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Volcanological and petrogenetic characteristics of komatiites of the 3.3 Ga Saw Mill Complex, Weltevreden Formation, Barberton Greenstone Belt, South Africa

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VOLCANOLOGICAL AND PETROGENETIC CHARACTERISTICS OF KOMATIITES OF THE 3.3
GA SAW MILL COMPLEX, WELTEVREDEN FORMATION, BARBERTON GREENSTONE BELT,
SOUTH AFRICA

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
In partial fulfillment of the
requirements for the degree of
Master of Science

in

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by
Matthew Stephen Huber
B.S., University of Tennessee at Martin, 2007
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Abstract

The Saw Mill Complex (SMC) is a 1275 m thick layered komatiitic sequence in the 3.3 Ga Weltevreden Formation, uppermost stratigraphic unit of the Onverwacht Group in the northern part of the Barberton Greenstone Belt, South Africa. A series of ultramafic complexes in the Weltevreden Formation have been interpreted as layered ultramafic intrusions, consisting of thick, layered ultramafic units of peridotite, pyroxenite, dunite, and gabbro. However, recent work on the Pioneer complex of the Weltevreden Formation has demonstrated an extrusive origin of komatiites and tuffs. The Weltevreden Formation has been less studied than other Onverwacht Group units. It is likely composed of a number of individual tectonically juxtaposed terrains brought in by thrust faulting during deposition of Fig Tree Group sediments and felsic volcanics in a magmatic arc setting. It is currently regarded as a product of plume-based eruptive centers. This study represents an ongoing effort to elucidate the structure, stratigraphy, and petrogenesis of the Weltevreden Formation.

A new 1:1000 scale map and stratigraphic section of the SMC reinterpret the igneous complex as extrusive, with lithologic units interpreted as layered komatiitic flows and interbedded tuffs. The SMC was rapidly emplaced, not allowing any sediment other than tuff to be deposited. Flows preserved in the SMC dominantly formed as open flow pathways, allowing for large quantities of olivine to accumulate in the lower portions of flows. Some flows formed as closed systems, possibly as a result of deforming tuffs below the flows to form lava lakes. Large cm-sized lapilli, including those with aerodynamic shapes, suggest some subaerial explosions, possibly near-vent. Cross-bedding in the tuffs represent shallow marine environments.

Geochemically, the SMC is very similar to Weltevreden Formation komatiites recently studied in the Pioneer complex. They have $\text{Al}_2\text{O}_3/\text{TiO}_2$ near 30, Gd/Lu normalized values between 0.8 and 1.2, maximum liquid compositions of approximately 33% MgO, and olivines up to Fo₉₄. Oxygen fugacity of the mantle source is determined from V to have -0.18 ΔNNO . MELTS modeling suggests eruption temperature in excess of 1615°C, representing some of the hottest volcanism experienced on the early Earth.

1. Introduction

The mid-Archean Barberton Greenstone Belt (BGB) has been an area key to the understanding of ultramafic extrusive rocks (e.g. Viljoen and Viljoen, 1969a). Within the BGB, the 3.3 Ga Weltevreden Formation (Lowe and Byerly, 1999) has exquisitely preserved komatiites, with mesoscopic structures, fine microscopic textures and unaltered olivine, pyroxene, and chromite (Kareem, 2005; Cooper, 2008). The Saw Mill Complex (SMC) is a suite of ultramafic igneous rocks within the Weltevreden Formation originally interpreted as a layered ultramafic intrusion (Wuth, 1980; Anhaeusser, 1985). It is one of several ultramafic complexes in the Weltevreden Formation. Among them, the Pioneer Complex has recently been shown to be extrusive and characterized by komatiitic flows and tuffs (Cooper, 2008), complete with sedimentary structures (Stiegler et al., 2008). These findings cast doubt on the intrusive interpretation of ultramafic complexes in the Weltevreden Formation.

This paper demonstrates that the SMC represents extrusive volcanism, not intrusive igneous activity, and characterizes the nature of the extrusive rocks making up the SMC. A new geologic map and stratigraphic section of the SMC are presented, along with new geochemical data and a revised interpretation of the SMC. The geochemical relationship between the Saw Mill and Pioneer complexes is examined in order to suggest a possible structural relationship between the complexes. Eruption temperature of SMC komatiites are calculated from an estimated original liquid composition. An interpretation of the physical volcanology of komatiites of the Weltevreden is presented, including olivine accumulation, flow propagation, mineral fractionation, and the relationship between komatiites and komatiitic basalts.

1.1 Barberton Greenstone Belt

The Barberton Greenstone Belt (BGB), South Africa, is a structurally complex sequence of igneous and sedimentary rocks metamorphosed to greenschist facies (e.g. Lowe and Byerly, 2007). While the general stratigraphy of the BGB is largely understood (Lowe and Byerly, 1999), the finer-scale stratigraphy is not well constrained. The BGB is divided into a northern and southern domain by the Inyoko thrust fault (Lowe et al, 1999), and each domain has a distinct (though related) stratigraphy. The two major domains are composed of the same three formal stratigraphic groups: the Onverwacht Group, Fig Tree Group, and the Moodies Group (e.g. Lowe and Byerly, 1999).

The Onverwacht Group in the southern domain is represented by 12 km of predominantly mafic and ultramafic volcanics, ranging in age from 3550 Ma to 3290 Ma, with the komatiitic Mendon Formation (Byerly, 1999) as the youngest stratigraphic unit. In the northern domain, the only representation of the Onverwacht Group is the 3298 Ma Weltevreden Formation (Lahaye et al, 1995; Byerly et al, 1996; Lowe and Byerly, 2007). Both the Mendon Formation and the Weltevreden Formation are characterized by komatiitic volcanism, though there are major differences. While there are several stratigraphic marker beds in the Mendon Formation that allow for correlation across structural blocks, no such marker beds have been found in the Weltevreden Formation (Lowe and Byerly, 1999). The Mendon Formation is subdivided into five stratigraphic members, M1-M5, and of those members, M1, M2, and M4 have extensive komatiitic volcanism, each with a distinctive geochemistry. Volcanic units of the Weltevreden Formation, however, are not subdivided because no distinctive subunits are recognized. Only rarely are sedimentary black cherts found between eruptive events, though thick unsilicified tuffs are common (Lowe and Byerly, 2007). The Onverwacht Group ends with the end of komatiitic volcanism in the BGB. The 3260-3225 Ma Fig Tree Group (Kröner et al, 1991) is characterized

by extensive sedimentation that represents the tectonic change from mafic-ultramafic plume related volcanism to dacitic volcanism and structural shortening attributed to subduction (Lowe, 1999; Lowe and Byerly 2007). In the lower Fig Tree Group, ferruginous cherts dominate sedimentation. At least four major spherule beds associated with impacts are described in the BGB, and the S2 impact layer is deposited in the basal Fig Tree sediments, including outcrops geographically proximal to the SMC (Lowe and Byerly, 1986a).

Rocks throughout the central portions of the greenstone belt have been altered to greenschist facies (Xie et al, 1997). Some have been metasomatically altered, causing carbonation and silicification of some of the flows and tuffs (Lowe and Byerly, 1986b). This has resulted in mobilizing some elements within the BGB, such as Ca, K, Na, and Mn (e.g. Duchac and Hanor, 1987). Important immobile elements can be reliably used for discrimination of differences between komatiitic flows, such as Mg, Ti, Al, Cr, V, Sc, and Ni (Byerly, 1999; Kareem and Byerly, 2003). Most of the REE's have been shown to be immobile, with HREE's particularly immobile (Duchac and Hanor, 1987; Hanor and Duchac, 1990).

1.2 Weltevreden Formation and Ultramafic Complexes

The Weltevreden Formation represents the oldest exposed rocks in the Northern domain of the BGB. The Weltevreden Formation was originally described as consisting of both serpentinized komatiitic rocks and peridotitic layered intrusive rocks, along with tuffs and rare beds of black chert (Wuth, 1980; Anhaeusser et al, 1981; Anhaeusser, 1985), though more recent workers have suggested that rocks originally interpreted as peridotitic are actually komatiitic flows (Cooper et al, 2005). Half of the 28 layered complexes described by Anhaeusser are in the Weltevreden Formation, characterized as high MgO intrusive igneous rocks (Anhaeusser, 1985). These complexes are described as sill-like intrusions into the volcanic rocks of the BGB.

Anhaeusser described units of dunite, orthopyroxenite, and harzburgite, as well as gabbros in layered sequences. Fine-grained ultramafic rocks in the complexes are described as shear zones. Anhaeusser regarded the layered complexes as being the intrusive equivalents to extrusive flows between the complexes. While komatiitic flows and tuffs have continued to be described, intrusive peridotitic layers have not been found in layered complexes in the Weltevreden Formation. Three adjacent ultramafic complexes in the western part of the Weltevreden were originally interpreted as intrusive: the Pioneer Complex, Emmenes Complex, and SMC (Anhaeusser, 1985, Lowe and Byerly, 1999) (Fig. 1). The Pioneer Complex, an 8 km by 1 km complex, has recently been studied by Cooper et al (2005). Cooper found the complex to be extrusive in origin, with tuffs, layered komatiitic flows, and massive komatiitic flows the principle lithologies present. Other recent studies suggest that fine-grained slaty rocks in the Pioneer complex, the Emmenes complex, and the SMC erupted pyroclastically (Stiegler et al., 2008). Tuffs sometimes preserve fine bedding, lapilli, convolute bedding, and cross-laminations. The eruptive environment of the tuffs is considered to be a shallow marine environment such that the volcanic sediments interacted with currents above wave base after experiencing airfall. Tuffs may have come from multiple sources in the Weltevreden, as there are distinct chemical signatures for different tuff bodies (Stiegler et al., 2008). The interpretation of layered complexes as intrusive has not been supported by these recent studies.

1.3 Komatiites

Komatiites were first described in the BGB at the type location on the Komati River (Viljoen and Viljoen, 1969a). Komatiites are defined as extrusive ultramafic rocks, containing > 18 wt.% MgO, which typically have olivine or pyroxene spinifex texture at the upper chilled margin (Kerr and Arndt, 2001; Le Bas, 2000). Olivine is the first mineral phase to crystallize in

Figure 1: Geologic map of a northwestern section of the Barberton Greenstone Belt. The Emmenes, Saw Mill, and Pioneer ultramafic complexes are outlined from descriptions by Anhaeusser (1985). The Pioneer complex is directly south of the SMC. (Modified from Cooper et al, 2005).

komatiites, and they are typically dominated by accumulated olivine. Komatiitic basalts, which have less than 18% MgO, are genetically associated with true komatiites. Komatiitic basalts are typically characterized by augite rather than olivine. Though these rocks technically fall into the category of basaltic andesites or boninites based on bulk chemistry (Le Maitre et al, 2002), the preferred term for rocks genetically related to komatiites that have <18 wt. % MgO is komatiitic basalts (Viljoen and Viljoen, 1969a). In both of these lithologies, the original mineral assemblage is inferred to be almost entirely olivine, enstatite, pigeonite, augite, and chromite. Crystallization temperature of olivine in komatiitic flows has been inferred to be as high as 1650°C (Kareem and Byerly, 2003), which would make these among the hottest known lava flows in the history of the planet.

Komatiites are important to an understanding of early history of the Earth, as they represent a significant portion of the preserved Archean crust. Komatiites are interpreted to originate from mantle plumes (Arndt, 2003; Kareem and Byerly, 2003), so that they are representative of Archean mantle processes. Komatiites can be divided into three separate geochemical groups based on melting depth: Al-undepleted, Al-depleted, and Al-enriched komatiites (Nisbet et al., 1993). Al-undepleted komatiites have $\text{Al}_2\text{O}_3/\text{TiO}_2$ between 15 and 30 (ratio in wt. %), Al-depleted komatiites are below 15, and Al-enriched komatiites have $\text{Al}_2\text{O}_3/\text{TiO}_2$ above 30. Byerly (1999) has also shown that $\text{Al}_2\text{O}_3/\text{TiO}_2$ in rocks correlates with $\text{Cr}_2\text{O}_3/\text{Al}_2\text{O}_3$ in chromites, and $\text{Al}_2\text{O}_3/\text{TiO}_2$ in orthopyroxene, pigeonite, and augite.

Despite years of study on komatiites in the BGB and elsewhere, several critical questions remain unresolved. This includes whether the rocks represent extrusive or intrusive igneous activity, temperature at the time of eruption or emplacement, and the physical nature of eruptions. Komatiites do not have a modern analogue, though they have been compared to boninites and flood basalts (Arndt, 2003), and some komatiitic basalts have the composition of

boninites (Parman et al., 2004). The tectonic setting of the komatiites in the BGB is disputed as well, having been proposed as either a mantle plume (Arndt, 2003) or a subduction zone (Parman et al., 2001). This paper will attempt to answer the questions of the emplacement mechanism of the Saw Mill Complex, temperature of eruption of SMC komatiites, and the mechanisms resulting in growth of lava flows.

2. Methods

2.1 Sample Collection

Samples were collected by the author (designated HB##) during the 2008 field season. Sample numbers, lithologies, and locations are listed in Table 1. The SMC was mapped (Fig. 2) and samples were chosen to represent distinct flows and petrologic endmembers within flows. Rocks collected in a previous field season by Gary Byerly from the SMC (designated SA##) were used to add lithologic and stratigraphic diversity to the study.

Twenty-four samples were selected from the Saw Mill Complex (SMC) for detailed chemical analysis of three layered flows and thirteen massive flows with representative distribution through the full stratigraphy of the SMC (Fig. 3). Where layered flows were found, samples representing different horizons within the flows were analyzed with an effort made to analyze the lithologic endmembers of flows. Massive flows are represented by single samples. Fourteen analyses represent layered flows (Flow 2: HB 2-5, 2-6, 2-7, 2-8, 2-9; Flow 3: HB 3-10, 3-9, 1-7; Flow 510: SA 510-1, 510-2, 510-3, 510-4; Flow 442: SA 442-3, 442-5) and eleven represent massive flows, with two dunitic komatiites (SA 500-1, HB 3-8), three pyroxenitic komatiites (SA 500-7, 500-4, and HB 3-4), four peridotitic komatiites (HB 2-4, 2-3, 2-2, and 2-1) and one massive komatiitic basalts (SA 442-2).

2.2 Electron Microprobe

Twelve thin sections were polished and carbon coated in order to be analyzed by the JEOL JAX-733 electron microprobe at Louisiana State University. The microprobe was calibrated relative to Smithsonian standards. The beam was set to 10nA current with an accelerating voltage of 15kV with a focused spot having an approximately 1 μ m diameter

Figure 2: Geologic map of the Saw Mill Complex (SMC) at 1:1000 scale. Beds are correlated along strike. SMC is divided into three distinct structural blocks, the eastern block, central block, and western block. Coarse line running across alluvial fill of Queen's River is a proposed fault which displaces approximately 300 meters of strata in the western block. Stratigraphic section is taken from A-A' and B-B' (Fig 3). Selected strike and dip symbols are plotted.

Figure 3: Stratigraphic section through the Saw Mill Complex. Sample numbers are indicated by stratigraphic position. Samples 2-5 through 2-9 are taken from the Western block of the SMC.

Table 1: Sample numbers, lithologies, and locations.

Sample ID	Lithology	Latitude	Longitude
SA 510-1	Peridotitic Komatiite	S 25° 49.742'	E 30° 53.431'
SA 510-2	Pyroxenitic Komatiite	S 25° 49.742'	E 30° 53.431'
SA 510-3	Dunitic Komatiite	S 25° 49.742'	E 30° 53.431'
SA 510-4	Dunitic Komatiite	S 25° 49.742'	E 30° 53.431'
SA 442-5	Komatiitic Basalt	S 25° 49.765'	E 30° 53.233'
SA 442-3	Peridotitic Komatiite	S 25° 49.802'	E 30° 53.285'
SA 442-2	Komatiitic Basalt	S 25° 49.866'	E 30° 53.335'
SA 500-1	Dunitic Komatiite	S 25° 50.024'	E 30° 53.431'
SA 500-3	Pyroxenitic Komatiite	S 25° 50.047'	E 30° 53.433'
SA 500-4	Pyroxenitic Komatiite	S 25° 50.083'	E 30° 53.467'
SA 500-7	Spinifex Textured Komatiite	S 25° 50.215'	E 30° 53.347'
HB 2-1	Peridotitic Komatiite	S 25° 50.070'	E 30° 52.365'
HB 2-2	Peridotitic Komatiite	S 25° 50.113'	E 30° 52.422'
HB 2-3	Peridotitic Komatiite	S 25° 50.091'	E 30° 52.526'
HB 2-4	Peridotitic Komatiite	S 25° 50.070'	E 30° 52.586'
HB 2-5	Spinifex Textured Komatiite	S 25° 50.070'	E 30° 52.586'
HB 2-6	Peridotitic Komatiite	S 25° 50.070'	E 30° 52.586'
HB 2-7	Peridotitic Komatiite	S 25° 50.070'	E 30° 52.586'
HB 2-8	Pyroxenitic Komatiite	S 25° 50.070'	E 30° 52.586'
HB 2-9	Dunitic Komatiite	S 25° 50.070'	E 30° 52.586'
HB 3-10	Pyroxenitic Komatiite	S 25° 49.948'	E 30° 53.354'
HB 3-9	Pyroxenitic Komatiite	S 25° 49.957'	E 30° 53.383'
HB 3-8	Dunitic Komatiite	S 25° 49.971'	E 30° 53.439'
HB 1-7	Pyroxenitic Komatiite	S 25° 49.967'	E 30° 53.455'
HB 3-4	Dunitic Komatiite	S 25° 50.047'	E 30° 53.422'

volume. Eight samples were analyzed for olivine, six samples for chromite, and seven samples for orthopyroxene, pigeonite and augite.

Any analytical point totaling greater than 101 wt. % or less than 99 wt. % was removed from the data set. Points were also removed that did not meet the expected stoichiometry for the analyzed mineral. Olivine with > 1.02 or < 0.98 Si were removed. Pyroxenes with > 2.1 Si+Al were removed to prevent amphiboles from being counted with pyroxenes. Results for all mineral analyses are listed in Appendix. Standards and uncertainty for JAX-733 can be found in Appendix A of Cooper, 2008.

2.3 X-Ray Fluorescence and Inductively Coupled Plasma Mass Spectrometry

Twenty-four samples were powdered at LSU. Weathered rims were removed manually and slabs of samples were broken into 1-2 cm blocks prior to being powdered by a carbon steel rock crusher. Approximately 100 grams were powdered for each sample and sent to the geochemical lab at Washington State University (WSU) for bulk rock chemical analysis by X-ray fluorescence (XRF) and trace elements by inductively coupled plasma mass spectrometry (ICPMS). For XRF analysis, rock powders were ground to a fine powder, mixed with di-lithium tetraborate flux and fused at 1000°C at WSU. The resulting glass beads were reground, refused, cleaned and polished. Samples were then analyzed by the ThermoARL XRF. The XRF was calibrated based on nine United States Geological Survey standards. Replicate error, lower limit of detection and information on standards can be found at the WSU website (<http://www.sees.wsu.edu/Geolab/note/xrf.html>).

For ICP-MS, powders prepared at LSU were sent to WSU, where they were mixed with di-lithium-tetraborate and fused. The fused bead is then dissolved by HNO_3 , HF, HClO_4 , and H_2O_2 . After two evaporations, samples are mixed into a solution of DI water, HNO_3 , and H_2O_2 .

Solutions are then analyzed by an Agilent model 4500 ICP-MS after being diluted by a factor of 1:4800 relative to fused sample. Internal standards are used to correct instrumental drift. More information on analytical method can be found at the WSU website (<http://www.sees.wsu.edu/Geolab/note/icpms.html>). Data for trace elements are normalized to primitive mantle using data from McDonough and Sun (1995).

2.4 MELTS Modeling

Liquidus temperature and a crystallization model for minerals were generated by the MELTS program version 5.0.0 (Asimow and Ghiorso, 1998; Ghiorso and Sack, 1995). For the initial liquid composition, the whole rock composition of a random olivine spinifex sample (HB 2-5) was used assuming spinifex is representative of the quenched margin of volcanic liquids (Smith et al, 1980, Nesbitt and Sun, 1976). Sample HB 2-5 consistently falls on olivine accumulation trends with all other komatiitic samples analyzed in this study, confirming that it is representative of the original melt (Fig. 4). Mobile elements in the spinifex composition were slightly adjusted to be more representative of an unaltered liquid based on analyses of melt inclusions in petrographically similar komatiites by Kareem and Byerly (2003). The ratios of CaO, NaO, and K₂O to Al₂O₃ from Kareem and Byerly (2003) were used in HB 2-5 to correct for mobilization of these three elements. The starting model composition is: 47.72 wt. % SiO₂, 0.21 wt. % TiO₂, 5.99 wt. % Al₂O₃, 1.70 wt. % Fe₂O₃, 0.33 wt. % Cr₂O₃, 7.77 wt. % FeO, 0.16 wt. % MnO, 30.59 wt. % MgO, 0.14 wt. % NiO, 4.81 wt. % CaO, 0.53 wt. % Na₂O, 0.029 wt. % K₂O, 0.019 wt. % P₂O₅. The program was used to calculate the liquidus temperature with mineral phases olivine, orthopyroxene, clinopyroxene and spinel crystallizing. Simulations were run assuming -0.18 ΔNNO (calculated by the method of Canil, 1997), solids fractionating from liquids, and temperatures starting at 1700°C and decreasing at increments of 25°C.

Figure 4: Rock chemistry. A) MgO vs V. Samples follow a clear olivine accumulation trend when compared to this incompatible element. Olivine composition determined from maximum measured MgO and plotted along best-fit line through data.

Figure 4: Rock chemistry. B) MgO vs Sc. Orthopyroxene composition determined from distribution coefficient of 0.64 and augite composition from a distribution coefficient of 3.0 (Adam and Green, 2006). Tuff (composition from Stiegler et al, 2008) found in the SMC falls along the same olivine control line as flows. Olivine composition determined from an olivine accumulation trend line and plotted at maximum measured value. A pyroxene accumulation trend is not evident.

Figure 4: Rock chemistry. C) MgO vs Al_2O_3 . Although Al_2O_3 is not present in olivine, whole rock data reveals an olivine accumulation trend, but a pyroxene influence on composition is questionable. Mineral compositions determined from electron microprobe.

Figure 4: Rock chemistry. D) MgO vs Cr. While MgO is controlled by olivine accumulation, Cr is sensitive to minor chromite accumulation. This could be a result of fractionation of komatiites as the flows cooled, or it could be an analytical artifact of the nugget effect. Mineral composition determined from electron microprobe. Error for Cr in olivine plotted.

Figure 4: Rock chemistry. E) Al_2O_3 vs TiO_2 . $\text{Al}_2\text{O}_3/\text{TiO}_2$ has been used to distinguish different sources for komatiites (e.g. Byerly, 1999). The SMC and Pioneer ultramafic complex have similar ratios. One pyroxenitic komatiite has a higher $\text{Al}_2\text{O}_3/\text{TiO}_2$, but this could be due to augite accumulation.

3. Field Studies

3.1 Lithologic Variation

The Saw Mill Complex contains komatiitic lava flows and beds of tuff (Fig. 2). The SMC was mapped using simplified field terms that describe identifiable lithologic differences. The unit terms are pyroxenitic komatiites (Fig. 5A), peridotitic komatiites (Fig. 5B), dunitic komatiites (Fig. 5C), komatiitic basalts, and tuffs (Fig. 6). These are field distinctions and are not intended to have mechanistic implications or follow strict igneous classification. Dunitic komatiites are olivine cumulates characterized by a fine-grained texture, usually deep green to black in color, with a grey to white weathering rim. Dunitic komatiites are highly serpentinized with no fresh olivine, very little fresh pyroxene and minor fresh chromite, and are found at the bases of layered flows or as thick massive flows. Pyroxenitic komatiites are easily distinguished because of differential erosion between poikilitic orthopyroxene crystals and the surrounding groundmass. These rocks contain large (up to 1.3 cm) poikilitic orthopyroxene crystals trapping olivine crystals and tend to have only minor fresh olivine but substantial fresh orthopyroxene, augite, and pigeonite. Peridotitic komatiites in the field have a tan weathering rim with a granular texture. Such flows often exhibit elephant-hide weathering. They tend to have a higher percentage of unaltered minerals, especially olivine, compared to other komatiites, which can be seen using hand lens on hand samples as pale yellow-green crystals in direct sunlight. Where the tops of flows can be identified, olivine and pyroxene spinifex are sometimes found (Fig. 5D). The field area was covered in tall grass during the field season. Combined with the extensive erosion that has taken place on the outer margins of flows, it is difficult to establish in the field where the precise top and bottoms of flows are. There were often covered sections between flows that required interpretation. Where tuffaceous material was identified in the soil between

Figure 5: Outcrops of komatiites. A) Differential weathering allows poikilitic orthopyroxenes to be expressed as knobs on the weathered surface of pyroxenitic komatiites. Pencil for scale. B) Elephant hide weathering is a typical texture on peridotitic komatiites. Pencil and field book (18 cm) for scale. C) Dunitic komatiite are often found in blocky, highly weathered outcrops. Top of 5-lb hammer for scale (~15 cm). D) Olivine spinifex from the top of flow 2 that is used for estimation of liquid composition for komatiites in the SMC. Pencil in images is ~14 cm long; metal tip is ~1.5 cm.

Figure 6: Various expressions of tuffs in the SMC. A) Typical tuff outcrop with fissile partings. Such exposures of tuffs of ultramafic composition led previous workers (Anhaeusser, 1985; Wuth, 1980) to interpret them as sheared ultramafic rocks. Slaty outcrops are often easily eroded and have minimal surface expression. B) Massive tuff deposits reveal sedimentary structures, such as cross-bedding, which allow for stratigraphic up direction to be determined. The SMC is oriented up to the north. C) Lapilli tuff from outcrop in the SMC. Lapilli have only been identified at two locations within the SMC. D) Inset of lapilli reveals aerodynamic shape of lapilli, suggesting that this rock formed as a result of a nearby subaerial explosion.

outcroppings of flows and no other outcrop could be identified, the area between flows was mapped as tuff. Rocks of separate lithologies were identified as being part of the same flow if there was a minimal distance between lithologies (<5 m) and no tuffaceous material was located within that space.

Flows are found as either massive flows, which have near homogeneous lithology throughout, or layered flows. Layered flows tend to be thicker than massive flows. In the lower third of the stratigraphy of the SMC, most of the flows are massive pyroxenitic flows. In the upper portions of the SMC, most of the flows are massive peridotitic komatiites. Throughout the rest of the SMC, particularly in the central portion of the exposed SMC characterized by a topographic ridge, flows are layered. Layered flows have a consistent pattern: dunitic komatiites at the base of a flow, pyroxenitic komatiites above, and peridotitic komatiites at the top, sometimes with a layer of komatiitic basalt above and sometimes including a zone of spinifex texture. Flows can be over 100 m thick or as thin as 10 m (Fig 3). Tuffs are found as very fine-grained rocks with a grey to tan color and often featuring slaty cleavage. Some tuffs have multiple cleavage directions, resulting in pencil cleavage (Fig 6A). Some preserve original sedimentary textures that allow an up direction to be determined, such as cross-bedding or convolute bedding (Fig. 6B). In two location in the SMC, 1-2 cm lapilli were found within the tuff. At the upper location (Fig 3), lapilli are found with aerodynamic quench textures (Fig. 6C and 6D). The tuff layers tend to be highly weathered, resulting in topographic lows along strike. Beds of tuff can be up to 80m thick.

3.2 Mapping

The SMC, mapped over a 4 square kilometer area, is a 1275-meter thick sequence generally striking ENE. The SMC is divided into three distinct structural blocks (Fig 2). The

eastern block is a heavily deformed synclinally folded segment on the eastern boundary of the SMC. It does not preserve much of the original stratigraphy of the SMC, though it does offer a window into the fault-bounded base of the SMC. The eastern block is not as well exposed as the other blocks. The central block is not folded and seems to be relatively intact structurally, preserving most of the thickness of the Weltevreden Formation that is found in the SMC. There are small faults and offsets within the central block, but these offsets do not upset the overall stratigraphic arrangement in the SMC. Two major dikes cut through the central block, but they do not seem to upset the stratigraphic sequence. The western block is anticlinally folded and preserves the upper stratigraphy of the SMC. A significant normal fault in the western block removes about 250 m of section that is found in the central block of the SMC.

Where significant exposures of tuffs can be found, cross-bedding can be used to determine the original orientation of the beds. Topsets are found in three locations pointing to a top in the N-NW direction (Table 2, Fig. 2). In the eastern block, tuffs are found with topsets pointing to the west, which suggests that folding in the eastern block was not the result of overturning in the block. In the western block, spinifex is found at the top of a flow, indicating up to the north. The general layering of flows is consistent with the top of beds being to the north. Dunitic komatiites are found at the bases of flows (Cooper, 2008), and flows in the SMC consistently are found with dunitic bases to komatiitic flows being south of the tops of flows (Fig. 3).

The SMC is bounded at the base by a fault and at the top by either a fault or late-Onverwacht/early Fig Tree ferruginous cherts (Figs. 2, 3). No directional indicator was found in the chert, and field evidence is not compelling for an argument that the chert is either depositionally conformable to the SMC or faulted into place. There is an approximately 10 meter covered section between the final peridotitic komatiite flow and chert beds. Though an

Table 2: Locations of structural and stratigraphic indicators.

Latitude	Longitude	Strike	Dip	Up
S 25° 50.024'	E 30° 53.198'	N75E	80NW	
S 25° 49.937'	E 30° 53.445'	N75E	79NW	
S 25° 50.039'	E 30° 53.438'	N77E	77SE	
S 25° 49.967'	E 30° 53.465'	N75E	84NW	
S 25° 49.852'	E 30° 53.149'	N87E	68NW	N
S 25° 49.836'	E 30° 53.291'	E-W	90	
S 25° 49.653'	E 30° 53.497'	N85W	88NE	
S 25° 49.761'	E 30° 53.618'	N65E	80NW	
S 25° 49.794'	E 30° 53.652'	N50E	85NW	
S 25° 49.523'	E 30° 53.543'	N78W	77SW	
S 25° 49.850'	E 30° 53.183'	N57E	75NW	
S 25° 49.489'	E 30° 54.023'	N48E	75SE	
S 25° 49.548'	E 30° 54.087'	N70E	78NW	
S 25° 49.642'	E 30° 54.130'	N60E	74NW	
S 25° 49.609'	E 30° 54.315'	N75E	85NW	
S 25° 49.547'	E 30° 54.397'	N50E	84NW	
S 25° 49.384'	E 30° 54.197'	N20W	46SW	W
S 25° 49.580'	E 30° 54.636'	N70E	74NW	N
S 25° 49.756'	E 30° 54.685'	N80E	74NW	
S 25° 49.965'	E 30° 54.748'	N54W	62SE	NW
S 25° 49.804'	E 30° 53.724'	E-W	87N	
S 25° 49.859'	E 30° 53.528'	N60E	77SE	
S 25° 49.793'	E 30° 53.571'	N85E	74SE	
S 25° 49.788'	E 30° 53.420'	N65E	70SE	

attempt was made in the field to find a contact, it was not discernable. The lack of outcrop could indicate fault gouge, an easily weathered rim, or tuff deposits. Lack of thermal alteration or shearing in the peridotitic komatiite are consistent with the beds being conformable with the overlying chert, though it is still possible that the rocks are juxtaposed against one another due to faulting.

There are undoubtedly significant faults in the SMC. One fault is inferred to remove about 250 m of upper SMC. Beds below the fault can be traced about 700 m along strike across the Queen's River Valley to the western block (Fig. 2). This is based on the interpretation that the flows are continuous across the alluvial valley that covers a significant portion of relevant outcrop, though across the gap, flows have the same strike and lithology. Chemical analyses do not show any discrepancy between the beds on either side of the stream. There must be a fault separating the uppermost peridotitic beds from the underlying flow, as can be seen by the truncation of the beds against the flow. The fault is therefore extrapolated to conform with the peridotitic beds.

Other faults have displacement of beds on the order of 50-100m. In the eastern block of the SMC (Fig. 2), beds are rotated to roughly 90° of the general strike of the SMC. Less mapping was possible in the eastern block because this section was more remote than other areas of the SMC and it was also more heavily covered by vegetation than other areas in the SMC. At the base of the heavily deformed eastern block, the SMC is in apparent fault contact with Fig Tree sediment, where the S2 impact layer positively identifies the stratigraphic position of the cherts (Byerly, 1999). There is clearly a major fault juxtaposing the older Weltevreden Formation on top of the younger Fig Tree sediments, but the exact location of the fault is difficult to establish due to lack of exposure between flows in the Weltevreden and cherts in the Fig Tree. This fault may extend across the base of the entire SMC. Beds are covered south of the mapped section for

a distance of approximately 400m. When beds are again exposed, they are members of the Pioneer complex, with stratigraphic up direction to the south, opposite of the SMC.

The layers have near-vertical dip throughout the SMC. Measured dip directions ranged from 68° NW to 62° SE, though most beds dip within 10° of vertical. The near-vertical dip is confirmed by tracing beds across changes in topography where no offset is seen. Vertical beds are characteristic of the BGB (Lowe et al, 1999). Strike is measured on tuff layers and ranges from N48E to N75E (Table 2). The dip allows for stratigraphy of the SMC to be determined from map view. The high dip is convenient for determining the evolution of the Weltevreden Formation through time, but spatial changes in beds can only be analyzed along strike. Exposures in the SMC are dependent on the rock type. Komatiites sometimes feature exposures 5m above ground, but such exposures are rare. Most tuffs are more easily eroded than komatiites, and as a result, tuffs have the most limited outcrops within the SMC.

Two diabase dikes cross-cut the SMC. These dikes have little expression in outcrop and are inferred from area maps that show the dikes cutting through the granites that surround the greenstone belt and into the belt itself. Wuth (1980) mapped the dikes in these locations. The field expression of dikes is erosional valleys with little surface exposure. Post-BGB dikes (Lowe, 1999) do not have a major impact on the chemistry, stratigraphy or structure of SMC komatiites, and samples that are geochemically analyzed in this study are not taken from locations near dikes.

Some of the rocks are mapped as “sheared.” These are places where it was clear that faulting had produced a gouge of some sort. The lithologies of these shear zones are not equivalent to one another. These sheared rocks are not equivalent to Wuth’s (1980) shear zones, which generally correspond to where tuffs are mapped. A large shear zone in the eastern SMC results in several offset and rotated blocks. There are several smaller shear zones between the

SMC komatiitic rocks and Fig Tree sedimentary rocks, which is consistent with a major thrust fault representing the base of the SMC and juxtaposing older rocks stratigraphically atop younger rocks.

3.3 Stratigraphy

What is most immediately notable about stratigraphy in the SMC is the dominance of tuffs throughout the complex (Fig. 3). Tuffs account for almost half of the stratigraphic thickness of the SMC. In some places, tuffs appear to bend around lava flow terminations. Wuth (1980) originally interpreted these rocks as sheared ultramafic rocks in the SMC, but sedimentary structures and bedding features reveal a much different story (Stiegler et al., 2008 and this study). Although it is possible that because the tuffs are mechanically weaker than flows, they are deformed more easily than flows and therefore represent shear planes, the depositional nature of the tuffs is indisputable from sedimentary structures found in the tuff units (Fig. 6).

The SMC can be divided into three distinct stratigraphic sequences (Fig. 3). From the base of the SMC to 250 m, the stratigraphy is entirely composed of interbedded pyroxenitic komatiites and tuffs, forming the first sequence. Deposition shifts to a more dunitic komatiitic composition, still interbedded with tuffs, from 250 m to 700 m, forming a second sequence. The third sequence is from 700 m to 1225 m and is dominated by peridotitic komatiitic flows, again interbedded with tuffs. This general division of flows does not strictly follow the deposition of flows, as there are pyroxenitic and dunitic komatiites high in the sequence associated with layered flows, and there are komatiitic basalts interspersed in the stratigraphy of the SMC. However, peridotitic komatiites are not found below 780 m in the stratigraphic sequence. The SMC clearly, then, is not a structurally repeated sequence of flows.

Flows do not maintain the same thickness along strike (Fig. 2). Flows are observed to pinch and swell in the SMC, causing some variation laterally across the section. Few flows

completely pinch out in the SMC. Of the flows that do pinch out, there are no flows that doubly pinch out. Lateral changes in flows occur in all flow types, with individual flows varying from as little as 40 m thick to as much as 100 m thick. More variation in flow thickness in individual flows is observed in the upper portions of the central block of the SMC due to better exposure of flows. Flow thickness in the western block is consistent with observed thicknesses in the central block along strike. The eastern block does not preserve flows well enough to measure stratigraphic thicknesses or variation along strike.

4. Petrology

4.1 Petrography

Four flows are analyzed: Flow 2, flow 3, flow 510, and flow 442 (Fig. 3). Flow 2 (HB 2-5, 2-6, 2-7, 2-8, and 2-9) was sampled from its dunitic base to the spinifex layer at the top. The spinifex layer from flow 2 (HB 2-5) is used throughout this paper to represent the general liquid composition of the SMC. Flow 2 is located stratigraphically at the top of the layered sequence, but is taken from the western block of the SMC. Flow 3 (HB 3-10, 3-9, and 1-7) is stratigraphically below flow 2. Flow 3 is taken from the lower portion of the dunitic komatiitic sequence in the central block of the SMC. Samples are analyzed from the dunitic, pyroxenitic, and peridotitic layers of flow 3. A spinifex layer was not located at the top of the flow. Flow 510 (SA 510-1, 510-2, 510-3, and 510-4) is interpreted to be stratigraphically equivalent to flow 2, but taken from the central block of the SMC. Samples were analyzed from the dunitic, pyroxenitic, and peridotitic layers, but a spinifex layer was not located on this flow. Flow 442 is only represented by two samples, one from the peridotitic layer and one from the komatiitic basalt at the top of the flow. The flow has a dunitic base that was not sampled, and it abuts against a pyroxenitic flow that may be an undifferentiated equivalent (Fig. 2).

Olivine is by far the most common primary phase in komatiites. Euhedral octahedrons of olivine range in size from about 180 μm to about 900 μm in diameter, with most having approximately 300 μm diameter. Olivine forms as a cumulate in komatiites. The distinction between komatiite types can be defined by the type of olivine accumulation taking place. Peridotitic komatiites have the largest quantity of orthopyroxene, pigeonite, augite and interstitial glass of the three komatiite types, as well as the most exquisitely preserved olivine and pyroxene chemistry.

Chromites are found scattered throughout all samples, making a minor mineral phase, but potentially containing a high percentage of the total Cr in a rock. They are generally slightly smaller than olivines, with average size being about 100 μm . In plane polarized light, chromites often have a translucent red coloration on thin edges. Crystals of chromite are usually euhedral. In some places, chromites abut against olivine crystals, though the petrogenetic relationship between the two is difficult to establish from thin section. Chromites are not found as inclusions within olivines, nor are olivines found as inclusions in chromites. The two minerals have been shown to accumulate simultaneously in komatiites (Cooper, 2008). Chromites and olivines sometimes are found to have melt inclusions, which have previously been analyzed (Kareem, 2005).

Orthopyroxene, pigeonite, and augite are found in Weltevreden Formation komatiites (Cooper et al, 2005; Kareem and Byerly, 2003). Orthopyroxenes are not commonly observed petrographically in the SMC, which may be the result of orthopyroxenes reacting with the liquid and altering to pigeonite and augite as the lava evolved. Augite crystals are often observed growing in the interstitial space between olivines. Pigeonites grow as acicular crystals in the space between olivines, similar to small scale spinifex texture, or as overgrowths of orthopyroxene (Fig. 7A and 7B).

In all samples, alteration has profoundly affected the mineralogy of komatiites. Some rocks preserve olivine cores, sometimes up to 80% of the original olivine (Fig. 7A), but no samples from the SMC are observed to have completely preserved any olivine from rim to core. The most highly altered samples are completely serpentinized, with no remaining fresh olivine. In these samples, fine magnetite crystals, a product of serpentinization, outline olivine (Fig. 7B). Like olivine, pyroxenes are often highly altered. In most cases, when olivine cores are preserved, pyroxene is also preserved. In more highly altered samples, determining the original

Figure 7: Exceptional preservation of minerals in the SMC. A) Olivine and pyroxene in plane-polarized light in a peridotitic komatiite. Original crystal shapes can clearly be seen, though some of the material has been altered. Pyroxene and glass fill the interstitial space between olivine crystals. B) SEM image of crystals shows elongate crystals of pyroxene growing between large euhedral crystals of olivine, with significant original mineralogy preserved. Alteration results in magnetite (white) and serpentine minerals (black). C) Chromite crystal showing magnetite overgrowth.

position of pyroxene crystals can be difficult. Often, olivine and pyroxene crystals are replaced by amphibole and serpentine minerals, which variably preserves the original textures. Chromites usually have magnetite overgrowths, but are otherwise only slightly altered (Fig. 7C).

Komatiitic basalts are relatively low-MgO flows associated with komatiites. These flows have some of the same textures as pyroxenitic komatiites, though they often have groundmass crystals of plagioclase and secondary calcite as well as the other minerals common to komatiites. Komatiitic basalts do not have olivine crystals. Pyroxenes are not well preserved in komatiitic basalts, with only occasional augites found to have original material.

Spinifex texture is found at the tops of three flows along the upper chilled margin. Spinifex is a texture of olivine and pyroxene that results from rapid cooling of a high MgO liquid (Green et al., 1975). Olivine and pyroxene spinifex can be distinguished by the crystal habit. Olivine spinifex is typically blade-like, whereas pyroxene spinifex is typically needle-like (Dann, 2001). Olivine spinifex in flow 2 is observed to represent a chilled margin 15 cm thick, though the observed thickness is not likely to represent the true thickness. When not found at the chilled margin, spinifex can be found in chilled pockets of liquid in rocks. Many samples of peridotitic komatiite have small, <0.5 cm pockets of pyroxene spinifex, which may represent filled vesicles.

Vesicles are found in several samples in small quantities. Vesicles are usually about 100 μm in diameter. They are often lined with spinel crystals, which may be either chromite or magnetite. A few crystals are sometimes found within vesicles, but they were not consistently aligned in such a way that they could be used as a geopetal indicator. Vesicles are sometimes associated with devitrified glass in the interstitial space between crystals of olivine or pyroxene.

4.2 Mineral Chemistry

4.2.1 Olivine

Olivines were chemically analyzed by electron microprobe in peridotitic komatiites; other lithologies did not have sufficient fresh olivine for analysis. Olivine compositions range from $(\text{Mg}_{1.8}, \text{Fe}_{0.2}, \text{Cr}_{0.004}, \text{Ca}_{0.004}, \text{Ni}_{0.01})\text{SiO}_4$ to $(\text{Mg}_{1.9}, \text{Fe}_{0.1}, \text{Cr}_{0.004}, \text{Ca}_{0.004}, \text{Ni}_{0.01})\text{SiO}_4$, with an average composition of $(\text{Mg}_{1.9}, \text{Fe}_{0.1}, \text{Cr}_{0.004}, \text{Ca}_{0.004}, \text{Ni}_{0.01})\text{SiO}_4$. Most olivines are $\text{Fo}_{93 \pm 7}$. Of the eight komatiites in which olivine was measured, the highest overall MgO content is in sample HB 2-3 at 53.2. The same sample has the highest Fo, Fo_{94} . Olivines have up to 0.45 wt.% NiO, 0.22 wt.% Cr_2O_3 , and 0.18 wt.% CaO (Fig. 8). Intragranular zonation is not discernable in most olivines due to alteration. Where multiple analyses are taken on a single grain of olivine, compositions do not show significant variation. Typical analysis of olivine can be found in Table 3, and all data points are listed in Appendix.

4.2.2 Chromite

Chromites in the SMC have an average composition of $(\text{Fe}_{3.6}, \text{Mg}_{4.4})\text{Cr}_{12.8}\text{Al}_{2.4}\text{O}_{32}$. Chromites are mostly homogeneous. An average SMC chromite has 11.7 wt. % MgO (± 1.7), 60.8 wt. % Cr_2O_3 (± 1.9), 7.6 Al_2O_3 (± 0.8), 15.71 wt. % FeO (± 2.6), and 3.2 wt. % Fe_2O_3 (± 0.9), with minor amounts of other elements. Stoichiometry was used to calculate the proportions of FeO and Fe_2O_3 (Barnes, 1998). Where chromites have the most variance is in Fe# $[100 * \text{Fe}^{2+} / (\text{Fe}^{2+} + \text{Mg})]$, which ranges from 30 to 70 in SMC chromites. Cr#'s $[100 * \text{Cr} / (\text{Cr} + \text{Al})]$ have very little variance. Cr#'s have been attained up to 86.5 in the SMC samples. When Cr# is plotted against Fe#, chromites can be seen to be in the field for those found in other Al-undepleted komatiitic rocks (Fig. 8B) (Byerly, 1999). Mg#s in the chromites range from 47.3 to 67.6. Chromites have up to 0.3 wt.% NiO and up to 1.0 wt.% MnO. A typical chromite analysis can be found in table 3.

Figure 8: Mineral chemistry. A) Lower portion of Wo-En-Fs ternary diagram for pyroxene compositions determined from electron microprobe. Compositions plotting between pigeonite and augite are likely the result of points taken along exsolution lamellae.

Figure 8: Mineral chemistry. B) Cr# vs Fe# for chromites compared to fields for Type 1, Type 2, and Type 3 komatiites (Byerly, 1999). SMC komatiites clearly are Type 2 Al-undepleted komatiites.

Table 3: Typical mineral analyses from electron microprobe.

	Augite	Pigeonite	Enstatite₁	Enstatite₂	Olivine	Chromite
SiO₂	50.60	55.31	55.06	53.52	40.83	0.13
TiO₂	0.44	0.07	0.06	0.10	0.03	0.19
Al₂O₃	5.41	1.29	1.15	1.03	0.05	8.34
Cr₂O₃	0.11	0.26	0.51	0.75	0.24	59.78
FeO	4.94	7.25	6.99	15.09	7.45	15.71
Fe₂O₃	-	-	-	-	-	3.18*
MnO	0.12	0.18	0.16	0.48	0.16	0.28
NiO	0.13	0.12	0.08	0.00	0.41	0.14
MgO	19.35	30.32	33.40	27.13	50.67	11.54
CaO	19.62	4.90	1.60	1.25	0.16	0.01
Total	100.88	99.72	99.11	99.39	100.03	99.49
Si	1.83	1.95	1.94	1.95	0.99	0.04
Ti	0.01	0.00	0.00	0.00	0.00	0.04
Al	0.23	0.05	0.05	0.04	0.00	2.62
Cr	0.00	0.01	0.01	0.02	0.00	12.62
Fe^T	0.15	0.21	0.21	0.46	0.15	4.22
Fe²⁺	0.15	0.21	0.21	0.46	0.15	3.51
Fe³⁺	-	-	-	-	-	0.71
Mn	0.00	0.01	0.00	0.01	0.00	0.06
Ni	0.00	0.00	0.00	0.00	0.01	0.03
Mg	1.04	1.59	1.75	1.47	1.84	4.59
Ca	0.76	0.19	0.06	0.05	0.00	0.00
Total	4.04	4.02	4.03	4.02	3.00	24.27
Mg#	87.47	88.17	89.49	76.22	92.38	56.69
Cr#	-	-	-	-	-	82.78

Note: Fe³⁺ calculated by stoichiometry (Barnes, 1998)

4.2.3 Pyroxene

Plotted on a Wo-En-Fs ternary diagram (Fig. 8A), pyroxenes plot as augite, pigeonite, and enstatite. Some of the pyroxenes exhibit compositional zoning, which typically have orthopyroxene cores with pigeonite and augite rims, visible in backscatter electron images. There are two populations of orthopyroxene, with one having an average composition averaging $(\text{Mg}_{1.74}, \text{Fe}_{0.20}, \text{Ca}_{0.06}) (\text{Si}_{1.95}, \text{Al}_{0.03}) \text{O}_6$ and the other orthopyroxene having an average composition of $(\text{Mg}_{1.47}, \text{Fe}_{0.46}, \text{Ca}_{0.05}) (\text{Si}_{1.94}, \text{Al}_{0.05}) \text{O}_6$. Augites have an average composition of $(\text{Ca}_{0.76}, \text{Na}_{0.01}, \text{Mg}_{1.06}, \text{Fe}_{0.16}, \text{Al}_{0.01}) (\text{Si}_{1.92}, \text{Al}_{0.08}) \text{O}_6$. Pigeonites have an average composition of $(\text{Ca}_{0.20}, \text{Mg}_{1.53}, \text{Fe}_{0.24}) \text{Si}_{1.92} \text{Al}_{0.08} \text{O}_6$. Some of the measured pyroxene compositions are not possible in nature. This may result from chemical or physical anomalies that represent mixtures between pigeonite and augite. Analyses may be taken near the edge of zones within the pyroxenes or may reflect fine intergrowths of augites and pigeonites, or Ca-amphibole alteration along cracks and cleavage planes. A less likely alternately is that Al may preferentially substitute for Fe and Mg rather than Ca, resulting in an apparently higher wollastonite content. Typical analysis for orthopyroxene, pigeonite, and augite can be found in table 3.

4.3 Rock Chemistry

4.3.1 Major Elements

In the SMC, bulk rock chemistry corresponds closely with other studies of the Weltevreden Formation (XRF analysis in table 4). SMC lavas have normalized anhydrous equivalent MgO wt. % between 26.43 and 44.99 for komatiites and between 11.25 and 12.64 for

Table 4: Whole rock data from XRF presented as normalized anhydrous equivalent.

	BYE SA 510-1	BYE SA 510-2	BYE SA 510-3	BYE SA 510-4	BYE SA 442-5	BYE SA 442-3	BYE SA 442-2	BYE SA 500-1	BYE SA 500-3	BYE SA 500-4	BYE SA 500-7	BYE HB 2-1	BYE HB 2-2
Normalized Major Elements (Weight %):													
SiO₂	46.24	46.53	46.50	46.75	55.13	46.48	54.35	45.92	47.60	46.77	52.70	45.94	45.83
TiO₂	0.10	0.09	0.07	0.07	0.54	0.12	0.36	0.08	0.15	0.12	0.16	0.11	0.14
Al₂O₃	3.10	2.89	1.91	2.21	9.20	3.12	9.76	2.40	4.19	3.81	4.71	2.96	3.29
FeO*	7.86	6.85	6.83	4.54	11.29	8.79	10.00	7.58	9.39	9.15	7.54	8.71	8.19
MnO	0.12	0.08	0.06	0.09	0.18	0.15	0.18	0.14	0.15	0.17	0.16	0.10	0.12
MgO	40.27	41.87	44.25	44.99	11.25	39.23	12.64	43.80	35.30	37.06	26.43	42.01	39.83
CaO	2.23	1.59	0.34	1.31	8.91	2.04	9.56	0.05	3.11	2.86	8.17	0.05	2.47
Na₂O	0.05	0.06	0.02	0.02	3.39	0.04	3.06	0.02	0.07	0.05	0.11	0.06	0.08
K₂O	0.02	0.01	0.00	0.00	0.07	0.01	0.06	0.00	0.02	0.01	0.01	0.03	0.01
P₂O₅	0.01	0.01	0.01	0.01	0.04	0.01	0.03	0.01	0.02	0.01	0.01	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Normalized traces (ppm)													
Ni	2358.89	2802.68	2487.34	3263.47	3282.91	212.70	2173.00	171.85	2663.61	1700.41	1763.67	487.36	2512.00
Cr	2211.41	2383.54	2115.36	2169.38	2491.17	690.64	4211.74	924.13	2462.39	5395.82	3975.40	3112.55	2358.13
Sc	13.83	14.76	13.10	10.52	12.03	35.87	15.36	38.39	12.29	17.90	17.14	25.78	11.54
V	69.93	73.68	65.39	45.08	47.34	205.92	73.60	227.59	56.09	111.61	82.56	103.95	62.51
Ba	9.01	9.46	8.40	40.35	8.86	21.84	13.06	27.64	13.34	18.54	9.58	8.07	25.33
Rb	0.51	0.86	0.76	0.53	0.00	1.72	1.54	1.62	0.00	1.65	1.13	0.36	2.40
Sr	2.28	3.01	2.67	8.15	22.48	67.14	1.92	98.76	1.31	10.03	2.39	5.42	3.37
Zr	4.14	4.25	3.78	2.21	2.75	31.74	6.08	17.51	2.72	6.91	4.86	7.15	9.36
Y	3.68	3.73	3.31	2.10	2.91	10.92	3.71	9.95	2.88	3.81	2.77	5.18	3.37
Nb	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ga	2.79	3.44	3.05	1.05	0.26	8.28	2.43	8.21	1.18	4.95	3.78	4.10	3.69
Cu	18.40	13.19	11.70	3.81	2.91	148.55	5.50	3.12	1.44	17.78	22.06	2.05	30.77
Zn	48.10	42.14	37.40	32.86	33.98	77.49	55.55	48.34	43.28	65.01	58.48	35.90	98.26
Pb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.00	0.00	0.00
La	2.79	4.73	4.20	0.92	2.91	7.47	4.61	2.54	3.66	4.70	3.15	0.00	0.00
Ce	0.00	1.86	1.65	0.00	0.00	3.68	0.00	0.00	0.00	0.00	0.00	0.00	2.08
Th	0.00	0.00	0.00	0.00	2.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16
Nd	0.00	2.29	2.04	1.05	0.53	4.37	1.79	1.04	0.00	0.00	1.64	0.48	2.40
U	0.38	0.72	0.64	0.39	0.00	0.00	1.02	0.00	1.31	0.63	0.76	0.00	0.00

Table 4: Whole rock data from XRF presented as normalized anhydrous equivalent (cont.).

	BYE HB 2-3	BYE HB 2-4	BYE HB 2-5	BYE HB 2-6	BYE HB 2-7	BYE HB 2-8	BYE HB 2-9	BYE HB 3-10	BYE HB 3-9	BYE HB 3-8	BYE HB 1-7	BYE HB 3-4
Normalized Major Elements (Weight %):												
SiO ₂	45.71	46.36	49.30	45.47	45.55	48.04	46.70	45.66	45.22	45.82	46.11	45.92
TiO ₂	0.12	0.13	0.21	0.11	0.10	0.13	0.08	0.20	0.11	0.07	0.09	0.10
Al ₂ O ₃	2.99	3.92	6.19	3.18	2.97	4.03	2.64	3.59	3.06	2.14	2.65	3.49
FeO*	7.70	8.98	9.60	7.85	7.76	9.22	5.73	9.45	9.58	6.98	6.77	7.55
MnO	0.10	0.14	0.17	0.13	0.13	0.13	0.14	0.19	0.20	0.10	0.17	0.14
MgO	41.50	37.12	31.60	40.50	41.22	35.42	43.77	36.72	39.01	44.82	44.10	40.76
CaO	1.78	3.16	2.65	2.69	2.20	2.92	0.89	4.10	2.78	0.03	0.05	1.97
Na ₂ O	0.06	0.10	0.08	0.04	0.05	0.05	0.03	0.05	0.03	0.03	0.04	0.04
K ₂ O	0.02	0.07	0.17	0.02	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.01
P ₂ O ₅	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Normalized traces (ppm)												
Ni	2281.02	2523.44	1897.30	1450.07	2345.15	2411.91	1844.10	3248.06	2113.30	2113.90	2826.69	2626.86
Cr	2324.51	2178.32	4335.85	3417.44	2515.18	2390.09	5348.75	3515.85	4080.22	3414.48	3279.71	3226.03
Sc	15.50	14.01	17.09	24.16	14.07	13.32	18.78	12.67	16.00	16.14	9.29	13.40
V	82.06	72.73	89.37	133.76	69.10	63.85	95.46	52.33	96.97	72.85	48.43	58.36
Ba	3.13	0.63	6.74	16.99	6.72	3.06	23.67	9.67	6.34	1.12	8.64	0.98
Rb	0.47	0.47	3.45	13.72	1.09	1.84	4.10	0.00	0.48	0.00	0.00	0.00
Sr	1.25	1.89	5.80	19.33	4.22	3.83	10.41	20.17	3.64	3.04	0.65	1.80
Zr	9.92	7.79	9.31	13.88	8.35	7.12	9.68	7.26	14.11	6.64	5.49	7.28
Y	4.07	3.94	4.23	5.14	4.38	3.37	3.79	3.67	6.02	4.47	2.61	3.92
Nb	0.63	0.00	0.16	0.47	0.00	0.00	0.32	0.00	0.48	0.00	0.00	0.49
Ga	3.60	2.99	2.19	6.08	2.66	3.83	4.58	1.67	3.33	2.72	0.33	1.63
Cu	21.45	13.54	26.34	43.81	18.14	19.29	45.13	5.17	10.77	19.33	3.10	109.85
Zn	50.89	43.76	58.95	72.96	53.00	52.36	62.17	53.83	86.19	72.37	53.64	78.30
Pb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00
La	0.00	0.00	0.00	0.94	0.94	2.45	3.16	2.33	0.00	0.80	0.00	2.13
Ce	0.00	0.00	0.31	3.12	0.00	1.22	0.00	0.33	7.61	0.64	0.00	3.92
Th	1.57	0.00	0.00	0.16	0.47	0.00	0.00	2.17	0.00	0.00	0.33	0.49
Nd	2.04	0.47	0.78	1.87	1.72	0.61	0.00	0.00	1.90	0.00	0.00	1.31
U	2.35	0.00	1.57	1.56	0.16	0.15	0.00	1.00	0.00	0.00	0.00	0.98

komatiitic basalts (Fig. 4). MgO wt % in flow 510 ranges from 35.83 to 38.42, in flow 442 from 11.25 to 39.23 (two samples), in flow 2 from 31.60 to 43.77, and in flow 3 from 36.72 to 44.82. All Fe in komatiites was treated as FeO for simplicity. When plotted against MgO, immobile elements plot along olivine control lines. Rocks plotted with MgO against Al_2O_3 , TiO_2 , and V all have trends that intersect the MgO axis at between 53 and 54 wt % MgO, which is the composition of the olivines accumulating as the rocks were forming (Fig. 4). This is consistent with other workers who have shown that komatiites of the Weltevreden follow an olivine control line (e.g. Cooper, 2008; Kareem, 2005).

The majority of rocks fall along the same olivine control line (Fig. 4A), though there are a few exceptions. Sample 500-7 falls off of the olivine control line for V, Ni, and Al. Rocks seem to only partly be controlled by olivine when MgO is plotted against Cr. The other controlling factor is possibly minor chromite accumulation. However, this does not account for the observed difference in 500-7. Komatiitic basalts also plot away from an olivine control line with respect to Cr. SMC $\text{Al}_2\text{O}_3/\text{TiO}_2$ for whole rocks put them in the range of Al-undepleted komatiites (Gruau et al, 1990; Byerly, 1999). Komatiite $\text{Al}_2\text{O}_3/\text{TiO}_2$ ranges from 23.61 to 34.66 (Fig. 4E), though there is one outlier komatiitic sample, 3-10, which has $\text{Al}_2\text{O}_3/\text{TiO}_2$ of 18.02. This sample may have experienced enrichment in augite (Fig. 4E). Komatiitic basalts are measured to be 16.96 and 27.23. The disparity between $\text{Al}_2\text{O}_3/\text{TiO}_2$ may represent distinct lavas or severe fractionation in parts of the flows.

4.3.2 Rare Earth Elements

Rare earth elements were normalized to primitive mantle for this study using data from McDonough and Sun (1995). Results of analysis of SMC rocks by ICP-MS are in Table 5. The sample taken to represent liquid composition in komatiites, HB 2-5, is very close to the composition of primitive mantle. Other samples have similar trends, but lower amounts of all

Table 5: Trace element composition from ICP-MS.

	BYE 510-1	BYE 510-2	BYE 510-3	BYE 510-4	BYE 442-5	BYE 442-3	BYE 442-2	BYE 500-1
Th ppm	0.03	0.04	0.06	0.03	0.18	0.04	0.05	0.03
U ppm	0.01	0.01	0.02	0.01	0.06	0.01	0.02	0.01
Nb ppm	0.15	0.12	0.09	0.07	1.43	0.21	0.54	0.08
Ta ppm	0.01	0.01	0.01	0.00	0.10	0.01	0.04	0.00
La ppm	0.24	0.21	0.18	0.15	2.11	0.32	0.77	0.15
Ce ppm	0.61	0.58	0.46	0.43	5.56	0.88	2.17	0.41
Pr ppm	0.10	0.09	0.07	0.06	0.91	0.14	0.35	0.06
Nd ppm	0.51	0.47	0.32	0.33	4.69	0.72	1.90	0.33
Hf ppm	0.14	0.13	0.09	0.09	0.88	0.17	0.51	0.09
Zr ppm	4.34	4.10	3.02	2.90	29.70	5.21	15.76	3.00
Sm ppm	0.19	0.17	0.12	0.12	1.53	0.25	0.74	0.12
Eu ppm	0.08	0.07	0.05	0.04	0.62	0.10	0.29	0.05
Gd ppm	0.29	0.26	0.17	0.20	1.95	0.35	1.12	0.19
Tb ppm	0.06	0.05	0.03	0.04	0.35	0.07	0.23	0.04
Dy ppm	0.41	0.38	0.23	0.27	2.25	0.48	1.61	0.31
Ho ppm	0.09	0.08	0.06	0.06	0.47	0.11	0.38	0.07
Y ppm	2.32	2.12	1.38	1.57	11.03	2.61	9.15	1.70
Er ppm	0.26	0.25	0.16	0.18	1.27	0.31	1.05	0.19
Tm ppm	0.04	0.04	0.03	0.03	0.18	0.05	0.16	0.03
Yb ppm	0.26	0.24	0.17	0.18	1.11	0.29	1.05	0.21
Lu ppm	0.04	0.04	0.03	0.03	0.17	0.05	0.17	0.03
Sc ppm	10.52	9.59	7.60	7.95	32.11	11.75	34.54	9.95
Normalized to Primitive Mantle (McDonough and Sun, 1995)								
Th ppm	0.38	0.51	0.72	0.40	2.23	0.49	0.63	0.38
U ppm	0.40	0.67	0.96	0.48	2.80	0.62	0.77	0.52
Nb ppm	0.23	0.18	0.14	0.11	2.16	0.31	0.81	0.12
Ta ppm	0.20	0.22	0.18	0.12	2.72	0.32	0.99	0.10
La ppm	0.37	0.32	0.28	0.24	3.25	0.49	1.19	0.24
Ce ppm	0.37	0.34	0.28	0.25	3.31	0.52	1.29	0.24
Pr ppm	0.39	0.35	0.26	0.25	3.64	0.57	1.41	0.25
Nd ppm	0.41	0.37	0.26	0.27	3.75	0.58	1.52	0.26
Hf ppm	0.51	0.46	0.33	0.33	3.13	0.59	1.81	0.31
Zr ppm	0.41	0.39	0.29	0.28	2.83	0.50	1.50	0.29
Sm ppm	0.47	0.42	0.29	0.30	3.74	0.61	1.80	0.29
Eu ppm	0.55	0.49	0.36	0.24	4.14	0.69	1.95	0.34
Gd ppm	0.54	0.48	0.32	0.38	3.62	0.65	2.07	0.35
Tb ppm	0.59	0.53	0.34	0.38	3.54	0.69	2.28	0.41
Dy ppm	0.62	0.57	0.35	0.41	3.35	0.71	2.41	0.46
Ho ppm	0.61	0.56	0.38	0.42	3.13	0.73	2.50	0.46
Y ppm	0.54	0.49	0.32	0.37	2.57	0.61	2.13	0.39
Er ppm	0.58	0.56	0.37	0.42	2.88	0.69	2.38	0.43
Tm ppm	0.58	0.54	0.37	0.42	2.70	0.66	2.32	0.45
Yb ppm	0.58	0.56	0.38	0.42	2.51	0.67	2.39	0.47
Lu ppm	0.63	0.56	0.40	0.43	2.55	0.70	2.47	0.47
Sc ppm	10.52	9.59	7.60	7.95	32.11	11.75	34.54	9.95

Table 5: Trace element composition from ICP-MS (cont.).

	BYE 500-3	BYE 500-4	BYE 500-7	BYE HB 2-1	BYE HB 2-2	BYE HB 2-3	BYE HB 2-4
Th ppm	0.03	0.04	0.04	0.10	0.06	0.10	0.05
U ppm	0.01	0.01	0.01	0.04	0.03	0.03	0.02
Nb ppm	0.17	0.14	0.19	0.27	0.21	0.15	0.22
Ta ppm	0.01	0.01	0.01	0.02	0.02	0.01	0.02
La ppm	0.28	0.22	0.28	0.47	0.30	0.28	0.29
Ce ppm	0.78	0.61	0.75	1.09	0.84	0.74	0.83
Pr ppm	0.12	0.10	0.12	0.15	0.13	0.10	0.13
Nd ppm	0.66	0.51	0.69	0.68	0.65	0.54	0.67
Hf ppm	0.18	0.16	0.19	0.18	0.21	0.18	0.16
Zr ppm	5.83	4.91	6.26	5.85	7.13	6.01	5.84
Sm ppm	0.25	0.21	0.25	0.22	0.25	0.20	0.24
Eu ppm	0.13	0.08	0.09	0.09	0.10	0.09	0.11
Gd ppm	0.41	0.32	0.38	0.29	0.39	0.34	0.38
Tb ppm	0.08	0.07	0.08	0.05	0.08	0.07	0.08
Dy ppm	0.60	0.49	0.58	0.36	0.57	0.47	0.54
Ho ppm	0.13	0.11	0.14	0.08	0.12	0.11	0.12
Y ppm	3.41	2.74	3.47	2.07	3.02	2.65	2.90
Er ppm	0.40	0.32	0.40	0.25	0.35	0.30	0.35
Tm ppm	0.06	0.05	0.06	0.04	0.05	0.04	0.05
Yb ppm	0.39	0.32	0.42	0.25	0.33	0.28	0.32
Lu ppm	0.06	0.05	0.07	0.04	0.05	0.05	0.05
Sc ppm	15.12	13.51	22.02	10.42	11.84	11.35	13.35
Normalized to Primitive Mantle (McDonough and Sun, 1995)							
Th ppm	0.34	0.45	0.46	1.29	0.79	1.27	0.64
U ppm	0.61	0.70	0.51	1.79	1.62	1.40	0.90
Nb ppm	0.25	0.22	0.29	0.41	0.31	0.23	0.34
Ta ppm	0.28	0.20	0.40	0.54	0.49	0.36	0.44
La ppm	0.43	0.34	0.43	0.72	0.46	0.43	0.44
Ce ppm	0.47	0.37	0.45	0.65	0.50	0.44	0.49
Pr ppm	0.49	0.40	0.49	0.60	0.53	0.42	0.52
Nd ppm	0.53	0.41	0.55	0.54	0.52	0.43	0.53
Hf ppm	0.66	0.56	0.69	0.63	0.74	0.63	0.59
Zr ppm	0.56	0.47	0.60	0.56	0.68	0.57	0.56
Sm ppm	0.61	0.52	0.61	0.53	0.60	0.48	0.59
Eu ppm	0.84	0.51	0.57	0.62	0.70	0.58	0.75
Gd ppm	0.75	0.59	0.71	0.53	0.72	0.63	0.71
Tb ppm	0.81	0.66	0.83	0.53	0.80	0.69	0.78
Dy ppm	0.89	0.73	0.87	0.54	0.85	0.70	0.81
Ho ppm	0.90	0.74	0.92	0.56	0.82	0.73	0.79
Y ppm	0.79	0.64	0.81	0.48	0.70	0.62	0.68
Er ppm	0.90	0.73	0.92	0.57	0.80	0.68	0.79
Tm ppm	0.85	0.72	0.89	0.58	0.75	0.65	0.73
Yb ppm	0.89	0.73	0.95	0.57	0.74	0.63	0.72
Lu ppm	0.95	0.75	0.97	0.59	0.78	0.71	0.79
Sc ppm	15.12	13.51	22.02	10.42	11.84	11.35	13.35

Table 5: Trace element composition from ICP-MS (cont.).

	BYE HB 2-5	BYE HB 2-6	BYE HB 2-7	BYE HB 2-8	BYE HB 2-9	BYE HB 3-10	BYE HB 3-9
Th ppm	0.07	0.07	0.04	0.05	0.05	0.07	0.07
U ppm	0.03	0.03	0.02	0.02	0.02	0.02	0.02
Nb ppm	0.32	0.21	0.16	0.18	0.16	0.44	0.13
Ta ppm	0.02	0.02	0.01	0.01	0.01	0.03	0.01
La ppm	0.44	0.30	0.25	0.30	0.28	0.51	0.23
Ce ppm	1.27	0.79	0.71	0.79	0.74	1.37	0.56
Pr ppm	0.20	0.11	0.10	0.12	0.11	0.24	0.08
Nd ppm	1.03	0.58	0.55	0.63	0.53	1.24	0.38
Hf ppm	0.29	0.16	0.14	0.17	0.11	0.30	0.12
Zr ppm	9.56	5.17	4.44	5.57	3.97	10.45	4.02
Sm ppm	0.39	0.20	0.18	0.24	0.19	0.42	0.15
Eu ppm	0.17	0.09	0.08	0.10	0.09	0.08	0.05
Gd ppm	0.59	0.30	0.27	0.37	0.27	0.59	0.23
Tb ppm	0.12	0.06	0.06	0.07	0.05	0.11	0.05
Dy ppm	0.83	0.43	0.41	0.52	0.36	0.72	0.33
Ho ppm	0.19	0.10	0.09	0.12	0.08	0.15	0.08
Y ppm	4.57	2.41	2.27	2.95	2.05	3.92	1.96
Er ppm	0.54	0.27	0.27	0.34	0.23	0.43	0.22
Tm ppm	0.08	0.04	0.04	0.05	0.04	0.07	0.03
Yb ppm	0.51	0.28	0.27	0.34	0.23	0.41	0.24
Lu ppm	0.08	0.04	0.04	0.05	0.04	0.07	0.04
Sc ppm	20.37	11.93	11.37	15.16	10.28	13.65	13.50
Normalized to Primitive Mantle (McDonough and Sun, 1995)							
Th ppm	0.89	0.85	0.48	0.59	0.66	0.93	0.82
U ppm	1.28	1.25	0.84	0.90	0.80	1.17	1.24
Nb ppm	0.48	0.31	0.24	0.27	0.24	0.67	0.19
Ta ppm	0.58	0.41	0.32	0.36	0.38	0.84	0.31
La ppm	0.68	0.46	0.39	0.46	0.43	0.79	0.35
Ce ppm	0.76	0.47	0.42	0.47	0.44	0.82	0.33
Pr ppm	0.79	0.44	0.41	0.49	0.44	0.94	0.32
Nd ppm	0.82	0.46	0.44	0.51	0.42	0.99	0.30
Hf ppm	1.04	0.57	0.49	0.60	0.39	1.06	0.43
Zr ppm	0.91	0.49	0.42	0.53	0.38	1.00	0.38
Sm ppm	0.94	0.49	0.44	0.58	0.46	1.02	0.36
Eu ppm	1.15	0.60	0.53	0.68	0.63	0.52	0.33
Gd ppm	1.09	0.55	0.50	0.68	0.49	1.09	0.43
Tb ppm	1.16	0.65	0.59	0.73	0.53	1.05	0.48
Dy ppm	1.24	0.64	0.61	0.77	0.53	1.07	0.49
Ho ppm	1.23	0.63	0.60	0.78	0.52	1.03	0.51
Y ppm	1.06	0.56	0.53	0.69	0.48	0.91	0.46
Er ppm	1.22	0.62	0.62	0.77	0.53	0.98	0.51
Tm ppm	1.18	0.65	0.61	0.77	0.53	0.96	0.50
Yb ppm	1.16	0.63	0.61	0.78	0.52	0.92	0.54
Lu ppm	1.22	0.65	0.64	0.78	0.55	0.97	0.59
Sc ppm	20.37	11.93	11.37	15.16	10.28	13.65	13.50

Table 5: Trace element composition from ICP-MS (cont.).

	BYE HB 3-8	BYE HB 1-7	BYE HB 3-4
Th ppm	0.05	0.04	0.06
U ppm	0.01	0.02	0.02
Nb ppm	0.10	0.12	0.14
Ta ppm	0.01	0.01	0.01
La ppm	0.15	0.17	0.22
Ce ppm	0.45	0.51	0.65
Pr ppm	0.06	0.07	0.09
Nd ppm	0.29	0.38	0.52
Hf ppm	0.08	0.12	0.16
Zr ppm	2.77	3.76	4.96
Sm ppm	0.10	0.14	0.18
Eu ppm	0.05	0.06	0.09
Gd ppm	0.17	0.22	0.28
Tb ppm	0.03	0.05	0.06
Dy ppm	0.26	0.35	0.46
Ho ppm	0.06	0.08	0.10
Y ppm	1.43	1.94	2.58
Er ppm	0.17	0.22	0.30
Tm ppm	0.03	0.03	0.05
Yb ppm	0.17	0.23	0.29
Lu ppm	0.03	0.04	0.05
Sc ppm	9.22	10.81	13.89
Normalized to Primitive Mantle (McDonough and Sun, 1995)			
Th ppm	0.59	0.48	0.79
U ppm	0.74	0.92	1.00
Nb ppm	0.15	0.18	0.21
Ta ppm	0.26	0.24	0.35
La ppm	0.23	0.27	0.33
Ce ppm	0.27	0.31	0.39
Pr ppm	0.24	0.29	0.37
Nd ppm	0.24	0.31	0.41
Hf ppm	0.30	0.41	0.56
Zr ppm	0.26	0.36	0.47
Sm ppm	0.24	0.35	0.44
Eu ppm	0.33	0.42	0.61
Gd ppm	0.32	0.41	0.52
Tb ppm	0.34	0.50	0.64
Dy ppm	0.39	0.52	0.69
Ho ppm	0.40	0.52	0.68
Y ppm	0.33	0.45	0.60
Er ppm	0.39	0.50	0.67
Tm ppm	0.38	0.50	0.67
Yb ppm	0.40	0.51	0.65
Lu ppm	0.43	0.54	0.71
Sc ppm	9.22	10.81	13.89

REE's (Fig. 9). Most komatiites exhibit slight HREE enrichment, as can be shown by Gd_N/Lu_N . Almost all samples have $Gd_N/Lu_N < 1$, with most being between 0.80 and 0.90 and the lowest value being 0.57. One komatiite sample, HB 3-10, has Gd_N/Lu_N of 1.11, and one komatiitic basalt, SA 442-5, has Gd/Lu of 1.40. Enrichment of HREE's is consistent with other workers from the Weltevreden (Kareem and Byerly, 2003, Cooper et al, 2005). Most komatiites and komatiitic basalts are slightly depleted in LREE's. La_N/Sm_N for most samples is < 1 with most samples having values between 0.75 and 0.90, with sample 2-1 being the major exception with La_N/Sm_N of 1.34. The lowest La_N/Sm_N is 0.65 in SA 500-4.

Both positive and negative Eu anomalies appear in some REE analyses. Only a handful of samples have major Eu anomalies, with Eu/Eu^* being 0.48 in sample 3-10, 0.82 in 3-9, and 0.70 in 510-4 (where Eu^* is the interpolated Eu value if no fractionation were taking place, determined by averaging Sm and Gd values [Ragland, 1989]). Most other samples have Eu/Eu^* between 1.0 and 1.2. Sample 2-9 has the most enrichment, with Eu/Eu^* of 1.28. Kareem and Byerly (2003) described similar Eu anomalies, but attributed them to mobilization of Eu rather than source depletion. Lahaye et al (2001) showed that Eu anomalies are present in flows, but not melt inclusions in the same flows, indicating that mobilization alters Eu composition of komatiites.

Komatiitic basalts in the SMC have enriched REE patterns compared to komatiites (Fig. 9A). The two komatiitic basalts differ, however, in that one sample is depleted in LREE's relative to HREE's, while the other is not. Both of these komatiitic basalts are similar to komatiitic trends, which are slightly depleted in LREE's. One of the komatiitic basalts is depleted in HREE's, with Gd_N/Lu_N of 0.83. Overall enrichment of REE's in komatiitic basalts is likely due to concentration of incompatible elements in the melt as high-temperature phases crystallized.

Figure 9: Rare earth elements. A) Layered flows (multiple lithologies in flow) and komatiitic basalts in the SMC. Liquid composition and komatiitic basalts also plotted. Note that liquid is near primitive mantle composition.

Figure 9: Rare earth elements. B) Massive flows (single lithology in flow).

5. Discussion

5.1 Extrusive Origin and Volcanology

Wuth (1980) and Anhaeusser (1985) concluded that the SMC, along with other ultramafic complexes of the BGB, represent intrusive igneous activity. However, while Wuth included dunites, pyroxenites and gabbros in his map of the SMC, they were not found in this study. While there are olivine cumulates in the SMC, they are not dunite *sensu stricto* by igneous classification (Le Maitre et al, 2002) because they are a maximum of 70% olivine cumulate. What were labeled pyroxenites by Wuth (1980), while undoubtedly pyroxene-rich rocks, are not pyroxene cumulates, but rather fine olivine cumulates with a modest proportion of very large poikilitic orthopyroxenes. Further, textures such as spinifex and elephant hide weathering, characteristic of komatiites, were found in the rocks of the SMC. What Wuth mapped as shear zones are clearly observed to have sedimentary structures such as cross-beds, lapilli, and convolute bedding. The findings in the field are consistent with other recent studies of the late Onverwacht Group in the BGB (Lowe and Byerly, 1999) – that it represents extrusive volcanism or invasive volcanic emplacement, not deep intrusion. The characterization of the SMC as a layered ultramafic intrusion is misleading. Flows may have invaded thick tuff units (though the tuffs also have komatiitic composition and they may be co-magmatic [Stiegler et al., 2008]), but this sort of “intrusion” would not qualify as the sheeted dike complexes of de Wit et al (1992) or layered sills of Anhaeusser (1985) and Wuth (1980). The mineralogy of olivines and the rare occurrence of vesicles in flows indicates that lavas were cooling at the surface and contained low percentages of water.

However, distinguishing flows from shallow sills is more difficult. Arndt et al. (2004) note key differences between flows and sills: flows have thicker quench zones (up to 48 cm),

often have flow-top breccia, do not cause thermal alteration of overlying units, and may have a highly vesicular layer near the top of the flow. Unfortunately, flow tops in the SMC are poorly exposed, so the presence of these features is difficult to determine. The interior characteristics of komatiitic flows and shallow sills are very similar. There are no signs in the SMC of komatiites cross-cutting other komatiites, so that any intrusion would necessarily be an intrusion into tuff. Thermal alteration of tuffs is not observed at the tops of flows, but few outcrops were exposed for such observations to be made. Arndt et al (2004) also argued that unconsolidated sediment is more difficult for rising komatiitic magma to penetrate because of density contrasts and the rheological difference between cutting through brittle rock and soft sediment, although the fact that komatiitic flows are associated with tuffs does not necessarily imply that they must have been intrusive. Magma would not need to rise through the sediment if the komatiitic vent were located in brittle rock, allowing the flows to originate on the surface and propagate over soft sedimentary rocks. The irregularity of some flows may suggest surface topography, consistent with surface flows, and the abundance of glass in peridotitic komatiites is suggestive of rapid cooling, again consistent with surface flows.

Within the SMC, the only sedimentary rocks are tuffs. Cherts and sandstones are present in the overlying Fig Tree sediments, but the SMC represents a depositional environment controlled only by volcanic activity. Other papers have suggested that the Weltevreden Formation was deposited above wave base due to the lack of sediment failure characteristics that would be expected from study of modern volcanoes (Stiegler et al., 2008). The SMC may be rapidly emplaced. Studies of komatiites at Kambalda in the Yilgarn province of Australia (Williams et al, 1998) have suggested emplacement of individual komatiite flows in < 2 weeks, though analogous modern volcanoes, such as Kilauea, have shown that individual eruptions can last for years at a time. The eruptive environment is suggested by large cm-sized lapilli,

including those with aerodynamic shapes, which suggest subaerial explosions (Fig. 6C and 6D). This may represent near-vent environments, though littoral rootless vents can develop 100's of km's from actual volcanic vents. Littoral cones form from large volumes of lava interacting with water, such as an a'a flow entering the ocean (Moore and Ault, 1965). This could imply that a breakout of komatiitic lava from a lava tube or that the komatiitic vent was near the site where the airfall deposit was found. Large-scale lapilli are not known to travel long distances, suggesting that the SMC may have been proximal to the vent forming the lavas making up portions of the Weltevreden Formation.

5.2 Comparison with Other Locations

5.2.1 Weltevreden Formation

The full thickness of the Weltevreden Formation is not known because of several conspiring factors. Komatiites are difficult to correlate across the frequent covered intervals in the Weltevreden and there are no distinctive sedimentary layers to aid in correlation. Blocks within the Weltevreden alternately face south (Pioneer Complex) and north (SMC), thus making structural repetitions in the Weltevreden Formation likely. However, in the SMC, there is not significant repetition, as can be seen from the heterogeneity within the stratigraphy (Fig. 3). The lower portions of the SMC are composed of predominantly pyroxenitic flows, whereas the upper portions of the SMC are dominated by peridotitic flows. The SMC features continuous volcanic deposition until it terminates into Fig Tree sedimentation.

The Pioneer Complex, which is stratigraphically similar to the SMC, has approximately the same thickness as the SMC (Cooper et al, 2005). The Pioneer is bounded by faults at both the upper and lower margins. The SMC may represent the uppermost kilometer of deposition in the Weltevreden. Lack of other sedimentation in the Weltevreden besides airfall tuffs seems to

indicate relatively rapid volcanic accumulation. However, if each tuff does represent an airfall deposit, then almost half of the thickness of the SMC must be accounted for by explosive eruptions (Stiegler et al., 2008). This is consistent with shallow marine deposition near wave base, as Stiegler et al. (2008) and Cooper et al (2005) have previously concluded about the Weltevreden Formation.

At 93.2, olivine Mg#s are higher in the SMC than in most other greenstone belts, such as the Abitibi (88.3-93.4, Arndt et al, 1977) or the Belingwe (maximum of 91.3, Nisbet et al, 1987). These values are consistent with the upper values taken from the Weltevreden (92.5-95.6, Kareem and Byerly, 2003), though they are higher than most values determined from the Pioneer Complex (91.0-92.9, Cooper et al, 2005). Komatiites of the SMC are closely comparable to other komatiites in the Weltevreden Formation.

A strong indicator of the genetic origin of magmas is $\text{Al}_2\text{O}_3/\text{TiO}_2$ (Gruau et al, 1990). The SMC has an overall average of 29.0 ± 2.2 $\text{Al}_2\text{O}_3/\text{TiO}_2$ (though this excludes two anomalously high TiO_2 samples), while the Pioneer complex has 30.4 $\text{Al}_2\text{O}_3/\text{TiO}_2$, a statistically equivalent value. Elsewhere in the Weltevreden Formation, Kareem and Byerly (2003) found $\text{Al}_2\text{O}_3/\text{TiO}_2$ between 26 and 33, consistent with studies in the ultramafic complexes. Other elements show some variation between the complexes and other locations in the Weltevreden Formation (Kareem and Byerly, 2003), but within statistical uncertainty. Rocks from these complexes have REE's with values similar to those in the SMC.

Similar textures and stratigraphy between the Pioneer complex and SMC implies similar processes during emplacement. The lithologic variation is identical between the two complexes. Important differences are 1) original orientation: the Pioneer complex is up to the south and the SMC is up to the north; 2) relative abundances of facies: less komatiitic basalt is found in the SMC than in the Pioneer and more tuff found in the SMC than the Pioneer; and 3) the

stratigraphic arrangement of flows in the SMC, with distinct sequences of flows that are not observed in the Pioneer complex. The mineralogy of the two complexes is nearly identical. The Pioneer olivines have slightly lower, though similar, MgO. Pigeonites and augites have similar compositions in both complexes, though orthopyroxenes in the Pioneer complex have only one composition, while the SMC has a low-En set of orthopyroxenes. Chromites in both complexes are representative of those from Al-undepleted komatiites with Cr# of 0.85 (Fig. 8B).

Overall, the suggestion is that the Pioneer complex may have been produced by the same processes as the SMC, but it is unlikely that the two complexes represent precisely the same volcanic events. The SMC is a slightly higher temperature suite than the Pioneer. This could represent different stages in the propagation of komatiites across the Archean surface or different eruptive sequences. The SMC is fault bounded at its base and possibly the top, and the Pioneer is fault bounded at both the top and base. Evidence is consistent with the two complexes representing different stages in the Weltevreden Formation, though lack of exposure and severe structural deformation makes definitive determination of this relationship unlikely.

Kareem and Byerly (2003) studied an isolated block of the Weltevreden Formation. That block was found to have similarly high-temperature flows, erupting at 1650°C. Cooper et al (2005) have shown that the Pioneer complex is geochemically and texturally similar to these flows, noting that the main difference is in the complex layering of the Pioneer flows that is not found in Kareem's flows. The SMC may represent a transitional block between Kareem's flows and the Pioneer, with intermediate temperature of eruption, MgO, and some complex layering in flows, but less than is found in the Pioneer. The three structural blocks are currently in close proximity to one another. It is possible that the three blocks actually represent different portions of the same flows from different positions along the flows, but this is speculative at best. What

can be concluded is that the three blocks all belong to the Weltevreden Formation and seem to have all formed from the same eruptive and depositional processes.

5.2.2 Mendon Formation

South of the Inyoka Fault, the youngest-Onverwacht unit is the Mendon Formation (Byerly, 1999). Stiegler et al. (2008) have noted depositional differences between the Weltevreden Formation and Mendon Formation, implying a much longer period of time required for deposition for the Mendon Formation. It is not entirely clear if the Weltevreden Formation is equivalent to a member of the Mendon Formation, though ages for the two formations overlap (Byerly et al, 1996; Lahaye, 1995). There are three major volcanic members that can be compared to the SMC: M1v, M2v, and M4v, and M4v is divided into upper and lower subunits (Byerly, 1999). SMC komatiites have MgO between 30 and 45 wt. %, which compares to Mendon M1v and lower M4v. Mendon komatiites have $\text{Al}_2\text{O}_3/\text{TiO}_2$ of either 10 (Al-depleted) for M2v and upper M4v or >40 (Al-enriched) for M1v and lower M4v, but SMC komatiites are Al-undepleted, with $\text{Al}_2\text{O}_3/\text{TiO}_2$ of 28.5. Immobile elements, such as Sc and V, follow the same trend in Mendon komatiites as the SMC. SMC komatiites have similar Cr to M1v, but less than lower M4v and more than other Mendon komatiites. Cr enrichments probably represent chromite accumulation, which is to say that the similarity between the SMC and Mendon komatiites only represents similarity of shallow processes, not mantle genesis.

There does not seem to be a suggestion that the Mendon and SMC formed through the same set of mantle processes or in the same depositional environment, even though they are chronostratigraphically equivalent. Only superficial similarities can be found between the SMC and M1v and lower M4v, but differences in critical chemical indicators, such as $\text{Al}_2\text{O}_3/\text{TiO}_2$, do not allow for the flows to be from the same mantle source or melting event. This is consistent

with previous studies that compared the Weltevreden to the Mendon Formation (e.g. Kareem and Byerly, 2003, Cooper et al, 2005, Byerly, 1999).

5.3 Petrogenesis

The liquid composition of komatiites was modeled in MELTS to determine theoretical values for olivine, pyroxene, and chromite compositions, as well as the temperatures at which the minerals begin to crystallize. MELTS, based largely on experimental data, appears broadly consistent with observations. The liquidus temperature is modeled to be 1615°C for olivine, which has a composition of Fo₉₅. This is similar to the maximum measured olivine value (Fo_{94.5}) or the estimated value from olivine control lines (Fo₉₄). Chromites begin crystallizing at 1550°C in models. The liquid composition in MELTS evolves to be more silica rich at lower temperatures. This is consistent with komatiitic basalts being fractionated equivalents to komatiites, as komatiitic basalts have much higher SiO₂/MgO than komatiites. The liquidus temperature given by MELTS is consistent with other komatiites in the Weltevreden. The majority of komatiites in the SMC are Al-undepleted, Munro-type komatiites. The rocks follow a tight olivine control line for most incompatible elements (Fig. 4). The liquid composition of the komatiites has REE's closely resembling the primitive mantle (Fig. 9). The most notable difference is a depletion in LREE's relative to mantle, which may be accounted for by either the first stage of melting the mantle source or by loss of elements through alteration.

5.4 Distribution Coefficients and Oxygen Fugacity

Distribution coefficients for olivine-liquid were determined using multiple techniques. Where elements were measured for both the liquid and olivine composition, those values were used to calculate the distribution coefficient. Because electron microprobe does not measure for all elements, elements with compositions below the lower limit of detection or not measured by

microprobe were determined from olivine control lines. The value of the olivine control line at 53.2 wt. % MgO was taken as representative of olivine (maximum measured from electron microprobe). As compared to the results of other workers in the Weltevreden, the D values compare favorably in most cases. Results are plotted in Table 6. Elements are found to have remarkably similar D values to previous workers on olivines in komatiites, such as Cooper (2008), Kareem (2005), or Canil (1997).

Canil (1997) has proposed that D_V can be used as a proxy for oxygen fugacity, as V distribution is redox sensitive, and V is not mobilized by metamorphism. He calculated, based on experimental data, the relationship of $D_V^{Ol/Liq}$ to oxygen fugacity based on the change of $\log(fO_2)$ relative to the nickel-nickel-oxide buffer (ΔNNO) to be $D_V^{Ol/Liq} = 0.03e^{(-0.547 * \Delta NNO)}$. This is the best tool for estimating oxygen fugacity in komatiites that has been developed to date. Oxygen fugacity for SMC komatiites, based on this formula, is $-0.18 \Delta NNO$. Canil determined that for most komatiites, oxygen fugacity should be between $+0.3$ and $-0.9 \Delta NNO$, though he did find some komatiites as low as $-3.0 \Delta NNO$. SMC komatiites are well within the range of previously determined oxygen fugacity. SMC komatiites do, however, have slightly lower ΔNNO than other komatiites of the Weltevreden. Cooper (2008) determined that Pioneer Complex komatiites have $+0.26 \Delta NNO$, and Kareem (2005) determined that other Weltevreden komatiites have $+2.0 \Delta NNO$, but expressed doubts about the accuracy of the number. Kareem's data is not as tightly constrained as Cooper's. While there is a difference between oxygen fugacity for Pioneer and SMC rocks, the values are statistically equivalent, which is consistent with the two complexes having magma sources from the same mantle process and suggests a true oxygen buffer close to $0.00 \Delta NNO$.

Table 6: Distribution coefficients for olivines crystallizing from a komatiitic liquid.

Location	SMC	Pioneer	Weltevreden	Experimental
D_{Ni}	2.44	2.7	2	-
D_{Cr}	0.50	0.38	0.46	-
D_{Sc}	0.11	0.07	0.11	0.11
D_V	0.03	0.03	0.01	0.01
D_{Ti}	< 0.01	0.01	0.01	0.01
D_{Al}	<0.01	0.01	0.01	0.01
D_{Ca}	0.06	0.02	-	-
K_D^{FeO-MgO}	0.34	0.37	0.37	-
Source	This Study	Cooper, 2008	Kareem, 2005	Canil, 2001

5.5 Mass Balance

Komatiitic basalts present a difficulty in understanding komatiite fractionation, because while there is a continuous accumulation trend between liquid compositions inferred from spinifex rocks and olivine, there is not a continuous fractionated sequence between liquid and komatiitic basalts (Fig. 9). If MgO is accumulating in flows, there should be also be highly fractionated flows to maintain mass balance. Arndt (2008) uses the ratio of MgO in olivine and in flows to determine the amount of excess MgO in flows by the formula:

$$\% \text{ Excess olivine} = 100 \times \frac{\text{MgO}_{\text{flow}} - \text{MgO}_{\text{lava}}}{\text{MgO}_{\text{olivine}} - \text{MgO}_{\text{lava}}} \quad \text{Equation 1}$$

Where MgO_{flow} is the bulk weight percent of MgO in a given flow, MgO_{lava} is the MgO weight percent of the source liquid, and $\text{MgO}_{\text{olivine}}$ is the average MgO weight percent of olivine.

When this Eq. 1 is applied to the SMC, the majority of samples from both layered flows and massive flows fall into the category of open-flow pathways, with >40% excess olivine for most of the flows. At least one flow, flow 442, is in the category of ponded flows (Arndt, 2008), with +18% excess olivine and a thickness of 75 m. Komatiitic basalts have very negative values of -96%, and -103% excess olivine, and one pyroxene spinifex sample has a value of -26%. These may represent the highly fractionated lavas that result from crystallization of olivine in the flow.

Using these numbers, mass balance can be established based on stratigraphic thickness of the complex. Since the Pioneer Complex has greater stratigraphic thickness of komatiitic basalt, it may be a better example of mass balance. Based on the stratigraphic column presented by Cooper et al (2005), komatiitic basalts make up almost 30% of the flows in the Pioneer complex,

meaning that there is 2.5x greater volume of komatiitic lavas as komatiitic basalts. Mass balance would predict that these komatiites would have 40% excess olivine. The average komatiite has 45% excess olivine. This would seem to suggest that the lava is mass-balanced with respect to MgO. In the SMC, however, the flows are not mass balanced with respect to olivine, as komatiitic basalts make up only 15% of the flow thickness. The lack of mass balance presents a problem, as there must be fractionated flows to correspond to the accumulated flows observed in the SMC. This may be a result of the particular exposures in the SMC, which may represent an area where komatiitic basalts are thin, but may be thicker in areas now covered or faulted away. It is also possible that the olivine-depleted layers are stratigraphically below the fault boundary at the base of the SMC. Komatiitic basalts must be present along strike of the flows in some direction in order to account for the enrichment of olivine in SMC komatiites. This may be a sampling error in the SMC due to covered flows that could not be mapped resulting in the lack of analyses in the upper portions of flows where fractionated rocks would be expected. Because there is not mass balance in the SMC, it is highly unlikely that the stratigraphic section presented here is representative of the full thickness of the Weltevreden. This also constrains the mechanisms by which the current komatiites became emplaced in the SMC and suggests that most of the flows formed not only as open systems, but also that flows were deposited in such a way that the lava could continue to propagate to deposit the depleted portion of the flow elsewhere.

5.6 Accumulation of Minerals in Komatiites

Komatiites of the Weltevreden are typified by layered flows with distinct geochemical horizons. Olivine accumulation explains most of the chemical trends in the Weltevreden. The amount of olivine accumulation varies in SMC komatiites from 30% to 70% (Fig. 4). The

distinction between olivine cumulates is significant enough that they are given separate field designations (peridotitic vs pyroxenitic vs dunitic komatiites), which also translate to different textures when viewed in thin section. Though the cumulate process may not be identical to intrusive processes from which the textural names derive, dunitic komatiites can be described as adcumulates (Arndt, 1986), where olivines nucleate in the lower portions of the flow then continue to grow as fluids mix with the main body of lava. When crystals grow, it pushes out still molten liquid, resulting in a rock composed primarily of olivine. Dunitic komatiites are the most olivine-rich komatiites, with 70% olivine accumulation in some cases. Pyroxenitic komatiites are poikilitic cumulates, although the distinction between heteradcumulate and adcumulate for these is difficult to determine based on mineral textures, as the defining characteristic, zoning in olivine crystals, has been removed by subsequent alteration. The intercumulus liquid has mobility, allowing pyroxene crystals to poikilitically enclose olivine crystals. Peridotitic komatiites and basaltic komatiite form as orthocumulates from the remaining liquid. Since crystals in the early stage of cooling would form at various places within the flow, crystal sedimentation must contribute to the early development of flows. MELTS modeling suggests olivine begins crystallizing at 1615°C, chromite begins crystallizing at 1550°C, and orthopyroxene begins crystallizing at about 1315°C. The formation of dunitic komatiites, therefore, occur well before pyroxene begins crystallizing. Rates of sedimentation for olivines in the liquid can be calculated to help understand the process of accumulation that generates differentiated layers in komatiites.

McBirney and Noyes (1979) demonstrated that once basaltic liquids begin to crystallize, they do not behave as Newtonian fluids. In their study, they found that basalts only allow crystal settling near the liquidus temperature. However, their study only heated basalts to 1200°C, which is 300-400°C lower than the estimated eruption temperatures of komatiites. If a komatiitic

liquid at $>1300^{\circ}\text{C}$ is assumed to behave as a Newtonian fluid and sedimentation of minerals is assumed not to occur prior to flow velocity decreasing to the point that laminar flow is established, Stokes' Law can be used to calculate the rate of crystal settling. Arndt (2008) offers a calculation of viscosity and density of komatiitic lava at different points in crystallization. Using his estimations and an average value of olivine density of 3.27 g/cc and using an average radius of $.25\text{ cm}$, settling rate of olivine crystals can be estimated for a closed system.

As shown in Table 6, olivines can settle quite rapidly until $\sim 30\%$ of the liquid is crystallized in a closed system. This helps to explain why the lower portions of the flows are olivine cumulates. As crystals form in the flow, they quickly settle to the bottom (falling 1 meter in ~ 125 seconds). By the time that enough of the liquid has frozen to trap crystals in the upper portions of the flow, crystals are no longer able to overcome the viscosity of the liquid to settle to the bottom. Sedimentation of crystals stops completely at approximately 1250°C , slightly below the approximate temperature that orthopyroxene begins crystallizing (Cooper et al, 2005; Kareem and Byerly, 2003; this study). In Hawaiian basalts, it has been observed that the maximum amount of crystals in a flowing basalt is near 39% (Keszthelyi and Self, 1998), which compares favorably to the calculations here and to observations of the relative portions of glass to crystals in peridotitic komatiites in this study. This is also consistent with pyroxene laths and poikilitic pyroxenes forming late in komatiite crystallization, as such structures would be less likely to form or be preserved in mobile lavas.

In an open system, olivine precipitation would continue in the upper portions of the flow at high temperatures, which would allow much higher percentages of flows to be crystallized as olivine without limiting the viscosity of the upper portions of the flow. This undoubtedly occurs in the SMC and dominates crystallization. A constant supply of lava allows for flows to grow thick with accumulating olivine, such as dunitic komatiites, in short periods of time. By building

Table 7: Sedimentation of olivine crystals

Fraction Crystallized (%)	Temperature (°C)	Viscosity of Lava	Density of Lava	Rate of Settling (cm/sec)
0	1567	0.9	2739	0.8031
10	1514	4	2740	0.1803
20	1456	16	2741	0.0450
30	1394	96	2743	0.0075
40	1327	820	2746	0.0009
50	1256	15482	2748	0.0000

up a solid base of olivine, flows are able to grow in thickness during flow propagation. After a thick portion of olivine cumulate is deposited, a solid mass of crystals is formed as flows continue to propagate, which may leave behind some of the massive flows that are found in the SMC with no associated layered flow above them. At some point, the lava must transition from an open system to a closed system, which may account for the multiple orthopyroxene compositions observed in the SMC. The Mg-rich orthopyroxenes may be from open-system crystallization, while the Mg-depleted orthopyroxenes represent a later, more fractionated lava cooling as a closed system. This could even represent a local closed system, where lava continues to flow as an open system above the crystal mush at the base of the flow, but the crystal lattice isolates portions of the flow so that fractionation can take place.

Because of the smaller radius of chromites in SMC komatiites, they would settle at approximately 62% the rate of olivines at all temperatures. Chromites do not begin crystallizing in SMC komatiites until the liquid has cooled below 1550°C, when olivine has already crystallized a significant portion of the liquid in closed system. Cooper et al (2005) found that chromites do not form in the Pioneer complex until approximately 1500°C. Because olivine dominates accumulation, highly chromite-enriched layers are not found in the Weltevreden. This is also true in an open system, because flows crystallizing chromite are well within the temperature range for olivine to be crystallizing, and olivine precipitation will occur at a faster rate than chromite precipitation in flows. However, there are occurrences where minor Cr enrichment can be observed in flows. The maximum Cr enrichment in SMC flows is 1.71 times the amount predicted by olivine control (Fig. 4D). This can be accounted for by a 1% accumulation of chromite in the flow. Chromite accumulation would effectively be impossible by the time 30% of the flow had crystallized, and enrichment probably represents movement of

crystals from the upper portion of the flow into the lower parts of the flow. After the liquid cools below 1250°C, minerals lack mobility in the fluid so that accumulation can no longer take place. The remainder of the liquid would either crystallize in place as olivine, pyroxene, or chromite, or freeze as glass.

Kareem and Byerly (2003) found 5-10 cm thick dikes of spinifex texture which may represent mobilization of trapped liquid from the base of komatiitic flows. This would form a conduit that would solidify separately from the bulk of the flow with the same composition as the chilled margin. The conduits would not have a major effect on the cooling history of the lava, but it could provide another method by which minor Cr enrichment could occur. If a conduit broke through the mostly frozen portion of the lava, it could re-activate still molten parts of the lava, thus moving depleted fluid away from already crystallized chromites and resulting in enrichment. While such conduits have been observed in the Weltevreden Formation, they have not yet been observed in the SMC, which makes crystal settling the more likely way in which Cr enrichment has taken place in the flows. Another explanation for Cr accumulation in samples is the nugget effect. Chromites are not homogeneously dispersed throughout komatiites, so a 100 g sample may not be representative of the composition of the rock as a whole. Though care was taken to ensure that altered samples were not analyzed, the difference of a single chromite crystal in a small analysis could be responsible for the observed variation in Cr.

A possible pyroxene accumulation trend is observed when average orthopyroxene composition is compared to whole rock compositions by $\text{Al}_2\text{O}_3/\text{MgO}$ (Fig 4B and 4C). Pyroxenitic komatiites are sections of the flow that have slightly less olivine accumulation, which allows for large orthopyroxene crystals to grow in the interstitial space between olivine crystals from the melt liquid. Pyroxenitic komatiites seem to represent a transition between early orthocumulate growth of lavas and later adcumulate growth. The elongate nature of augites in

peridotitic komatiites in the upper portions of flows suggests that they formed late in the crystallization sequence of lavas after they had ceased flowing, which would otherwise have been preserved had they formed in a mobile lava (Fig 7B). Many of the augites are present as overgrowths of orthopyroxene, and many orthopyroxenes show dissolution features characteristic of resorption by the liquid (Fig 7B). Some pyroxenitic komatiites may have experienced augite mobilization, possibly by movement of late komatiitic liquid through already cooled rock by spinifex dikes (Kareem and Byerly, 2003) and possibly by a prolonged period of cooling between 1300°C and 1250°C, when mobilization through the liquid would be less likely.

5.7 Flow Propagation

Sedimentation rates of minerals early in crystallization can be estimated if the fluid is not experiencing turbulent flow. There has been extensive discussion about the role of turbulent flow in komatiites (see Cas et al, 1999 and Williams et al, 1998, for differing opinions). There is general consensus that komatiites would have had turbulent flow for a short distance near the vent. After the growth of a crust and inflation begins, the rate of flow at the vent could be three to four orders of magnitude greater than the rate of flow at the flow front, as is estimated from modern pahoehoe flows (Cas et al, 1999). At flow velocities under 3 m/s, modern basalts do not experience turbulent flow (Keszthelyi and Self, 1998), nor do slow-moving expansions of flow fronts, such as pahoehoe lobes. Turbulent flow does occur when a lava is flowing at a high gradient, but this typically results in the formation of a 'a flow, which is texturally distinct from pahoehoe flows and has been observed to have a shorter flow regime (<100 km) than flood basalts (Keszthelyi and Self, 1998). Komatiites have most often been interpreted as having vast flow fields (Williams et al, 1998), with associated thin flow fronts, making laminar flow more likely.

There is also general agreement that komatiites would have flowed turbulently if they were moving at expected velocities (2 to 10 m/s, Huppert and Sparks, 1985) in lava tubes. Turbulent flow would result both from the high velocity of the flow and from accumulating olivine crystals at the base of the flow (Arndt, 2008). However, this does not necessarily have to be the case, as laminar flow has been observed at Kilauea (Huppert and Sparks, 1985), and the transition to turbulent flow for basaltic flows with radii of 5 to 30 m is estimated to take place when the lava's velocity is between 2.5 and 100 m/s, meaning that komatiites in lava tubes could be flowing near the velocity of transition to turbulent flow. Note that if lavas were flowing turbulently for the full period of deposition, the same relative relationships listed above would hold true, but the specific rates of deposition would potentially be significantly different.

In short, there is no compelling evidence that the lavas were turbulently flowing for their duration, though it is certainly the case for the earliest part of the flow regime. However, as lavas expanded, the overall velocity would decrease as viscosity increased, allowing a transition to laminar flow prior to the majority of crystals being deposited at the base of flows. Turbulent flow may entrain crystals until flows slow to the point that laminar flow is taking place. In the event that lavas ponded, flow velocity would drastically decrease, allowing another situation where sedimentation would follow Stoke's Law.

5.8 Ponding

Some flows within the SMC appear to have ponded prior to crystallization. A ponded lava forms a closed system which causes fractionation to behave more predictably than in open systems. Ponded lavas must have balanced olivine accumulation to account for mass balance. One flow, sampled by SA 442-3 and 442-5 (Fig 3), seems to represent balanced olivine accumulation in a single flow, and the flow swells along strike, possibly indicating a place where

thickening could take place as a result of paleotopography. There are only two analyses for this flow, but the two samples have olivine accumulation of +38.64 and -102.97. A dunitic base is mapped, but is not analyzed in this study or included in the stratigraphic column in Figure 3. If it is consistent with other dunitic komatiites, the olivine accumulation would be about +62. This flow is, therefore, representative of a closed system and suggests that multiple lavas in the SMC may have formed as closed systems. It is also possible that at different lateral stages in komatiite propagation, flows may have behaved alternately as open and closed systems.

In order for lava to pond, the liquid must encounter some barrier to flow. In the case of lavas in the SMC, this may take place when tuffs deform beneath flows to make accommodation space. Sedimentary structures in several places within the Weltevreden show that tuffs were deformed as soft sediments. Elsewhere in the Weltevreden, tuffs show dramatic convolute bedding. One tuff unit in the SMC clearly folds around a komatiitic layer, suggesting the flow burrowed into unlithified tuff (Fig 2). The flow layers are not folded and the tuff unit still preserves fine sedimentary structures (Fig 6), such as cross-bedding and convolute bedding, which implies that it was deformed as soft sediment rather than through tectonic processes. Though the sediment could have developed convolute bedding through a number of processes, including liquefaction as a result of an earthquake, it is consistent with a lava propagating on top of the tuff to produce an uneven bed load. Two mechanisms have previously been proposed to result in ponding of lavas: 1) the presence of pre-existing topography and 2) thermal erosion of the substrate by the lava (Cas et al, 1999). However, flow-loading could provide a third mechanism by which ponds of komatiitic lava could form. Further research will be needed to understand the mechanical constraints of such a process.

Massive komatiites and layered komatiites may form through separate processes. Layered komatiites seem to consistently be thicker than massive komatiites, but the mechanism

generating the separate expressions is not clear. In layered flows, some layers are not always present, and massive flows may have the lithology of any of the layers from a layered flow. It may be that a layer can be isolated from the flow when it becomes rheologically stable and behaves as a solid rather than as a liquid. The accumulated portion may then behave as a dam, with the liquid portion moving to a different channel, but following the same accumulation process that generates layered flows.

6. Conclusions

Careful mapping and interpretation of the Saw Mill Complex reveals that the complex represents extrusive volcanism, not a layered ultramafic intrusion. Rocks previously mapped as gabbros, peridotites, dunites, and pyroxenites (Wuth, 1980), are shown to be extrusively formed komatiites, and fine-grained rocks previously interpreted as shear zones are now recognized as tuffs, consistent with other recent studies of layered ultramafic complexes in the Weltevreden Formation (Stiegler et al., 2008; Cooper et al, 2005; Kareem and Byerly, 2003). The SMC represents the upper 1200 m of the Weltevreden Formation, with conformable Fig Tree Group sediments capping the depositional sequence. The SMC and Pioneer complex are from a similar magma source. The two complexes have similar rare earth elements and $\text{Al}_2\text{O}_3/\text{TiO}_2$, though MgO in SMC komatiites is higher than those in the Pioneer complex. SMC komatiites are not similar to any of the age-equivalent Mendon Formation komatiites.

The SMC is divided into three sequences of volcanic activity: a pyroxenitic komatiite dominated sequence, a dunitic komatiite dominated sequence, and a peridotitic komatiite dominated sequence. Komatiites are interbedded with tuffs throughout the entire stratigraphic sequence. The SMC represents the end of Weltevreden Formation deposition, as it is bound at the top by sediments representing the end of the Onverwacht Group or the beginning of Fig Tree sedimentation. Large, cm-scale lapilli suggest subaerial explosions, and combined with cross-bedding found in tuffs, suggest deposition in shallow marine environments. The deposits may represent near-vent eruptions to produce aerodynamic shapes in the lapilli, though littoral rootless vents can form distally to eruptive vents. Weltevreden komatiites are rapidly emplaced and represent a short period of deposition.

Komatiites in the SMC are exquisitely preserved. SMC komatiites formed from a liquid with 31 wt. % MgO and are fractionated up to 45 wt. % MgO. Incompatible elements follow

olivine accumulation trends consistent with previous studies on komatiites showing that they form as olivine cumulates.

Flows began crystallizing at 1615°C at $-0.18 \log(fO_2)$ relative to the nickel-nickel oxide buffer. Most komatiitic flows have excess olivine, suggesting that they formed as part of an open system where olivine was allowed to precipitate out of the liquid and accumulate to form the various layers of komatiites. Flows begin accumulating olivine quickly after it crystallizes, which prevents chromite-rich layers from forming. Orthopyroxene accumulates in SMC komatiites in the late stages of the liquid cooling, which can allow for crystal growth to push aside other liquids. When flows have formed in closed systems, they form layered flows capped by komatiitic basalts. Ponding in SMC komatiites may occur by flow-loading, causing depressions in tuffs that then fill with pooling lava.

Questions remain about the SMC. In some places, inverted stratigraphy seems to be present, where pyroxenitic komatiites are found below dunitic komatiites. The relationship between the uppermost peridotitic lava and the Fig Tree Group needs to be better constrained to determine if the Fig Tree sediments are juxtaposed against SMC rocks by faulting or by deposition, as this may represent a place where the transition between the Onverwacht Group and Fig Tree Group can be studied.

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Appendix: Electron Microprobe Results

Olivine

Oxide Weight Percent:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO ₂	41.13	41.44	41.07	41.64	41.54	41.08	41.20	41.31	41.34	41.32	40.89	41.22	41.41	41.25	40.80
TiO ₂	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.01	0.02
Al ₂ O ₃	0.05	0.05	0.06	0.08	0.09	0.07	0.06	0.04	0.05	0.07	0.07	0.06	0.05	0.09	0.07
Cr ₂ O ₃	0.21	0.20	0.20	0.20	0.21	0.28	0.12	0.26	0.21	0.17	0.22	0.22	0.22	0.21	0.24
FeO	6.46	6.29	6.96	6.44	7.32	7.20	7.41	7.20	6.45	6.78	6.16	6.02	5.78	6.28	6.90
MnO	0.13	0.10	0.12	0.06	0.14	0.15	0.12	0.11	0.11	0.14	0.10	0.11	0.09	0.09	0.15
NiO	0.48	0.50	0.41	0.40	0.40	0.43	0.43	0.47	0.44	0.45	0.48	0.47	0.49	0.44	0.45
MgO	52.04	51.82	51.32	51.71	50.94	50.75	50.76	51.18	51.76	51.75	52.50	52.38	52.25	51.44	51.86
CaO	0.17	0.19	0.18	0.18	0.21	0.19	0.21	0.20	0.17	0.18	0.15	0.18	0.19	0.19	0.15
Na ₂ O	0.00	0.00	0.00	0.04	0.07	0.02	0.01	0.00	0.00	0.00	0.00	0.03	0.01	0.01	0.00
K ₂ O	0.00	0.00	0.01	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V ₂ O ₅	0.00	0.00	0.01	0.03	0.02	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00
Total	100.69	100.63	100.33	100.78	100.97	100.17	100.34	100.78	100.53	100.87	100.58	100.70	100.50	100.00	100.64
Sample	HB 2-2	HB 2-2	HB 2-2	HB 2-2	HB 2-3	HB 2-3	HB 2-3	HB 2-3	HB 2-3	HB 2-3	HB 2-3	HB 2-3	HB 2-3	HB 2-3	HB 2-3

Normalized Oxygen Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Si	0.99	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.99	0.99	1.00	0.98
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.13	0.13	0.14	0.13	0.15	0.15	0.15	0.15	0.13	0.14	0.12	0.12	0.12	0.13	0.14
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mg	1.87	1.85	1.85	1.85	1.83	1.83	1.83	1.84	1.86	1.85	1.88	1.87	1.87	1.85	1.87
Ca	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	3.01	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.01	3.01	3.00	3.00	3.01
Mg #	0.93	0.94	0.93	0.93	0.93	0.93	0.92	0.93	0.93	0.93	0.94	0.94	0.94	0.94	0.93

Olivine

Oxide Weight Percent:	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
SiO ₂	40.78	40.85	41.09	41.05	40.91	40.94	41.08	40.63	40.59	41.33	41.07	41.18	39.99	40.12	40.56
TiO ₂	0.02	0.00	0.00	0.00	0.02	0.00	0.02	0.02	0.00	0.02	0.02	0.04	0.00	0.00	0.00
Al ₂ O ₃	0.06	0.04	0.07	0.05	0.05	0.02	0.05	0.04	0.05	0.05	0.06	0.04	0.04	0.06	0.05
Cr ₂ O ₃	0.29	0.23	0.19	0.22	0.25	0.26	0.21	0.24	0.21	0.27	0.18	0.19	0.24	0.20	0.24
FeO	7.01	6.66	5.60	7.46	7.75	7.60	7.80	7.20	7.41	7.20	7.98	7.85	7.46	7.18	7.53
MnO	0.11	0.07	0.13	0.10	0.14	0.12	0.15	0.08	0.14	0.13	0.13	0.14	0.11	0.16	0.14
NiO	0.41	0.53	0.42	0.45	0.43	0.41	0.35	0.35	0.39	0.44	0.35	0.39	0.43	0.49	0.48
MgO	50.95	51.70	53.24	50.63	50.34	50.68	50.11	50.08	50.40	50.91	50.12	50.01	50.54	51.00	50.68
CaO	0.18	0.17	0.19	0.15	0.13	0.17	0.16	0.15	0.16	0.16	0.18	0.15	0.16	0.17	0.17
Na ₂ O	0.01	0.00	0.00	0.06	0.03	0.01	0.00	0.00	0.03	0.01	0.00	0.00	0.00	0.00	0.00
K ₂ O	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.02
V ₂ O ₅	0.02	0.00	0.01	0.00	0.00	0.01	0.02	0.00	0.01	0.00	0.00	0.03	0.00	0.01	0.00
Total	99.85	100.25	100.94	100.19	100.04	100.23	99.95	98.79	99.40	100.53	100.08	100.03	98.97	99.40	99.86
Sample	HB 2-3	HB 2-3	HB 2-3	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-4

Normalized Oxygen Units	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Si	0.99	0.99	0.98	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	1.00	0.98	0.98	0.99
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Fe	0.14	0.13	0.11	0.15	0.16	0.15	0.16	0.15	0.15	0.15	0.16	0.16	0.15	0.15	0.15
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mg	1.85	1.86	1.90	1.83	1.83	1.83	1.82	1.83	1.84	1.83	1.82	1.81	1.85	1.86	1.84
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	3.00	3.01	3.01	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.99	3.01	3.01	3.01
Mg #	0.93	0.93	0.94	0.92	0.92	0.92	0.92	0.93	0.92	0.93	0.92	0.92	0.92	0.93	0.92

Olivine

Oxide Weight Percent:	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
SiO ₂	40.88	41.16	41.21	40.94	40.83	40.58	40.54	39.98	40.62	40.03	40.81	41.26	40.45	40.38	40.99
TiO ₂	0.00	0.01	0.00	0.00	0.03	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.02	0.01
Al ₂ O ₃	0.05	0.05	0.06	0.06	0.05	0.05	0.06	0.07	0.04	0.06	0.06	0.05	0.14	0.05	0.06
Cr ₂ O ₃	0.24	0.24	0.20	0.22	0.24	0.19	0.27	0.24	0.26	0.27	0.26	0.24	0.25	0.03	0.27
FeO	7.25	7.17	7.40	7.50	7.45	7.37	6.42	6.99	6.44	7.01	6.26	6.29	6.51	9.55	7.44
MnO	0.12	0.12	0.10	0.11	0.16	0.12	0.07	0.10	0.11	0.11	0.11	0.12	0.13	0.16	0.11
NiO	0.41	0.39	0.42	0.38	0.41	0.34	0.48	0.48	0.45	0.46	0.43	0.44	0.43	0.41	0.43
MgO	50.79	51.18	51.05	50.98	50.67	50.82	51.44	51.15	51.79	51.06	52.02	51.65	51.44	49.35	50.50
CaO	0.18	0.17	0.18	0.18	0.16	0.14	0.15	0.15	0.17	0.16	0.17	0.16	0.16	0.11	0.17
Na ₂ O	0.00	0.02	0.00	0.02	0.01	0.01	0.00	0.02	0.04	0.03	0.01	0.02	0.00	0.03	0.01
K ₂ O	0.02	0.01	0.01	0.00	0.01	0.01	0.02	0.02	0.00	0.00	0.00	0.00	0.02	0.01	0.00
V ₂ O ₅	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Total	99.95	100.52	100.62	100.39	100.03	99.62	99.44	99.21	99.94	99.21	100.14	100.24	99.52	100.08	100.00
Sample	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-4	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-7	HB 2-7

Normalized Oxygen Units	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Si	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.98	0.99	1.00	0.99	0.99	1.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.01
Fe	0.15	0.14	0.15	0.15	0.15	0.15	0.13	0.14	0.13	0.14	0.13	0.13	0.13	0.20	0.15
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mg	1.84	1.84	1.84	1.84	1.84	1.85	1.87	1.87	1.87	1.87	1.87	1.86	1.87	1.80	1.83
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	3.00	3.00	3.00	3.01	3.00	3.01	3.01	3.02	3.01	3.02	3.01	3.00	3.01	3.01	3.00
Mg #	0.93	0.93	0.92	0.92	0.92	0.92	0.93	0.93	0.93	0.93	0.94	0.94	0.93	0.90	0.92

Olivine

Oxide Weight Percent:	46	47	48	49	50	51
SiO ₂	41.07	41.52	41.46	41.53	41.32	41.52
TiO ₂	0.01	0.01	0.00	0.01	0.03	0.00
Al ₂ O ₃	0.05	0.05	0.06	0.07	0.04	0.06
Cr ₂ O ₃	0.24	0.24	0.26	0.20	0.31	0.24
FeO	7.93	6.16	7.04	6.31	6.78	6.05
MnO	0.12	0.09	0.13	0.10	0.10	0.11
NiO	0.46	0.45	0.45	0.45	0.43	0.44
MgO	50.17	51.81	51.28	51.90	51.07	52.27
CaO	0.17	0.15	0.17	0.15	0.14	0.16
Na ₂ O	0.02	0.01	0.04	0.00	0.00	0.01
K ₂ O	0.01	0.01	0.02	0.01	0.01	0.01
V ₂ O ₅	0.01	0.01	0.00	0.02	0.00	0.00
Total	100.24	100.51	100.91	100.74	100.23	100.88
Sample	HB 2-7	HB 2-7	HB 2-7	HB 2-7	HB 2-7	HB 2-7

Normalized Oxygen Units	46	47	48	49	50	51
Si	1.00	1.00	1.00	1.00	1.00	0.99
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.01	0.00	0.01	0.00
Fe	0.16	0.12	0.14	0.13	0.14	0.12
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.01	0.01	0.01	0.01	0.01	0.01
Mg	1.82	1.86	1.84	1.86	1.84	1.87
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00
Total	3.00	3.00	3.00	3.00	3.00	3.00
Mg #	0.92	0.94	0.93	0.94	0.93	0.94

Chromite

Oxide Weight Percent:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO ₂	0.18	0.11	0.13	0.16	0.18	0.17	0.13	0.16	0.26	0.12	0.14	0.14	0.14	0.15	0.13
TiO ₂	0.13	0.18	0.14	0.15	0.15	0.13	0.15	0.11	0.15	0.14	0.16	0.16	0.17	0.14	0.15
Al ₂ O ₃	10.11	7.07	6.94	7.68	7.80	7.75	7.29	7.88	7.71	7.88	8.06	8.31	8.19	8.08	8.08
Cr ₂ O ₃	61.45	60.24	61.51	61.61	60.59	60.38	61.71	60.61	60.00	62.74	62.25	60.36	60.69	60.79	59.65
FeO	10.32	18.67	15.10	14.37	14.74	15.63	15.63	15.34	14.90	13.85	13.91	13.39	15.00	14.83	15.70
Fe ₂ O ₃	2.75	2.77	2.99	2.24	3.04	3.37	2.31	2.77	3.60	1.81	1.89	3.18	2.73	2.60	3.31
MnO	0.16	0.20	0.24	0.19	0.24	0.20	0.25	0.23	0.22	0.15	0.14	0.17	0.16	0.21	0.16
NiO	0.19	0.09	0.10	0.17	0.10	0.18	0.12	0.13	0.17	0.11	0.15	0.16	0.16	0.13	0.11
MgO	15.30	9.45	11.74	12.30	12.10	11.59	11.44	11.66	11.85	12.58	12.71	13.02	12.02	11.94	11.48
CaO	0.00	0.06	0.03	0.03	0.05	0.04	0.06	0.03	0.04	0.02	0.02	0.04	0.06	0.06	0.07
Na ₂ O	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.08	0.02	0.00	0.00	0.03	0.01
K ₂ O	0.01	0.02	0.00	0.00	0.00	0.01	0.00	0.01	0.03	0.00	0.02	0.00	0.01	0.00	0.00
V ₂ O ₅	0.12	0.17	0.12	0.13	0.10	0.13	0.15	0.12	0.10	0.13	0.13	0.11	0.14	0.11	0.15
Total	100.82	99.03	99.04	99.03	99.10	99.58	99.23	99.07	99.07	99.62	99.59	99.06	99.48	99.07	99.01
Sample	HB 2-2	HB 2-2	HB 2-2	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6

Normalized Oxy. Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Si	0.05	0.03	0.04	0.04	0.05	0.04	0.03	0.04	0.07	0.03	0.04	0.04	0.04	0.04	0.03
Ti	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Al	3.03	2.28	2.20	2.41	2.46	2.44	2.31	2.49	2.44	2.45	2.51	2.60	2.57	2.54	2.56
Cr	12.37	13.02	13.10	12.99	12.81	12.77	13.10	12.84	12.73	13.10	12.99	12.66	12.76	12.83	12.67
Fe ²⁺	2.20	4.27	3.40	3.21	3.30	3.50	3.51	3.44	3.34	3.06	3.07	2.97	3.34	3.31	3.53
Fe ³⁺	0.59	0.63	0.67	0.50	0.68	0.75	0.52	0.62	0.81	0.40	0.42	0.71	0.61	0.58	0.74
Mn	0.03	0.05	0.06	0.04	0.06	0.05	0.06	0.05	0.05	0.03	0.03	0.04	0.04	0.05	0.04
Ni	0.04	0.02	0.02	0.04	0.02	0.04	0.03	0.03	0.04	0.02	0.03	0.03	0.03	0.03	0.02
Mg	5.81	3.85	4.71	4.89	4.82	4.62	4.58	4.66	4.74	4.95	5.00	5.15	4.77	4.75	4.60
Ca	0.00	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Na	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.01	0.00	0.00	0.01	0.01
K	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00
V	0.02	0.03	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03
Total	24.22	24.24	24.26	24.19	24.26	24.29	24.20	24.24	24.31	24.15	24.16	24.27	24.23	24.22	24.28
Mg#	72.55	47.44	58.09	60.41	59.41	56.92	56.61	57.54	58.63	61.82	61.96	63.42	58.82	58.93	56.59
Cr#	0.80	0.85	0.86	0.84	0.84	0.84	0.85	0.84	0.84	0.84	0.84	0.83	0.83	0.83	0.83

Chromite

Oxide Weight Percent:	16	17	18	19	20	21	22	23	24	25	26	27
SiO ₂	0.12	0.14	0.62	0.09	0.11	0.13	0.14	0.13	0.45	0.15	0.12	0.22
TiO ₂	0.16	0.14	0.13	0.17	0.16	0.19	0.11	0.16	0.20	0.18	0.16	0.21
Al ₂ O ₃	7.89	8.38	9.74	7.62	8.47	8.34	6.97	7.94	9.81	7.34	7.89	9.56
Cr ₂ O ₃	60.43	59.41	60.53	61.88	59.79	59.78	62.52	58.33	53.48	61.42	59.74	55.90
FeO	15.44	15.79	11.17	13.76	15.40	15.71	15.70	22.78	16.77	16.28	18.13	22.33
Fe ₂ O ₃	2.93	3.60	1.74	2.49	3.14	3.19	1.95	2.63	6.32	2.30	2.92	3.75
MnO	0.24	0.20	0.12	0.18	0.18	0.28	0.22	0.20	0.21	0.24	0.25	0.20
NiO	0.12	0.11	0.13	0.16	0.13	0.14	0.15	0.07	0.16	0.11	0.08	0.11
MgO	11.45	11.51	15.02	12.65	11.77	11.54	11.27	6.91	11.23	11.06	9.99	7.81
CaO	0.04	0.03	0.01	0.02	0.03	0.01	0.04	0.02	0.16	0.04	0.03	0.07
Na ₂ O	0.07	0.03	0.03	0.00	0.02	0.02	0.00	0.04	0.02	0.01	0.00	0.00
K ₂ O	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.01
V ₂ O ₅	0.17	0.15	0.12	0.11	0.14	0.15	0.08	0.18	0.19	0.14	0.16	0.24
Total	99.08	99.51	99.36	99.14	99.35	99.49	99.16	99.40	99.00	99.25	99.47	100.40
Sample	HB 2-6	HB 2-6	HB 2-6	HB 2-7	HB 2-7	HB 2-7	HB 2-7	HB 2-7	HB 2-7	HB 2-7	HB 2-7	HB 2-7

Normalized Oxy. Units	16	17	18	19	20	21	22	23	24	25	26	27
Si	0.03	0.04	0.16	0.02	0.03	0.04	0.04	0.04	0.12	0.04	0.03	0.06
Ti	0.03	0.03	0.02	0.03	0.03	0.04	0.02	0.03	0.04	0.04	0.03	0.04
Al	2.50	2.64	2.96	2.39	2.66	2.62	2.21	2.58	3.11	2.33	2.51	3.05
Cr	12.82	12.55	12.34	13.02	12.61	12.62	13.30	12.74	11.39	13.06	12.77	11.97
Fe ²⁺	3.46	3.53	2.41	3.06	3.44	3.51	3.53	5.26	3.78	3.66	4.10	5.06
Fe ³⁺	0.66	0.80	0.38	0.55	0.70	0.71	0.44	0.61	1.42	0.52	0.66	0.85
Mn	0.06	0.05	0.03	0.04	0.04	0.06	0.05	0.05	0.05	0.06	0.06	0.05
Ni	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.02	0.02	0.02
Mg	4.58	4.59	5.77	5.02	4.68	4.59	4.52	2.85	4.51	4.43	4.03	3.15
Ca	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.05	0.01	0.01	0.02
Na	0.04	0.02	0.02	0.00	0.01	0.01	0.00	0.02	0.01	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.03	0.03	0.02	0.02	0.03	0.03	0.01	0.03	0.03	0.02	0.03	0.04
Total	24.25	24.31	24.14	24.21	24.27	24.27	24.17	24.23	24.55	24.20	24.25	24.32
Mg#	56.94	56.50	70.56	62.10	57.67	56.69	56.13	35.09	54.41	54.77	49.55	38.40
Cr#	0.84	0.83	0.81	0.84	0.83	0.83	0.86	0.83	0.79	0.85	0.84	0.80

Orthopyroxene

Oxide Weight Percent:	1	2	3	4	5	6	7	8
SiO ₂	55.18	55.30	54.66	55.52	55.06	55.97	55.46	55.43
TiO ₂	0.10	0.10	0.07	0.07	0.06	0.05	0.07	0.04
Al ₂ O ₃	2.48	1.63	1.74	0.82	1.15	1.22	1.38	1.02
Cr ₂ O ₃	0.45	0.23	1.83	0.50	0.51	0.50	0.65	0.36
FeO	6.36	6.86	6.98	6.67	6.99	7.05	7.42	7.53
MnO	0.16	0.19	0.21	0.17	0.16	0.16	0.18	0.20
NiO	0.15	0.17	0.10	0.08	0.08	0.08	0.08	0.08
MgO	32.85	31.92	30.46	33.71	33.40	33.96	32.46	32.84
CaO	2.35	4.19	3.31	1.52	1.60	1.71	2.10	2.17
Na ₂ O	0.00	0.03	0.04	0.02	0.03	0.00	0.00	0.02
K ₂ O	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00
V ₂ O ₅	0.01	0.02	0.02	0.08	0.08	0.08	0.08	0.08
Total	100.08	100.63	99.44	99.17	99.11	100.79	99.88	99.77
Sample	HB 2-2	HB 2-6	HB 2-6	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8

Normalized Oxy. Units	1	2	3	4	5	6	7	8
Si	1.92	1.93	1.93	1.95	1.94	1.94	1.94	1.94
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.10	0.07	0.07	0.03	0.05	0.05	0.06	0.04
Cr	0.01	0.01	0.05	0.01	0.01	0.01	0.02	0.01
Fe	0.19	0.20	0.21	0.20	0.21	0.20	0.22	0.22
Mn	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.01
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.70	1.66	1.60	1.76	1.75	1.75	1.69	1.72
Ca	0.09	0.16	0.13	0.06	0.06	0.06	0.08	0.08
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	4.02	4.03	4.01	4.02	4.03	4.03	4.02	4.03
Mg#	90.20	89.24	88.61	90.01	89.49	89.57	88.63	88.60
Wo	0.04	0.08	0.06	0.03	0.03	0.03	0.04	0.04

Augite

Oxide Weight Percent:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO ₂	53.75	50.60	52.93	53.47	52.10	52.81	52.89	51.95	52.38	53.77	52.96	54.27	51.47	51.81	52.63
TiO ₂	0.11	0.44	0.22	0.19	0.20	0.17	0.16	0.20	0.18	0.09	0.18	0.11	0.34	0.19	0.20
Al ₂ O ₃	1.07	5.41	2.86	2.05	2.37	2.12	2.19	2.85	2.14	1.10	2.46	1.04	4.02	3.33	2.69
Cr ₂ O ₃	0.72	0.11	0.45	0.33	0.63	0.65	0.50	0.60	0.13	0.72	0.16	0.81	0.19	0.34	0.36
FeO	15.31	4.94	3.96	5.88	6.56	8.44	6.65	7.08	5.06	15.29	6.27	15.46	6.29	5.49	5.01
MnO	0.49	0.12	0.08	0.18	0.24	0.23	0.21	0.25	0.13	0.52	0.20	0.58	0.17	0.14	0.17
NiO	0.01	0.13	0.08	0.10	0.09	0.08	0.07	0.08	0.13	0.01	0.14	0.01	0.08	0.04	0.03
MgO	27.31	19.35	19.29	21.05	20.00	23.23	20.99	19.50	19.43	27.39	22.05	27.41	18.91	19.46	19.67
CaO	1.27	19.62	21.02	16.65	16.94	11.89	15.67	16.59	19.40	1.36	15.68	1.24	18.67	18.99	18.95
Na ₂ O	0.02	0.08	0.05	0.13	0.11	0.06	0.10	0.17	0.06	0.00	0.08	0.00	0.12	0.13	0.12
K ₂ O	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.02	0.01	0.01	0.00	0.00	0.00
V ₂ O ₅	0.01	0.10	0.05	0.06	0.05	0.07	0.08	0.07	0.07	0.03	0.05	0.02	0.08	0.07	0.06
Total	100.08	100.88	101.00	100.11	99.29	99.76	99.52	99.35	99.11	100.31	100.24	100.98	100.33	100.01	99.89
Sample	HB 2-2	HB 2-2	HB 2-2	HB 2-2	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-8	HB 2-8

Normalized Oxy. Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Si	1.95	1.83	1.91	1.93	1.91	1.92	1.93	1.91	1.92	1.94	1.91	1.95	1.88	1.89	1.91
Ti	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01
Al	0.05	0.23	0.12	0.09	0.10	0.09	0.09	0.12	0.09	0.05	0.10	0.04	0.17	0.14	0.12
Cr	0.02	0.00	0.01	0.01	0.02	0.02	0.01	0.02	0.00	0.02	0.00	0.02	0.01	0.01	0.01
Fe	0.46	0.15	0.12	0.18	0.20	0.26	0.20	0.22	0.16	0.46	0.19	0.46	0.19	0.17	0.15
Mn	0.02	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.02	0.01	0.02	0.01	0.00	0.01
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.47	1.04	1.04	1.14	1.10	1.26	1.14	1.07	1.06	1.48	1.19	1.47	1.03	1.06	1.07
Ca	0.05	0.76	0.81	0.65	0.67	0.46	0.61	0.65	0.76	0.05	0.61	0.05	0.73	0.74	0.74
Na	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.01	0.01
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	4.02	4.04	4.02	4.01	4.02	4.02	4.01	4.02	4.02	4.02	4.03	4.02	4.03	4.03	4.02
Mg#	76.07	87.47	89.67	86.45	84.46	83.07	84.91	83.08	87.25	76.15	86.24	75.96	84.27	86.34	87.50
Wo	0.02	0.39	0.41	0.33	0.34	0.23	0.31	0.34	0.39	0.03	0.31	0.02	0.37	0.38	0.38

Augite

Oxide Weight Percent:	16	17	18	19	20	21	22	23	24	25	26	27	28
SiO ₂	51.19	51.79	50.86	50.10	50.55	51.77	51.74	50.91	52.81	52.18	52.29	51.52	51.57
TiO ₂	0.28	0.25	0.34	0.37	0.34	0.20	0.11	0.38	0.13	0.23	0.27	0.30	0.26
Al ₂ O ₃	3.10	3.58	4.26	5.34	4.43	2.87	2.06	4.25	2.13	2.92	3.53	4.67	3.08
Cr ₂ O ₃	0.68	0.42	0.42	0.25	0.32	0.74	0.46	0.43	0.55	0.59	0.06	0.07	0.45
FeO	5.08	5.32	5.68	6.28	5.46	5.25	5.84	5.56	5.76	5.05	6.63	6.64	5.55
MnO	0.12	0.16	0.15	0.14	0.16	0.17	0.34	0.16	0.17	0.17	0.17	0.15	0.13
NiO	0.07	0.11	0.07	0.07	0.05	0.06	0.08	0.08	0.07	0.03	0.10	0.10	0.08
MgO	18.59	19.21	18.00	16.89	17.00	19.64	20.24	17.58	21.65	19.00	20.09	18.48	19.11
CaO	19.79	19.06	19.45	20.99	21.60	18.43	18.58	20.27	15.78	20.00	17.29	18.41	19.35
Na ₂ O	0.10	0.13	0.14	0.15	0.12	0.15	0.11	0.12	0.15	0.12	0.08	0.10	0.13
K ₂ O	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
V ₂ O ₅	0.08	0.05	0.11	0.11	0.10	0.09	0.05	0.10	0.02	0.05	0.09	0.09	0.08
Total	99.07	100.06	99.47	100.68	100.13	99.38	99.61	99.85	99.23	100.35	100.61	100.52	99.79
Sample	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8

Normalized Oxy. Units	16	17	18	19	20	21	22	23	24	25	26	27	28
Si	1.89	1.89	1.87	1.83	1.86	1.90	1.90	1.87	1.92	1.90	1.89	1.87	1.89
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01
Al	0.13	0.15	0.18	0.23	0.19	0.12	0.09	0.18	0.09	0.13	0.15	0.20	0.13
Cr	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.00	0.00	0.01
Fe	0.16	0.16	0.17	0.19	0.17	0.16	0.18	0.17	0.18	0.15	0.20	0.20	0.17
Mn	0.00	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.00
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.02	1.04	0.99	0.92	0.93	1.07	1.11	0.96	1.18	1.03	1.08	1.00	1.04
Ca	0.78	0.74	0.77	0.82	0.85	0.72	0.73	0.80	0.62	0.78	0.67	0.72	0.76
Na	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	4.03	4.03	4.02	4.04	4.03	4.03	4.05	4.02	4.02	4.03	4.02	4.02	4.03
Mg#	86.71	86.55	84.96	82.74	84.73	86.96	86.07	84.93	87.01	87.02	84.38	83.22	85.99
Wo	0.40	0.38	0.40	0.42	0.44	0.37	0.36	0.41	0.31	0.40	0.34	0.37	0.38

Pigeonite

Oxide Weight Percent:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO ₂	54.95	54.15	54.79	53.84	52.23	55.37	51.73	54.87	54.38	55.31	55.24	53.82	54.31	54.02	53.95
TiO ₂	0.12	0.10	0.10	0.09	0.19	0.06	0.13	0.07	0.12	0.07	0.05	0.08	0.08	0.13	0.09
Al ₂ O ₃	1.52	1.40	1.19	1.27	3.26	1.51	2.52	1.21	2.06	1.29	1.22	1.69	1.27	2.03	1.59
Cr ₂ O ₃	0.50	0.83	0.28	0.62	0.03	0.23	0.39	0.46	0.17	0.26	0.70	0.60	0.86	0.25	1.33
FeO	6.46	7.27	8.33	7.32	9.00	3.44	6.74	7.76	8.21	7.25	5.30	7.85	7.27	7.45	7.20
MnO	0.22	0.22	0.21	0.21	0.20	0.12	0.23	0.23	0.21	0.18	0.14	0.21	0.20	0.18	0.19
NiO	0.09	0.10	0.14	0.08	0.11	0.11	0.13	0.15	0.14	0.12	0.08	0.08	0.08	0.08	0.13
MgO	29.65	27.91	28.24	28.56	28.35	26.18	31.70	30.74	29.10	30.32	28.35	28.27	31.05	26.62	27.78
CaO	6.24	7.04	6.29	7.30	6.13	12.67	6.30	3.64	5.38	4.90	9.66	6.80	4.06	8.13	7.23
Na ₂ O	0.00	0.05	0.07	0.05	0.05	0.16	0.07	0.04	0.07	0.03	0.06	0.02	0.00	0.06	0.06
K ₂ O	0.00	0.00	0.00	0.01	0.00	0.02	0.02	0.01	0.00	0.00	0.02	0.00	0.00	0.01	0.00
V ₂ O ₅	0.03	0.04	0.01	0.01	0.05	0.02	0.03	0.03	0.03	0.00	0.08	0.08	0.08	0.08	0.03
Total	99.79	99.10	99.64	99.36	99.60	99.88	99.99	99.22	99.87	99.72	100.91	99.52	99.27	99.06	99.59
Sample	HB 2-2	HB 2-2	HB 2-2	HB 2-2	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-8

Normalized Oxy. Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Si	1.94	1.94	1.95	1.93	1.87	1.96	1.84	1.95	1.93	1.95	1.94	1.92	1.93	1.94	1.93
Ti	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.06	0.06	0.05	0.05	0.14	0.06	0.11	0.05	0.09	0.05	0.05	0.07	0.05	0.09	0.07
Cr	0.01	0.02	0.01	0.02	0.00	0.01	0.01	0.01	0.00	0.01	0.02	0.02	0.02	0.01	0.04
Fe	0.19	0.22	0.25	0.22	0.27	0.10	0.20	0.23	0.24	0.21	0.16	0.23	0.22	0.22	0.22
Mn	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.56	1.49	1.50	1.52	1.52	1.38	1.68	1.63	1.54	1.59	1.48	1.51	1.64	1.42	1.48
Ca	0.24	0.27	0.24	0.28	0.24	0.48	0.24	0.14	0.20	0.19	0.36	0.26	0.15	0.31	0.28
Na	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	4.02	4.02	4.02	4.04	4.05	4.01	4.10	4.02	4.02	4.02	4.02	4.03	4.03	4.01	4.02
Mg#	89.11	87.25	85.80	87.43	84.88	93.13	89.34	87.60	86.34	88.17	90.51	86.52	88.39	86.43	87.31
Wo	0.12	0.14	0.12	0.14	0.12	0.24	0.11	0.07	0.10	0.09	0.18	0.13	0.08	0.16	0.14

Pigeonite

Oxide Weight Percent:	16	17	18	19	20	21	22	23	24	25	26	27
SiO ₂	54.05	54.34	54.62	54.23	51.82	55.08	54.93	54.94	54.74	55.61	55.30	55.07
TiO ₂	0.09	0.06	0.07	0.09	0.14	0.06	0.07	0.04	0.09	0.09	0.06	0.10
Al ₂ O ₃	1.86	1.86	1.68	1.95	2.13	1.20	1.44	1.20	1.69	1.02	1.41	1.48
Cr ₂ O ₃	1.99	2.08	1.73	1.97	1.09	0.65	0.76	0.60	0.30	0.21	0.43	0.28
FeO	7.08	7.18	7.59	6.84	6.40	7.71	7.63	7.32	7.77	7.74	7.68	7.84
MnO	0.19	0.25	0.21	0.20	0.14	0.26	0.21	0.22	0.21	0.16	0.20	0.16
NiO	0.09	0.05	0.07	0.07	0.06	0.12	0.11	0.11	0.17	0.14	0.11	0.13
MgO	28.71	29.48	29.27	29.18	27.71	30.52	30.54	30.56	30.17	30.87	30.47	29.74
CaO	5.62	4.86	4.73	5.03	10.65	4.00	4.95	4.02	4.26	3.77	3.96	4.35
Na ₂ O	0.05	0.07	0.00	0.07	0.06	0.04	0.06	0.05	0.00	0.04	0.00	0.05
K ₂ O	0.02	0.02	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00
V ₂ O ₅	0.03	0.00	0.02	0.02	0.04	0.02	0.02	0.00	0.04	0.03	0.04	0.01
Total	99.78	100.25	100.00	99.65	100.23	99.66	100.72	99.06	99.44	99.68	99.65	99.24
Sample	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8	HB 2-8

Normalized Oxy. Units	16	17	18	19	20	21	22	23	24	25	26	27
Si	1.92	1.92	1.93	1.92	1.86	1.95	1.93	1.95	1.94	1.96	1.95	1.95
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.08	0.08	0.07	0.08	0.09	0.05	0.06	0.05	0.07	0.04	0.06	0.06
Cr	0.06	0.06	0.05	0.06	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01
Fe	0.21	0.21	0.22	0.20	0.19	0.23	0.22	0.22	0.23	0.23	0.23	0.23
Mn	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.00
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.52	1.55	1.54	1.54	1.48	1.61	1.60	1.62	1.59	1.62	1.60	1.57
Ca	0.21	0.18	0.18	0.19	0.41	0.15	0.19	0.15	0.16	0.14	0.15	0.17
Na	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	4.01	4.02	4.01	4.01	4.08	4.02	4.03	4.02	4.02	4.01	4.01	4.01
Mg#	87.85	87.98	87.30	88.38	88.53	87.59	87.71	88.15	87.38	87.67	87.61	87.12
Wo	0.11	0.09	0.09	0.10	0.20	0.08	0.09	0.08	0.08	0.07	0.08	0.08

Pyroxene Mixtures

Oxide Weight Percent:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO ₂	53.69	53.40	52.12	52.94	53.03	53.71	52.97	53.41	53.32	53.57	53.61	53.46	53.96	53.35
TiO ₂	0.09	0.21	0.38	0.24	0.14	0.12	0.12	0.09	0.13	0.12	0.11	0.11	0.10	0.16
Al ₂ O ₃	1.07	2.61	3.98	2.57	1.74	1.72	1.73	1.42	1.74	1.81	1.05	1.06	1.10	1.70
Cr ₂ O ₃	0.76	0.39	0.17	0.04	0.56	0.70	0.55	0.67	1.13	0.14	0.70	0.63	0.69	0.05
FeO	15.20	5.70	6.56	7.99	6.46	5.87	6.06	7.15	6.43	6.61	14.63	15.04	15.17	7.41
MnO	0.48	0.15	0.19	0.20	0.18	0.22	0.14	0.19	0.20	0.17	0.54	0.46	0.56	0.19
NiO	0.00	0.09	0.08	0.16	0.11	0.08	0.10	0.12	0.12	0.16	0.00	0.03	0.01	0.09
MgO	27.50	23.14	22.88	24.61	22.66	23.57	22.14	25.55	23.05	24.75	27.28	27.46	27.42	23.44
CaO	1.25	14.93	13.58	10.80	14.73	14.20	15.42	10.59	12.91	11.93	1.26	1.36	1.26	14.09
Na ₂ O	0.04	0.05	0.06	0.08	0.10	0.12	0.12	0.05	0.13	0.00	0.00	0.02	0.01	0.04
K ₂ O	0.00	0.00	0.01	0.02	0.00	0.00	0.01	0.01	0.00	0.00	0.02	0.00	0.00	0.01
V ₂ O ₅	0.03	0.03	0.08	0.05	0.05	0.03	0.05	0.03	0.03	0.08	0.02	0.03	0.02	0.03
Total	100.12	100.69	100.08	99.68	99.76	100.33	99.42	99.27	99.19	99.35	99.21	99.67	100.31	100.57
Sample	HB 2-2	HB 2-2	HB 2-2	HB 2-2	HB 2-2	HB 2-2	HB 2-2	HB 2-2	HB 2-2	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-6

Normalized Oxy. Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Si	1.94	1.91	1.88	1.91	1.92	1.93	1.93	1.93	1.94	1.93	1.95	1.94	1.95	1.92
Ti	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.05	0.11	0.17	0.11	0.07	0.07	0.07	0.06	0.07	0.08	0.05	0.05	0.05	0.07
Cr	0.02	0.01	0.00	0.00	0.02	0.02	0.02	0.02	0.03	0.00	0.02	0.02	0.02	0.00
Fe	0.46	0.17	0.20	0.24	0.20	0.18	0.18	0.22	0.20	0.20	0.45	0.46	0.46	0.22
Mn	0.02	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.02	0.01	0.02	0.01
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.48	1.23	1.23	1.32	1.23	1.26	1.20	1.38	1.25	1.33	1.48	1.49	1.47	1.26
Ca	0.05	0.57	0.52	0.42	0.57	0.55	0.60	0.41	0.50	0.46	0.05	0.05	0.05	0.54
Na	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	4.02	4.02	4.03	4.03	4.03	4.03	4.03	4.03	4.01	4.02	4.01	4.02	4.02	4.04
Mg#	76.33	87.86	86.14	84.59	86.21	87.74	86.69	86.43	86.47	86.97	76.87	76.50	76.31	84.94
Wo	0.02	0.29	0.27	0.21	0.29	0.28	0.30	0.20	0.26	0.23	0.02	0.03	0.02	0.27

Pyroxene Mixtures

Oxide Weight Percent:	15	16	17	18	19	20
SiO ₂	54.22	54.16	54.44	53.52	53.12	53.88
TiO ₂	0.08	0.10	0.05	0.10	0.14	0.18
Al ₂ O ₃	1.23	1.06	0.98	1.03	1.86	2.17
Cr ₂ O ₃	0.28	0.67	0.77	0.75	0.31	0.08
FeO	9.00	15.15	14.74	15.09	5.73	7.35
MnO	0.25	0.51	0.48	0.48	0.18	0.18
NiO	0.11	0.02	0.00	0.00	0.10	0.08
MgO	27.30	27.84	28.02	27.13	22.26	25.79
CaO	6.94	1.27	1.35	1.25	15.70	9.79
Na ₂ O	0.05	0.00	0.00	0.02	0.14	0.04
K ₂ O	0.01	0.00	0.00	0.00	0.00	0.00
V ₂ O ₅	0.05	0.03	0.00	0.02	0.05	0.03
Total	99.52	100.82	100.84	99.39	99.59	99.57
Sample	HB 2-6	HB 2-6	HB 2-6	HB 2-6	HB 2-8	HB 2-8

Normalized Oxy. Units	15	16	17	18	19	20
Si	1.95	1.94	1.95	1.95	1.93	1.93
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.05	0.04	0.04	0.04	0.08	0.09
Cr	0.01	0.02	0.02	0.02	0.01	0.00
Fe	0.27	0.45	0.44	0.46	0.17	0.22
Mn	0.01	0.02	0.01	0.01	0.01	0.01
Ni	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.46	1.49	1.50	1.47	1.20	1.38
Ca	0.27	0.05	0.05	0.05	0.61	0.38
Na	0.00	0.00	0.00	0.00	0.01	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00	0.00	0.00
Total	4.02	4.02	4.02	4.02	4.03	4.02
Mg#	84.39	76.61	77.21	76.22	87.38	86.22
Wo	0.13	0.02	0.03	0.02	0.31	0.19

Vita

Matthew Stephen Huber is the son of Dr. Stephen John Huber and Carol Ann Huber. He attended high school at the Mississippi School for Mathematics and Science. In 2007, he received a Bachelor of Science degree in geoscience from the University of Tennessee at Martin.

In August 2007, he began studies for a Master of Science in geology at Louisiana State University studying under Dr. Gary Byerly. During the time he was studying in Louisiana, he was able to complete a field season in South Africa, an internship in Bakersfield California with Chevron, and a 117-mile journey from Baton Rouge to New Orleans on a unicycle. After completion of his master's degree, he will begin studying planetology as part of the doctoral program at the University of Vienna.