Petrogenesis of magnetite-rich layers and pipes in the Bushveld Complex, South Africa- Emily Fischer

Background: The Bushveld Complex is located in South Africa and was emplaced approximately 2.056 Ga. It is the largest layered mafic intrusion in the world, covering an area of 65,000 km^2 with a thickness ranging from 7-9 km[1]. The Bushveld is an important resource for the world, hosting major quantities of platinum and platinum group elements (PGE), titanium, iron, vanadium, tin, and chromium[2]. The mafic to ultramafic cumulate sequence of the complex is called the Rustenburg Layered Suite (RLS) and is divided into five zones: Marginal, Lower, Critical, Main, Upper, and Roof Zones. The Upper and Upper Main Zones (UUMZ) are genetically related to each other and are separated from the lower zones by a layer known as the Pyroxenite Marker (PM)[3]. The UUMZ hosts the most significant Fe, V, Ti, and P deposits[2].

The UUMZ is dominated by gabbro, anorthosite, and Fe-Ti-oxide rich rocks, which include magnetitite (magnetite and ilmenite) and nelsonite (magnetite, ilmenite, and apatite) mineral assemblages. Fe-Ti-oxide rich rocks make up the smallest proportion in the UUMZ but host the majority of economically significant minerals. The Fe-Ti-rich rocks are typified in 26 magnetite and 6 nelsonite layers documented in the western limb[4]; the same number of magnetite layers have also been mapped in the eastern limb[3].

The gabbro layers in the UUMZ are thought to have been formed by cooling and differentiation of the residual magma that produced the Pyroxenite Marker. However, the evolution and relationship between the anorthosite and magnetite/nelsonite layers is still poorly understood. Several models have been proposed to explain the genesis of these layers, including: immiscibility, fractional crystallization/mineral accumulation, disequilibrium crystallization, chamber rejuvenation and magma mixing, and hydrothermal enrichment[2-6, 9]. However, no consensus has been reached as to which model may most accurately describes the petrogenesis of the Fe-Ti-oxide rich layers because each authors' interpretation of the data has in turn been challenged by other workers.

Objective: To apply new techniques and ideas developing in magma chamber research to the magnetite layers in the Upper Zone of the Bushveld Complex and use the new datasets to test models for development and differentiation of UUMZ layers. The results will be applied to magnetite pipes that have similar mineral assemblages to the magnetite layers, but have contested origins.

Hypothesis: Testing different previously proposed models for the origin of Fe-Ti-oxide rich magnetite and nelsonite layers in the Bushveld Complex will result in a new model that combines certain aspects of these end-member processes to more accurately define the petrogenesis of the oxide-rich layers.

Methods: The western limb will be studied via samples from the *Bierkraal* cores and the magnetite layers in the eastern limb will be sampled during field-mapping. Bulk rock geochemistry analyzed with x-ray fluorescence (major elements) and LA-ICPMS (trace elements). Mineral compositions will be analyzed by EPMA and LA-ICPMS; the data will be integrated with photomicrographs collected using optical and scanning electron microscopy.

Testing models: *Immiscibility*. Silicate liquid immiscibility occurs when a homogenous silicate melt separates into two compositionally distinct liquids with identical mineralogy but in differing proportions. In mafic layered intrusions, this process begins after considerable crystal fractionation, resulting in a crystal mush. If the permeability of the crystal mush is high, liquid may separate by gravity, producing nearly monomineralic layers[5,6]. The presence of Fe-rich silicate inclusions in minerals such as plagioclase and apatite is evidence for liquid immiscibility. If the Fe-Ti-oxide rich layers formed through immiscible processes, then the crystallized Fe-rich melt inclusions will have major and trace element content similar to the magnetite layers. Additionally, the host mineral that crystallized from the Si-rich melt will have lower REE, HFSE, P, Ti, and FeO contents than the conjugate Fe-rich inclusions[7].

Fractional crystallization/mineral accumulation. Fractional crystallization of magma will lead to a dense residual magma that will begin to crystallize magnetite and accumulate into magnetite-rich layers. The resulting magma after magnetite crystallization will have a lower density and rise buoyantly continuing this process. If fractional crystallization occurred, a fractionation trend will be recorded in minerals with increasing height in the section. Consequently, stratigraphically higher magnetite and anorthosite layers will have increased iron enrichment, lower plagioclase An%, lower Mg# in pyroxene and olivine, lower V content in magnetite, and higher whole rock SiO_2 wt%[4]. Additionally, in a closed system with continuous fractionation, incompatible elements become more enriched and compatible elements depleted with increasing stratigraphic height. In magnetite, this will be recorded as decreased Ti, V, and Cr (compatible elements) and increased Si and Ca (highly incompatible)[8].

Disequilibrium crystallization. Another idea proposed for the genesis of magnetite-rich layers is rapid crystallization in disequilibrium conditions in response to increased oxygen fugacity (fO_2) towards the base of a magma chamber. As magnetite crystallization progresses, fO_2 is lowered. Vanadium (V) partitioning between magnetite (mt) and clinopyroxene (cpx) can be used as a proxy for oxygen fugacity, as it is sensitive to changes in fO_2. If V_{mt}/V_{cpx} increases, this corresponds to decreasing fO_2[2]. Additionally, if the Fe-Ti-oxide layers crystallized instantaneously in high fO_2, Mg, Al, and Si contents will be relatively enriched in magnetite from these layers compared to disseminated magnetite in anorthosite/gabbro layers[9].

Chamber rejuvenation and magma mixing. If new magma was injected periodically during the emplacement of the UUMZ to form the distinct Fe-Ti-oxide rich layers, step-like changes in mineral composition through a vertical unit, rather than a smooth fractionation trend, will be observed. Also, if the new magma is more primitive than the final fractionation stages of the previous injection then compositional reversals will be observed moving up-section. Compositional reversals in magnetite will be seen as higher Cr and V contents followed by an abrupt change to lower content[4].

Hydrothermal enrichment. This model is particularly applicable to the magnetite pipes that have a vertical structure. If the Fe-Ti-oxide rich layers formed by hydrothermal enrichment rather than having a magmatic origin, magnetite will be depleted in Ti, Al, and HFSE, as hydrothermal fluids have generally low concentrations of these minerals due to their relatively low solubility. In contrast, magmatic magnetite will be relatively enriched in compatible elements. Silicon and Ca are two elements that are highly incompatible with magnetite, so if these are enriched in the samples, it suggests hydrothermal activity. Another characteristic of magnetite that is indicative of hydrothermal enrichment is if the Ni/Cr ratio is >1 (in silicate magmas this ratio is always less than one)[9]. In addition, photomicrographs of magmatic magnetite commonly show concentric compositional zoning in contrast to patchy textures common of hydrothermal minerals[9].

Intellectual Merit: The UUMZ contains world class deposits of important strategic elements including vanadium, iron, and titanium. There are limited global resources of these minerals and global demand is growing exponentially[2]. Understanding how these ore deposits form is critical both globally and to U.S. interests, as the country is dependent on foreign sources for many of these important commodities. There is still much debate about the formation of magnetite layers in the Bushveld Complex, even though they have been identified and studied for many years. Results from this research may be applied to other parts of the extensive Bushveld Complex, as well as to other layered mafic intrusions around the world.

Broader Impacts: Impacts of this research of magnetite layers of the Bushveld Complex extend beyond Earth. One of the most exciting endeavors of the last century, sending humans to outer space, has propelled scientific curiosity perhaps more dramatically than any other scientific activity. As interest in deep-space exploration and establishing a human presence on Mars and other planets increases, so has the need to understand the processes of ore-deposit formation and exploitation. Lessons learned about the differentiation of magnetite layers in the Bushveld Complex may provide insight and strategies for sourcing iron and titanium (and other metals) that are crucial to permanent infrastructures, but are not cost effective to send from Earth.

Results from my research will be shared with colleagues through publications and presentations at conferences, including the national GSA and AGU conferences. Additionally, one of my long-term goals is to provide educators with resources they can implement in their classrooms to encourage curiosity in their students and create lifelong learners who can contribute to scientific advancement. Applying ore-forming processes to ideas of colonization on other planets offers the potential for stimulating STEM activities that can be leveraged into K-12 educations to increase engagement in science. Potential projects topics could include what would be required to mine resources on another planet, requiring students to engage strategy and research, and in the process hopefully garner a lifetime of scientific curiosity.

[1] Zeh et al. (2015) Earth Planet Sci Lett, v. 418, p. 103-114 [2] Fischer (2018) PhD Dissert., 129 p.

[3] Scoon and Mitchell (2012) S Afr J Geol, v. 115.4, p. 515-534 [4] Tegner et al. (2006) J Petrol, v. 47, p. 2257-2279 [5] Cawthorn (2015) *in* Layered Intrusions, p. 515-587 [6] VanTongeren and Mathez (2012) Geology, v. 40, p. 491-494 [7] Veksler et al. (2006) Contrib Mineral Petrol, v. 152, p. 685-702
[8] Dare et al. (2014) Miner Depos, v. 49, p. 785-796 [9] Klemm et al. (1985) Econ Geol, v. 80, p. 1075-1088