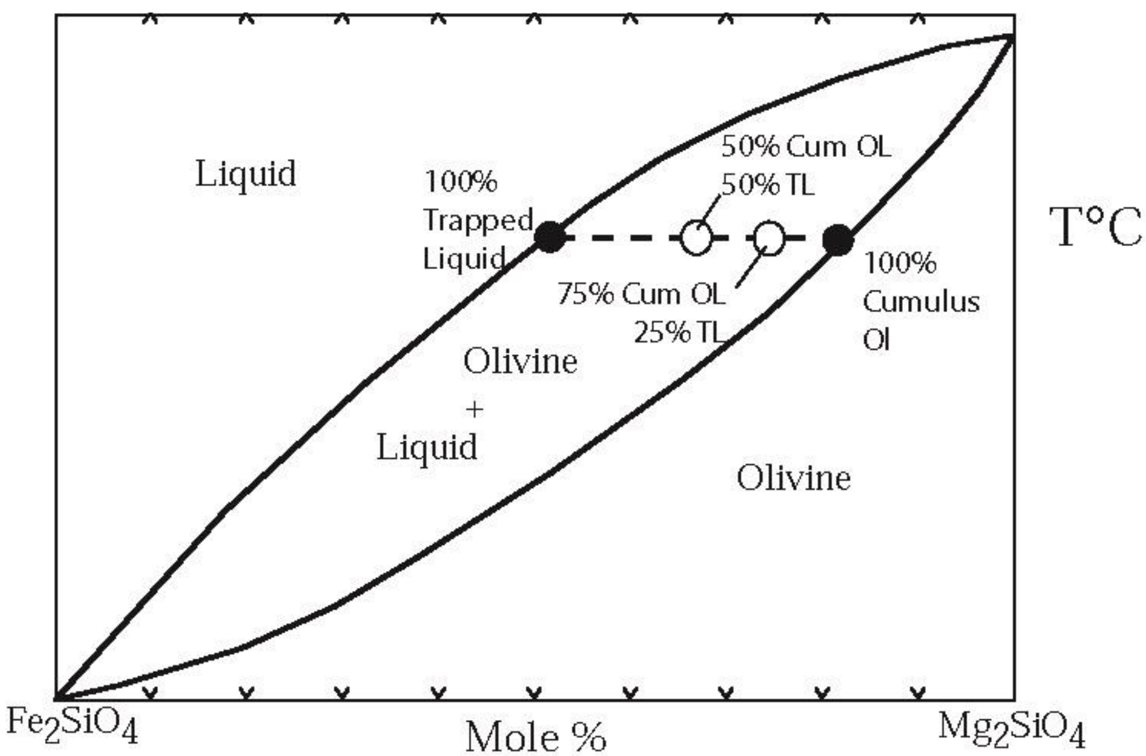


Figure 5.3: Olivine phase diagram illustrating the trapped liquid shift that can occur between cumulus olivine composition with 50% and 25% postcumulus overgrowths crystallized from trapped liquid. Figure by J. Miller.

If trapped liquid shift is operative in rocks with cumulus olivine, it should be manifest by a qualitative correlation between Fo content and proxies for the amount of trapped liquid in the cumulate rock. Such proxies include 1) the modal abundance of postcumulus minerals, 2) the development of foliation, which reflects the porosity of the cumulate, and 3) the abundance of incompatible trace elements which reside largely in the postcumulus minerals crystallized from the trapped liquid (Barnes, 1986; Chalokwu and Grant, 1987; Tegner et al., 2009). Tegner et al. (2009) evaluated the concentratiuon of incompatible trace elements to estimate the trapped liquid porosity of cumulates in the Skaergaard Intrusion, east Greenland. They observed that when Fe-Ti oxide became a cumulus phase, the amount of trapped liquid presently dropped significantly. They attributed this to a decrease in the cooling rate which resulted in a more efficient compaction, i.e. foliation, and less of a trapped liquid component. Tegner et al. (2009) concluded that the efficiency of compaction increases in the upper units of the Skaergaard Intrusion due to the thickening of the crystal pile and lower rates of crystal accumulation, and that the "increase in density of the crystal matrix at the level of oxide–in resulted in efficient compaction, low residual porosity and near-adcumulate textures in the top two-thirds of the Layered Series".

Although geochemical data were not acquired for the cumulate units of the WLI, the changes in postcumulus mineral modes and development of foliation (Fig. 4.20) imply that, like the Skaergaard, the intercumulus porosity of the WLI decreases dramatically with the appearance of Fe-Ti oxide in the OT and OG units (Fig. 5.5). Whereas the troctolitic subunits are poorly foliated orthocumulates with 20-30% intercumulus mineralogy (Augite, Fe-T- oxide, apatite, amphibole, biotite), the OT and OG units abruptly shift to being well foliated adcumulates with 2-8% intercumulus mineralogy in the upper OT unit (Fig. 5.5) Although all essential minerals are cumulus in the OG unit, this made it difficult to estimate the amount of postcumulus material, the unit is very well foliated thus indicating a very low porosity. In summary, it seems reasonable to conclude that the reversed to flat cryptic variation in mg# in olivine and augite in the three sample profiles through the WLI largely reflect the decreased effects of a trapped liquid shift up-section.

The lateral decrease in mg# to the east, as well as the disappearance of the oxide troctolite unit, is caused by the thinning of the intrusion which caused the eastern portion of the intrusion to cool more rapidly than the west. This more rapid cooling would have caused more trapping of intercumulus liquid (and thus a stronger trapped liquid shift) and would have promoted oxide and pyroxene to crystallize more synchronously since their liquidus temperatures are not very different.

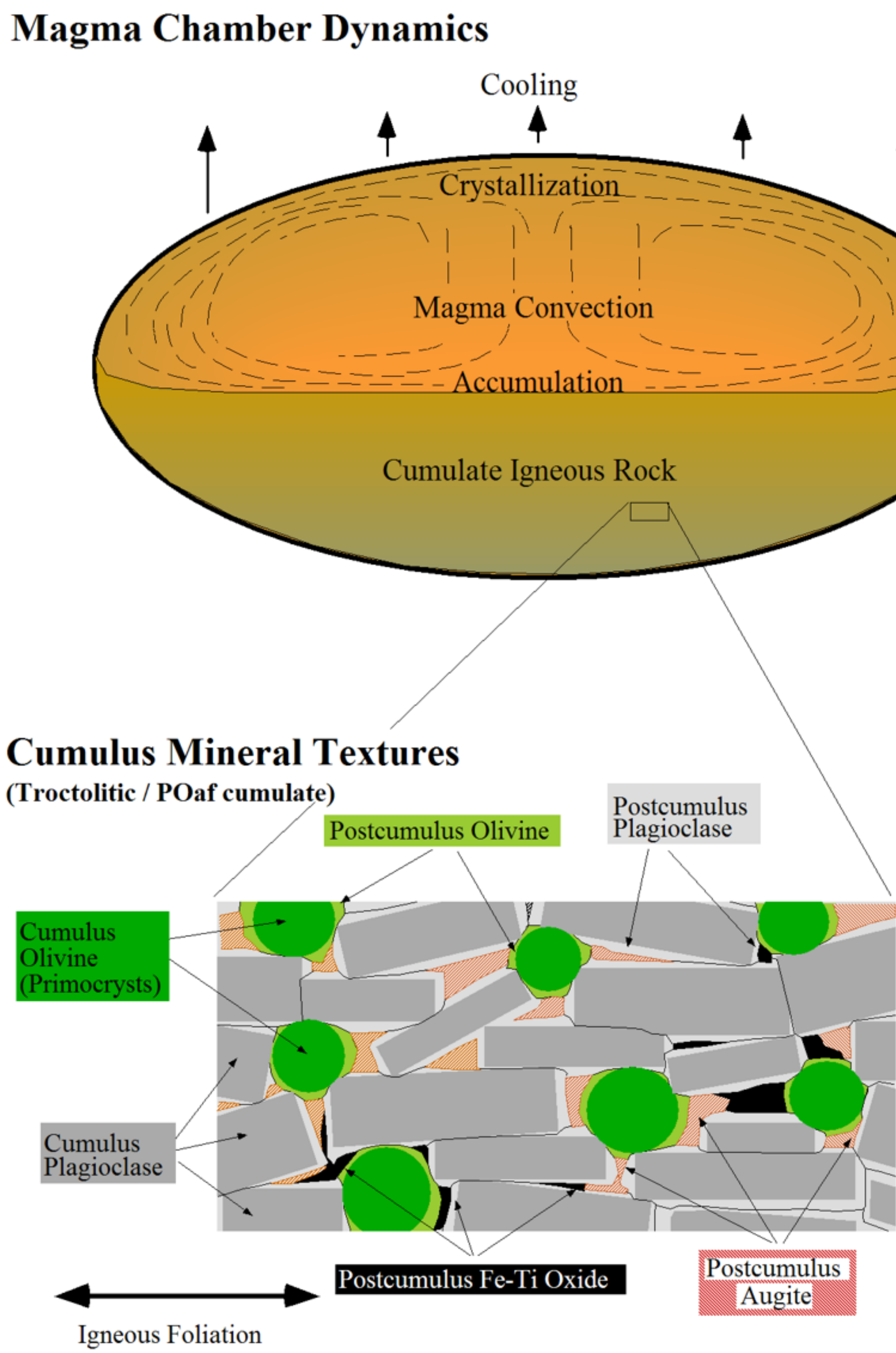


Figure 5.4: Cartoon illustrating the textural relationships of cumulus and postcumulus mineral textures in magma chambers. Cumulus phases of olivine (green) and plagioclase (gray) develop postcumulus overgrowths and postcumulus augite and Fe-Ti oxide fill intercumulus spaces. The zoning of olivine will homogenize due to subsolidus re-equilibration, but plagioclase zoning will be retained. Figure by j. Miller

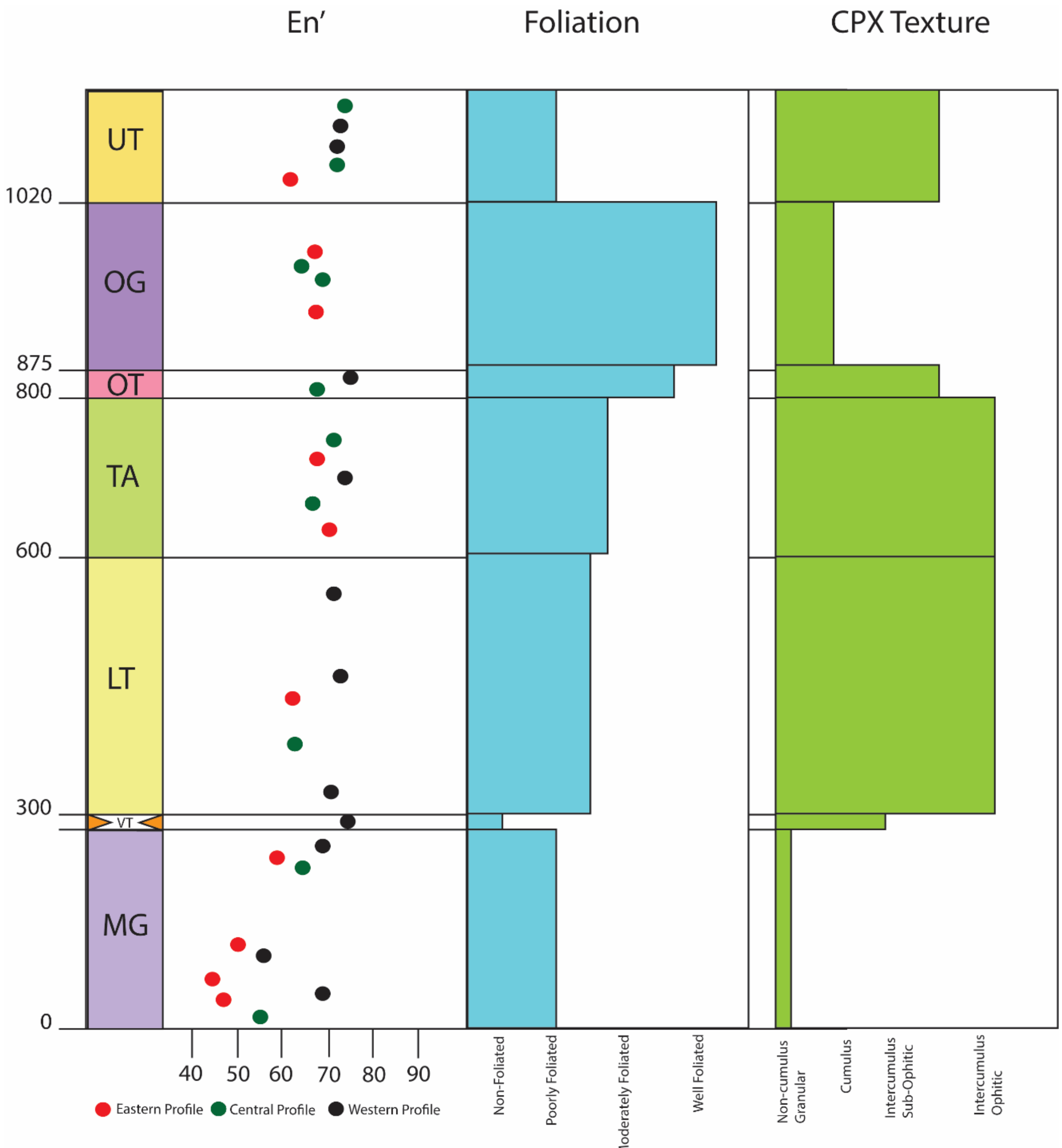


Figure 5.5: En' values compared to interstitial Cpx mode and foliation in the WLI. Note the strong increase in foliation moving from the AT unit into the OT unit, which coincides with the cumulus arrival of Fe-Ti oxides and, shortly thereafter, Cpx.

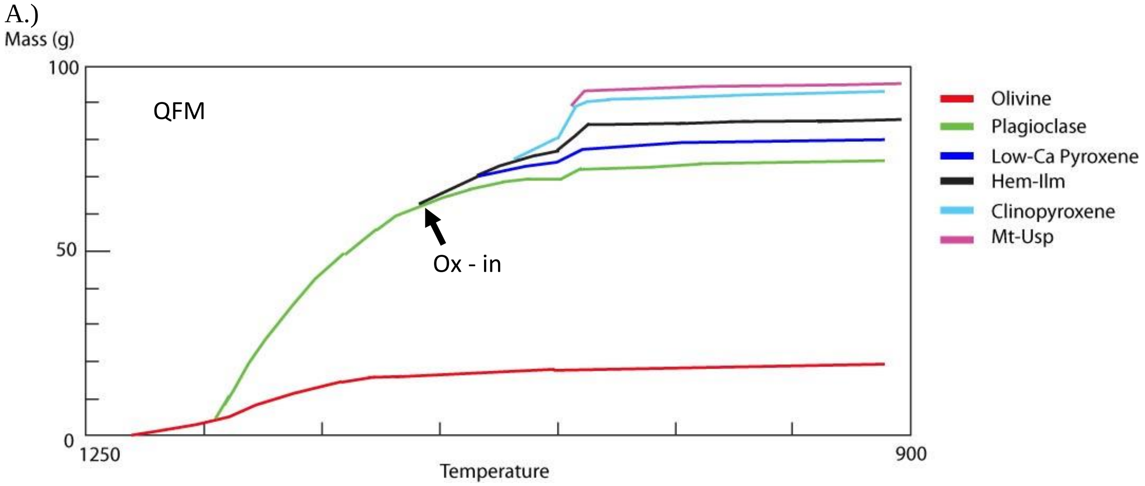
5.3 Early Cumulus Arrival of Fe-Ti Oxide

The most notable characteristic of the WLI that sets it apart from other Duluth Complex layered intrusions is the cumulus arrival of Fe-Ti oxides before clinopyroxene. This could have taken place because of two reasons: 1) oxygen fugacity might have controlled when the oxides entered the cumulus phase and thus could have triggered the onset of an Fe-Ti mineral phase prior to the onset of cumulus clinopyroxene, or 2) the WLI parent magma could have been enriched in Fe and Ti causing early saturation of Fe-Ti oxide relative to clinopyroxene. In an effort to test these ideas, samples were collected of olivine oxide gabbro from the marginal gabbro unit near its contact with country rock (Fig. 4.22) and were analyzed for their lithogeochemistry (Tables 4.2 and 4.3). As noted earlier, the fine-grained and non-foliated textures and robust trace element abundances of sample S2 suggest it may be the best sample to represent the WLI parental magma. Sample S2 was also collected near the lower contact as shown in Figure 4.22. It is also the sample that most closely matches the NSVG compositions from Brannon (1984).

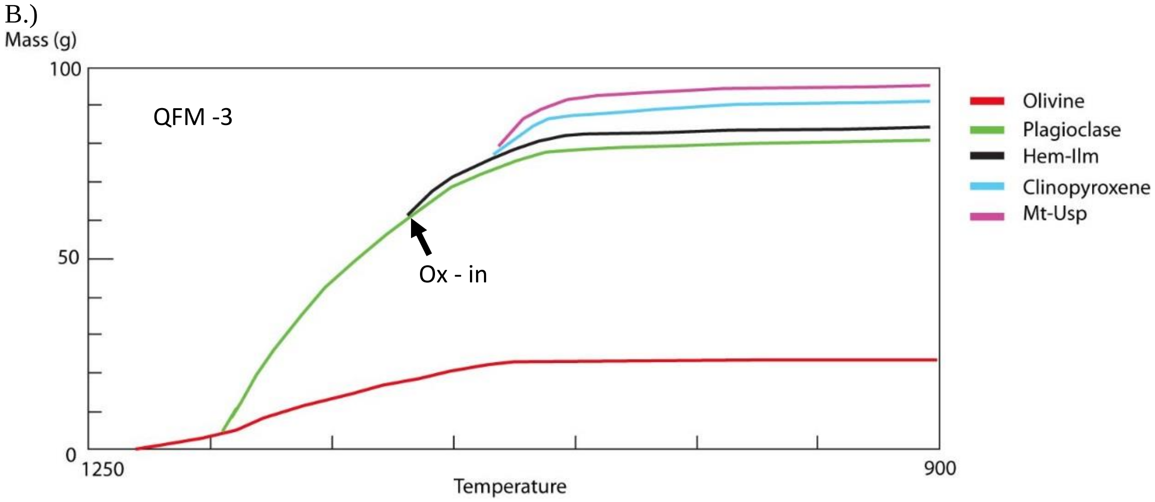
Applying the S2 composition of the marginal gabbro as an input into PELE, a MELTS-like thermodynamic modeling program (Boudreau, 2006), it can be determined whether this composition can yield a crystallization sequence such as observed in the WLI - (OL)→PL+OL→Pl+Ol+FeOx→Pl+Cpx+FeOx+Ol. It can also be used to test the effect of varying oxygen fugacities on that crystallization sequence. Crystallization conditions were set to model fractional crystallization at constant pressure over a temperature decrease in steps of 50ºC. Runs were made at a wide range of oxygen fugacities, and discussed here are the resulting, bracketing oxygen fugacities; fO_2 at the QFM buffer, 3 log units below QFM (reducing conditions), and 2 log units above QFM (oxidizing conditions) (Fig. 5.6 A, B, and C, respectively). The liquidus temperatures calculated for the marginal gabbro S2 sample at these three oxidation states are 1220ºC, 1235ºC, and 1205ºC, respectively. The fractional crystallization modeling was started from these temperatures and stopped at 900ºC, at which temperature all minerals should be crystallizing.

The crystallization of the S2 marginal gabbro composition at three oxygen fugacity conditions is shown in Figure 5.6A-C. This figure illustrates the initial crystallization of olivine followed shortly by plagioclase in all three cases. Then, in the case of the QFM buffer (Fig. 5.6A), low-Ca pyroxene and hematite/ilmenite begin to crystallize simultaneously, whereas in reducing conditions (Fig. 5.6B) there is no crystallization of low-Ca pyroxene, only the hematite/ilmenite phase. Finally, at both QFM and reduced oxidation conditions (5.6A and B), the S2 composition becomes saturated in clinopyroxene and subsequently the magnetite/ulvospinel phases before reaching the 900ºC stopping point. Oxidizing conditions (Fig. 5.6C), provide the only case where clinopyroxene crystallizes before the hematite/ilmenite phase. Under these conditions (oxidizing), a low Ca-pyroxene and alkali feldspars would enter the cumulus phase prior even to clinopyroxene, neither of which can be found in the WLI in high abundance. The oxidizing example then begins to crystallize clinopyroxene, hematite/ilmenite, and magnetite/ulvospinel phases, respectively. Because hematite/ilmentite components enter their cumulus phase before clinopyroxene in a wide range of oxygen fugacities (fO_2 = QFM-3 → QFM+1), the magma source must have been enriched in iron and titanium which would facilitate the onset of cumulus Fe-Ti oxide before clinopyroxene, which makes sense considering all of the Marginal Gabbro samples were rich in Fe and Ti with respect to the NSVG basaltic compositions (Table 4.2). Furthermore, this provides evidence that these rocks were not crystallized under oxidizing conditions of 2 log units or more above the QFM buffer.

A.)



B.)



C.)

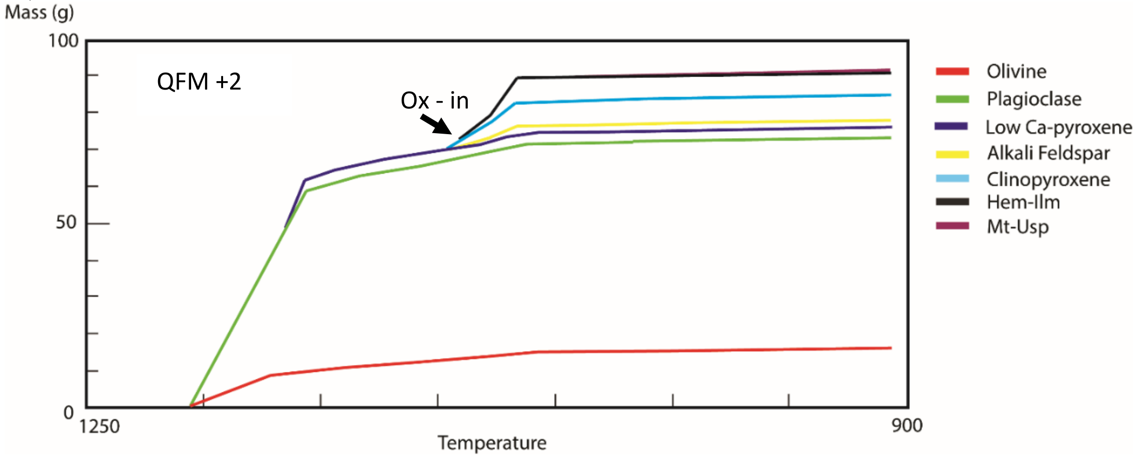


Figure 5.6: Mass solids plots of S2 composition at different oxygen fugacities. A.) QFM buffer B.) QFM -3, and C.) QFM +2

5.5 <u>Emplacement Model/ Fractionation History of the WLI</u>

The WLI was emplaced into the Anorthositic Series in three separate pulses. Initially the MG unit was emplaced and cooled rapidly. This early event paved the way for a more voluminous emplacement of similar magma above the MG unit. The pre-heating of the Anorthositic Series by the initial MG unit emplacement served to promote slower cooling and rather efficient fractionational crystallization. This magma would have intruded a largely solidified and cooled Anorthositic Series (Fig. 5.7), as evidenced by typically sharp contacts and locally very fine-graned texture in the MG units that irregularly coarsens away from the contact. The very irregular contacts between the marginal gabbro and the Anorthositic Series suggests that the anorthositic rocks were warm enough to behave ductily. A second pulse of magma would have followed, detaching and breaking up the anorthositic roof. Blocks of Anorthositic Series rocks dropped down into the magma column across the intrusion forming xenoliths as found abundantly in the AT unit and above. The initial emplacement of this second main pulse was evidently dynamic as evidenced by ubiquitous modal layering, graded bedding, and cross stratified layering of the troctolitic units. Progressive fractional crystallization and cooling of the system then further differentiated the residual magma resulting in the saturation of Ti-Fe oxides followed by clinopyroxene to form the upper OT and OG units, respectively. Finally, a third pulse of a similar parent magma intruded into the upper part of the chamber to form the upper troctolite. Emplacement of the UT unit locally scoured into the OG and OT cumulates. High concentrations of Anorthositic Series xenoliths were incorporated into the UT unit to produce a complex roof zone to the WLI.

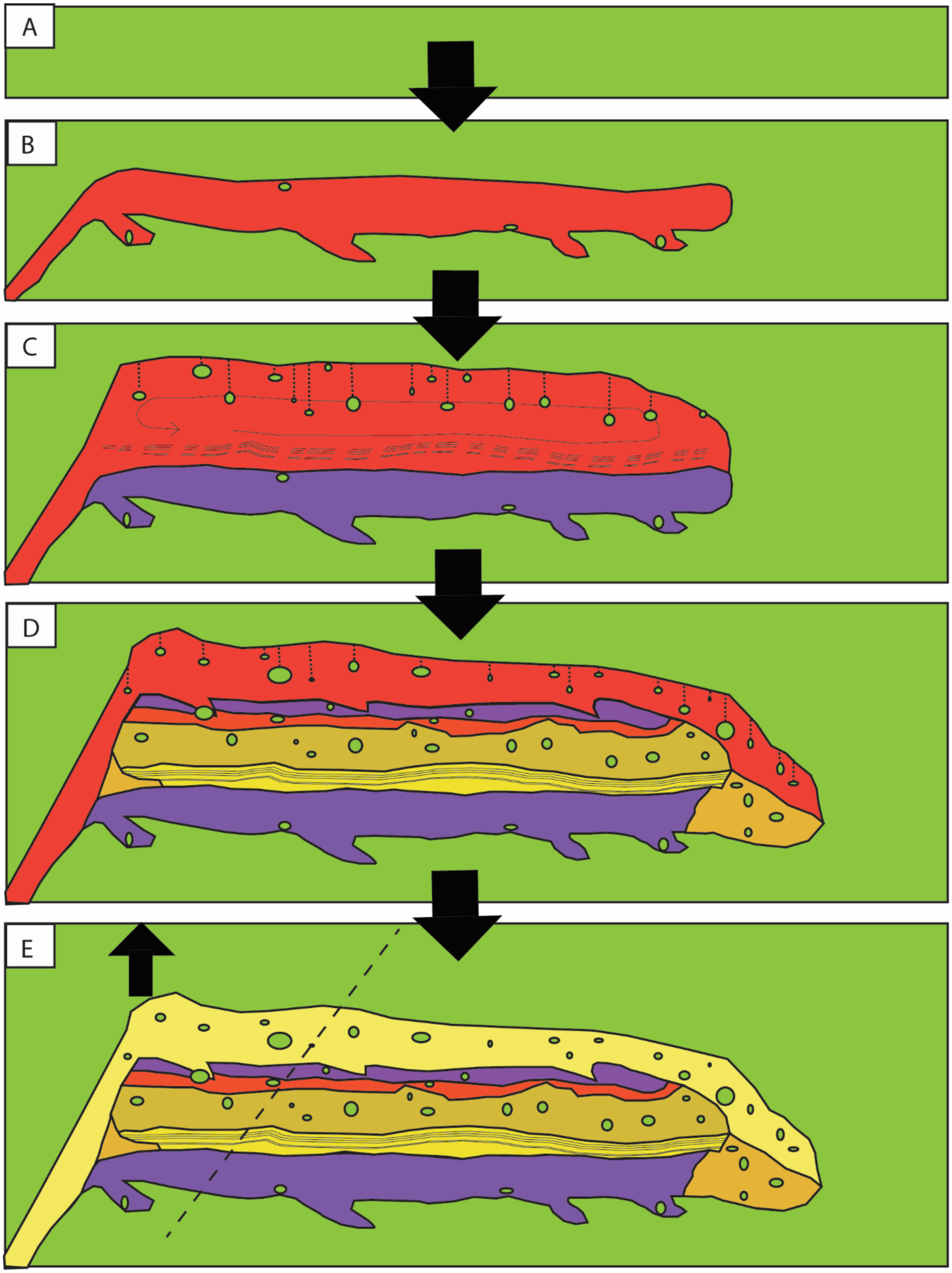


Figure 5.7: Cartoon illustrating the emplacement history of the Wilder Lake Intrusion. A –the Anorthositic country rock. B –the initial emplacement of the Marginal Gabbro Unit which served to preheat the country rock for the following pulses of magma. C –a second pulse of tholeiitic magma and internal differentiation.

D – illustrates a third pulse of magma. E –the subsequent faulting that shaped the intrusion. Green dots are chunks of Anorthositic Series rocks incorporated into the WLI from the roof.

6. Conclusion

Due to the 2011 Pagami Creek fire, the WLI became an incredibly important place to both hone my skills as a geologist and build on the geology that had previously been done in that area. Burning almost 12” of soil, the fire exposed outcrop and made accessible major extents of the WLI. That notwithstanding, the WLI is unique among its Duluth Complex counterparts (other LMIs), including its N-dip, its cumulate reversal from a well-foliated four-phase gabbro to a poorly foliated two-phase troctolite, its reversed cryptic variation, and its cumulate paragenesis. Compelling evidence was found in the northwestern portion of the intrusion at the contact between the four-phased gabbro and the two-phased troctolite that the upper troctolite must have been another injection of magma into the system after the WLI had cooled to below the liquidus temperatures of the four main essential minerals – olivine, plagioclase, augite and Fe-TI oxide. The emplacement of the upper troctolite scoured out the upper portion of the gabbro and small xenoliths of the gabbro can be found in the base of the upper troctolite.

The reversed cryptic variation that was first noted by Miller (1986) was confirmed and can be attributed to a decreased trapped liquid shift up-section, especially after Fe-Ti oxide appears as a cumulus phase. Evidence for this phenomenon comes from the development of strong foliation and decreasing abundances of interstitial phases.

Finally, the distinctive cumulus arrival of Fe-Ti oxide prior to clinopyroxene can be attributed to the primary magma being particularly rich in iron and titanium. Using a marginal gabbro sample as a reasonable estimate of the primary magma composition and applying it to a thermodynamic phase equilibrium model (PELE), it has been shown that the cumuluate stratigraphy of the WLI can be replicated in low to normal (QFM) oxygen fugacities. This indicates that elevated oxygen fugacity did not cause the cumulate introduction of Fe-Ti oxide prior to clinopyroxene, but rather that the primary magma must have been saturated in these components.

There are still many exciting investigations that should take place on the WLI. The complex upper contact between the Anorthositic Series and the WLI is still not well-mapped and deserves further investigation. Also, further mapping and study of this intrusion will elucidate the details of its history. More complete mapping of the central and eastern portions of the intrusion would be a perfect place to start because much of the mapping is still focused on the western portion of the WLI.

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