

**MINERAL CHEMISTRY OF MERENSKY REEF CHROMITITE
LAYERS IN THE MARIKANA DISTRICT**

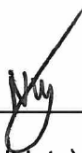
Nicole Tracy Wansbury

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University of the Witwatersrand,
Johannesburg,
in fulfillment of the requirement
for the degree of Master of Science

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DECLARATION

I, NICOLE TRACY WANSBURY declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.



(Signature of candidate)

31 day of October 2016 in Mari Karu

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ABSTRACT

An important feature of the Merensky Cyclic Unit in the Bushveld Complex is the association of platinum group metals with narrow chromitite layers. The appearance and removal of chromitite layers in this unit has been used to define facies types. This study explores the hypothesis that individual chromitite layers within the Merensky Cyclic Unit at Marikana have distinguishing major element concentrations or ratios which could assist in tracing the continuity of the chromitite layers between facies types which is characterized by single or multiple layers. The examination of field relationships of the chromitite layers at the transition between facies types will be useful to improve understanding of lithological continuity. This study has two approaches; the first being the examination of underground exposures and petrographic analysis, and secondly by chemical analysis of chromite grains within the chromitite layers.

No chromite mineral compositional trends or similarities were observed for grains in chromitite layers hosted by the same silicate mineral. The mineral chemistry evidence suggests that post cumulus processes are considered to have changed the primary chromite compositions and that reequilibration has occurred due to reaction with trapped intercumulus liquid. Little to no reaction with the host silicates of plagioclase and pyroxene is envisaged. The slow cooling of the Bushveld Complex has allowed intercumulus liquid a greater opportunity to equilibrate with the early minerals, destroying the early magmatic history by reaction and recrystallization. The cumulate deposition model envisaged to have formed the Merensky Cyclic unit at Marikana is by the emplacement of several pulses of superheated magma, supported by the occurrence of several chromitite layers within the sequence.

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CHAPTER ONE - INTRODUCTION

1.1 Introduction

The Lonmin Marikana mining district is located on the western limb of the Bushveld Complex in the North West Province of South Africa, near the town of Brits. Viljoen (1999) investigated the Merensky Reef across the western Bushveld Complex and broadly defined the Merensky Reef as “a mineralized zone within or closely associated with, an unconformity surface within the ultramafic cumulate at the base of the Merensky Cyclic Unit.” The Merensky Cyclic Unit is referred to by Cawthorn and Boerst (2006) as a sequence comprising a lower chromitite horizon, a feldspathic pyroxenite that may have a lower pegmatitic portion containing a thin layer of chromitite, a thin layer of norite, which is followed by a layer of anorthosite. They further define the Merensky Pyroxenite as the unit above the basal chromitite and may include further internal chromitite stringers. The Merensky Reef contains potentially exploitable PGE mineralization in a layer of rocks, whatever its lithology (Cawthorn and Boerst, 2006).

In the Marikana mining district, alternating pyroxenite and chromitite layers in the Merensky Cyclic Unit over a strike length of approximately 26 kilometres is a key characteristic of this PGE economic horizon. Here, the Merensky Cyclic Unit can be considered the central transitional zone where the lithological assemblage changes from a narrow one metre thick pegmatoidal pyroxenite assemblage to the west of the Lonmin Marikana mining right, and then thickens to a 12-metre thick pyroxenite assemblage in the far east.

The presence or absence of chromitite layers is the main distinguishing characteristic of the lithological assemblages for the Merensky Reef and thus have been used to define the facies type. The occurrence of one, two or three chromitite layers define five lithological assemblages, referred to as facies types. Facies has been defined here as “a body of rock with specified characteristics.” “Ideally, a facies is a distinctive rock unit that forms under certain conditions, reflecting a particular process or environment” (Reading, 1996). Associated with these facies is a variable vertical and lateral distribution of the PGEs within the Merensky Pyroxenite.

The transition from one facies type to another requires understanding and a large part of the uncertainty involves the continuity of the chromitite layers and whether they can be correlated between facies or whether they merge or are discontinuous as the facies types change.

At the mining operations, these facies types have been identified in early 2000 which assisted the implementation of an improved extraction. In 2008, the development of mineral resource estimation models resulted in the delineation of the facies into spatial domains and improved understanding of continuity of the mineralisation.

This study aims to improve the understanding of the continuity of the facies domains and will describe the facies and their transitions by examining underground exposures and subsequent analysis of the chromitite layers mineral chemistry in both vertical and lateral geological profiles.

1.1.1 Significance of chromitite layers within the Merensky Cyclic Unit

Chromitite layers of the Bushveld Complex have been studied in detail since 1865 when the occurrence of chromite in South Africa was first noted by Mauch (Silk, 1988). Chromitite layers are hosted by both mafic and ultramafic cumulates Lithologies and are generally restricted to the Critical Zone (Scoon & Teigler, 1994). Chromitite layers are considered to form at the base of crystallization cycles within the Critical Zone but are occasionally found within intermediate parts of some Upper Critical Zone cycles (Scoon and Teigler, 1994). Eales (2000) notes that one of the most difficult problems in the understanding of the Bushveld Complex is the development and location of the chromitite layers in the Critical Zone. He explains that many authors have approached the problem from different angles and that ultimately physiochemical reactions are used to explain the crystallization of chromite. A summary of the models of formation are given in Section 1.2.

Eales and Reynolds (1986) note that generally the chromite grains within the Merensky Cyclic Unit occur as disseminations within narrow layers rather than massive layers; and that poikilitic pyroxene or plagioclase feldspar grains separate the individual chromite grains. Cawthorn and Boerst (2006) note that chromite is scarce in the Merensky Cyclic Unit, and is generally restricted to within a few millimetres of the chromitite layers.

Eales and Reynolds (1986) comment that the studies of chromite composition and chromite textures are important in understanding the close association of platinum group elements with chromite in the Upper Critical Zone. Cawthorn (1999) notes that a definite relationship exists between chromite and PGE due to that fact that all chromitite layers contain high PGE concentrations. Vukmanovic et al. (2013) comment that the chromitite

layers are extensive within the Merensky Reef and that understanding these layers is key to understanding the PGE concentrations and the petrogenesis of the Merensky Reef as a whole. Cawthorn (2011) notes that historically in the Merensky Reef, geological interpretations have suggested that the mineralization occurs in a pegmatoidal pyroxenite bounded by two chromitite layers but comments that there are enough published exceptions to show that this is not always the case. He explains that the separation between the two chromitite layers or the absence of one chromitite layer is important in predicting the vertical distribution of the PGEs. He notes that where the layer separation is small or if only one chromitite layer is present, that the mineralization is concentrated in the footwall below the pyroxenite and the lower chromitite layer. As the separation between the chromitite layers increases, he notes that the mineralization will occur higher in the succession where the upper chromitite layer is present. He concludes that each chromitite layer is associated with some mineralization. Viljoen (1999) noted that the upper and lower limits of the main economic mineralization are frequently defined by two to four thin chromitite layers.

1.2 Models for the formation of chromitite layers

This study focuses on the chromitite layers, the origin and evolution of which remain highly debated. The most common proposed models for the formation of chromitite layers, as summarized by Hutchinson et al. (2015) and Mondal & Mathez (2007), include eight mechanisms put forward by various researchers: 1) magmatic differentiation proposed by Wager & Brown (1968) ; 2) changes in oxygen fugacity of the magma proposed by Cameron & Desborough (1969) and Ulmer (1969); 3) an increase in silica proposed by Irvine (1975) and Kinnaid et al. (2002) ; 4) mixing of primitive and evolved magma proposed by Irvine (1977), Barnes (1986) and Murck & Campbell (1986) ; 5)

increasing pressure proposed by Cameron, (1977) and Lipin (1993); 6) the breakdown of pyroxene in the presence of volatile-rich fluids proposed by Nicholson & Mathez (1991) and Mathez (1995) and 7) injection of a chromite slurry from a staging chamber as proposed by Eales (2000), or a conduit as proposed by Maier & Barnes (2008) and Voordouw et al. (2009). Recent publications by Latypov et al. (2013) and Vukmanovic (2013) proposed that chromites crystallized in situ from magma within the chamber.

The most widely accepted model for formation of chromitites is the magma mixing model proposed by Irvine (1977). He proposed the mixing of a chemically primitive magma with a more evolved magma within the magma chamber. He illustrates this process with the use of the Cr-saturation diagram from Barnes (1986) and Murck and Campbell (1986) shown in Figure 1.2.1. Primitive magma of composition P would change to a magma of composition D by cooling and differentiation. He visualized the addition of a new primitive liquid of composition P which would cause mixing with the existing differentiated resident magma of composition D. As the new and old liquids mix, they evolve into composition M1 which was oversaturated in chromite, thus forming a chromitite layer until the composition fell to that of M2. If the volume of the original liquid exceeded that of the newly injected liquid, the possibility exists that an alternating sequence of pyroxenite and chromitite layers may develop. He comments that the repetition of cyclic units appears to be due to the repeated introduction of primitive magma.

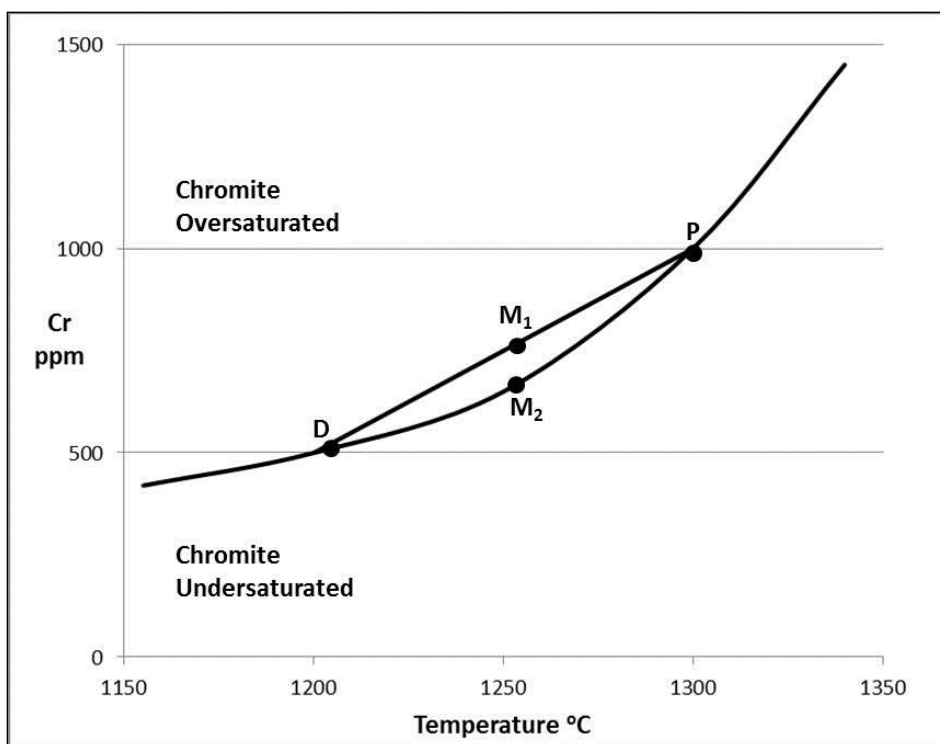


Figure 1.2.1: Relationship of Cr solubility in magma as a function of temperature.
(from Murck and Campbell, 1986)

Many authors (Eales & Cawthorn, 1996; Cawthorn & Walraven, 1998; Eales, 2000) recognized that a fundamental problem with this magma mixing model is that the amount of chromite contained in the chromite and silicate phases cannot be accounted for by the volume of magma from which they were derived. Cawthorn (2011) comments that at the composition of M₁, only 100 ppm Cr would have been extracted. In order to form the consistently thick chromitite layers, efficient mixing of 4 to 5km of magma would be required (Campbell & Murck, 1993). Although the volume of magma required to produce the Merensky Reef chromitites, which are only millimetres thick, would be different to the massive UG2 chromitite which is one metre or more in thickness, there would still need to be a sufficient volume to produce chromites with average values of Cr₂O₃ of 0.40%.

Nearly all chromitite layers in the Bushveld have a sharp basal contact, implying an abrupt process. In both cases, the question raised is why these processes would be so abrupt, particularly over such a large area. Cawthorn (2011) considers it unlikely that instantaneous and efficient mixing took place on such a lateral and vertical scale.

Irvine (1975) proposed that chromitite layers formed by contamination by silica from the roof rocks, but later rejected this due to the large amount of contamination required to induce the crystallization change. Kinnaird et al. (2002) propose a variation to the magma mixing model which incorporates the processes of magma mixing and crustal contamination based on Sr isotope ratios. The increase in this ratio for every chromitite layer show that the magma from which the chromite formed differed from the resident magma, and they conclude that chromite was produced by crustal contamination of the magma. It is envisaged that new magma erupted along weaknesses in the crust into the chamber and that both melted roof fragments and entrained material were the source of this contamination. This contamination induced chromite saturation and chromites sank to the chamber floor, creating layers. However it was argued by Seabrook et al. (2005) that the variations in Sr isotope ratios do not result from the mixing of magmas and that the processes are more complicated. They explain that the variation is rather from accumulation of orthopyroxene and plagioclase from a higher, isotopically distinct layer of magma into the underlying layer.

Cameron & Desborough (1969) and Ulmer (1969) proposed that mixing magmas with either different oxygen fugacity (fO_2) values or at different temperatures can theoretically produce magmas oversaturated in chromite. However Mondal & Murck (2007) state that there are no indications of any significant changes in fO_2 or temperature during formation

of any of the Bushveld pyroxenites that host chromitites and that the amounts of chromite formed by these processes to be small.

The model by Lipin (1993), as originally speculated by Cameron (1977), proposes that an instantaneous pressure change invoked on the entire magma chamber formed the Bushveld chromitites. Mondal & Murck (2007) comment that this model is attractive as it offers a way to produce chromitite layers for vast lateral distances, as pressure changes are propagated rapidly. Hutchinson et al. (2015) comment that a study by Roeder & Reynolds (1991) has shown experimentally that Cr solubility in a mafic melt may increase rather than decrease with an increase in pressure. They also note that a limitation with this model is that the roof of the complex was thought to be floating on the mafic melt (Kinnaird et al. 2002; Kruger 2005; Cawthorn 2013) which would not allow for closed-system changes. Hutchinson et al. (2015) note an important point, that pressure models cannot explain the variation in the numbers, thickness and relative positions of the Merensky Reef chromitites.

Eales (2000) proposed a model for the injection of liquids evolved in a deeper magma chamber that were hotter, more magnesian and richer in Cr than liquids within the Bushveld chamber. Injection of these partially crystallized liquids into the resident magmas already present in the Bushveld chamber would raise their average levels of chromium. This would result in deposition of cumulates from the Cr-enriched liquids. Cawthorn (2011) comments that the problem with this model is the lateral distribution of this injection of chromite-rich liquid within the Bushveld chamber. He comments that this slurry of chromite would be dumped close to the site of entry and show thinning away from this site. The layers of chromitite in the Bushveld are uniform in thickness and don't show this thinning effect.

Nicholson & Mathez (1991) propose that the chromitite layers of the Merensky Reef formed by isothermal melting of an initially melt-rich horizon due to hydration. They explain that volatiles are introduced through fractures in the footwall. Ford et al. (1972) and more recent experiments show that the addition of water to a silicate melt suppresses the crystallization temperatures of all pyroxene and plagioclase minerals and that chromite stability is enhanced. They conclude that the sequence of mineral stabilities through the hydration front account for the typical lithological sequence of the Merensky Reef and the variations in chromite compositions. Mondal & Mathez (2007) rejected this model as based on the Cr contents of ortho and clinopyroxene, that a large mass of these minerals would be required; approximately 67cm would be required to form a 9mm thick chromitite layer. They comment that it is also difficult to imagine the addition of a large mass of water to a large mass of partially molten rock. Hutchinson et al. (2015) comment that hydromagmatic models cannot account for the presence of texturally, mineralogically and geochemically different chromitites.

Latypov et al. (2013, 2015) argue that on cooling to the liquidus temperature of a hybrid magma, in situ crystallization of chromite took place at the magma-cumulate interface. The evidence they present for this conclusion is the development of chromitite seams on the sub vertical to overhanging walls of potholes. Vukmanovic et al. (2013) similarly describe the origin of chromites to be the modification of primary chromite morphologies, formed by rapid initial crystallization in a layer between hot magma and a cooler eroded crystal pile beneath, and followed by textural maturation. Hutchinson et al. (2015) argue that in situ crystallization of chromite would be expected to produce near-constant layer thicknesses. Hutchinson et al. (2015) note instead that Naldrett et al. (2009) show that the thickness of the chromite is controlled by undulations in the footwall contact and that chromite carried as a bottom load became concentrated in these hydraulic traps.

1.3 Previous studies of Merensky Reef chromitite layers

Comparative studies with published mineral chemistry data were compared and referenced in order to see whether differences or similarities were obvious or presented themselves. Data from seven other studies were obtained, one of which was unpublished data from Cawthorn, sampled at the Impala Platinum mine. Each study's main objective is detailed below. A locality plan showing approximate location of samples within the Western Bushveld Complex is shown in Figure 1.3.1.

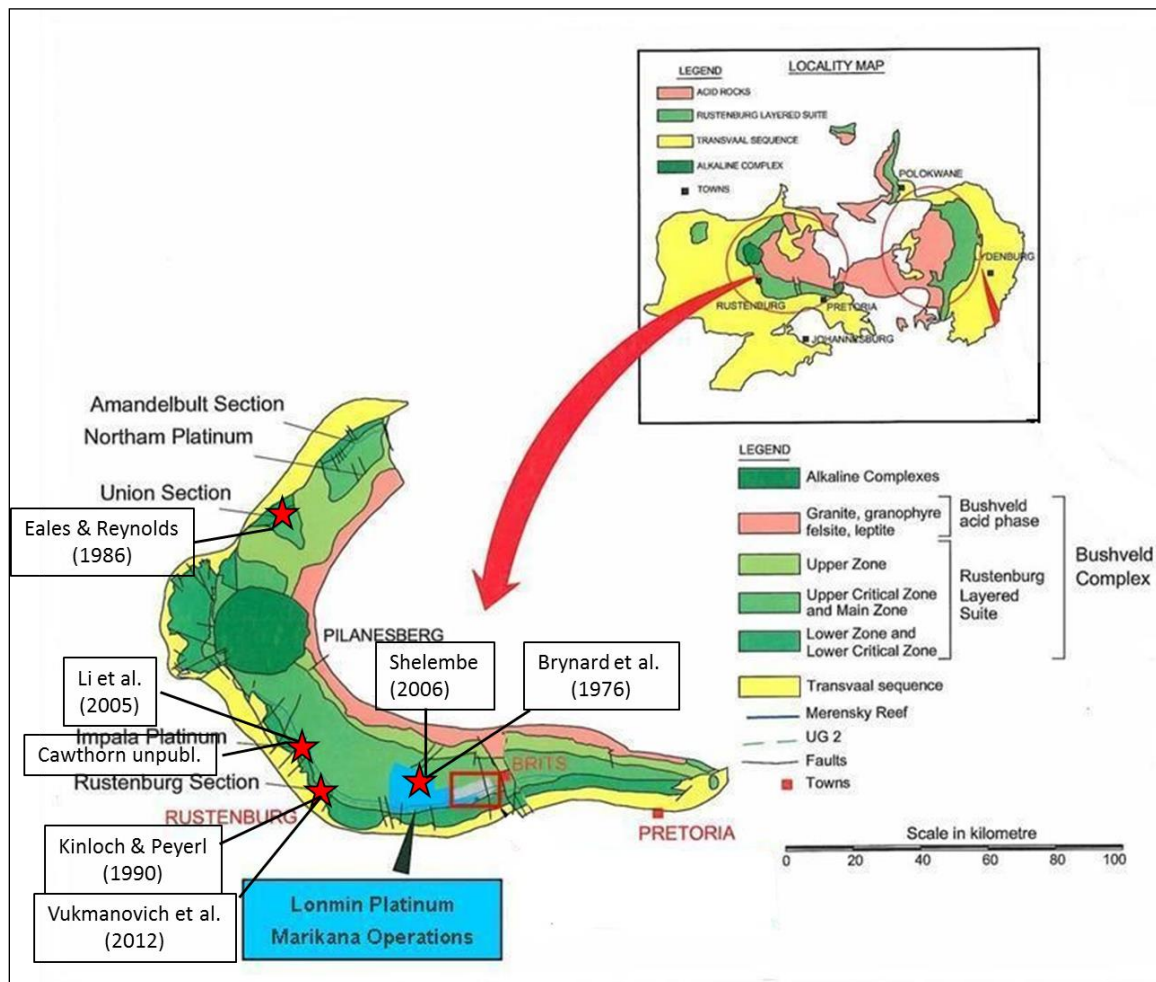


Figure 1.3.1 Locality map of the western Bushveld Complex showing the approximate locations of seven other studies of Merensky Reef chromitite layers along a strike length of approximately 90km.

The first comparative study by Brynard et al. (1976) performed a mineralogical investigation of the Merensky Reef at Western Platinum mine. Part of their analysis was electron microprobe analysis of the upper and lower chromitite bands of the Merensky Reef. From this analysis they note that there is little difference in composition between different chromite grains as well those hosted in different silicates. They also noted that the chromite from the upper chromitite layer is more Fe-rich than that of the lower chromitite layer.

The second study by Eales and Reynolds (1986) studied the structures, textures and composition of chromitites in order to understand the close association and behavior of platinum group elements within chromitite layers in the Upper Critical Zone of the Bushveld Complex. They undertook this in order to potentially develop genetic models of platinum group element crystallization. They found that although chromite and platinum-group elements are closely associated in both the UG2 and Merensky reefs, that the thickness, texture and composition of their chromitites are different.

The third study by Kinloch and Peyerl (1990) studied data from three underground mining sections of the Rustenburg Platinum Mines in the Western Bushveld Complex, namely the Rustenburg, Union and Amandelbult sections and one underground mining section in the Eastern Bushveld Complex, the Atok mine. They studied both disturbed reef conditions as well as what would be considered to be "normal" Merensky Reef. However, only data from the normal intersections were used to draw comparisons. They attribute the formation of the lower chromitite layer in their study to mixing of a new influx of magma with the fluid-rich magma of the critical zone. Their data show that the chromite was of the early, Cr > Fe, high Mg and Al type. They comment that the magma, from which the upper chromitite layer formed, underwent removal of Mg and Al due to

the crystallization of the Merensky Reef pegmatoid, as this upper chromitite developed at the contacts of the pegmatoid and the hangingwall pyroxenite. They note that the chromite is often fine grained and sporadically developed and is characterized by Fe > Cr, high Ti, and low Mg and Al.

The fourth study by Li et al. (2005) focused on the morphology, mineralogy and chemical and stable isotopic compositions of silicate inclusions present in the basal chromitite seam of the Merensky Reef at Impala Platinum Mine on the farm Vlakfontein. From this dataset, only the analyses on chromites were used for comparison. Li et al. (2005) investigated differences between inclusion-bearing chromites and inclusion-free chromites. They found that there was little chemical variation between inclusion-free chromites and inclusion-free zones of inclusion-bearing chromites and those inclusion-free chromites are not chemically zoned like the inclusion-bearing chromites. They attribute these chemical variations to the presence of inclusions, indicating that post-entrapment chemical exchange between the inclusions and host chromites took place.

The fifth study by Shelembe (2006) investigated the chromite mineral chemistry in order to show correlation of chromitite layers in one reef type to another at Lonplats' Mines. This was used to try and explain the variation of the thicknesses of the different reef types. Shelembe found that some of the chromitite layers were correlateable by both stratigraphic position and by their mineral chemistry. She found that the layers that were not correlateable may have experienced erosion by hot magmatic fluids or may have been originally discontinuous.

The final comparative study by Vukmanovic et al. (2013) performed a detailed comparative study on two chromitite layers from the Rustenburg Platinum mine. The aim

of the study was to expand the knowledge of chromite textures, crystallographic orientation, grain morphology, composition and intra-grain microstructures. The focus was to provide a reason why two compositionally similar layers, twenty centimetres apart, within a thick body could be so texturally different. Overall the upper and lower chromitite layers have contrasting ranges of major element compositions, in particular the Cr# and Mg# and TiO_2 and Fe_2O_3 concentrations. The chromites in the lower chromitite layer display relatively homogenous compositions and their data also show little detectable chemical zonation from cores to rims. This they show for both the lower and upper chromitite layers.

1.4 Objectives of the study

The objective of this study is to characterize each Merensky Reef facies through lithological, mineral assemblages and mineral chemical analyses. The study area also coincides with a regional transition in facies types and thus examination of field relationships between facies will be made to improve geological understanding of lithological continuity. This study will have two approaches; the first will be the examination of the underground relations and geological description which will be followed by chemical analysis of chromite in key lithological units.

A study of the mineral assemblages of the chromitite layers within each facies and mineral chemistry of the chromitite layers will be conducted. The mineral chemistry of the chromitite layers will be analysed to test if the individual layers have unique or distinguishing major element concentrations or ratios which could be used to distinguish each layer, and thus assist in correlation of the chromitite layers between facies. If the

chromitite layers show distinct chemistries, then this will be a useful tool for differentiating chromitite layers and possibly making correlations between facies.

CHAPTER TWO – GEOLOGICAL SETTING

2.1 Regional and Local Geology

The Bushveld Complex largely consists of two main phases of igneous rocks; a layered sequence of mostly basic igneous rocks known as the Rustenburg Layered Suite (RLS) and an overlying acidic phase of granitic rocks known as the Lebowa Granite Suite (LGS). The nomenclature used in this study is that used internationally and the updated naming conventions presented by the South African Committee for Stratigraphy (SACS) have not been used here. The RLS was derived from differential crystallization of multiple magma injections and contains four major stratigraphic zones. It comprises an ultramafic-rich Lower Zone, a mafic-rich Critical Zone, which hosts multiple chromitite layers, a mafic-rich Main Zone consisting mostly of gabbro-norites and norites, and the Upper Zone with iron-rich mineral assemblages. In the upper part of the Critical Zone, pyroxenite, norite, anorthosite and chromitite lithologies are found. The economic Platinum Group Element (PGE) mineralization occurs within two layers in the upper part of the Critical Zone known as the Upper Group 2 Reef (UG2) and the Merensky Reef.

The Merensky Cyclic Unit outcrops along the 26 kilometer strike length of the Marikana lease area and dips north at between 9° and 14°. The regional strike across the Marikana lease area is predominantly east-west with some local changes in strike observed, most noticeably to the west associated with the Spruitfontein monocline and coincident Iron Rich Ultramafic Pegmatite bodies (IRUP); and to the east within the Middlekraal depression area. The Merensky Cyclic Unit is locally disrupted by faults, dykes, potholes and other smaller IRUP bodies.

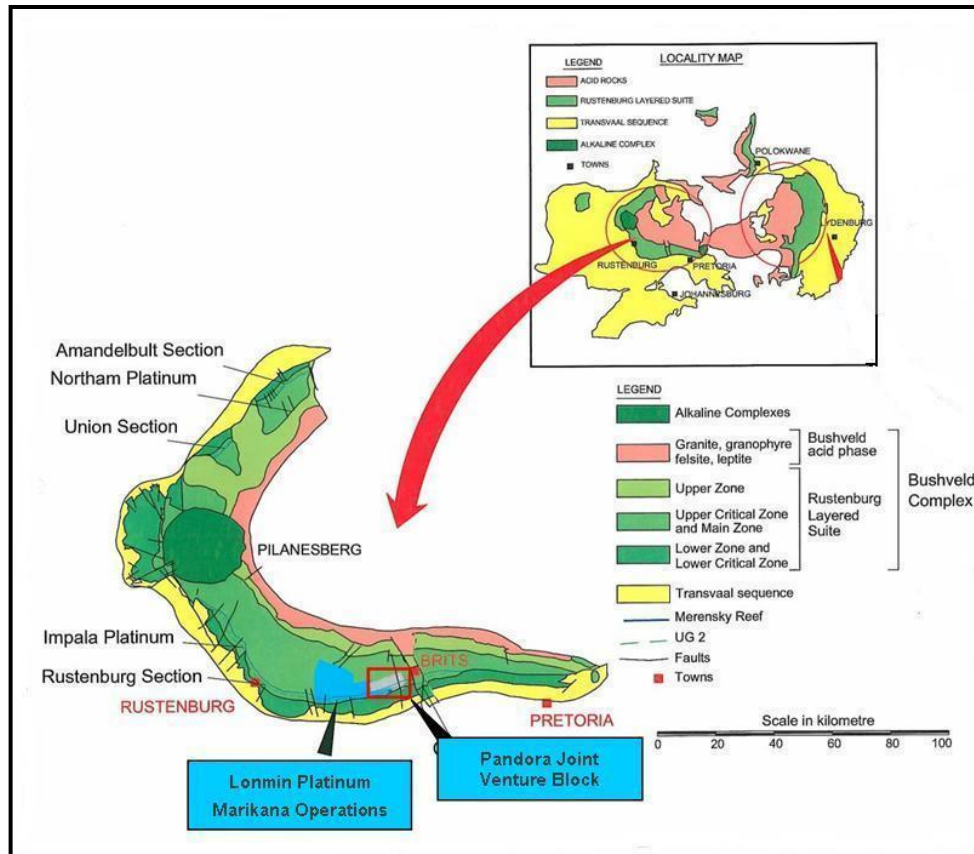


Figure 2.1.1 Geological map of the western Bushveld Complex showing the Marikana Operations relative to the major stratigraphic units and other mine locations.

2.2 The Merensky Reef

The Merensky Reef in the western Bushveld is well known to be variable in its assemblage of rock types and distribution of PGE mineralization. Wagner (1929) first recognised the regional variations in the geological characteristics of the Merensky Reef and divided the rocks of the western limb into a Swartklip Facies to the north and the Rustenburg Facies to the south of the Pilanesberg. This distinction was based on the narrower stratigraphic thicknesses between the UG2 and Merensky Reef and the presence of olivine-bearing layers in the Swartklip Facies. Viljoen (1994) furthered this

work and recognized four reef subfacies in the Rustenburg Facies and two in the Swartklip Facies based on (i) the thickness variations of the pyroxenite unit of the Merensky Reef, (ii) assemblages of layers and (iii) pothole structures. These four subfacies identified in the Rustenburg facies are referred to as rolling reef, potholed thin reef, chromitite contact reef and non-pegmatoidal wide reef (Viljoen 1994). According to Viljoen (1994), the distribution of the non-pegmatoidal wide reef subfacies coincides with the eastern extent of the Spruitfontein inlier which occurs at the western boundary of the Marikana mining district. Davey (1992) assumed that the inlier formed two separate chambers to the east and west and that similar but not identical magmatic process occurred, with some overflow and interaction between the two. Clarke et al. (2000) note that the Spruitfontein inlier had an effect on the lateral continuity and distribution of the RLS and that the major effects are thought to have occurred on the earlier evolution of the RLS until at least the late upper Critical Zone. They attribute the rapid intrusion of the RLS to the compartmentalization of the chamber.

Viljoen (1999) notes that regionally, the Merensky Reef does not represent a consistent well defined layer due to its dramatic variations in character. These regional variations in the Merensky Reef “are of fundamental importance in the understanding of the nature and origin of this enigmatic layer” (Viljoen 1999).

2.3 The Merensky Reef at Marikana

The Merensky Reef at Marikana is defined as that part of the Merensky Cyclic Unit which is economically exploitable. The reef is a mineralized zone within a variable thickness pyroxenite-rich stratigraphic unit. Peak mineralization values are associated

with the chromitite layers which are found as described below at various locations throughout the Merensky Reef.

Lateral variations in pyroxenite lithology thickness and distribution of PGE mineralization in the Merensky Reef occurs along strike of the lease area (Figure 2.3.2). The Merensky Pyroxenite at Marikana thickens from less than 0.9 metres in the west at Karee Mine in the Brakspruit facies to greater than 12 metres in the extreme east of the Marikana mining right. The lower contact of the pyroxenite with the underlying footwall anorthosite is sharp and is separated by a narrow chromitite layer. A pegmatoidal pyroxenite is sometimes developed above the bottom contact chromitite layer. This chromitite layer is known locally as the Basal Chromitite Layer. Additionally, a thin chromitite layer occurs along the pyroxenite/pegmatoidal pyroxenite contact, locally known as the Lower Chromitite Layer. Where the thickness of the pyroxenite increases, an additional chromitite layer (1-5 mm thick), known locally as the Upper Chromitite Layer, occurs below the upper contact of the pyroxenite with the hangingwall spotted anorthosite. Sulphides are commonly observed within the pyroxenite and in particular in the pegmatoidal pyroxenite. The upper contact of the pyroxenite is mostly gradational into the overlying spotted anorthosite and norite.

The local operational terms Basal, Lower and Upper prefixes for the different chromitites is confusing and thus a revised identification and nomenclature of the studied chromitite layers were applied:

- a) The Basal Chromitite Layer will be known as Type 1. This refers to the layer where the upper contact is a pegmatoidal pyroxenite and the lower contact is the footwall anorthosite (Figure 2.3.1).

- b) The Lower Chromitite Layer will be known as Type 2. There are two stratigraphic assemblages possible here, the first one having an upper contact of pyroxenite and the lower contact being the footwall anorthosite (Figure 2.3.1). This will be known as Type 2a. The second assemblage has an upper contact of pyroxenite and the lower contact of pegmatoidal pyroxenite (Figure 2.3.1). This will be known as Type 2b. It is important to separate Type 2 into an a and b due to 2a having an interstitial phase of plagioclase and 2b of pyroxene. Only once data has been presented separately, can possible correlations be made using the data presented.
- c) The Upper Chromitite Layer will be known as Type 3. This refers to the layer where both the upper and lower contact lithologies are pyroxenite (Figure 2.3.1).

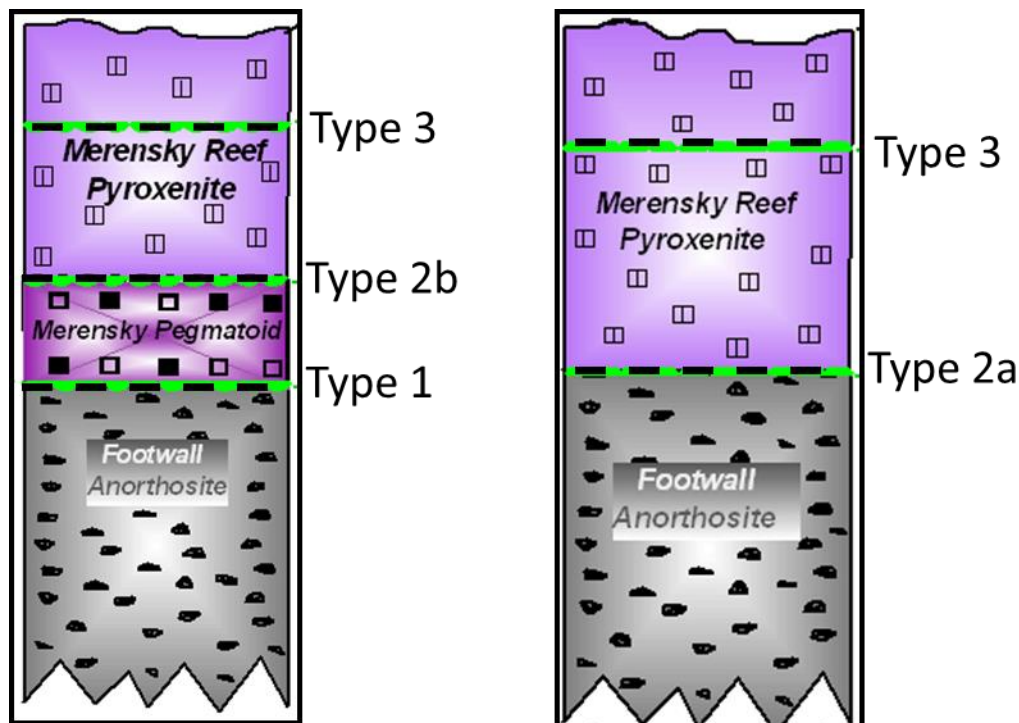


Figure 2.3.1 Image showing the location of the chromitite layer types in relation to the lithologies of the Merensky Cyclic Unit (Lonmin Platinum internal diagram).

Five Merensky Reef facies occur at the Marikana Operations as determined by a combination of variations in lithology, the thickness of the pyroxenite, the occurrence of chromitite layers and distribution of PGE mineralization within them. The five facies types are (i) the Marikana/Westplats Facies, (ii) the Eastplats Facies, (iii) the Thin Facies, (iv) the Rustenburg Platinum Mine (RPM) Facies and (v) the Brakspruit Facies (Figure 2.3.2).

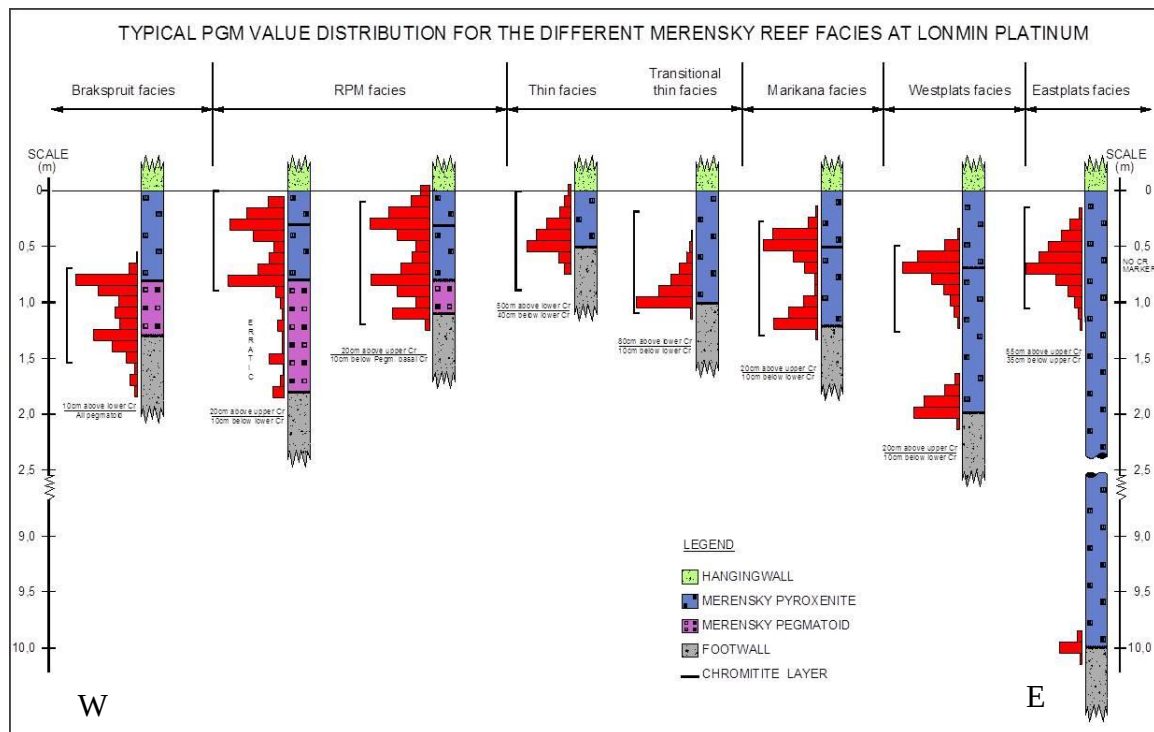


Figure 2.3.2 Lateral variations in thickness and distribution of PGE mineralization at Marikana Operations in the Merensky Pyroxenite Unit (Lonmin Platinum internal diagram).

A description of the five different facies types is given below: (Figure 2.3.2)

Brakspruit Facies: The Merensky Pyroxenite of the Brakspruit facies varies in thickness from 0.3m to 1m. This facies contains two chromitite layers, the Type 1, at the base of the pegmatoidal pyroxenite and the Type 2b, at the interface between the

pegmatoidal pyroxenite and the pyroxenite. The upper Type 3 chromitite layer is absent. Sulphide and PGE mineralization are concentrated mostly around the two chromitite layers on the upper and lower contacts of the pegmatoidal pyroxenite and can extend further into the footwall anorthosite.

R.P.M. Facies: The Merensky Pyroxenite varies in thickness from 0.3m to 2m in the R.P.M facies. Three chromitite layers are present in this facies, Type 1 at the base of the pegmatoidal pyroxenite, Type 2b at the interface between the pegmatoidal pyroxenite and the pyroxenite and a Type 3 within the Merensky Pyroxenite, 0.2m to 0.8m below the upper contact. Sulphide and PGE mineralization are concentrated mostly around the two chromitite layers on the upper and lower contacts of the pegmatoidal pyroxenite, with some mineralisation around the Type 3 layer and may extend into the footwall anorthosite.

Thin Facies: The Merensky Pyroxenite of the Thin Facies is generally less than one metre in thickness. The only chromitite layer, Type 2a, is present at the base of the pyroxenite. The pegmatoidal pyroxenite and the Type 3 chromitite layer are absent. Sulphide and PGE mineralization is concentrated around the lower contact and chromitite layer, but can extend into the underlying footwall anorthosite.

Marikana/Westplats Facies: The Merensky Pyroxenite of the Marikana/Westplats Facies has two chromitite layers, Type 3, 0.2m to 1m below the upper contact and Type 2a at the base of the pyroxenite. The chromitite layer separation is variable and can reach up to 8m in thickness at the eastern boundary with the Eastplats facies. The pegmatoidal pyroxenite is not present in this facies. Sulphide and PGE mineralization are concentrated predominantly near the Type 3 chromitite and less at the Type 2a

chromitite (Figure 2.3.2). The pyroxenite is largely barren between these two mineralisation layers.

Eastplats Facies: The Merensky Pyroxenite of the Eastplats Facies can exceed over 12m in thickness. Only a single chromitite layer, Type 2a, is present at the lower contact of the pyroxenite. No Type 3 chromitite or pegmatoidal pyroxenite are present. Sulphide and PGE mineralization are concentrated in the upper one to two metres of the pyroxenite, with an additional peak in mineralization at the chromitite layer. These two value zones are separated by largely barren pyroxenite.

Whereas these facies are readily recognized, the variability and transition from one facies type to another is not yet fully understood and a large part of the uncertainty is around the chromitite layers. The first facies plan was developed at the Marikana Operations in 2008 and involved a manual process of assigning a facies type to each surface borehole drilled on the property. This was done by investigation into the number of chromitite layers present in each borehole and any variation in lithology. Once all boreholes were assigned a facies type, broad facies domains were drawn where the same facies occurred. Boundaries between facies domains were drawn at the halfway mark between two boreholes of differing facies type. As further surface drilling took place at Marikana, the facies plan was updated accordingly. In 2012, the Lonmin Mineral personnel developed a system using underground channel sample data to further refine the facies domain boundaries and thus understanding whether these were gradational or sharp boundaries.

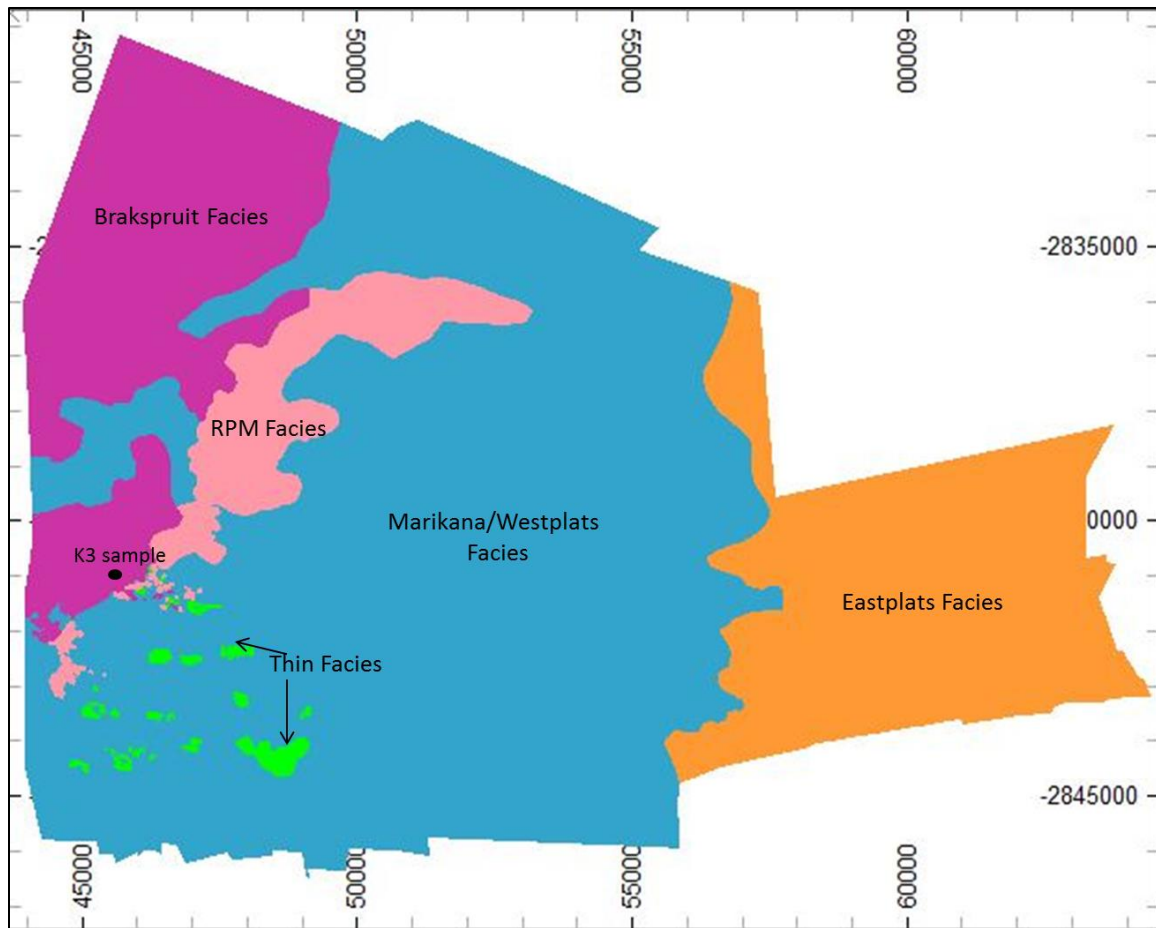


Figure 2.3.3 Facies plan at Marikana Operations showing location of the unique sample taken at K3 Vertical Shaft.

Each underground sample at the Marikana Operations is coded based on layer identification and assigned a numerical code. This is consistent with the coding used for the surface boreholes. Colour coding the underground channel samples based on the number of chromitite layers present, allowed for a visual distinction to be made between different facies domains and assisted in redefining the domain boundaries where channel sample data was available (Figure 2.3.3). In addition, underground mapping plans were studied by production geologists in an attempt to validate the domain boundaries.

2.4 Field Observations

A distinctive area at Marikana's K3 Vertical Shaft (Figure 2.3.3) was visited in order to study the field relations of various Merensky facies and of particular importance were areas where facies variability are known to exist.

The first area visited was a raiseline on 23 level. The initial underground mapping carried out by the geological observer and confirmed for this study, showed that the facies changed from a typical Thin Facies with only a Type 2a chromitite layer present, to a Brakspruit Facies type with Type 1 and Type 2b chromitite layers and pegmatoidal pyroxenite. It was noted that the Type 2a chromitite layer of the Thin Facies transgressed down into the footwall norite and goes on to form the Type 1 and 2b chromitite layers of the Brakspruit facies. (Figure 2.4.1)

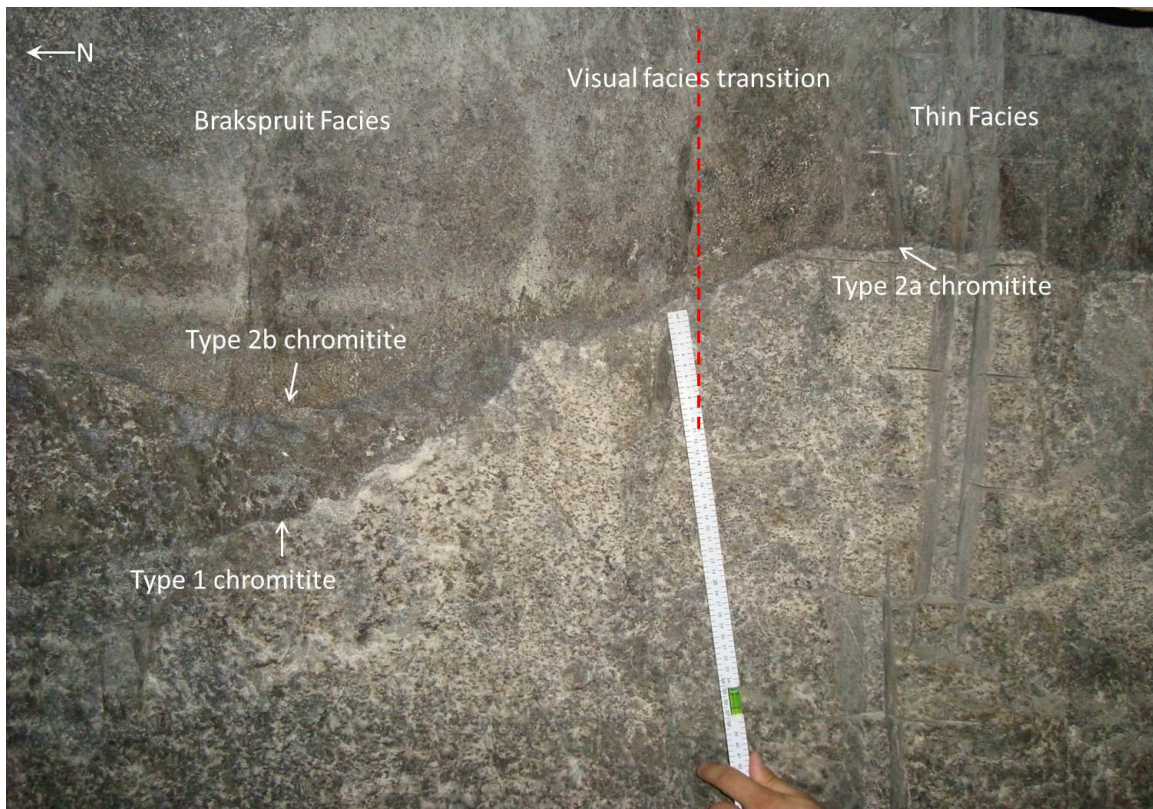


Figure 2.4.1: Photograph showing the transition from Thin facies to Brakspruit facies in an underground raiseline at 23 level, K3 Vertical Shaft.

With further examination, it was observed that the Type 2a chromitite layer of the Thin Facies, was not a single layer but two thin chromitite layers of less than half a centimeter in thickness each and were separated by approximately five cms of pyroxenite. (Figure 2.4.2)



Figure 2.4.2: Photograph showing a close up of the Type 2a chromitite layers from the Thin facies. An underground sample was cut from this portion at 23 level, K3 Vertical Shaft.

To the left of Figure 2.4.1 where the facies transitions from the Thin to the Brakspruit facies, the Type 2a chromitite layer thickens from less than half a centimeter in the Thin

facies to approximately one centimeter thick in the Brakspruit facies (Figure 2.4.3). Within the Thin facies, the Type 2a chromitite layer has a massive appearance with a fine-grained texture. From the transition, into the Brakspruit facies, the Type 1 and Type 2b chromitite layers become more disseminated and the grain size increases. The contact between the footwall anorthosite and the Type 1 chromitite layer is sharp, with the chromitite layer transgressing down into the footwall. The Type 2b chromitite layer transgresses down onto the pegmatoidal pyroxenite (indicated by the black dashed line in Figure 2.4.3), although this contact is less sharp than the footwall contact and the chromitite layer is thicker and more disseminated.

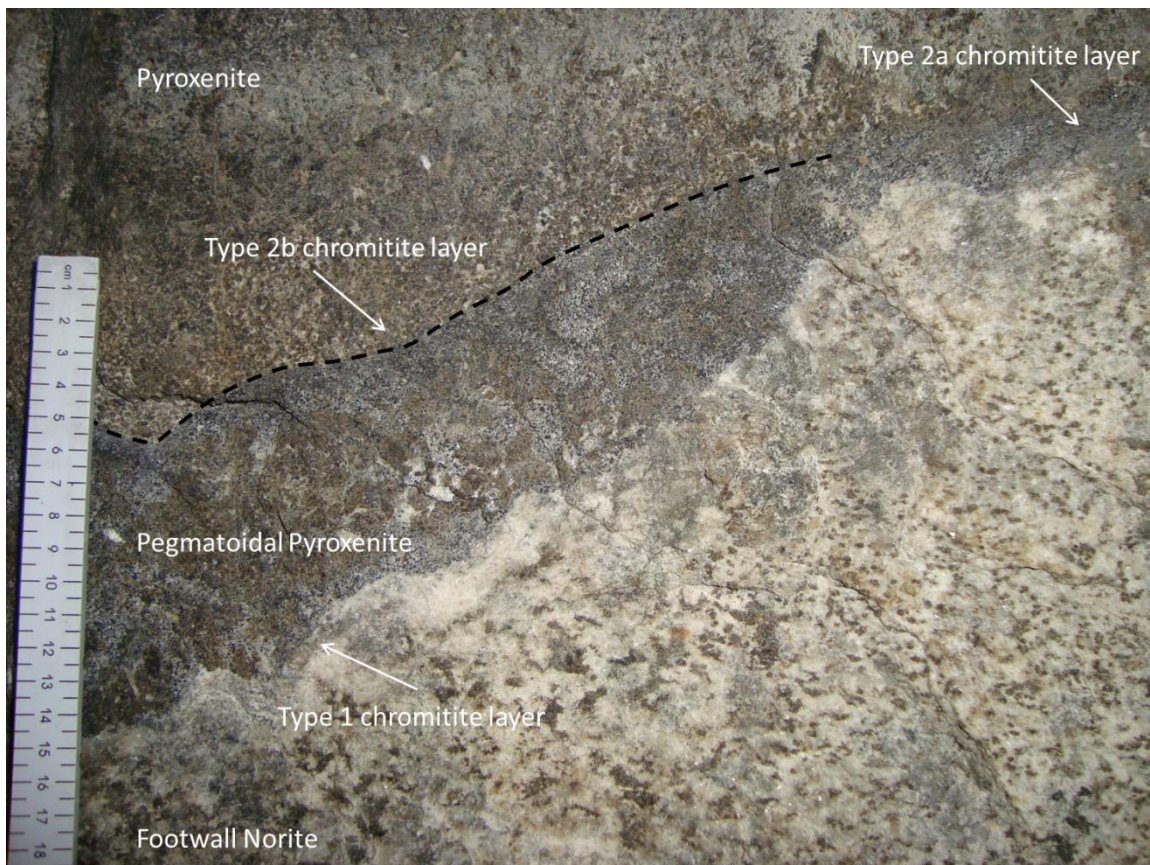


Figure 2.4.3: Photograph showing a close up of the transition zone between the Thin and Brakspruit facies at 23 level, K3 shaft.

In the transition zone, the chromitite layer thickens to between five and six centimeters (Figure 2.4.4). The Type 2b chromitite layer has more disseminated chromite than within the Thin facies. The contact with the footwall norite or the pyroxenite/pegmatoidal pyroxenite has some correlation with the mineral types that surround the chromite grains. Typically it was observed that either plagioclase when in contact with the anorthosite and pyroxene when in contact with the pyroxenite. This is dealt with in more detail in Chapter 4.

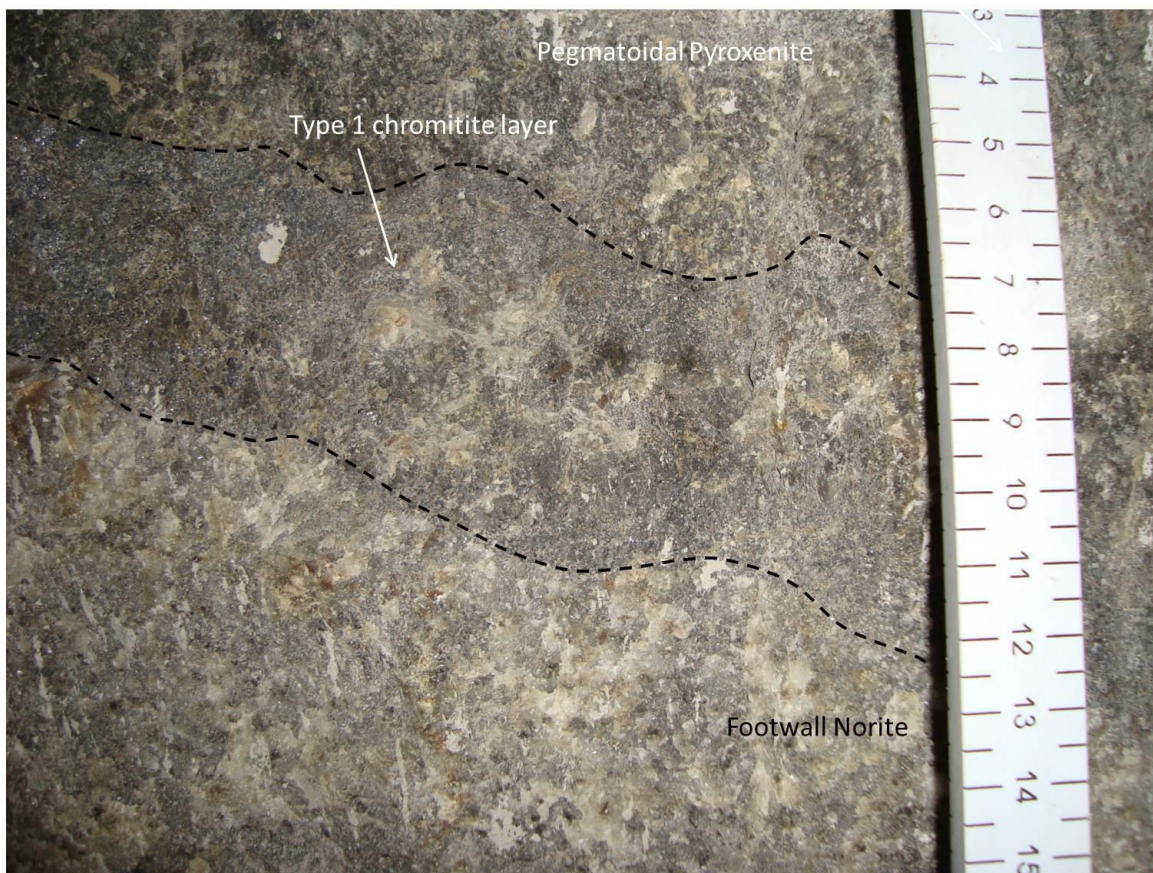


Figure 2.4.4: Photograph showing a close up of the Type 1 Chromitite layer within the transition zone between the Thin and Brakspruit facies at 23 level, K3 shaft.

At Marikana's K4 Vertical Project Shaft, only the RPM Facies has been exposed. The chromitite layers are separated by a thick pegmatoidal pyroxenite which is very coarse

grained. The contact between the footwall anorthosite and the Type 1 chromitite layer is sharp, with the chromitite layer transgressing down into the footwall as seen in the K3 Shaft example above (Figure 2.4.5).



Figure 2.4.5: Photograph showing the thinning of the RPM facies and transgression of the Type 1 chromitite layer into the footwall anorthosite in an underground raiseline at 26 level, K4 Vertical Project Shaft.

Another example of transgression of chromitite layers into the footwall anorthosite on a larger scale was observed in a reef drive (Figure 2.4.6). The contact with the footwall anorthosite is sharp and undulating and forms an erosional unconformity.

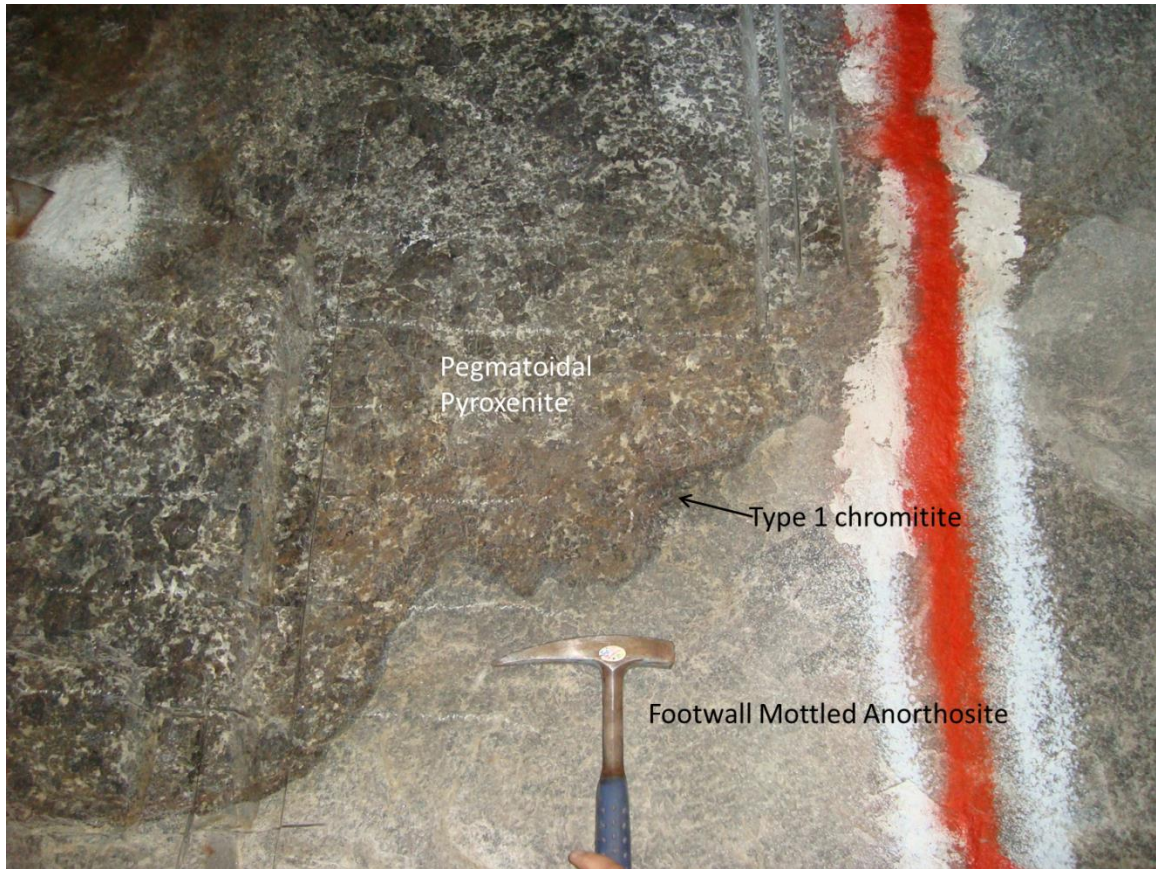


Figure 2.4.6: Photograph showing the transgression of the Type 1 chromitite layer into the footwall anorthosite in an underground reef drive at 26 level, K4 Vertical Project Shaft.

Figure 2.4.7 presents evidence that where the chromitite layer transgress into the footwall anorthosite, that erosional processes are taking place. Potholing and rolling of the chromitite layers are observed with a thickening of the chromitite layer against one side of the pothole and thinning on the exit side of the pothole to the right of the photograph.

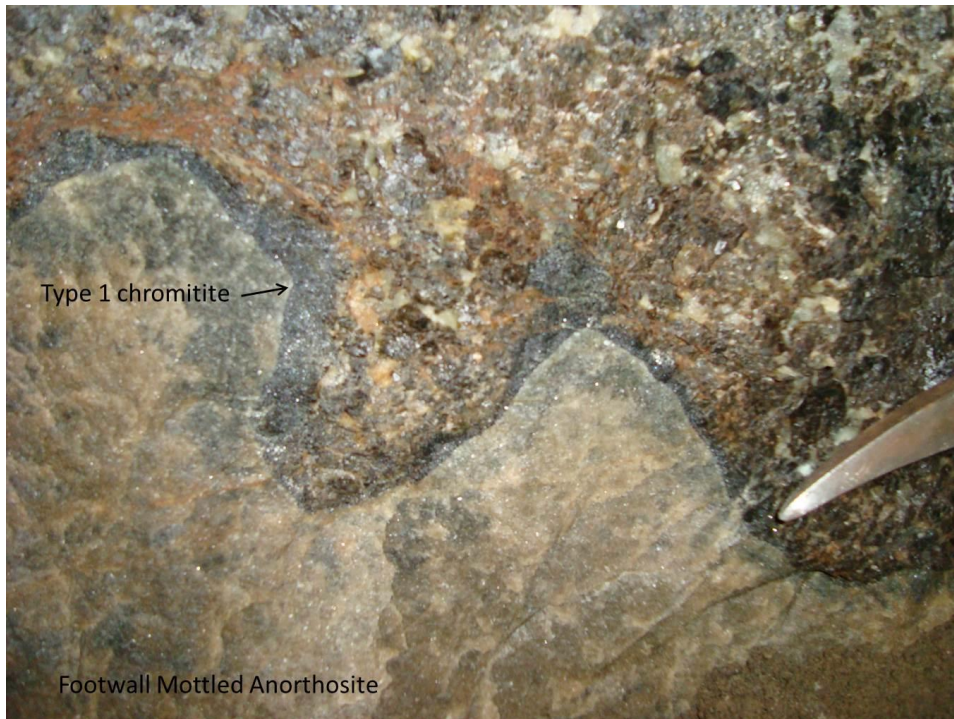


Figure 2.4.7: Photograph showing a close up of the sharp contact with the Type 1 chromitite layer and the footwall anorthosite. Erosional features show small scale rolling and potholing of the footwall.

Samples were taken from an underground exposure on 23 level at K3 Vertical Shaft (Figure 2.3.3). These were selected for mineral chemistry study of chromite grains and were analysed under the electron microprobe. It was observed that the facies changed from a typical Thin Facies type with only a Type 2a chromitite layer present, to a Brakspruit Facies type with Type 1 and Type 2b chromitite layers and pegmatoidal pyroxenite. From the Brakspruit facies, the Type 1 and 2b chromitite layers appear to merge and form the Type 2a chromitite layer from the Thin Facies (Figure 2.4.8). However it is considered to be unlikely that the layer splits or coalesces.

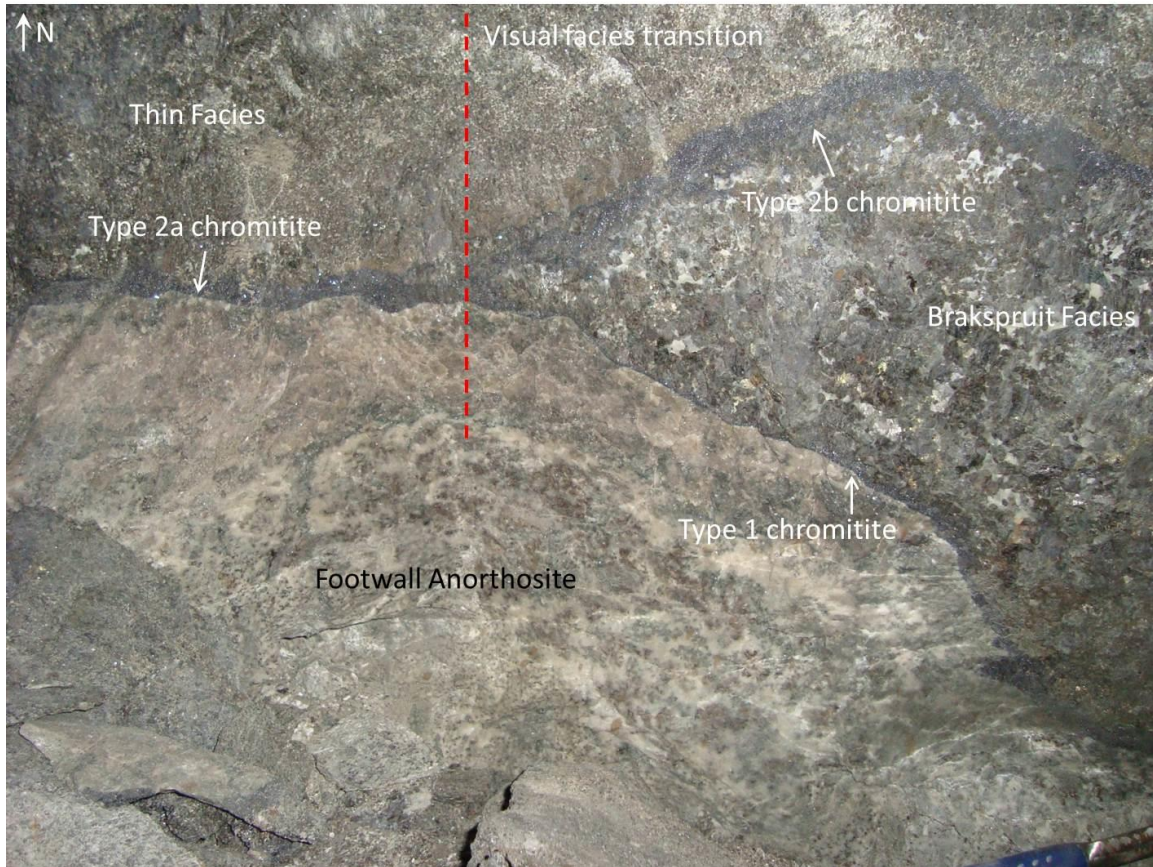


Figure 2.4.8: Photograph showing the transition from Thin facies to Brakspruit facies in an underground exposure at 23 level, K3 Vertical Shaft.

Within the transition zone between facies, the Type 2a chromitite layer of the Thin facies is a thick layer with fine to medium grain sizes. The Type 1 chromitite layer of the Brakspruit facies is a thin, tightly packed layer with a fine grain size and the Type 2b chromitite layer has fine to medium sized grains and is thicker than the Type 1 layer. Large sulphide grains are observed in contact with the Type 1 chromitite layer within the pegmatoidal pyroxenite.

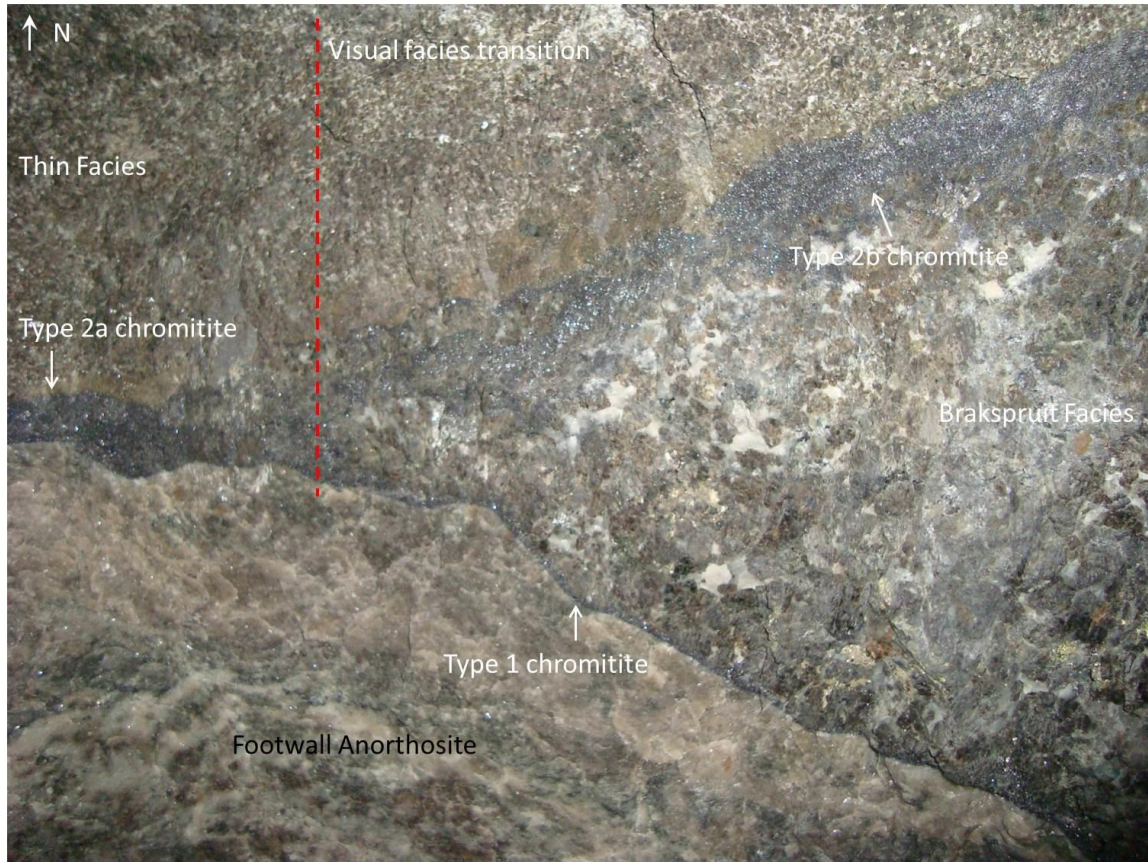


Figure 2.4.9: Photograph showing a close up of the transition from Thin facies to Brakspruit facies in an underground exposure at 23 level, K3 Vertical Shaft.

Further east of the facies transition, within the Brakspruit facies, the contact between the Type 1 chromitite layer and the footwall anorthosite is sharp, with the Type 1 chromitite transgressing into the footwall anorthosite and forms a small pothole (Figure 2.4.10).

Figure 2.4.9 and 2.4.10 are less than a metre apart and show more detail as the facies transition from Thin into Brakspruit Facies.



Figure 2.4.10; Photograph showing the Brakspruit facies with Type 1 chromitite layer transgressing into the anorthosite footwall and an erosional pothole like feature observed.

CHAPTER THREE – SAMPLING STRATEGY

3.1 Sampling

The sampling conducted was primarily of the chromitite layers within the Merensky Cyclic Unit, the objective being to draw comparisons and contrasts of the mineral chemistry between these four layers. The sample suite comprised samples from both borehole and underground channel exposures, typical of each facies described in Chapter 2. The samples were collected from undisturbed areas away from major structures such as faults and potholes, with no visible veins or alteration.

Borehole samples were taken of the entire chromitite layers within the Merensky Cyclic Unit for the different facies types. Some overlap into the hangingwall and footwall was taken to allow for sufficient material to be sampled and not exclude any material from the chromitite layer.

Seven boreholes were sampled (Figure 3.1.1), and summarized in table 1 below. All but one sample satisfied the sampling criteria. SL16 is classified as Marikana Facies but the Type 3 chromitite layer was not sampled. Furthermore, the Marikana boreholes used in the Shelembe (2009) study were also included in the dataset.

Table 1: Table showing borehole samples with their facies and chromitite layer type.

BHID	Facies Type	Chromitite layers
MK94	Thin	1
SL16	Marikana	2
SL21	Brakspruit	2

SL24	RPM	3
ZS50	RPM	3
ZS51	Marikana	2
ZS53	Brakspruit	2
*RS37	RPM	3
*ZS07	Thin	1
*TN71	Thin	1
*ML44	Marikana	2

* boreholes used in Shelembe's study.

Underground samples were taken at four different locations at Marikana (Figure 3.1.1), namely Lonmin's 4Belt, K3 Vertical Shaft, K4 Vertical Shaft and Rowland Vertical Shaft. The sample taken at 4Belt represents Thin Facies, the samples taken at K3 represent a transition zone between Thin and Brakspruit Facies (Figure 3.1.2), the sample at K4 represents RPM Facies and the sample at Rowland represents Marikana/Westplats Facies.

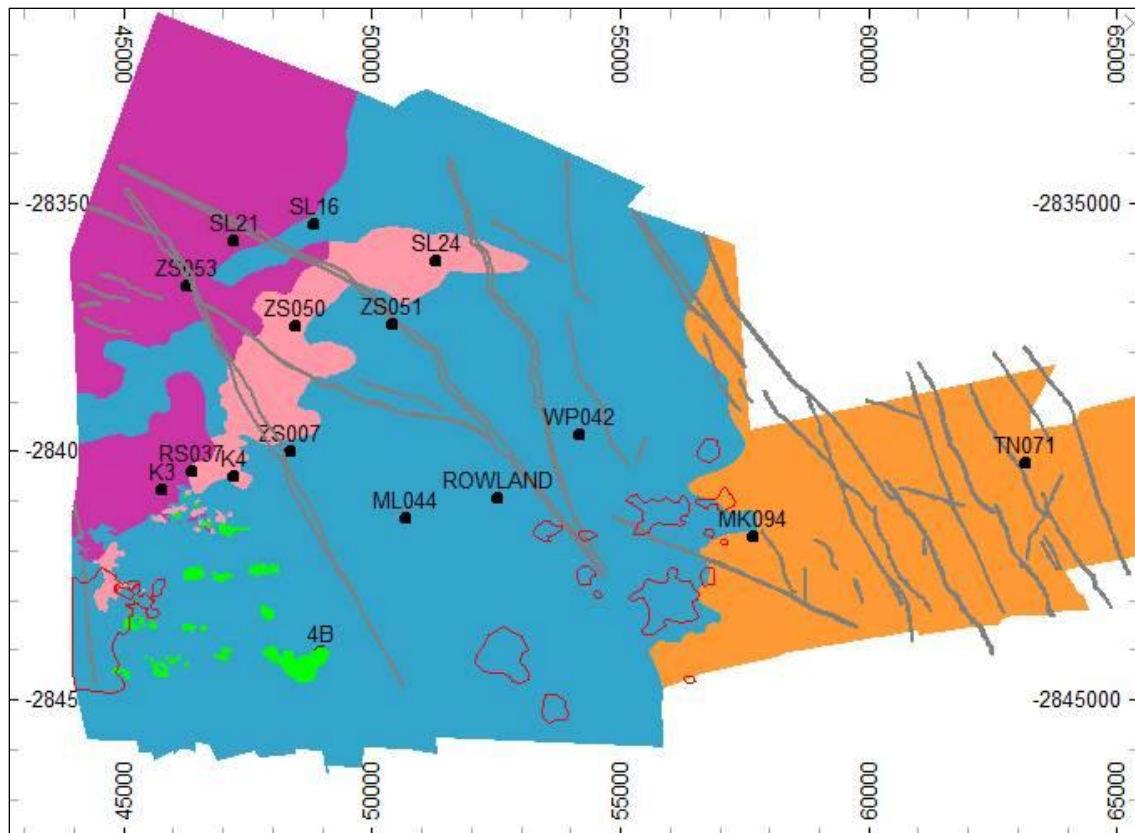


Figure 3.1.1: Sample locations within facies domains showing both underground and surface borehole samples. All major structures at Marikana (faults and dykes) are shown in grey and IRUP as red polygons. All samples were taken from undisturbed reef intersections. Facies types are as shown in Figure 2.3.3.

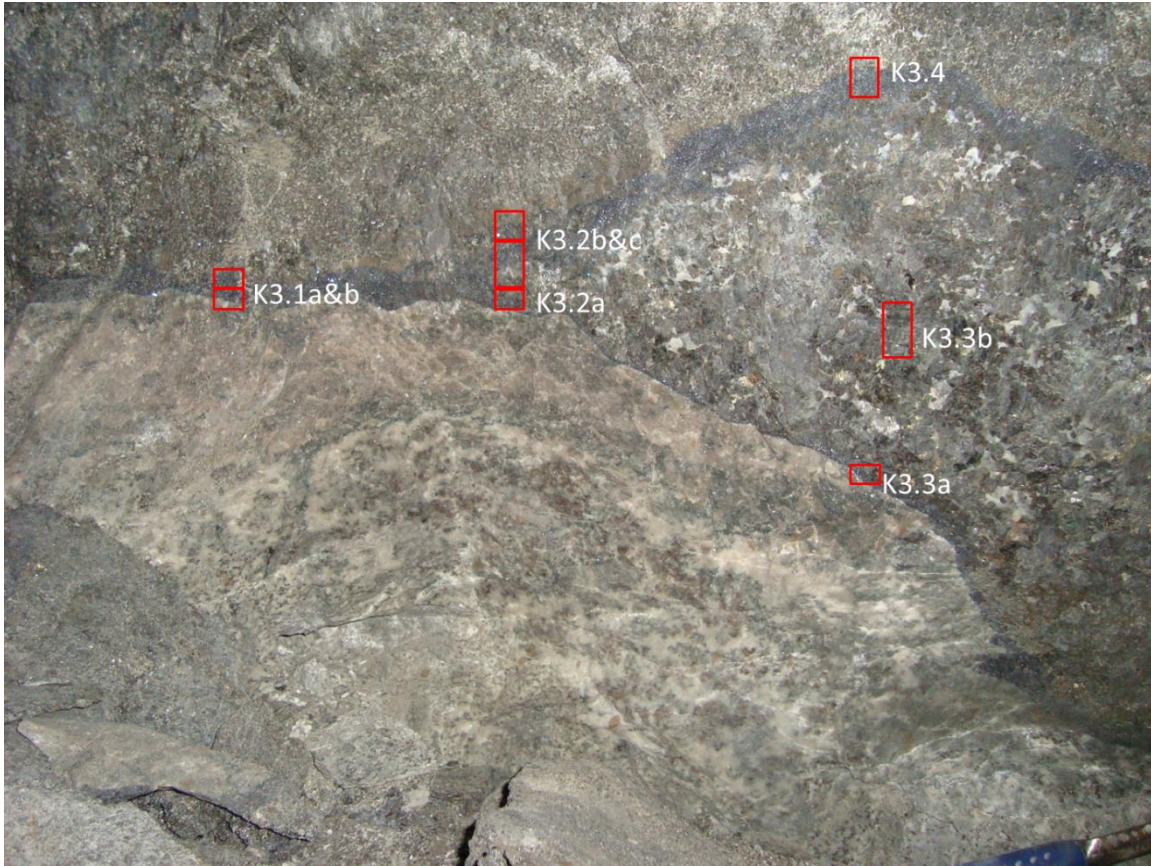


Figure 3.1.2 Underground sample location at K3 Vertical Shaft showing where samples were cut for analyses. Compare with Figure 2.4.8 shown previously.

The first two samples, K3.1a and K3.1b were taken from the Type 2a chromitite layer within the Thin facies, one with an overlap into the anorthosite footwall and a second with an overlap into the Merensky Pyroxenite. Three sections, K3.2 a, b and c, were taken within the transition zone between the Thin and Brakspruit facies where the chromitite layers are interpreted as Type 1 (K3.2a) and 2a (K3.2b&c). K3.2a was taken overlapping into the anorthosite footwall with some pegmatoidal pyroxenite in the top corner of the sample, K3.2b was taken in the middle of the chromitite layer within the pegmatoidal pyroxenite and K3.2c was taken overlapping into the Merensky Pyroxenite. Sample K3.3a was taken in the Type 1 chromitite layer within the Brakspruit facies and

sample K3.3b was taken layer within the pegmatoidal pyroxenite of a disseminated chromitite and has not been assigned a chromitite layer type. The final sample, K3.4, was taken of the Type 2b chromitite layer overlapping into the Merensky Pyroxenite.

The underground samples were broken off slabs exposed in mine excavations. Sufficient material was taken above and below the chromitite layer to ensure that the entire layer was included. The samples locations were recorded and some were photographed as seen in Figure 3.1.3 of samples K3.1a, K3.2a and K3.3a.

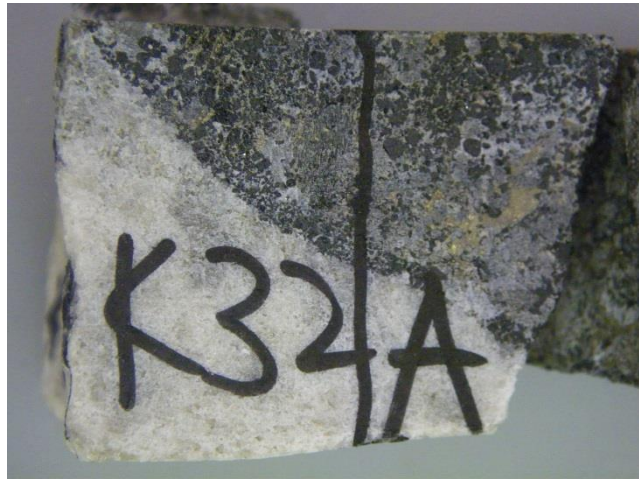




Figure 3.1.3: Photographs showing underground samples taken at K3 Shaft of samples K3.1a, K3.2a and K3.3a.

In total twenty five samples of the chromitite layers were taken, representing six of Type 1, nine of Type 2a, six of Type 2b and four of Type 3 chromitite layers. Seven of the total samples were from the Shelembe (2006) study. Data were obtained on the same electron microprobe at UJ using the same standards and so the two datasets were considered to have no analytical setting differences and thus suitable to combine.

In Table 2 below, all samples are listed and sorted using the x-coordinate from the most westerly sample at Marikana to that in the east of the property. Samples are listed from west to east. Chromitite layer thickness has been tabulated where available.

Table 2: Table showing all samples with their facies and chromitite layer type.
(* samples used in Shelembe's study)

Sample name	W-E coordinate	Facies type	Chromitite layer	Thickness
K3.1a	45923	Thin	2a	2cm
K3.1b	45923	Thin	2a	
K3.2a	45923	Thin	2a	
K3.2b	45923	Thin	2a	
K3.2c	45923	Brakspruit	2a	
K3.3a	45923	Brakspruit	1	
K3.3b	45923	Brakspruit	Not assigned	
K3.4	45923	Brakspruit	2b	
ZS53L	46300	Brakspruit	2b	10mm
ZS53B	46300	Brakspruit	1	20mm
*RS37U	46412	RPM	3	6mm
*RS37L	46412	RPM	2b	8mm
*RS37B	46412	RPM	1	3mm
SL21L	47250	Brakspruit	2b	25mm
K4U	47257	RPM	3	
K4L	47257	RPM	2b	
K4B	47257	RPM	1	
*ZS07L	48400	Thin	2a	25mm
ZS50U	48479	RPM	3	5mm
ZS50L	48479	RPM	2b	5mm
ZS50B	48479	RPM	1	10mm
SL16L	48845	Marikana	2a	5mm
4L	48996	Thin	2a	
ZS51U	50438	Marikana	3	
ZS51L	50438	Marikana	2a	
*ML44U	50700	Marikana	3	3mm
*ML44L	50700	Marikana	2a	7mm
SL24U	51302	RPM	3	
SL24L	51302	RPM	2b	
SL24B	51302	RPM	1	
MK94L	57694	Thin	2a	
*TN71L	63200	Eastplats	2a	3mm

CHAPTER FOUR – PETROGRAPHY

4.1 Introduction

This chapter focuses on the petrography of the chromitite layers by facies type. Textural relationships, chromite morphology and modal proportion of the chromitite host minerals were examined to see if any distinctions between layers and with layers on a micro-scale could be made. Furthermore, the interface of the chromitite layers with the enclosing host cumulates was examined.

4.2 Modal Proportion of Chromite

The modal percentages of chromite were measured in thin sections to obtain understanding of the variability within facies and along strike. It is anticipated that the modal proportions of chromite may have some influence on the chromite composition resulting from reequilibration.

26 selected thin sections were scanned with a high resolution scanner to produce enlarged equal scale digital images and printed to allow point counting to be performed (Table 4.2.1). Six samples were prepared as polished samples and so could not be processed in this way. Figure 4.2.1 shows the thin section image of K4L, this thin section has a high count of chromite grains. In contrast, Figure 4.2.2 shows the thin section image of 24B, a chromitite layer with a very low chromite count.

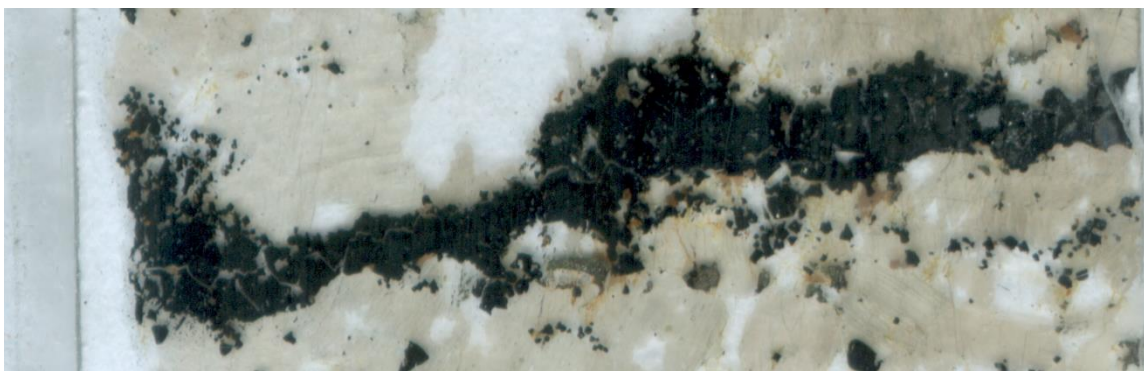


Figure 4.2.1 Thin section image used for point counting for sample K4L, showing a high total count of points within the chromitite layer.

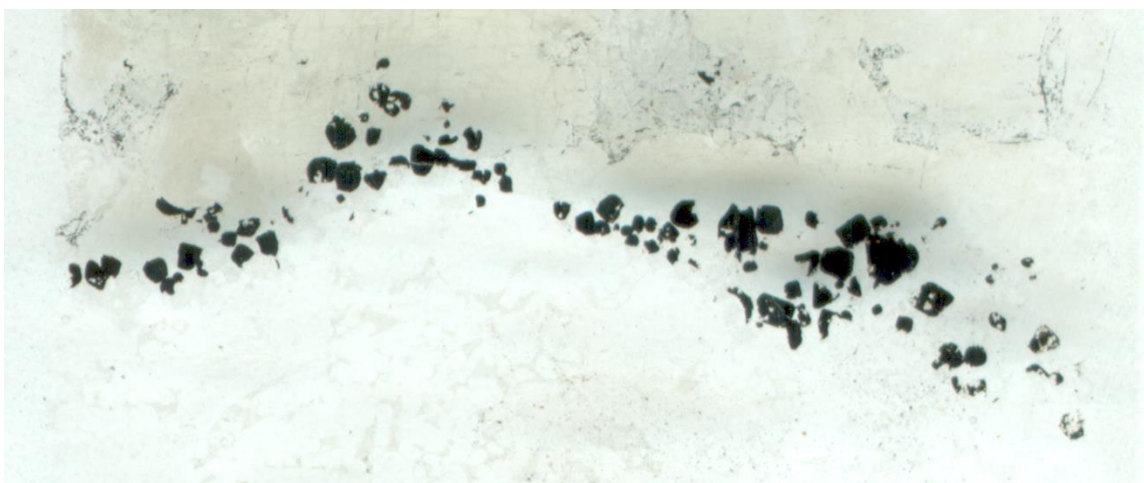


Figure 4.2.2 Thin section image used for point counting for sample 24B, showing a low total count of points within the chromitite layer.

On the printed images, the outline of the chromitite layer was drawn to constrain them during counting. A grid of dots was drawn on a transparency and this transparency was then placed onto each thin section image. The total number of counted points was controlled by the thickness of the layers, and so for some samples the numbers were not as large as desirable. Thus high precision is not claimed.

Table 4.2.1: Table showing point count results for all available thin sections with chromite type.

<i>Sample ID</i>	<i>Chromite</i>	<i>Gangue</i>	<i>Total count</i>	<i>% of chromite</i>	<i>Host Mineral</i>	<i>Chromitite layer</i>
K3.1a	42	28	70	60	plagioclase	2a
K3.1b	211	87	298	71	pyroxene	2a
K3.2a	35	37	72	49	pyroxene	2a
K3.2b	22	57	79	28	pyroxene	2a
K3.2c	119	52	171	70	plag&pyx	2a
K3.3a	35	29	64	55	plagioclase	1
K3.3b	135	73	208	65	pyroxene	n/a
K3.4	121	37	158	77	plag&pyx	2b
53B	266	278	544	49	plag&pyx	1
53L	18	93	111	16	pyroxene	2b
RS37U	180	149	329	55	plagioclase	3
RS37L	190	98	288	66	pyroxene	2b
RS37B	82	41	123	67	plag&pyx	1
K4U	91	49	140	65	pyroxene	3
K4L	192	87	279	69	pyroxene	2b
K4B	126	135	261	48	plag&pyx	1
50U	114	42	156	73	pyroxene	3
50L	17	102	119	14	pyroxene	2b
50B	117	103	220	53	plagioclase	1
16L	89	110	199	45	plag&pyx	2a
4L	14	23	37	38	pyroxene	2a
51U	159	78	237	67	pyroxene	3
51L	147	173	320	46	pyroxene	2a
24L	166	140	306	54	pyroxene	2b
24B	46	90	136	34	plagioclase	1
94L	72	95	167	43	pyroxene	2a

Plotting the percentage of chromite per sample from west to east using the samples x coordinate (Figure 4.2.3) shows that no clear pattern or groupings exists laterally by chromitite layer type.

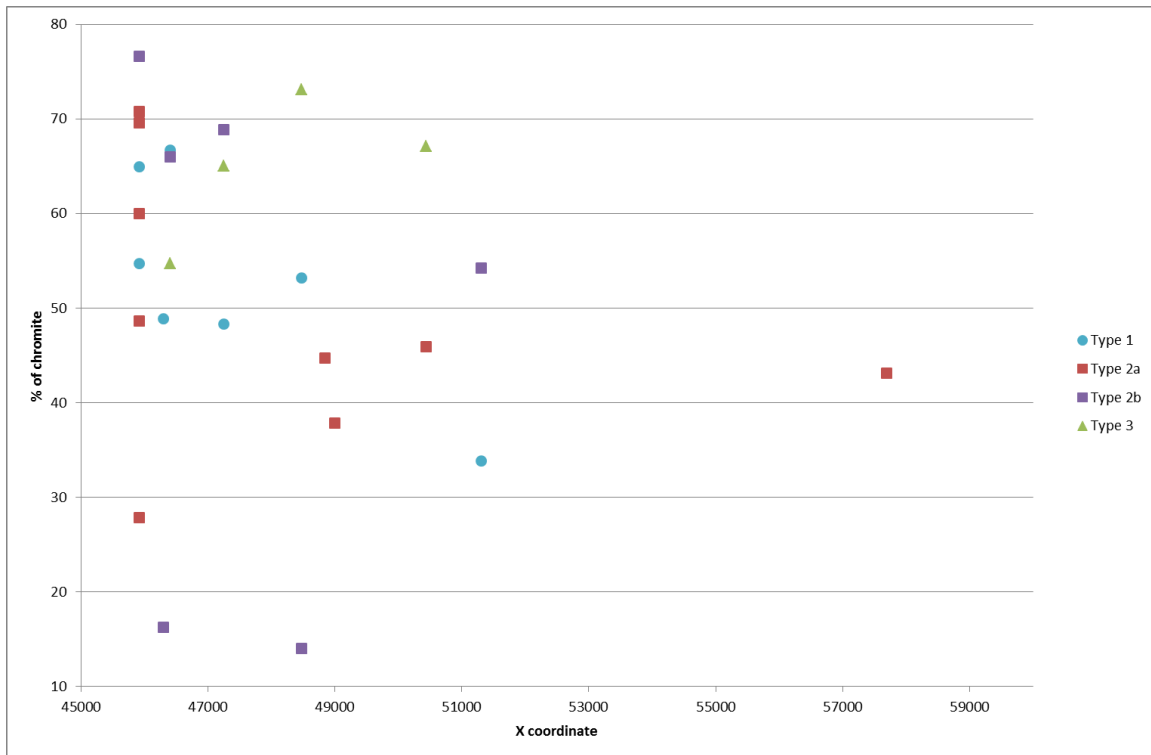


Figure 4.2.3 Plot showing the % of chromite per chromitite layer type from west to east using the x coordinate of the samples.

The purpose of point counting was to establish the nature of the chromitite layers and whether they are more massive or disseminated and whether the three layers display any distinct patterns or groupings related to the modal percentage of chromite (Figure 5.2.3.3).

4.3 Chromite Petrography

All 26 prepared thin sections were microscopically examined recording the grain shapes, textures, modal mineral proportions, nature of contacts, the prevalence of inclusions and the host minerals to the chromite grains. All images are shown with the base of the chromitite layer at the bottom.

In Figure 4.3.1, the Type 1 chromitite layers vary in thickness and range from between 2mm and 4mm. The typical textures of Type 1 chromitite layers are disseminated with chromite percentages of between 34 and 67%. The chromite grains are fine-grained (Figure 4.3.1a&d) to medium-grained (Figures 4.3.1b,c,e&f). The morphology of the chromite grains vary from being mostly euhedral and anhedral and rarely subhedral.

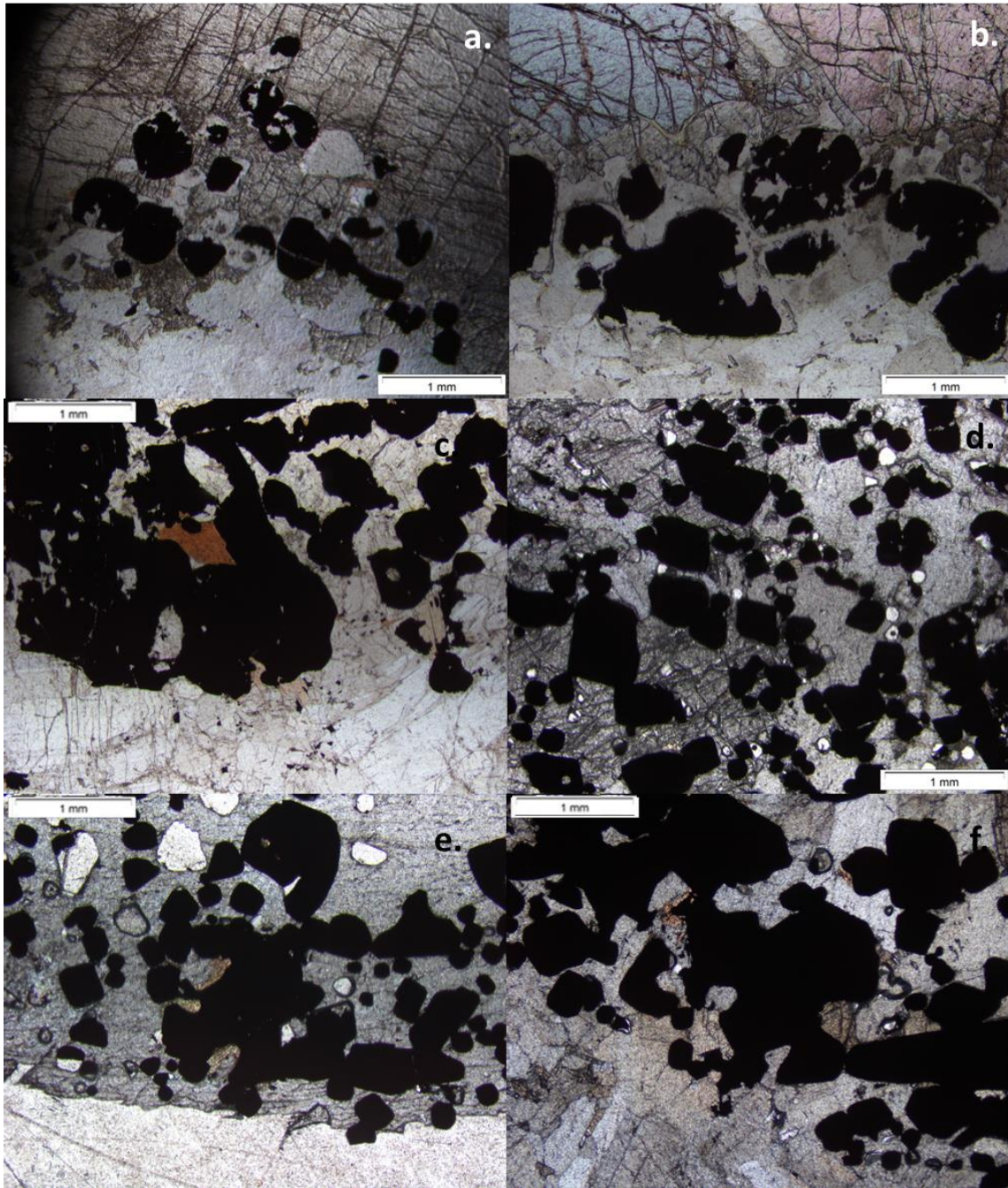


Figure 4.3.1 Photomicrographs of typical textures of Type 1 chromitite layers in plain polarised light from different facies types; a 24B and b 50B RPM facies, c 53B and f K3.3A Brakspruit facies and d K3.2A and e K3.2B from the merged layers of Thin/Brakspruit facies types.

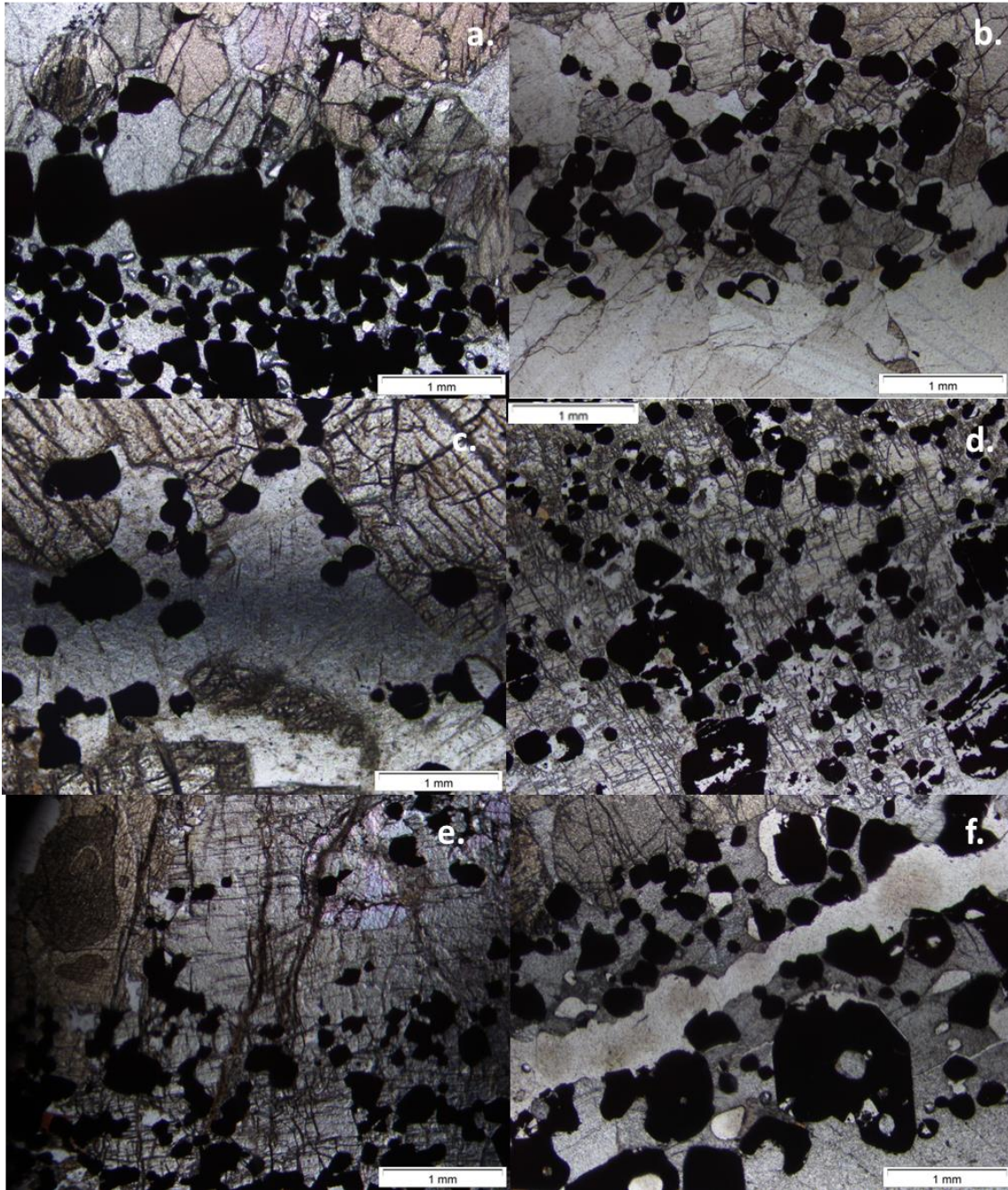


Figure 4.3.2 Photomicrographs of typical textures of Type 2 chromitite layers in plain polarised light from different facies types; a K3.4 and c 53L Brakspruit facies, b 94L and f 4L Thin facies, d 51L Marikana facies and e 24L RPM facies.

The Type 2 chromitite layers vary in thickness and range from between 2mm to 4mm. The typical textures of Type 2 chromitite layers (Figure 4.3.2) are disseminated with

chromite percentages of between 14 and 77%. The chromite grains are fine-grained (Figures 4.3.2a,b,c,d&e) to medium-grained (Figure 4.3.2f). The morphology of the chromite grains are mostly euhedral and rarely subhedral.

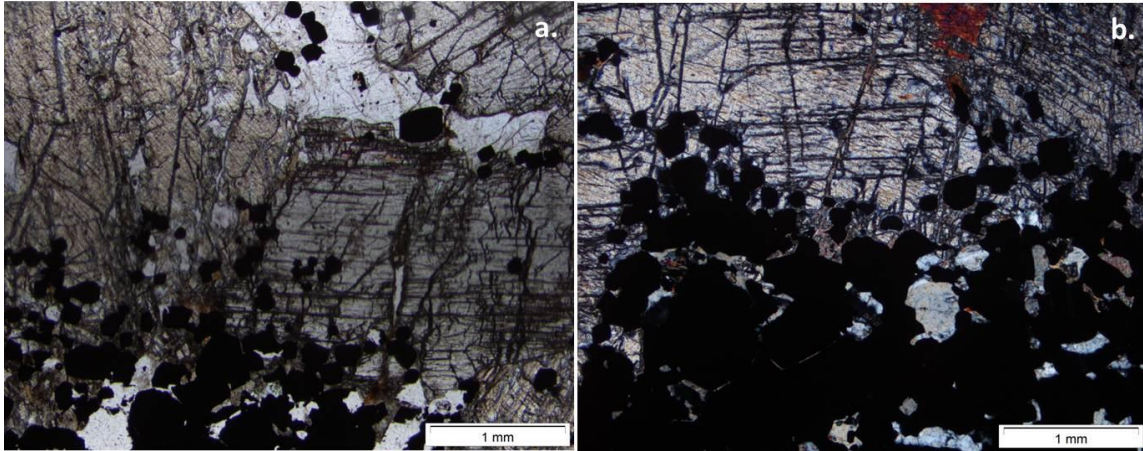


Figure 4.3.3 Photomicrographs of typical textures of Type 3 chromitite layers in plain polarised light from different facies types; a 50U RPM facies and b 51U Marikana facies.

Only two thin sections of Type 3 chromitite layers were investigated under the microscope. The Type 3 chromitite layers thicknesses range from between 1mm to 4mm. The typical textures of Type 3 chromitite layers (Figure 4.3.3) show more tightly packed or massive with chromite percentages measured between 55 and 73%. The chromite grains are fine to medium-grained. The morphology of the chromite grains vary from being mostly anhedral and subhedral in these two thin sections and are rarely euhedral. Here the grains make clusters and form bigger grains (Figure 4.3.3b).

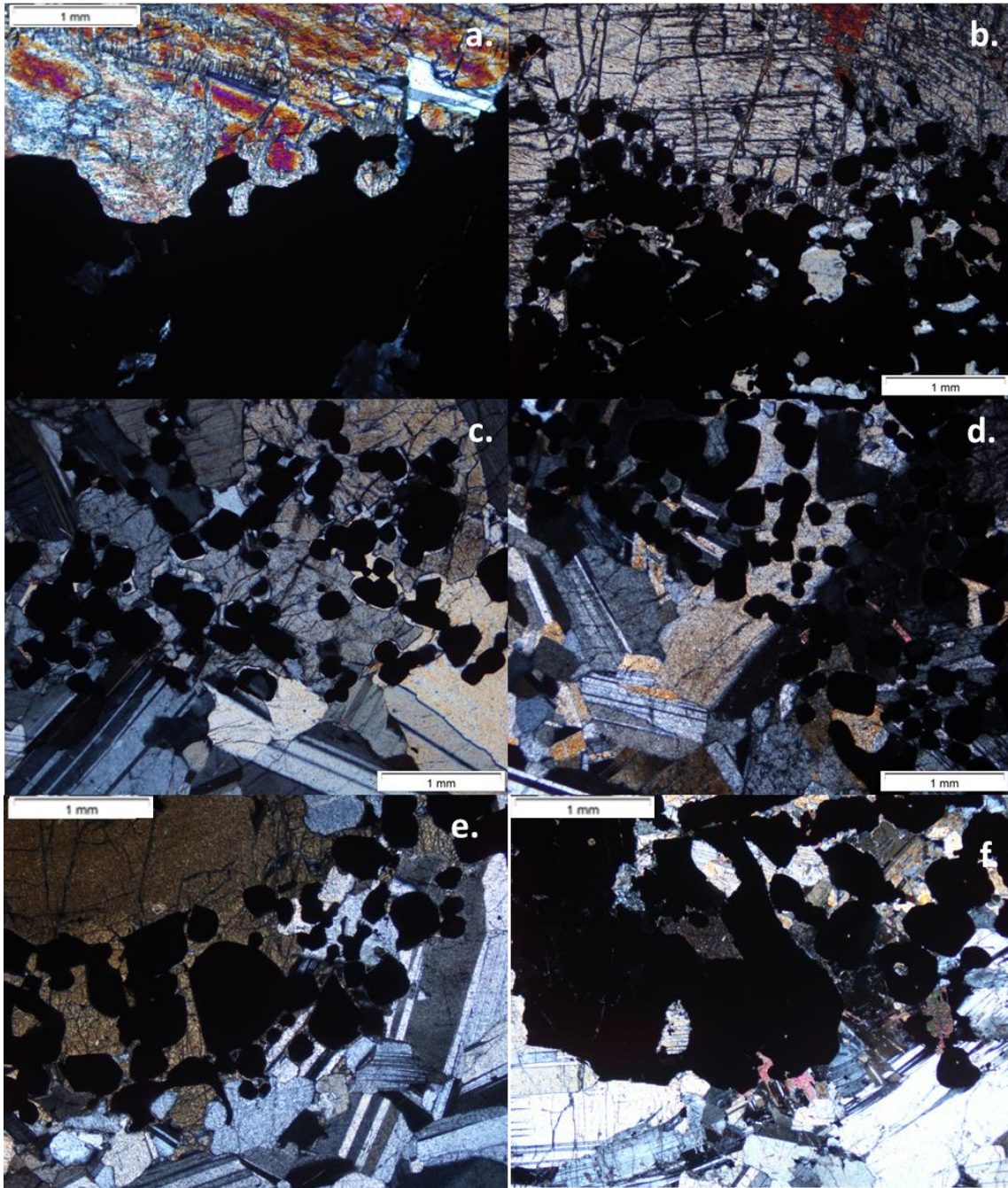


Figure 4.3.4 Photomicrographs of contacts for all three types chromitite layers in crossed polarised light from different facies types; a 50U Type 3 RPM facies, b 51U Type 3 Marikana facies, c 94L and d K3.1A Type 2 Thin facies and e K3.3A and f 53B Type 1 Brakspruit facies.

The chromitite layers are hosted in either pyroxene or plagioclase (Table 4.2.1) and are either found at contacts between anorthosite and pyroxenite (Figure 4.3.4c&d), anorthosite and pegmatoidal pyroxenite (Figure 4.3.4e&f), pegmatoidal pyroxenite and pyroxenite or within pyroxenite (Figure 4.3.4a&b). Contacts between the chromitite layers and their hosts are mostly sharp (Figure 4.3.4b,d,e&f) but can also be irregular (Figure 4.3.4a&c).

A microstructure that was prevalent in Types 1 and 2 chromitite layers, were grains with prominent amoeboidal shapes as shown in the examples of Figure 4.3.5 below. No amoeboidal shapes were identified in Type 3 chromite layers. These amoeboid grains vary in size but are typical medium-grained of 1 to 2 mm in width. In all cases, inclusions were observed. When studying the matrix of these inclusions, they display the same orientation as the host mineral to the chromite grain such as the plagioclase minerals in Figures 4.3.5a, c and f.

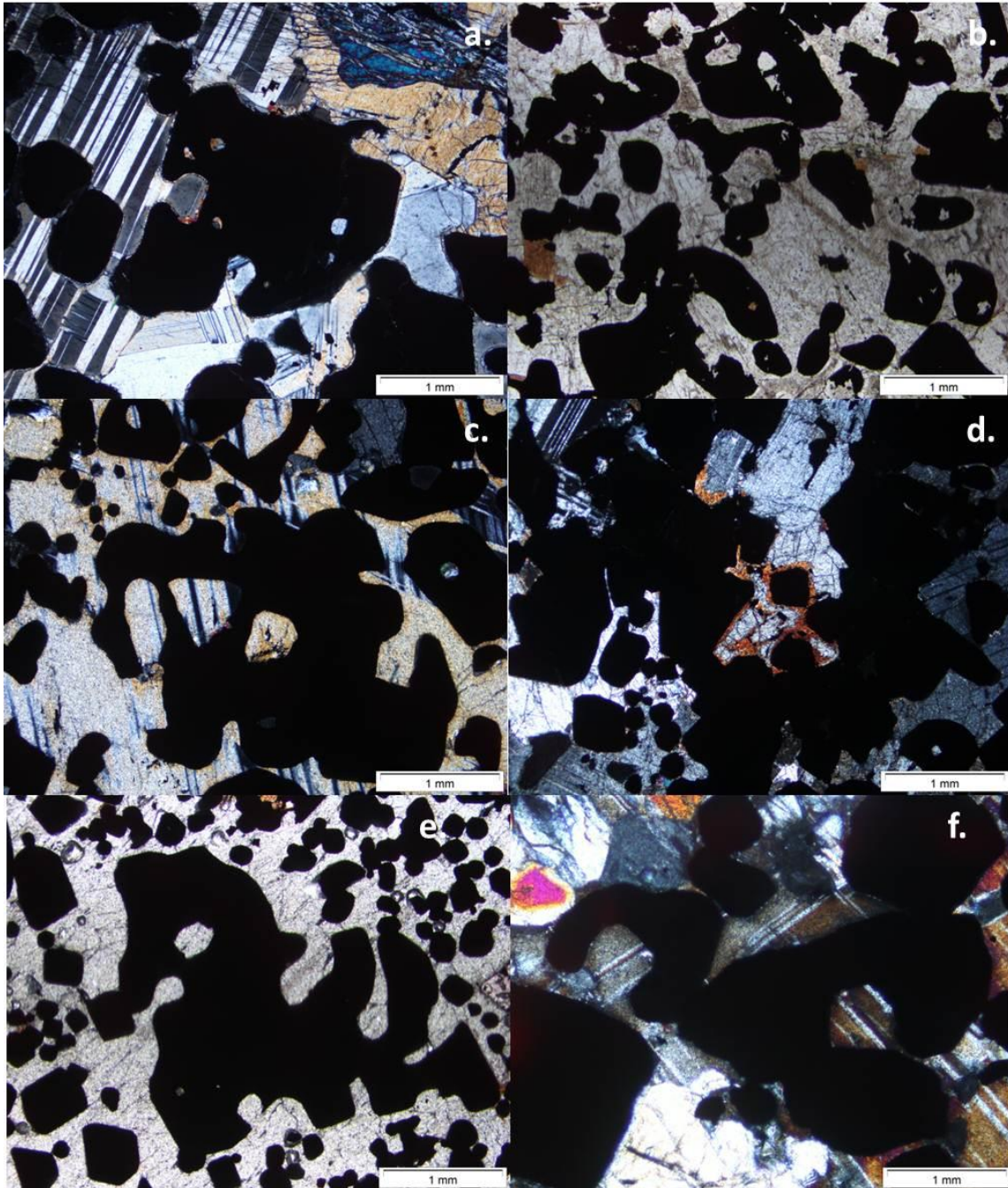


Figure 4.3.5 Photomicrographs showing microstructures, particularly amoeboid/irregular shaped grains for Type 1 and 2 chromitite layers in both plain and crossed polarised light from different facies types; a 50B Type 1 RPM facies, b 53B and e K3.3B Type 1 Brakspruit facies, c K3.1B Type 2 Thin facies and d K3.2 and f K3.4 Type 1 Brakspruit facies.

Scanned thin section images in Figure 4.3.6 show the textures and grain sizes of the chromitite layers with the biggest difference in appearance and texture being that of the Type 1 chromitite layer of the Brakspruit facies (c, bottom image) and the Type 2 chromitite layers of the Thin and Brakspruit facies. The Type 2 chromitite layers are visually both very similar in grain size, thickness and appearance of the layer.

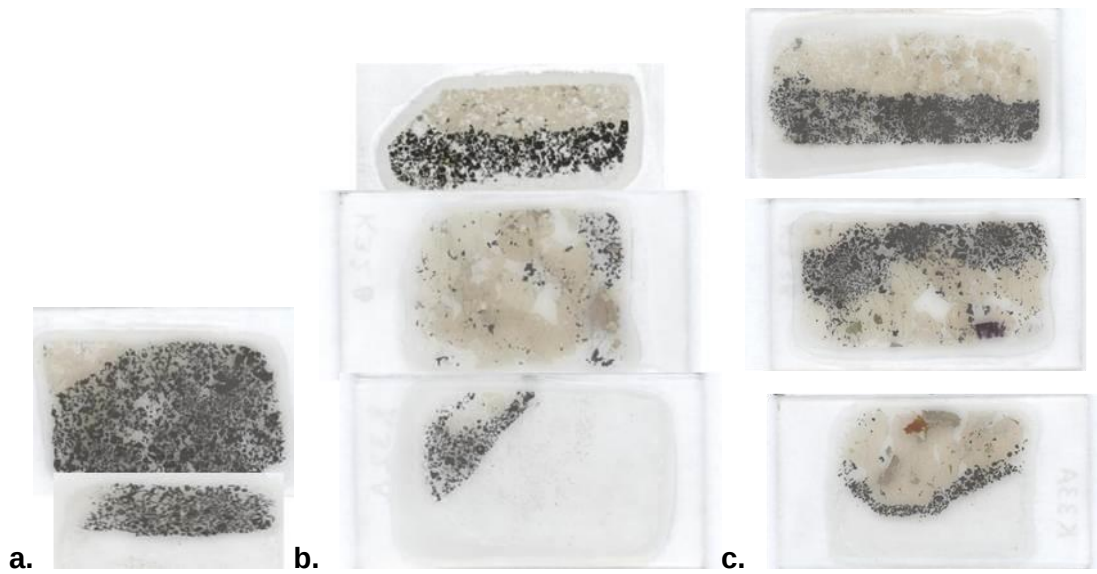


Figure 4.3.6: Thin section images showing the sampled locations from the underground exposure of a) K3.1a(bottom) & b(top) of Type 2a chromitite layer of the Thin facies, b) K.2a(bottom), b(middle) & c(top) of transition zone chromitite layer between facies and c) K3.3a(bottom – Type 1 chromitite layer), b(middle – chromitite layer within the pegmatoidal pyroxenite) and c (K3.4 – Type 2b chromitite layer of the Brakspruit facies).

CHAPTER 5 - MINERAL CHEMISTRY

5.1 Introduction

Polished sections and polished thin sections of all samples were prepared for microscopic investigation of the chromite grains within the chromitite layers, as well as electron microprobe analyses (EMPA) of chromite minerals. The mineral chemistry of the chromite will be used to compare the types of chromitite layers and thus interpret if each layer has comparable genetic history. All the mineral chemistry data are included in Appendix A and the electron microprobe settings and information in Appendix B.

Twenty five vertically orientated polished thin sections through chromitite layers from the Merensky Unit were analysed (Table 2). An average of six chromite grains was analysed per chromitite layer. Both the rims and the cores of the chromite grains were analysed. This gave on average a total 12 analyses per thin section. In total 305 analyses were conducted. The chromite grains were analysed vertically through the layer. The X and Y coordinates of the section through the chromitite layer were recorded to allow for visual plotting of the grains and show placement of the chosen grains as well as approximate thickness of the layer. Various sizes of chromite grains were analysed. The typical grain size ranged from between 100 μ and 400 μ , with a few larger grains of between 700 μ and 1000 μ analysed for comparative purposes. Six samples; K3.1b, K3.2a,b,c, K3.3a and K3.4 were specifically selected to establish whether grain size could be correlated with chemical compositions.

Two thin sections 21L and K3.3b were specifically analysed to investigate whether the host minerals have any influence over the chromite grain's chemical composition, since

both plagioclase and orthopyroxene were present as the host. In addition, analyses of grains in contact with sulphide minerals in thin section 50 μ , were investigated.

Plots of cations and cation ratios calculated from stoichiometry can be more rigorously interpreted than binary oxide diagrams and was the preferred method for analyses. A program of spinel stoichiometric calculations, including ferrous: ferric ratios was used to convert element oxides into cations in the chromite grains. The principle of using an ideal formula of XY_2O_4 , taking $X = (Fe^{2+}, Ni, Mn, Co, Zn)$ and $Y = (Cr^{3+}, Fe^{3+}, Al)$ is applied in the stoichiometric calculation. Iron is divided into ferrous and ferric to suit the condition $nY = 2nX$ where nY is total atoms of trivalent cations and nX is total divalent cations per unit cell. A shortcoming about the stoichiometric calculations is the uncertainty in major elements that propagates into larger uncertainty in the estimation of the ferric iron content (Wood and Virgo, 1989).

In an attempt to categorise the chromitite layers chemically into populations or test for any similarities, clustering, or trends, the Cr # and Mg # of all chromite grains analysed were produced. Ferrous and ferric iron contents were calculated to yield perfect stoichiometry.

The Cr# and Mg# are calculated by equations (1) and (2) respectively, using atomic proportions.

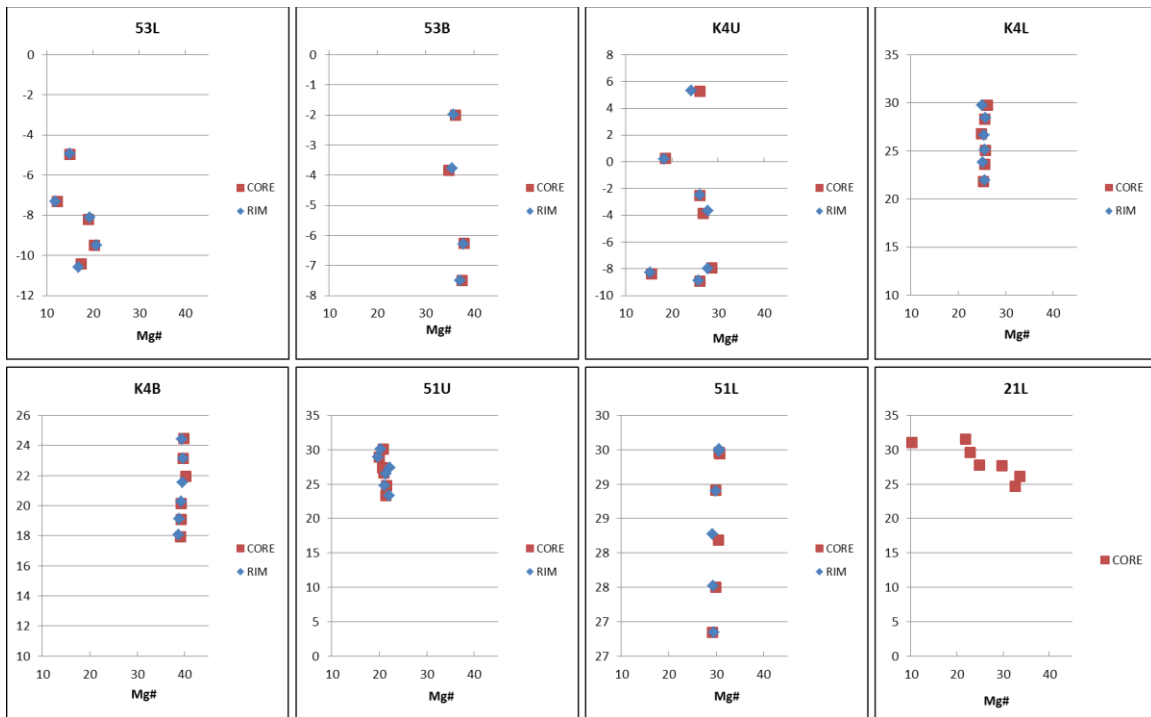
$$Cr\# = 100 \times Cr / (Cr + Al) \quad (1)$$

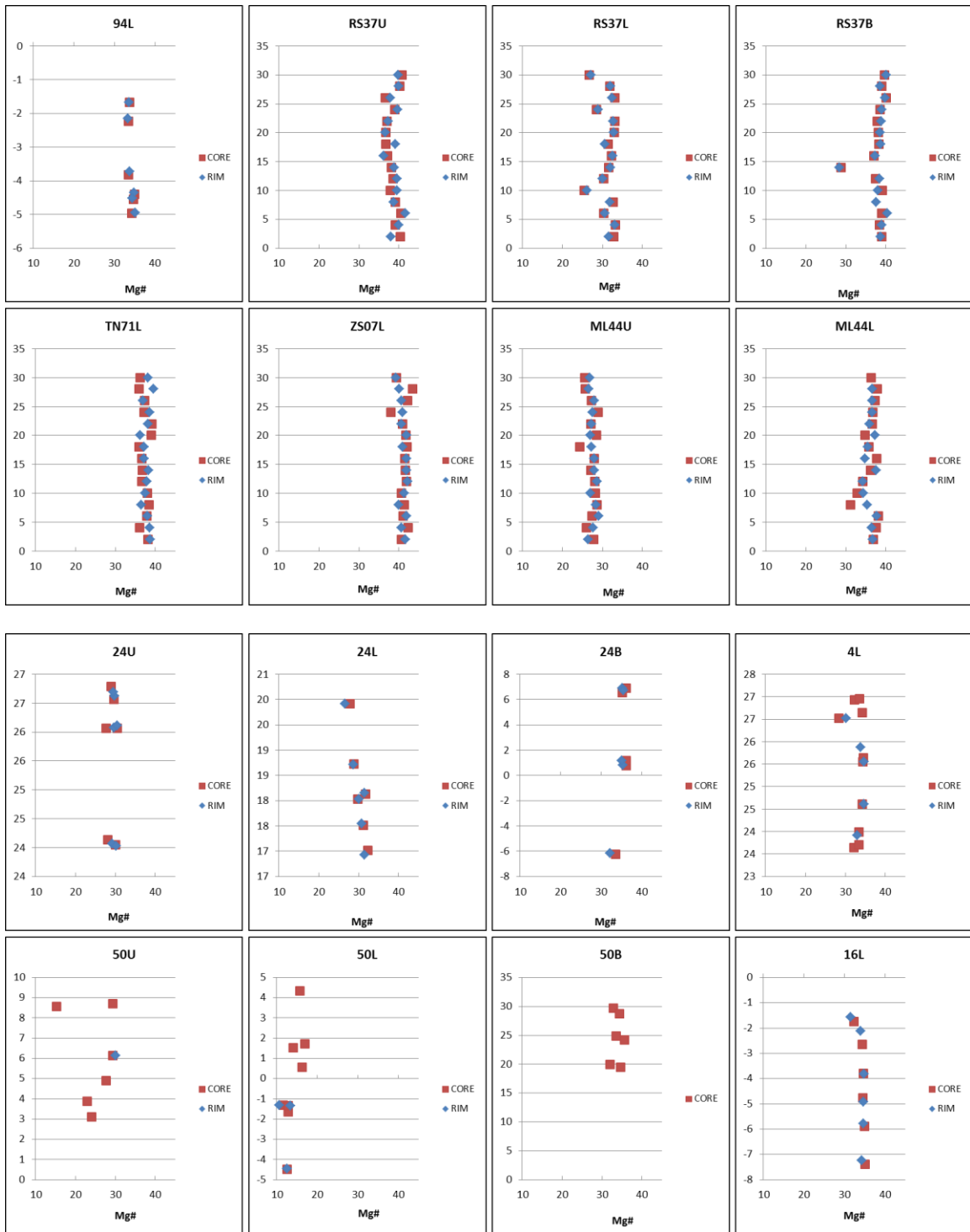
$$Mg\# = 100 \times Mg / (Mg + Fe^{+2}) \quad (2)$$

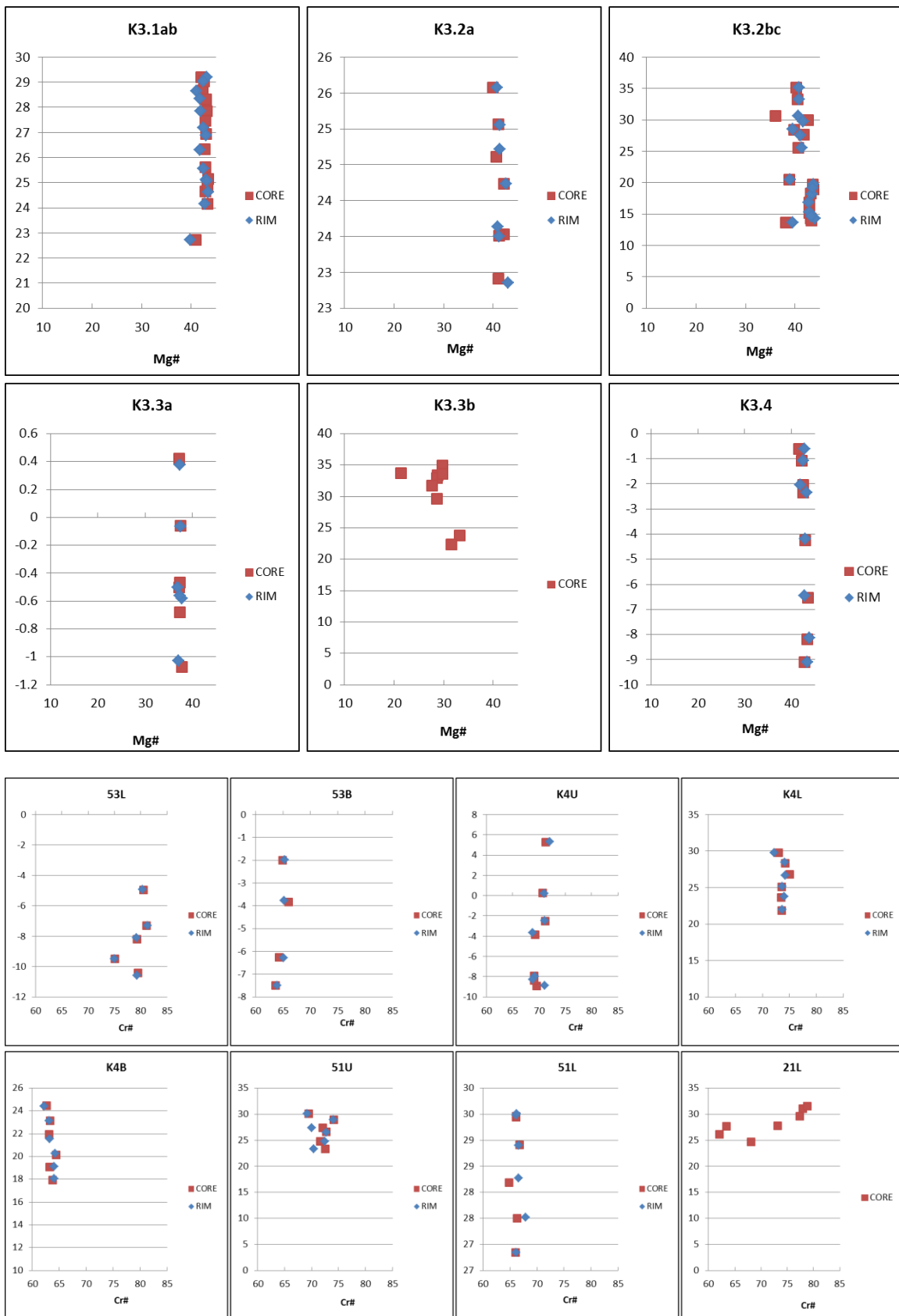
5.2 Chromite compositions

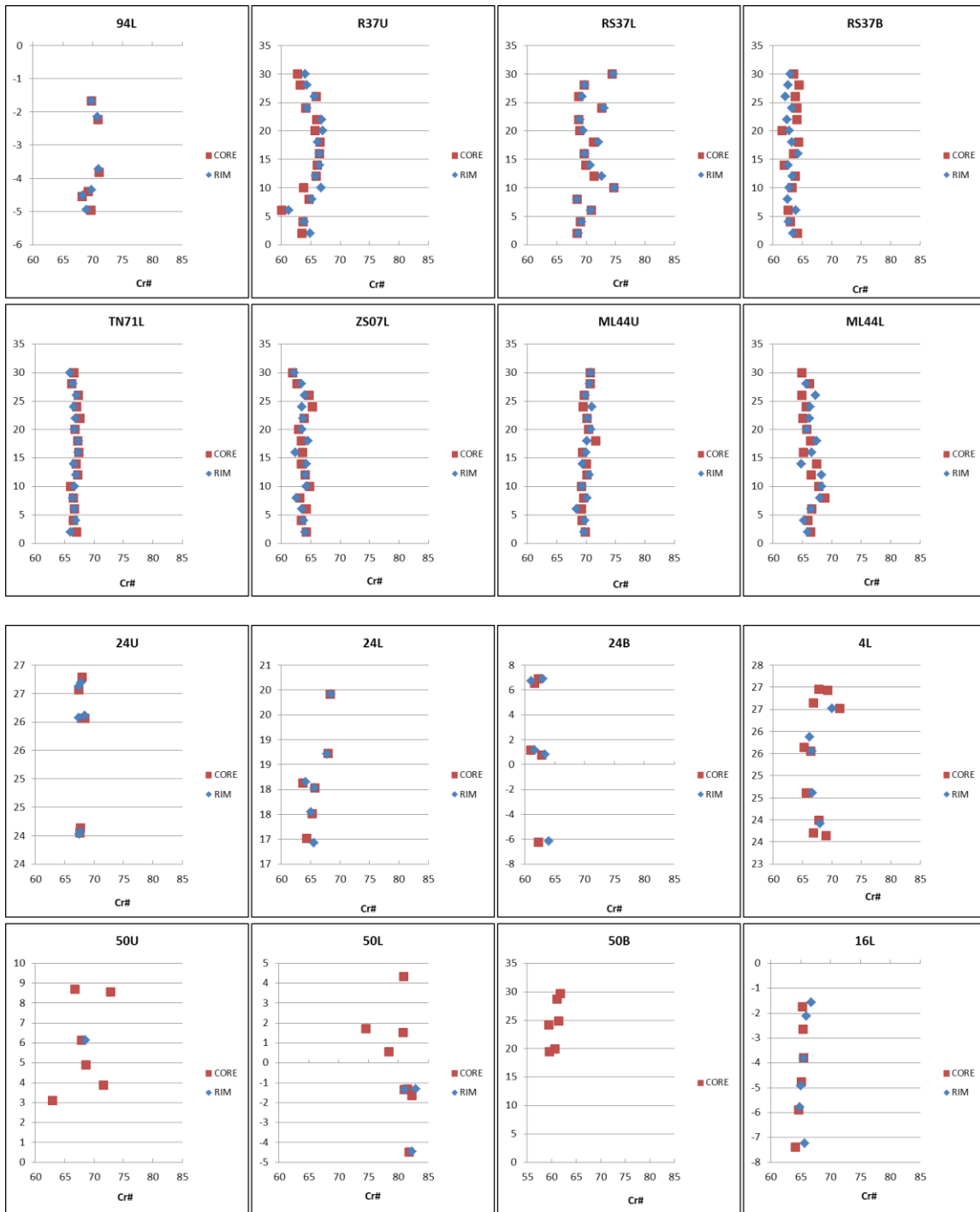
5.2.1 Cores and Rims

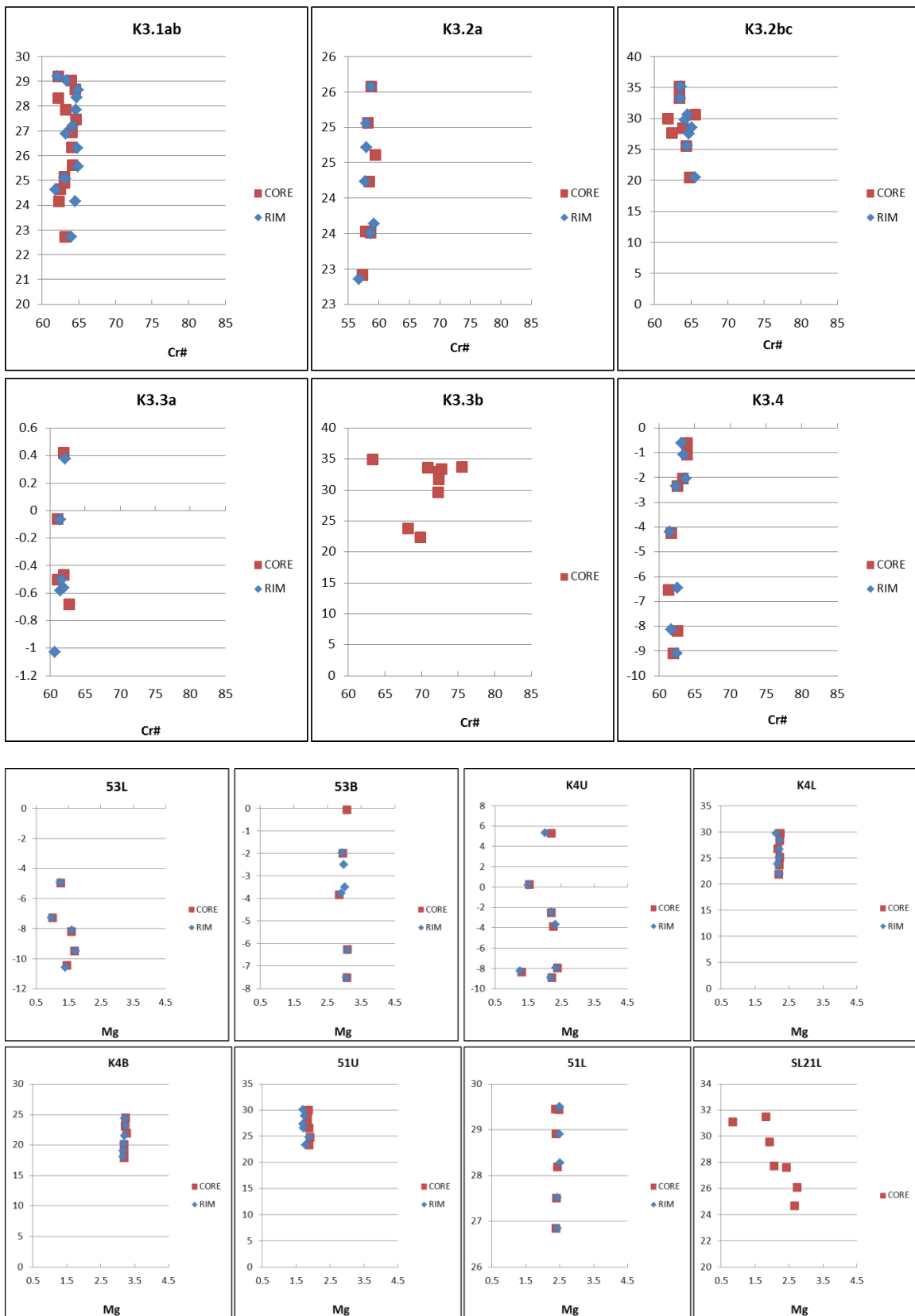
Cores and rims of each analysed chromite grain were recorded and plotted by sample in order to establish whether any variation in chemical composition exists between the two or whether any systematic zoning could be observed. In some cases only the core of the grain was analysed. For ease of reference and comparison, all elements are plotted with the same horizontal scale. The vertical scale was converted from microns, as measured by the EMPA, to millimetres. All figures in Figure 5.2.1.1 show that core and rim compositions are tightly constrained in their respective fields. This indicates that there are no major chemical variations between compositions of rims and compositions of chromite cores.



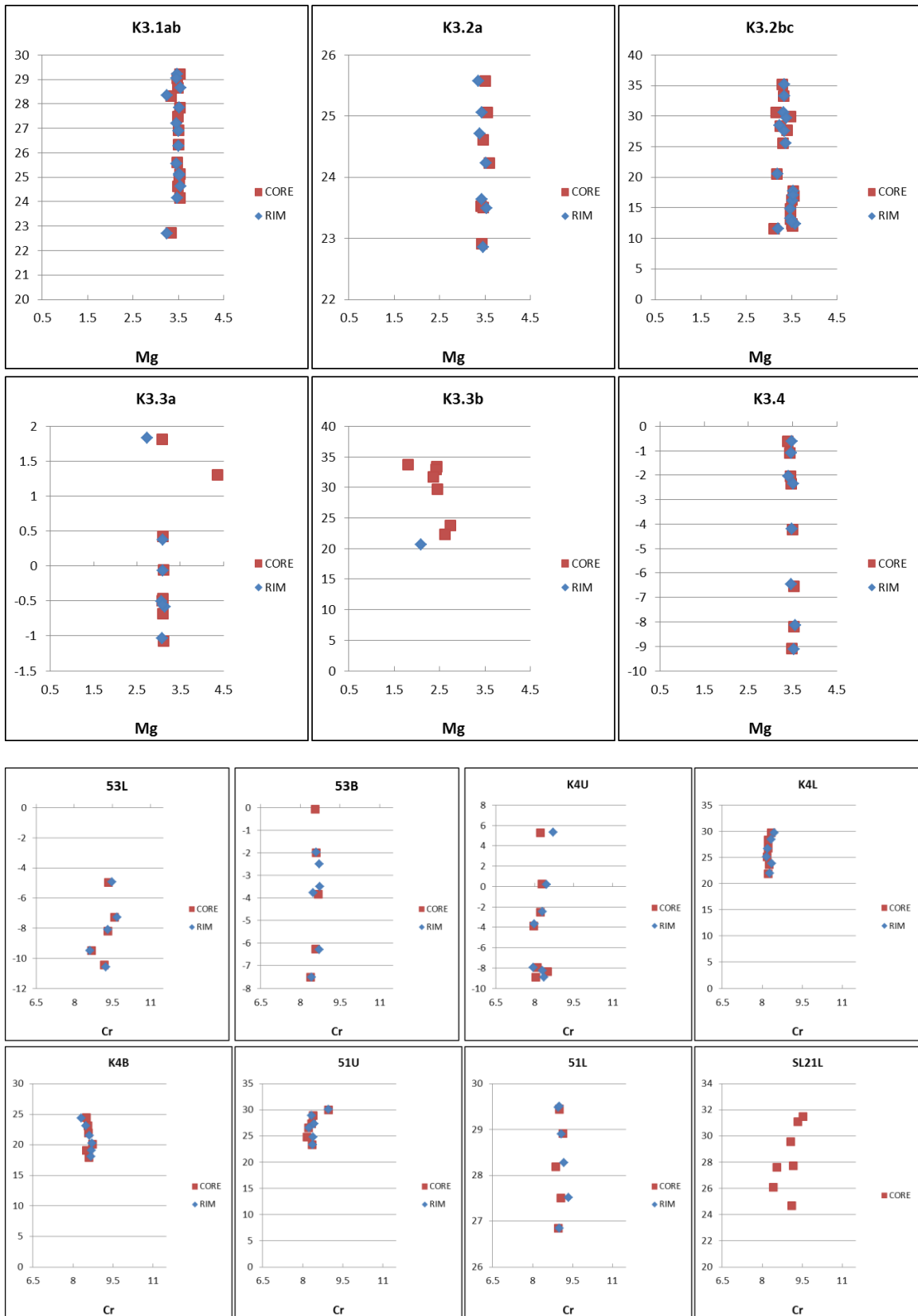


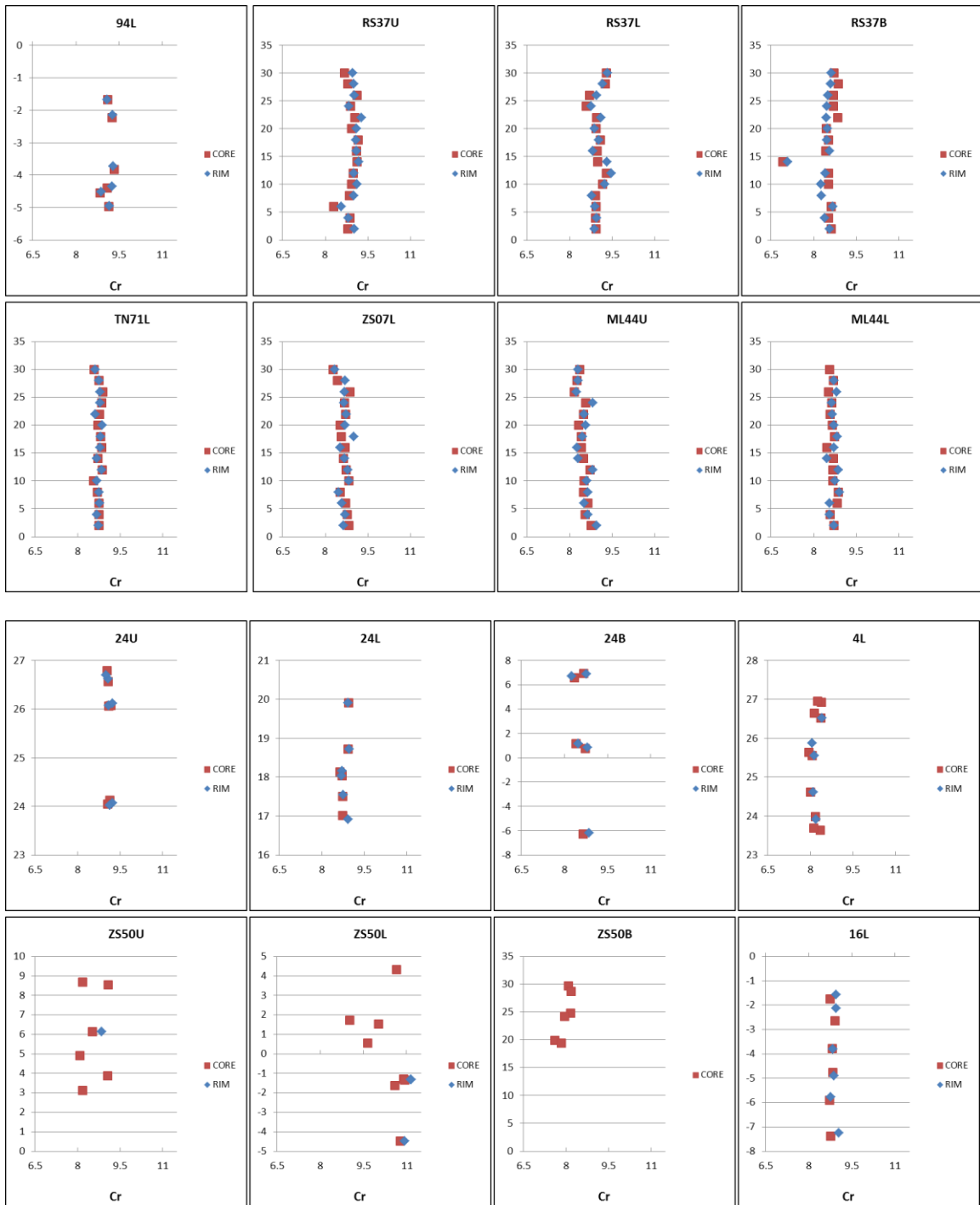


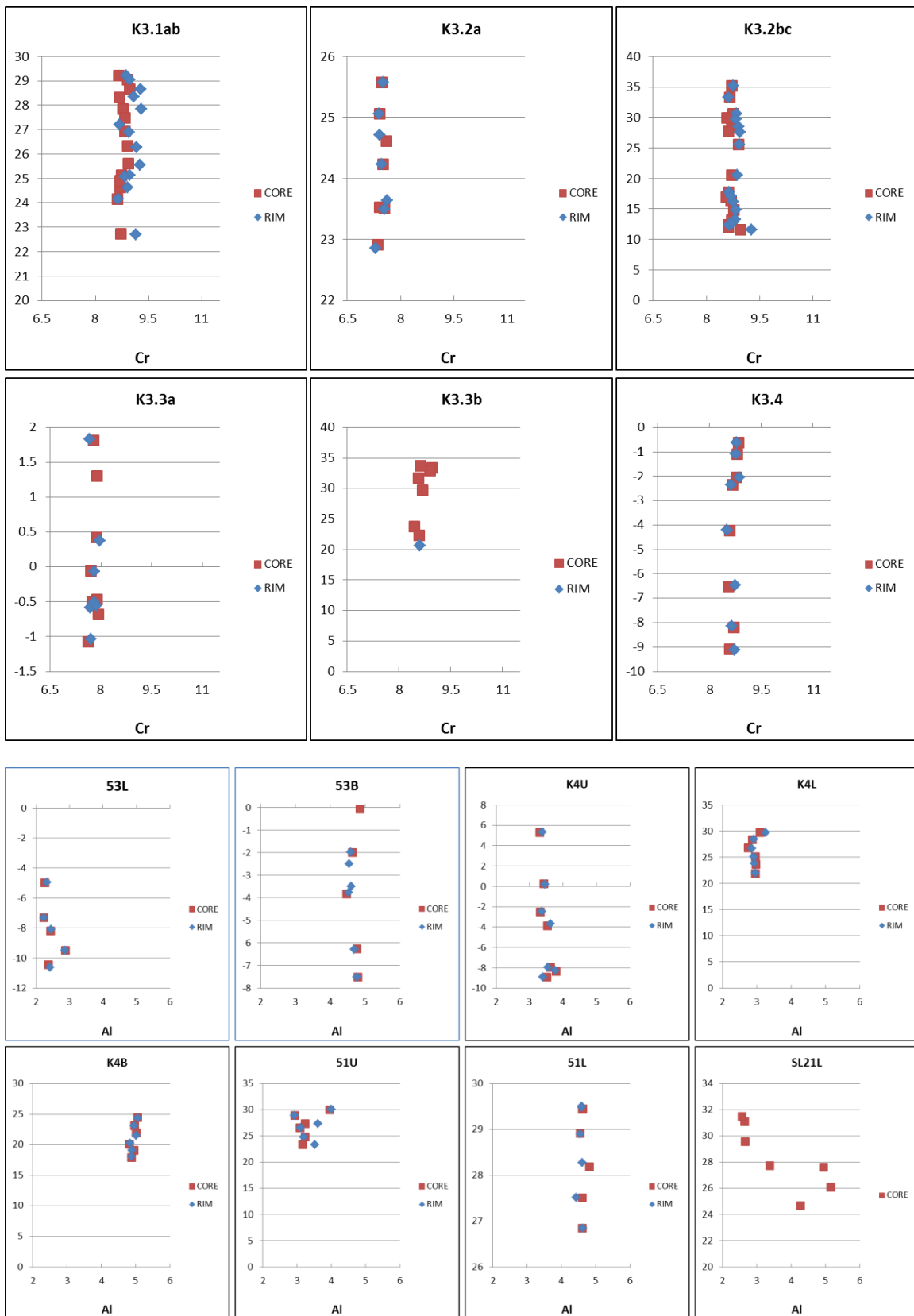


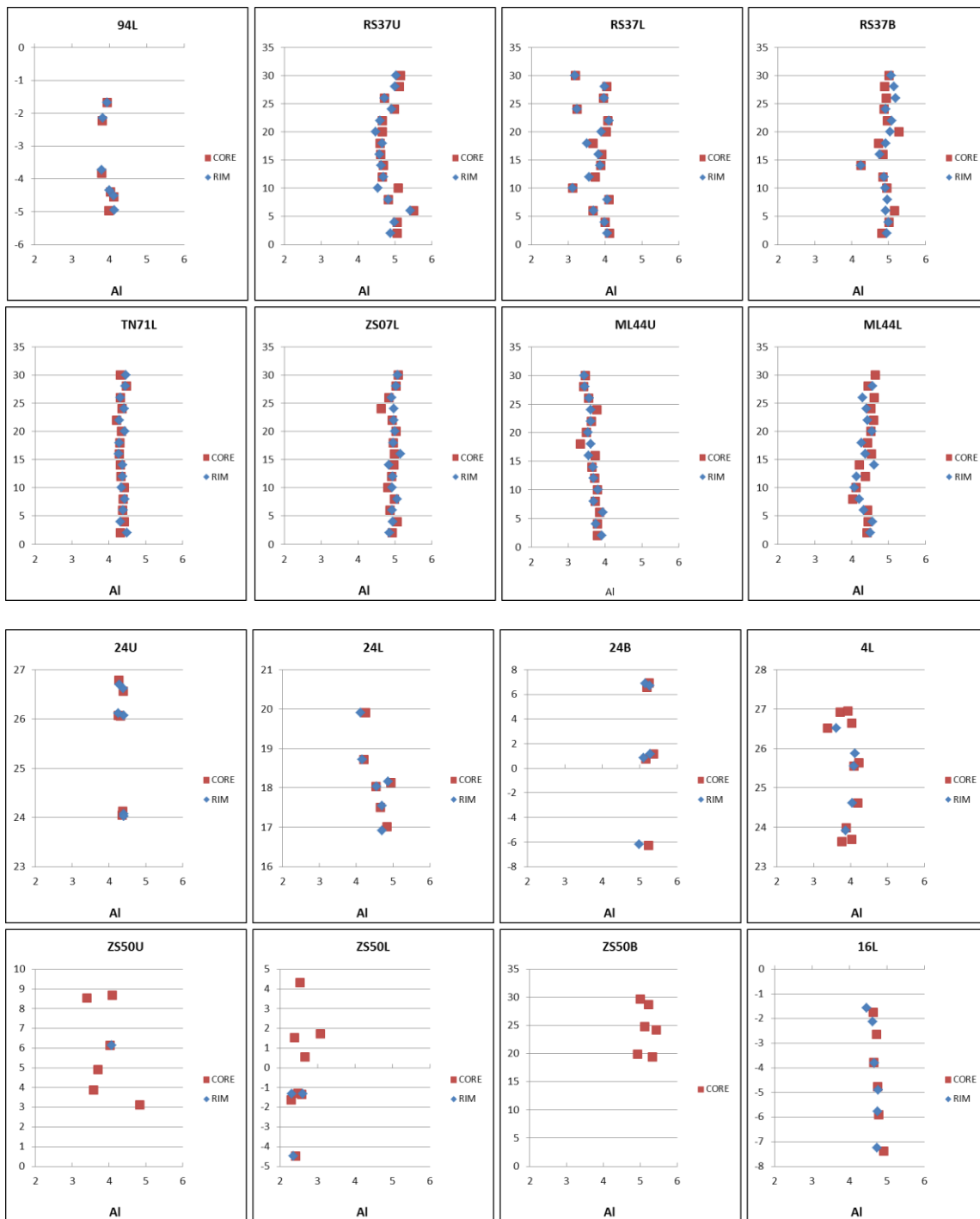


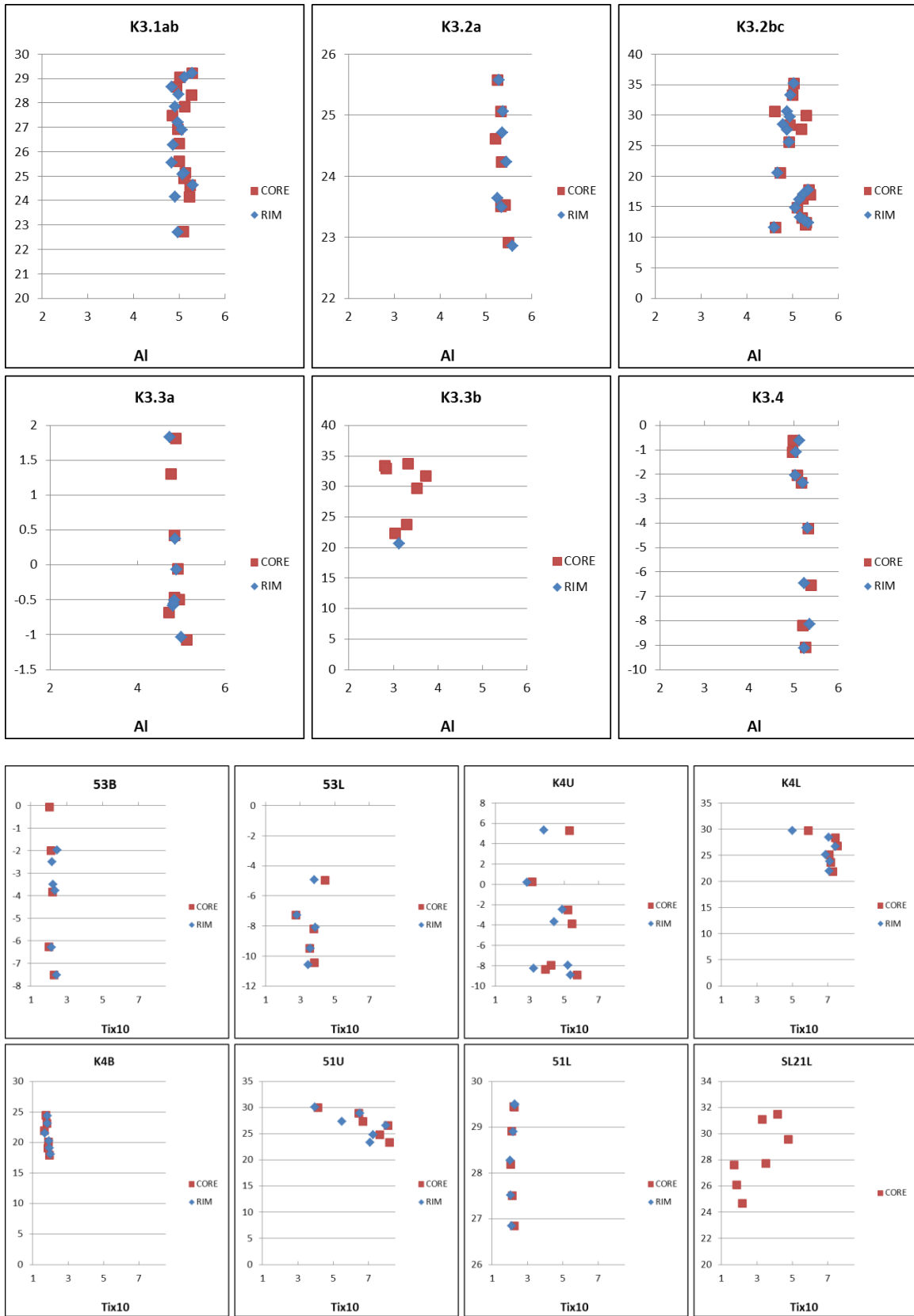


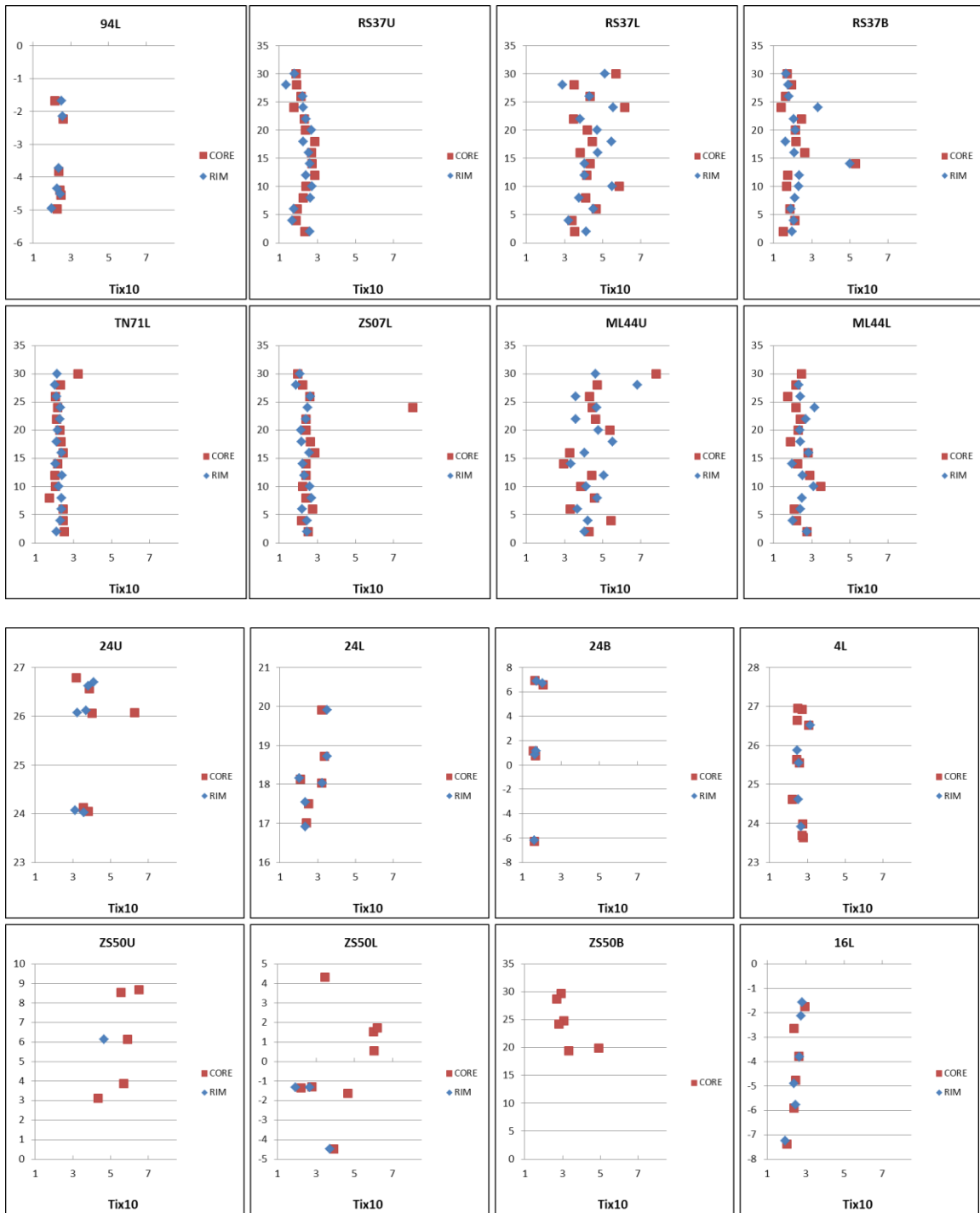


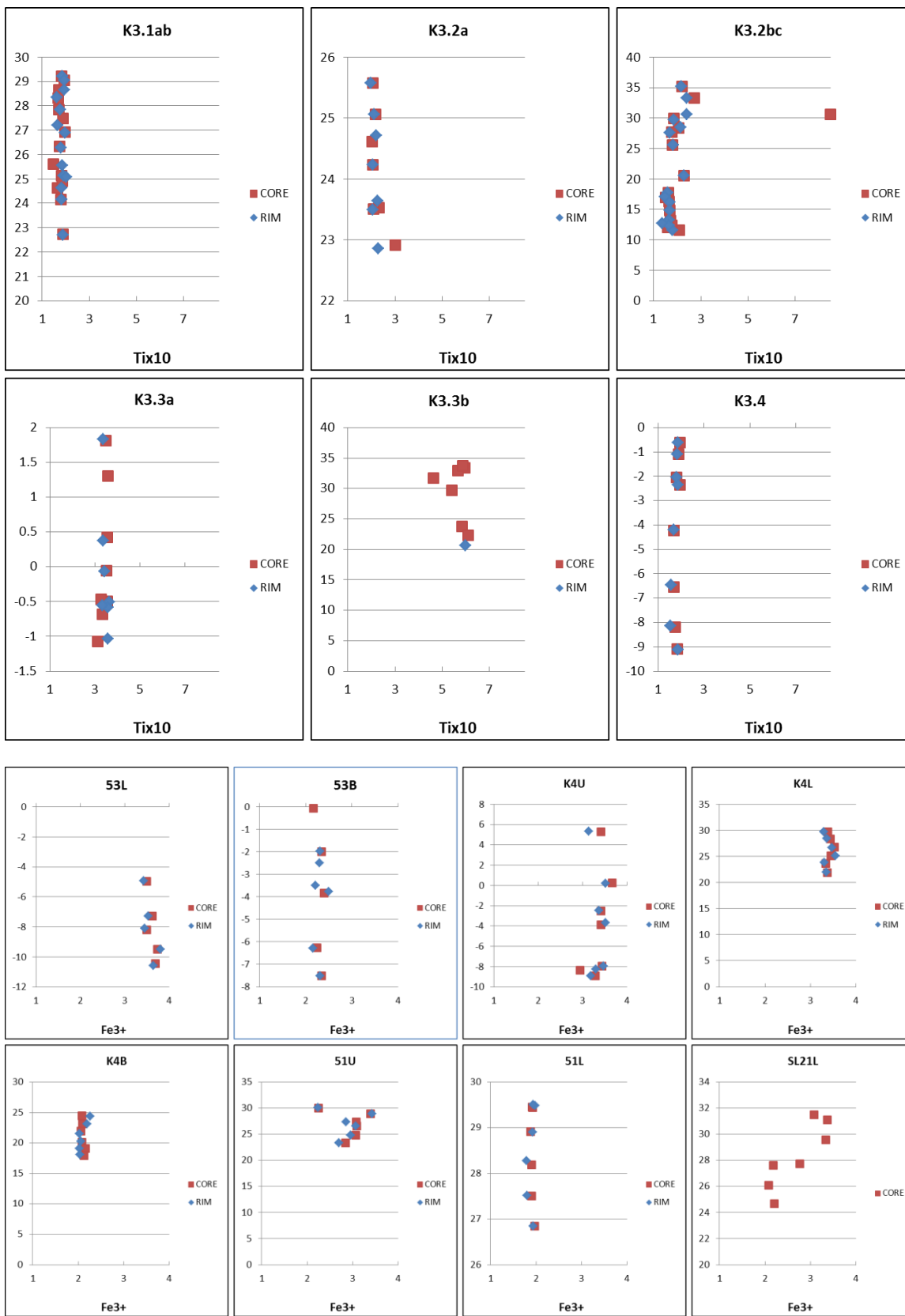


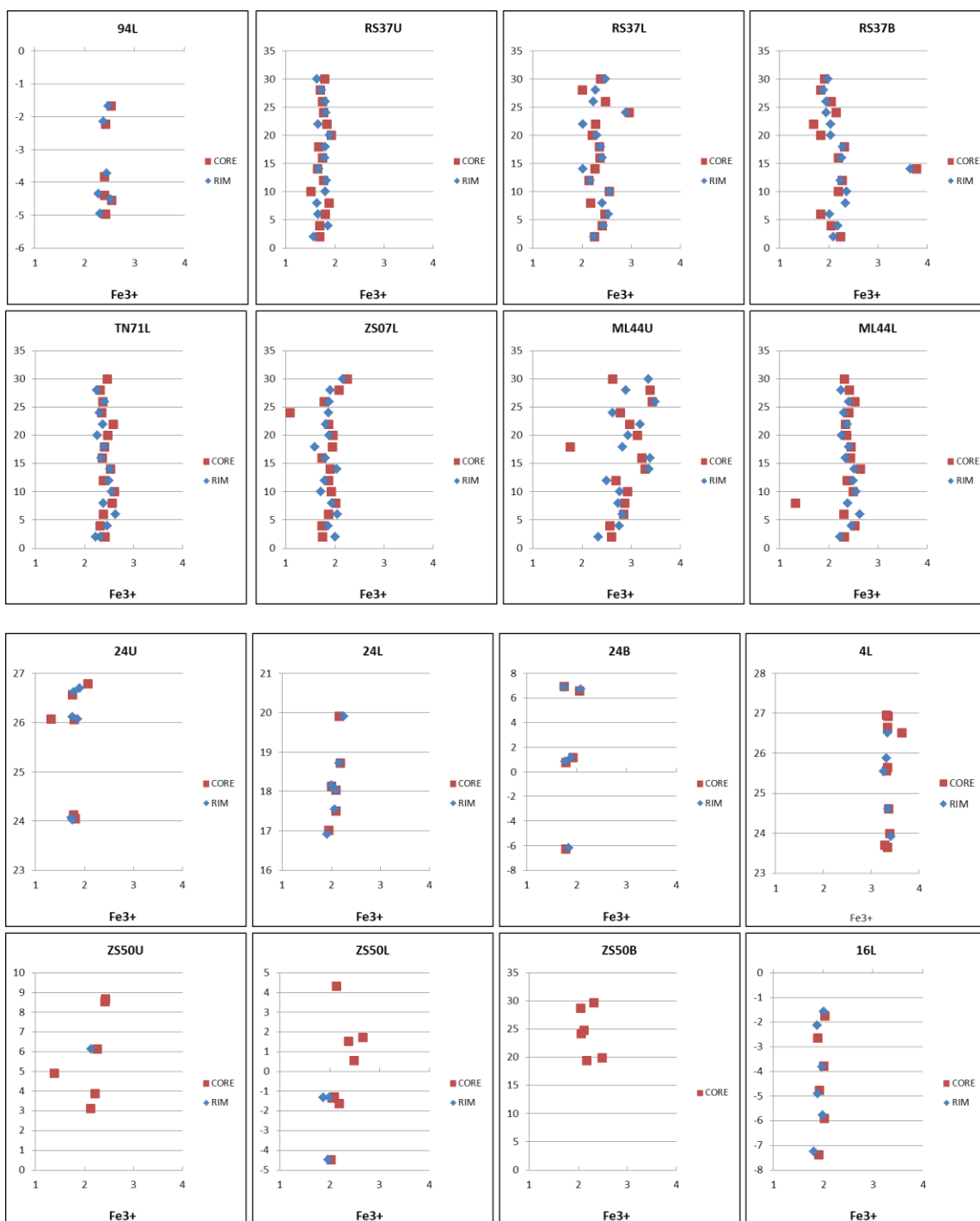


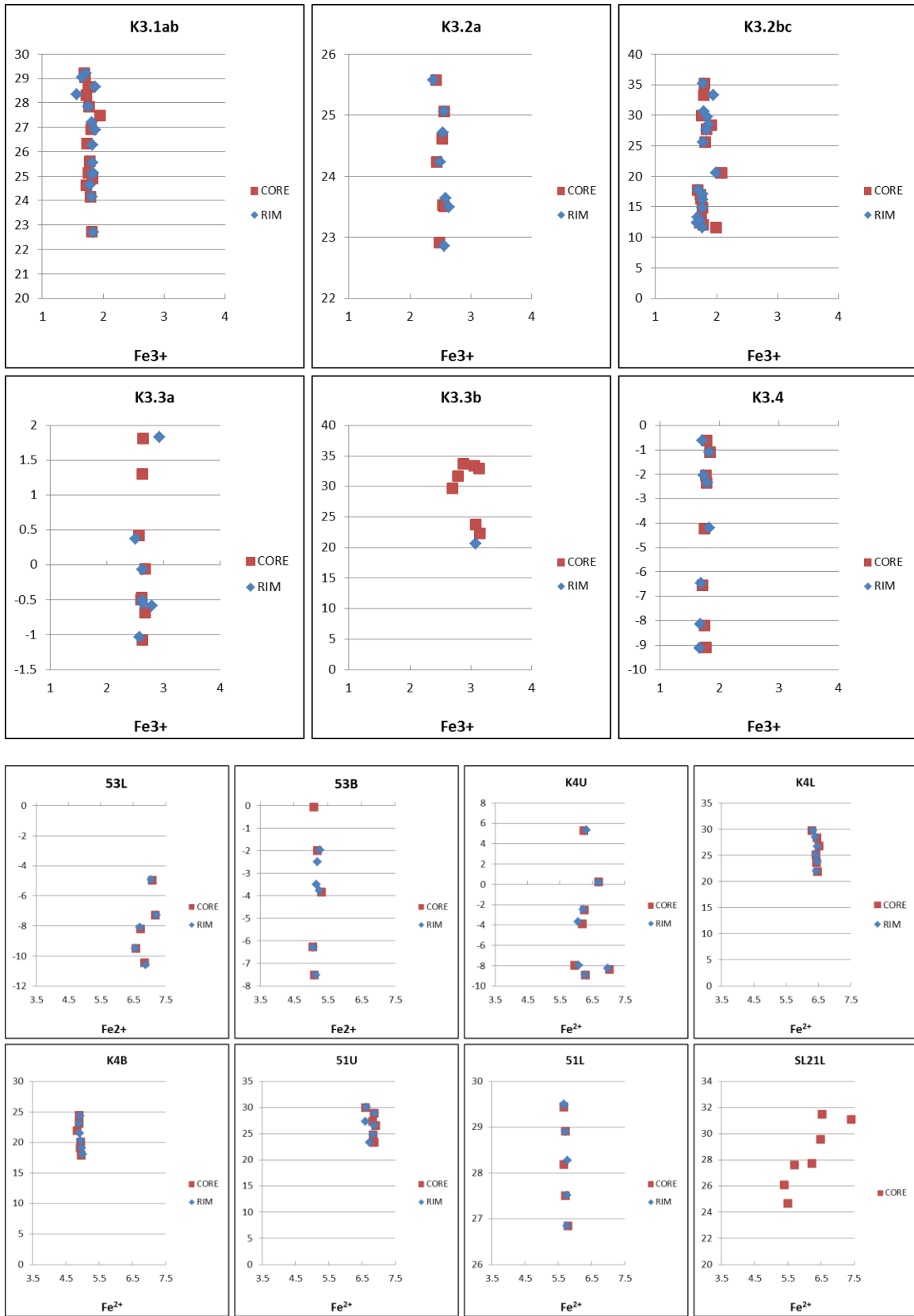


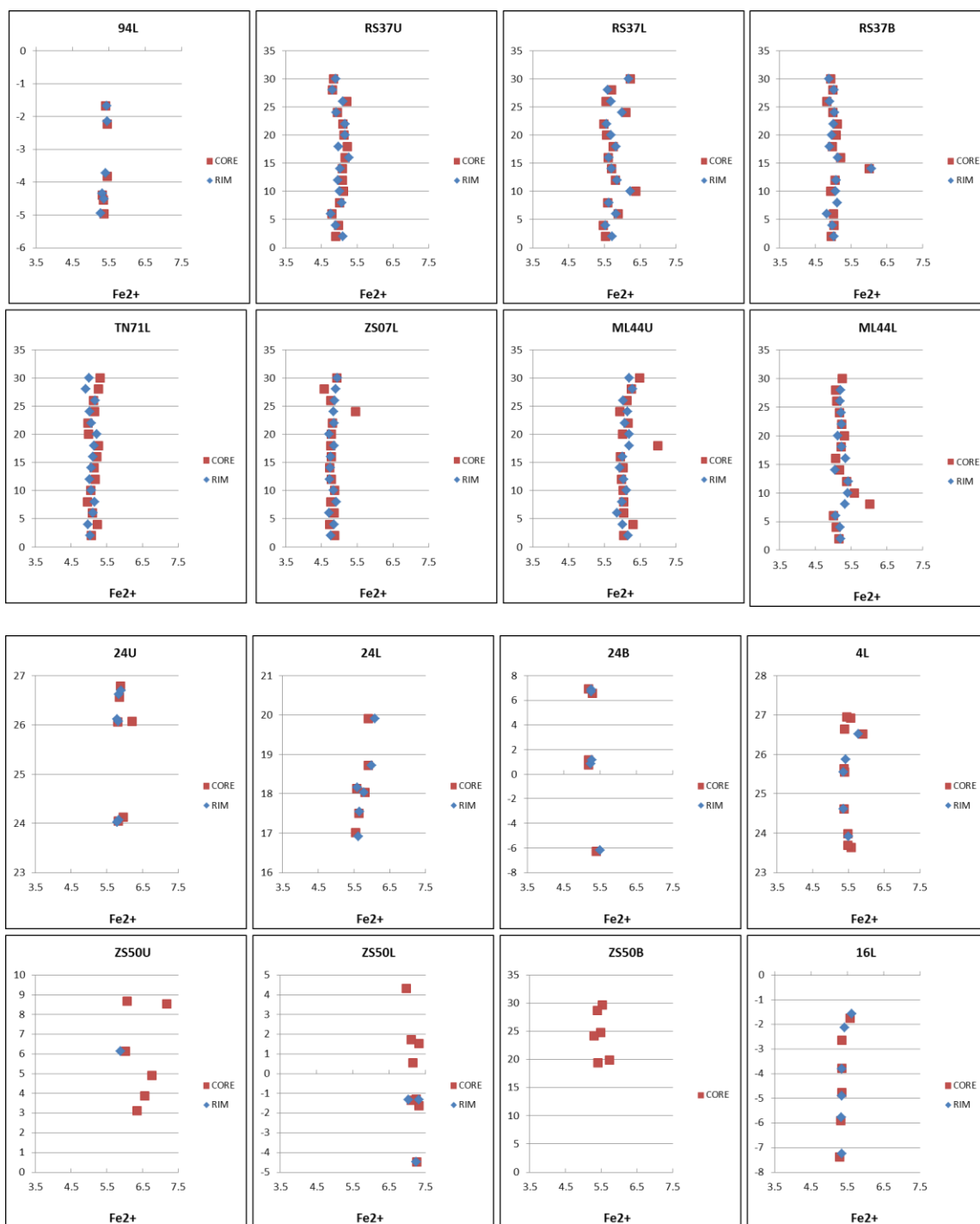












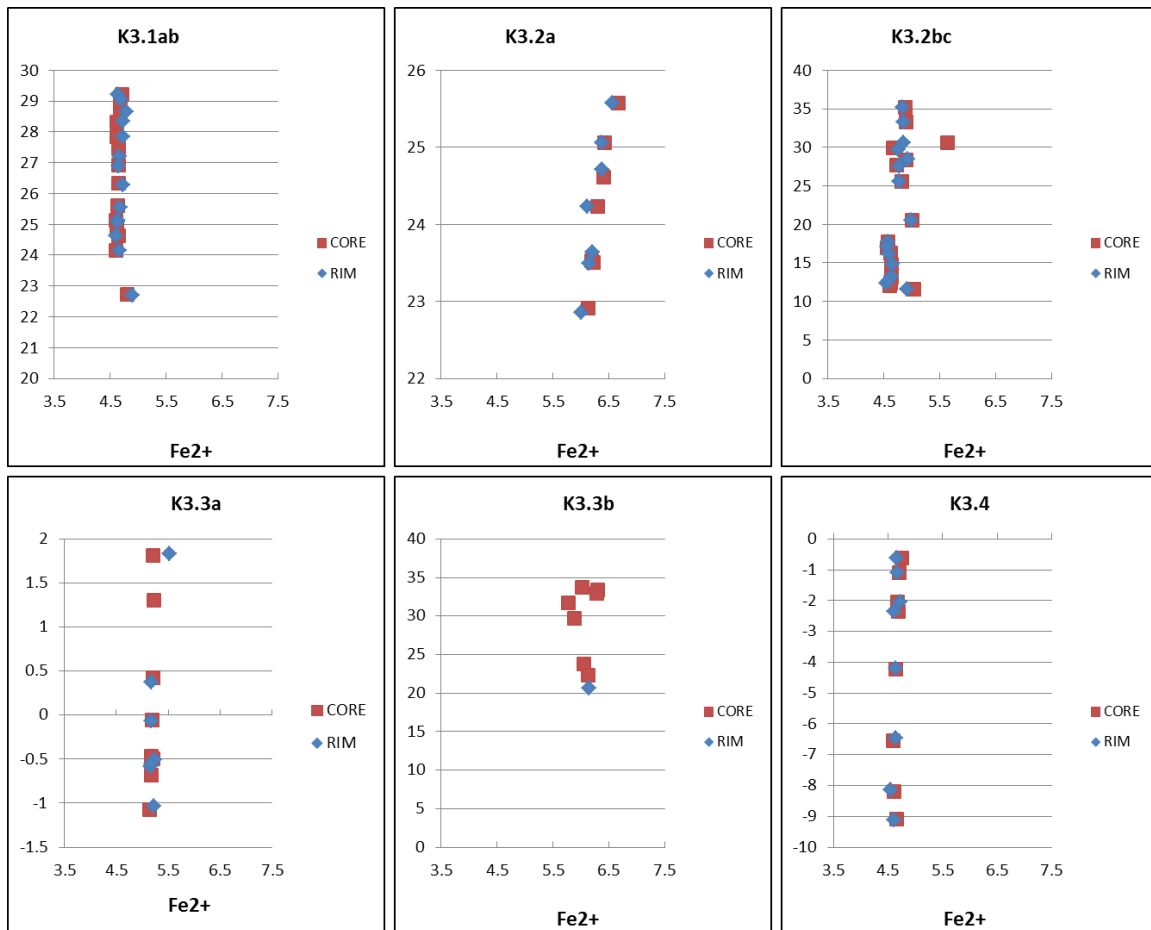


Figure 5.2.1.1 Plots showing vertical sections by height of chromite grain within the individual chromitite layers as measured by the electron microprobe, showing chromite compositions of rims and core analyses for all chromitite layers. Analyses show values for Mg#, Cr# and cations of Mg, Al, Cr, Tix10, Fe³⁺ and Fe²⁺. Y-axis is shown in mm and was originally recorded in microns by the EMPA.

5.2.2 Vertical Trends

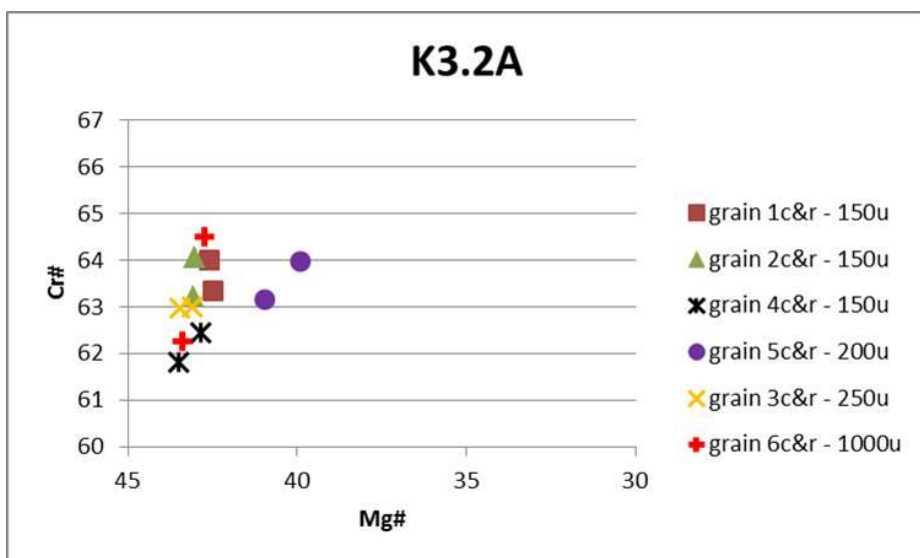
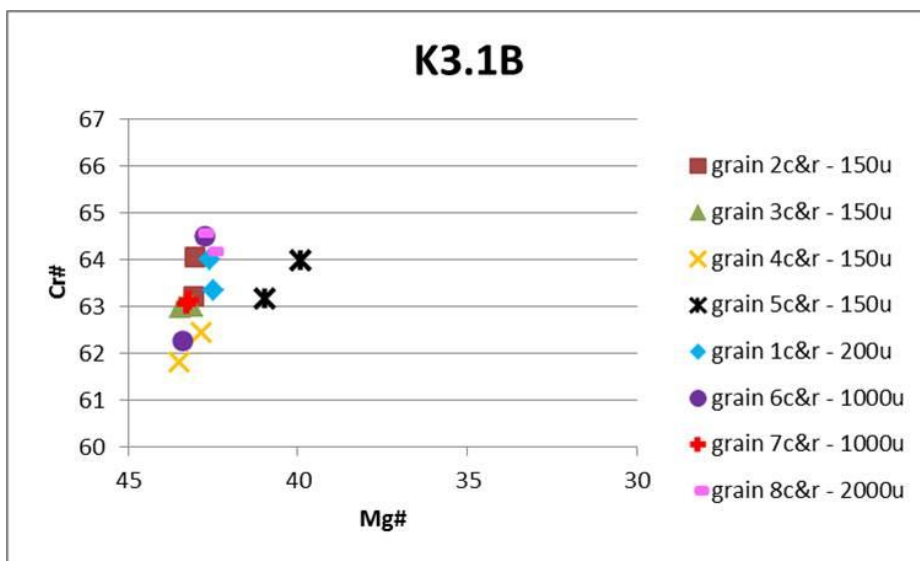
The plots in Figure 5.2.1.1 show that there is very little difference in chemical composition between grains vertically through the chromitite layers.

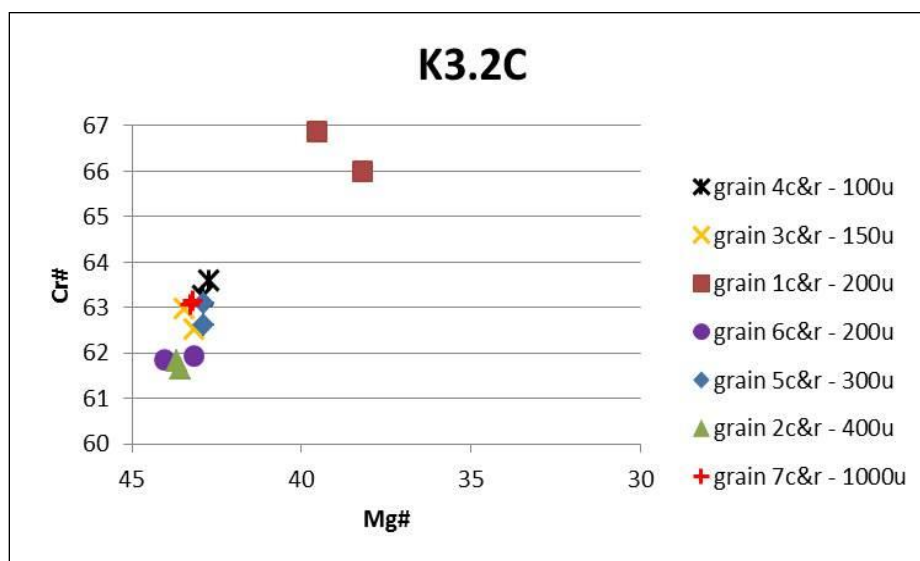
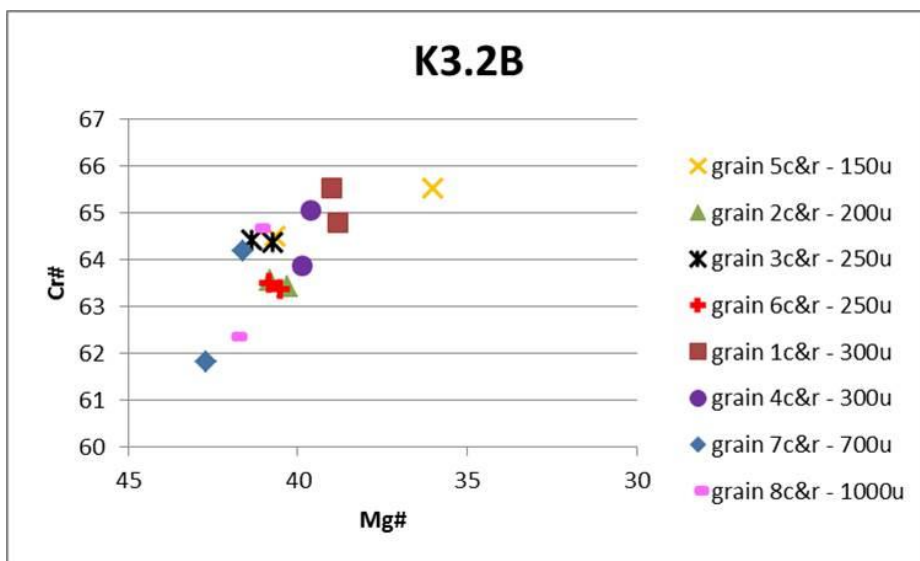
The compositional variations and statistics (averages, standard deviations and relative standard deviation) for the major elements, cations and calculated ratios of chromite grains analysed are presented in Appendix A. The results in this table show that the standard deviation of compositions within each chromitite layer is low indicating relatively homogenous compositions. The relative standard deviation is useful to express the standard deviation as a percentage of the mean. Overall very few samples show a relative standard deviation $\pm 20\%$ for all values. The exception is the relative standard deviations for the Ti cation, with 12 of 32 samples with values of the average $\pm 20\%$. It was noted that the majority of these were from the Type 3 chromitite layer. The reason for these high values is due to the low concentrations of Ti measured in the samples.

Due to this vertical homogeneity, it was possible to take the average of all values within each layer and use this value to represent the chromite composition for each vertical profile.

5.2.3 Chromite grain size

Different grain sizes were analysed in the six samples in Figure 5.2.3.1. The purpose of recording these was to establish if there was any correlation of grain size with the chemical compositions of the chromite grains. In all six samples checked, the chemical compositions had differences of a few percent between large and smaller grain sizes (100 μ to 1000 μ), which revealed that there was no correlation between these and that grain size is independent of composition. This could indicate that annealing did not influence the composition of the grains. It is suggested that the larger grains have been recrystallized and thus homogenising their chemical composition.





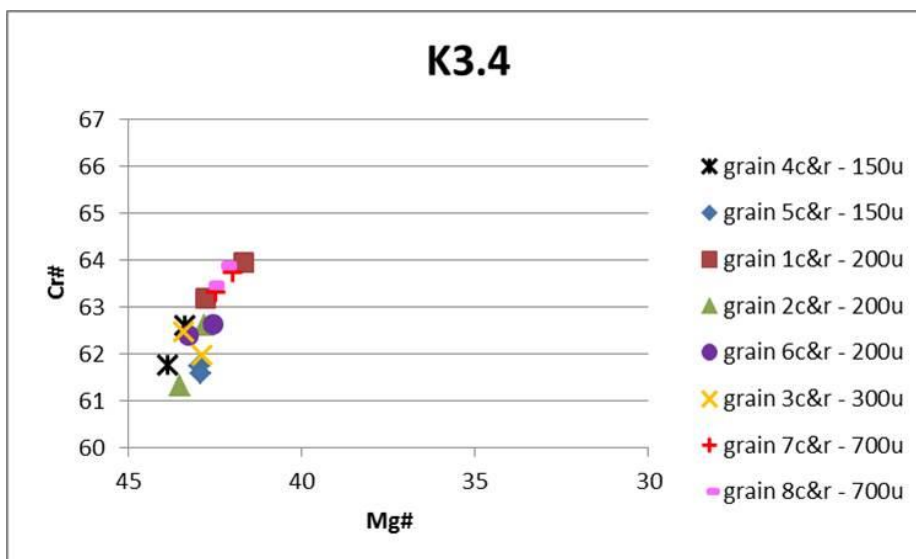
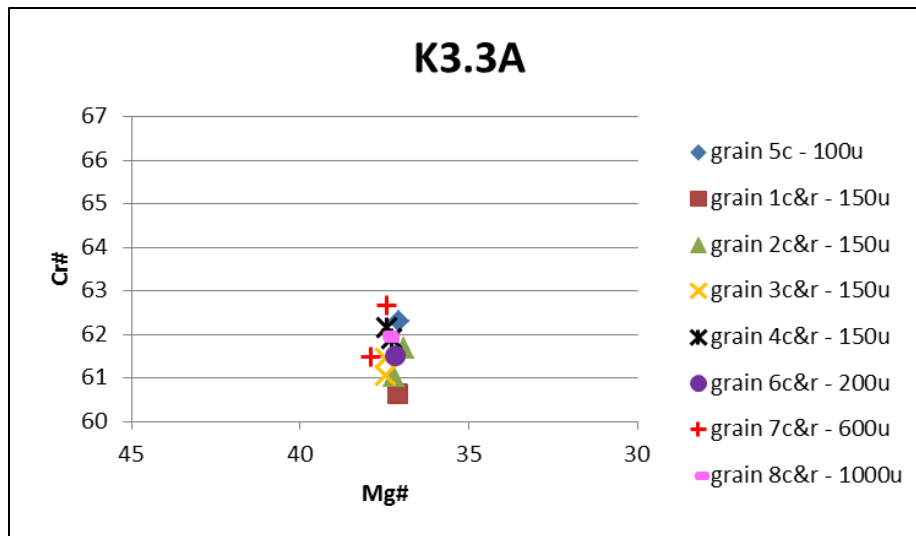


Figure 5.2.3.1 Compositions of different grain sizes analysed within six samples.

5.2.4 Chromite host mineral

Figure 5.2.4.1 shows the chromite compositions as a function of the different host minerals to the chromite grains from Type 2b and 3 chromitite layers. Chromite grains are commonly associated with plagioclase and orthopyroxene minerals. In some cases, the chromite grains can be in contact with both plagioclase and pyroxene minerals.

Occasionally, chromite grains may occur in contact with sulphide minerals and the effect of one such example was analysed to investigate for any systematic difference in chemical composition. Due to the small number of samples taken, there are no patterns that appear and it is assumed that there is no difference in chromite grain chemical composition when located in different host minerals in terms of Cr# and Mg#.

Similarly, Shelembe (2006) concluded in her study that no major compositional differences were observed by chromite grains hosted by different minerals.

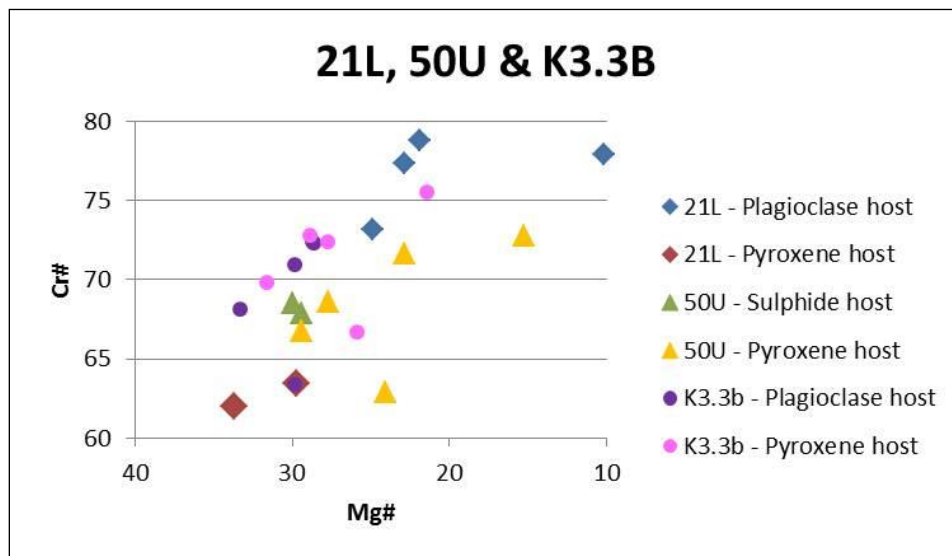


Figure 5.2.4.1 Compositions of different host minerals to chromite grains from Type 2 and 3 chromitite layers.

5.2.5 Chromite grain textures

Figure 5.2.5.1 shows the compositional variability of Mg# for chromite grains within chromitite layers that have amoeboid or idiomorphic grain textures, including data from Vukmanovic et al. (2013) study. Eales & Reynolds (1986) identified these amoeboid

textures as curved, lobate, and cusped forms which they interpret to represent coalescence and annealing of originally disseminated interstitial finer grains. In comparison, idiomorphic grains are grains that have shapes whose crystalline growth has not been interfered with.

In this study, no individual analyses were done on amoeboid and idiomorphic grains coexisting in the same layer. Data were plotted based on observations under the microscope of layers containing amoeboid grains and those without. These textures were only found in Types 1 and 2a chromitite layers. Vukmanovic et al. (2013) concluded from their study that the lower chromitite layer (equivalent to Type 2b) of the Merensky Reef in the Rustenburg section had both populations of amoeboid and idiomorphic grains, and that the upper chromitite layer (equivalent to Type 3) only contained idiomorphic grains. This study is in agreement with that observation as no amoeboidal grains were found in Type 3 chromitite layers but this may be due to the fact that only two thin sections were available for this type.

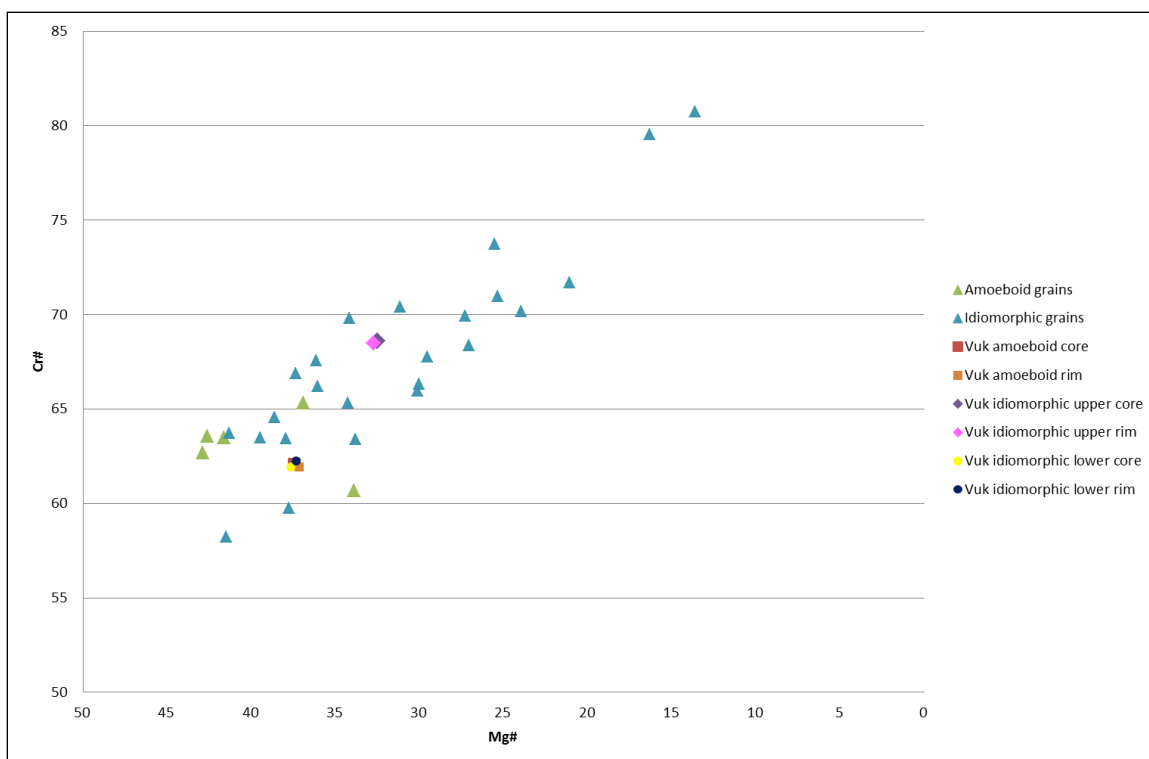


Figure 5.2.5.1 Average compositions of each sample values for amoeboid grains found in chromitite layers Type 1 and 2a and idiomorphic grains from all other layer types. Comparative data are from Vukmanovic et al. (2013).

5.2.6 Cation Compositions

Element oxides were converted to cations in the chromite grains using a program of spinel stoichiometric calculations. Cation compositions for all chromitite layers plotted against Mg# are presented in Figure 5.2.6.1. With decreasing Mg#, Cr cations remain mostly constant, Fe^{3+} and Fe^{2+} cations show enrichment and Al shows depletion. Ti cations show little variation, but the overall trend is one of enrichment.

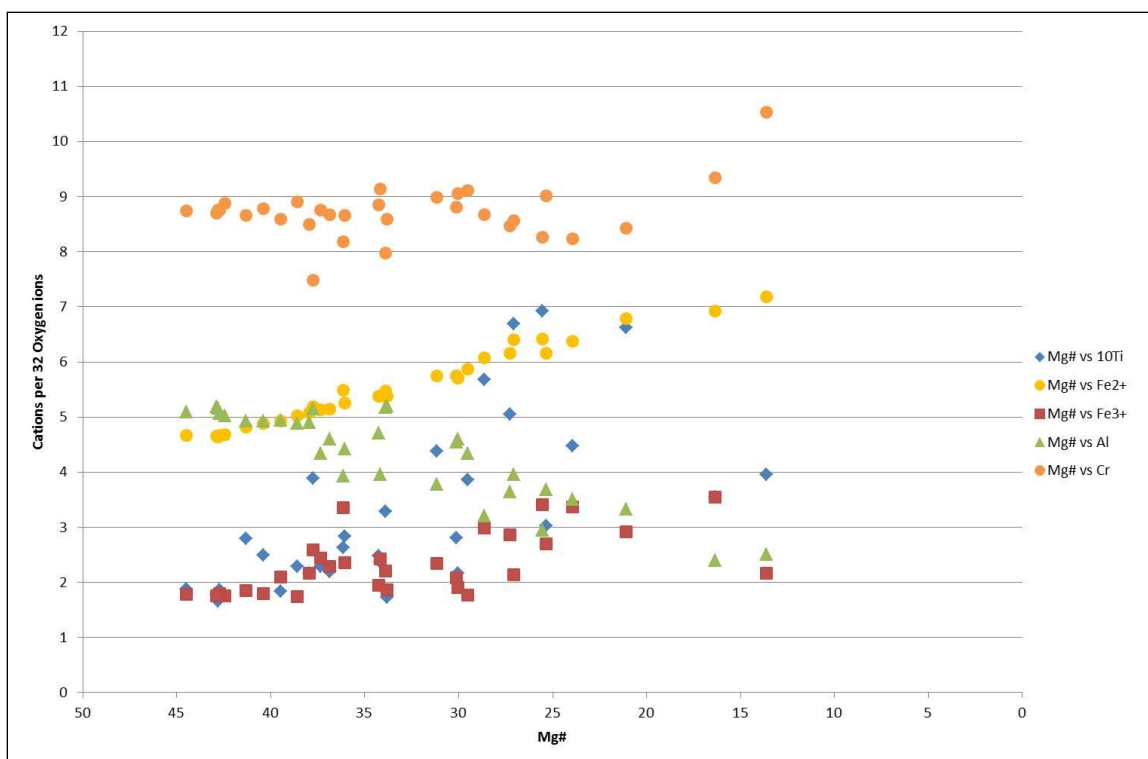
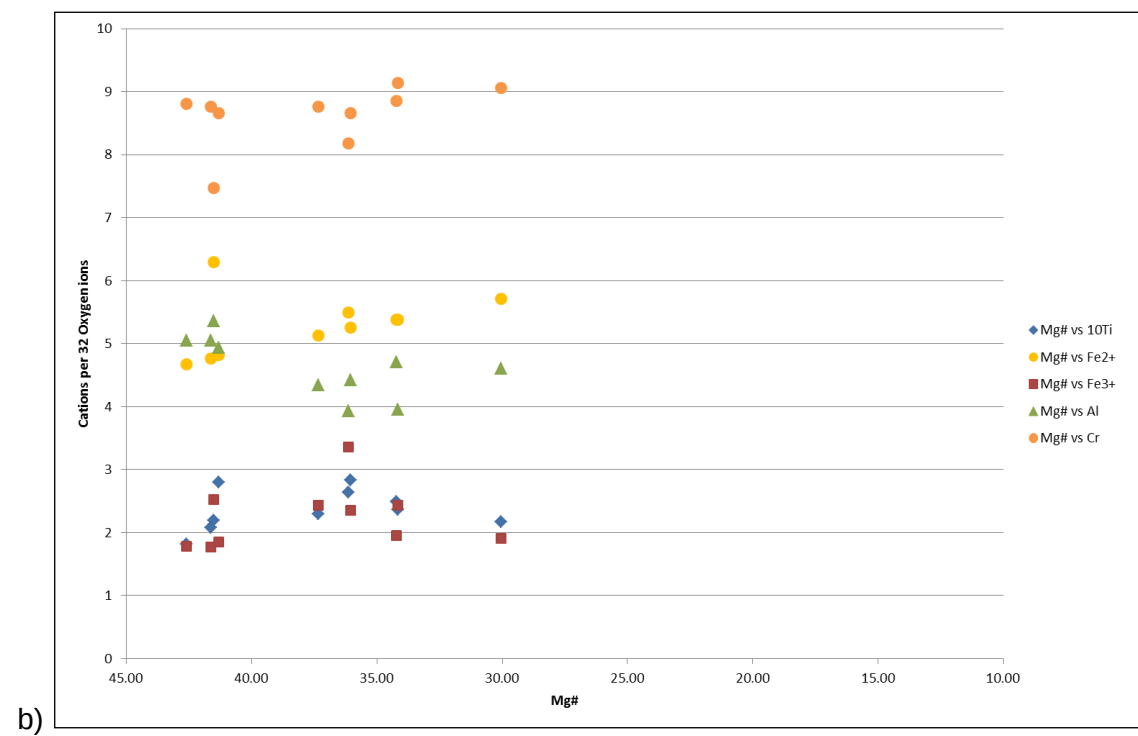
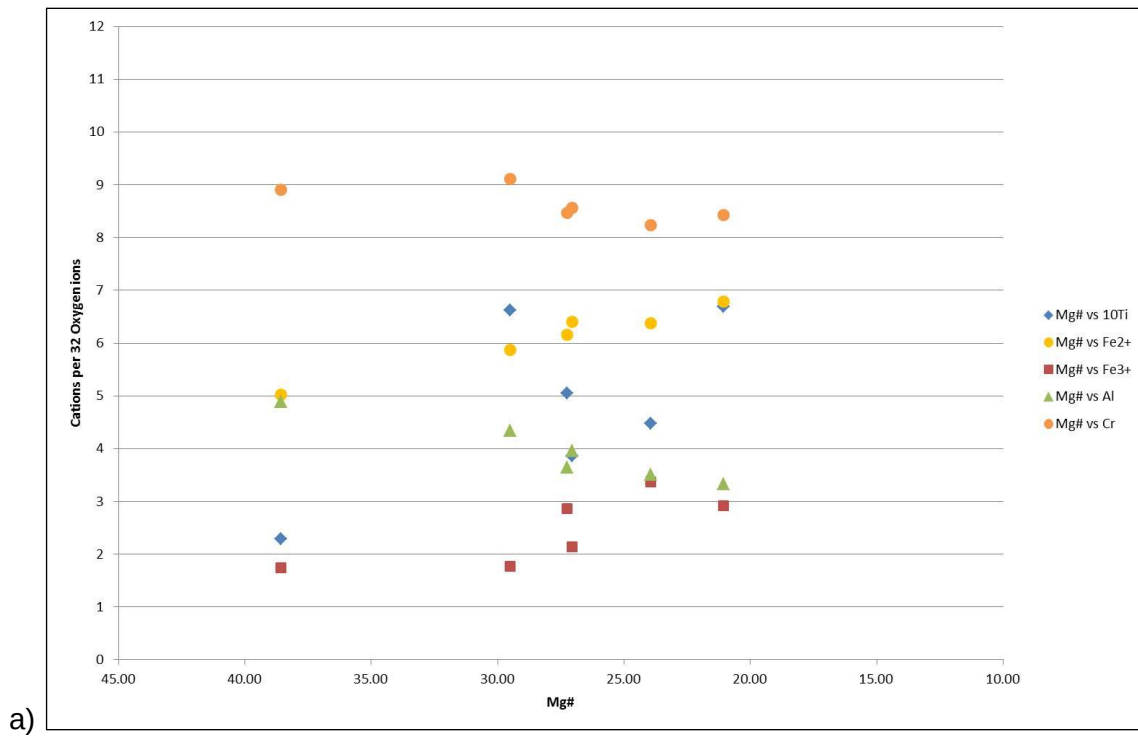


Figure 5.2.6.1 Plot of Cations per 32 oxygen ions of Ti x10, Fe²⁺, Fe³⁺, Al and Cr for all chromitite layer types versus Mg#.

When separating the data into the four different layer types, subtle differences are noted. The Type 1 chromitite layer has a more restricted range in Mg# than the other layer types (Figure 5.2.6.2d). Overall little variation is noted in the cation compositions with a slight enrichment trend observed for Fe²⁺ and Fe³⁺. For the Types 2a and 2b (Figure 5.2.6.2b&c), with decreasing Mg#, a slight enrichment in Fe³⁺ and Ti, Al cation depletion and a noticeable Fe²⁺ is noted. Type 3 chromitite layers (Figure 5.2.6.2a) generally have a much lower Mg#. It is possible that no trends were observed for Type 3 chromitite layers because only six layers were analysed. For all layer types the Cr cation values remain mostly constant.



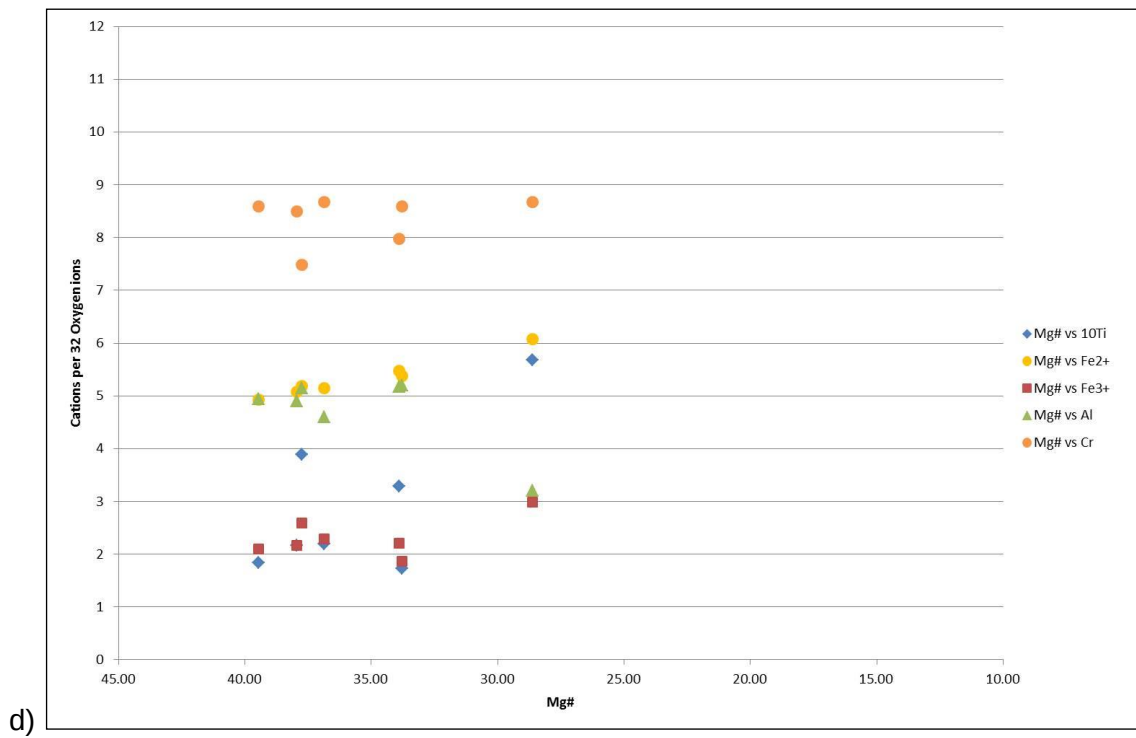
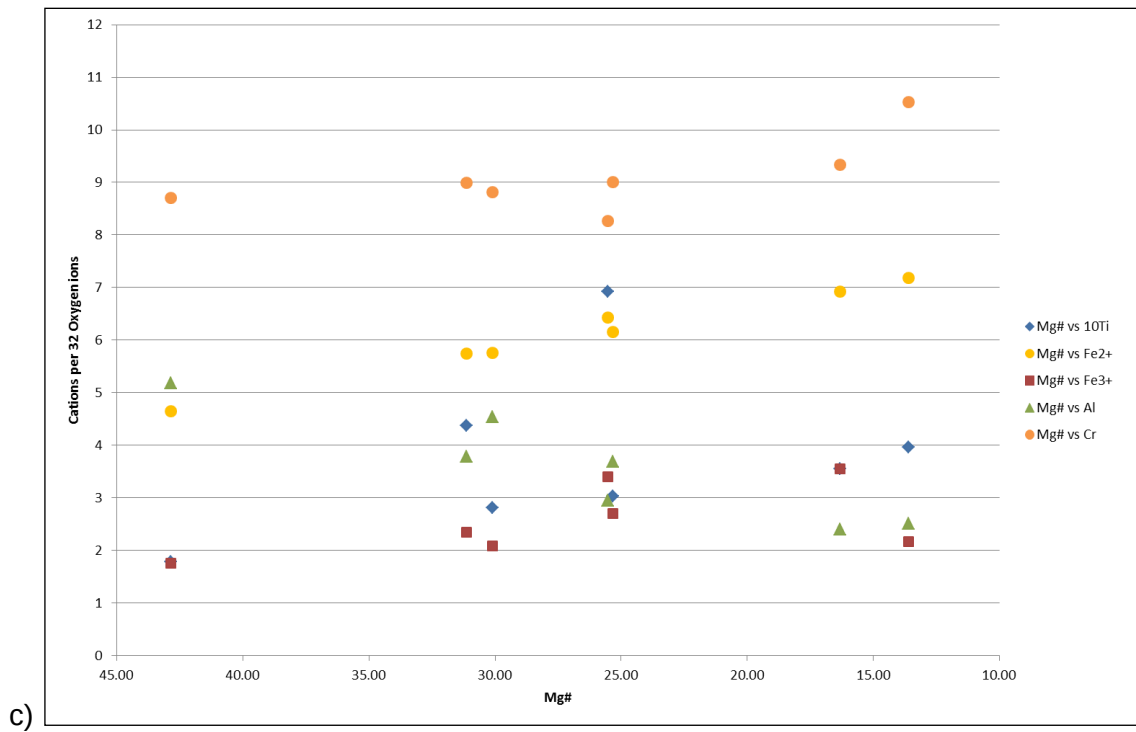


Figure 5.2.6.2 Plots showing cations per 32 oxygen ions of Ti x10, Fe²⁺, Fe³⁺, Al and Cr for the Type 3 chromitite layers (a), the Type 2a chromitite layers (b), the Type 2b chromitite layers (c) and the Type 1 chromitite layers (d) versus Mg#.

Cation compositions for all chromitite layers plotted against Cr# are presented in Figure 5.2.6.3. With decreasing Cr#, Al and Mg cations show enrichment, whereas Fe²⁺ and Fe³⁺ cations show depletion. Ti cations show little variation, but the overall trend is one of enrichment.

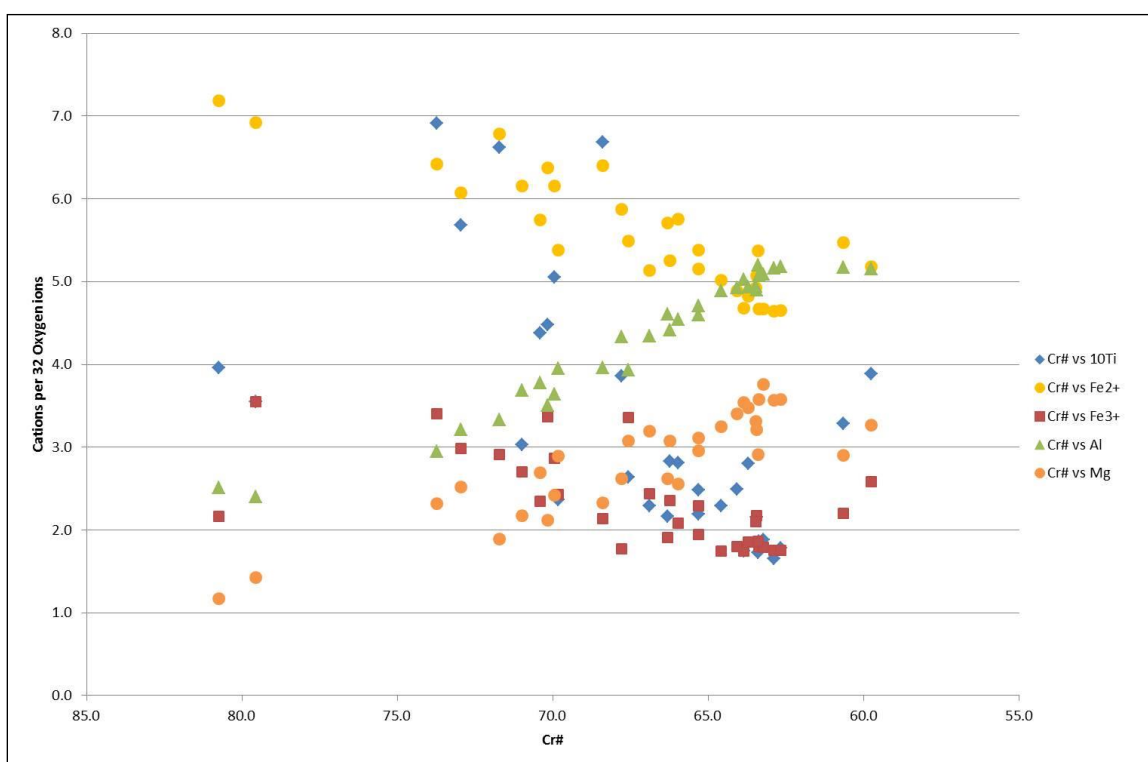
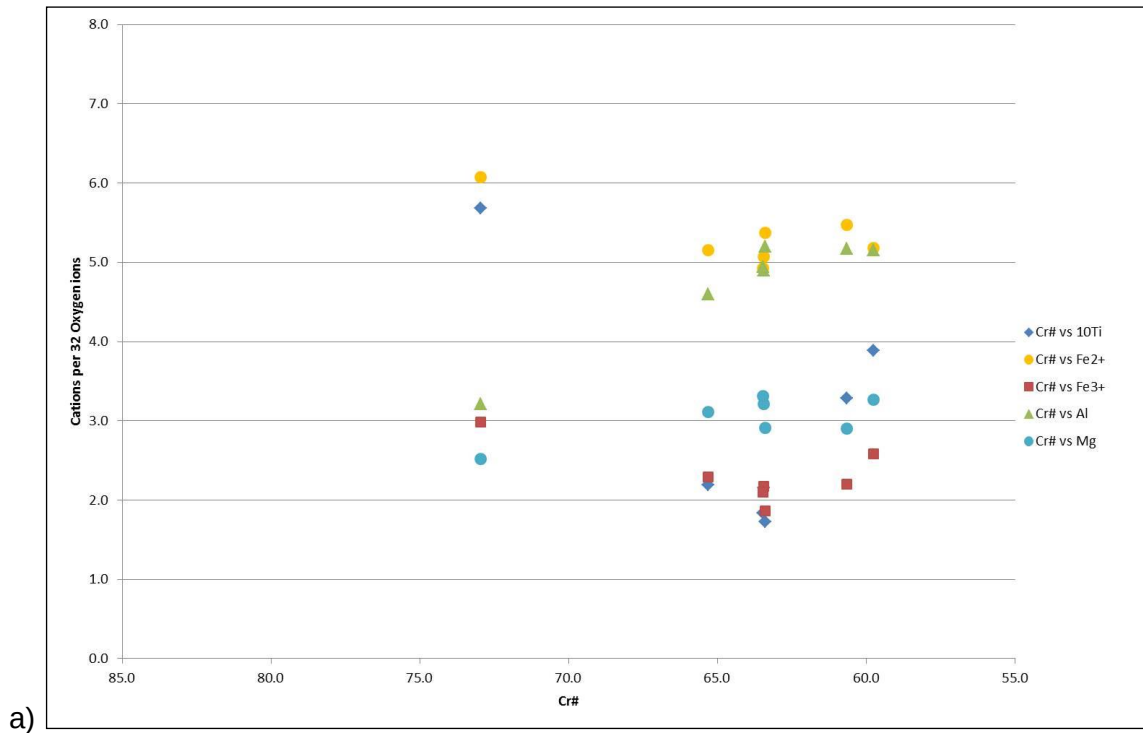
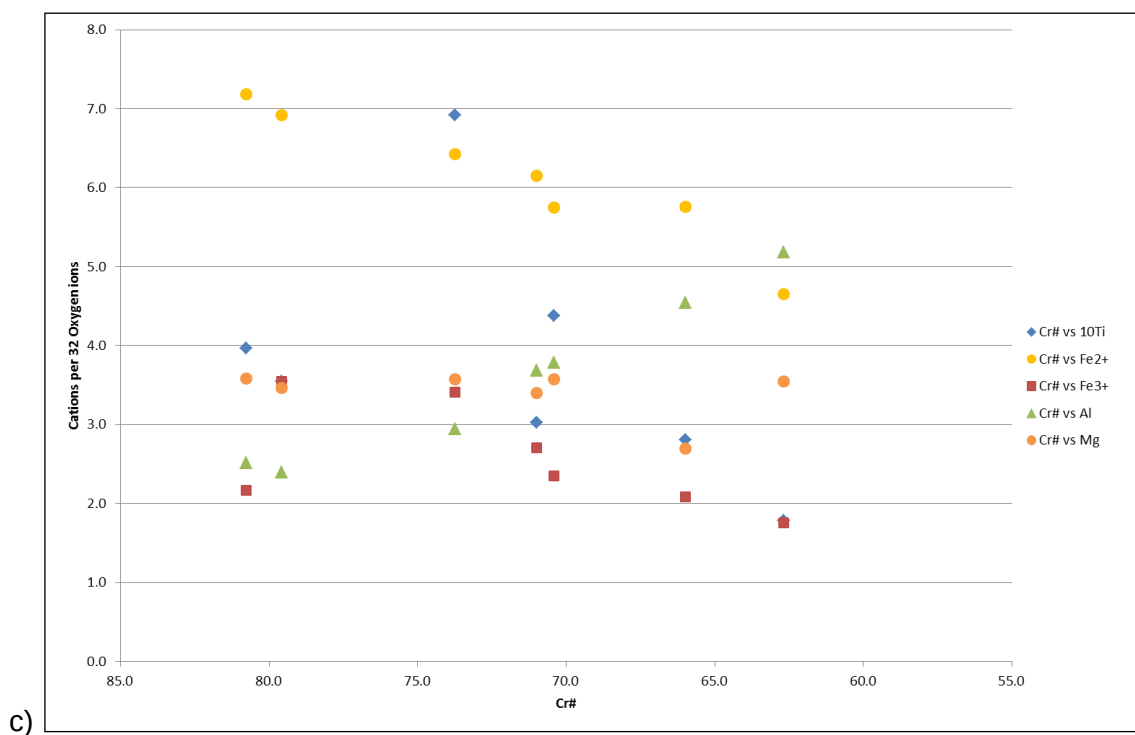
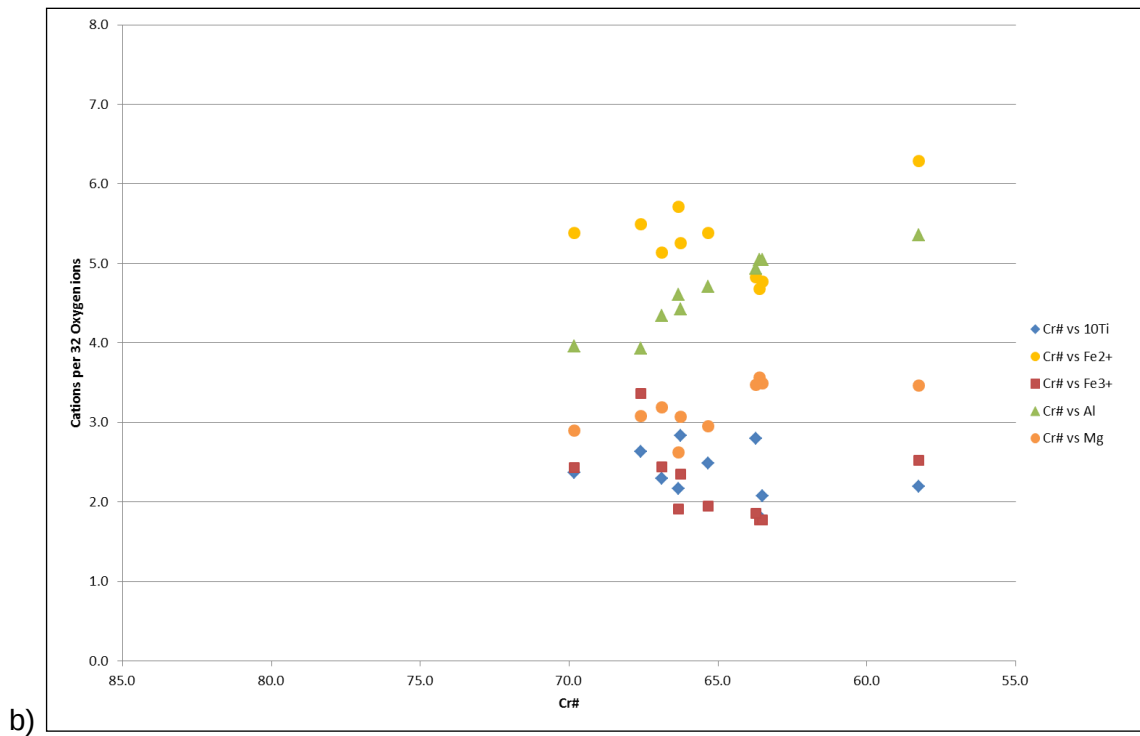


Figure 5.2.6.3 Plot of cations per 32 oxygen ions of Ti x10, Fe²⁺, Fe³⁺, Al, Cr and Mg for all chromitite layer types versus Cr#.

When separating the data into the four different layer types, similar enrichment and depletion trends are observed. For the Type 1 chromitite layer (Figure 5.2.6.4d), very little change in cations is observed. Type 2a (Figure 5.2.6.4b) and 2b chromitite layers

(Figure 5.2.6.4c) show strong Al enrichment with slight depletion in the Fe^{2+} and Fe^{3+} cations. The Type 3 chromitite layers (Figure 5.2.6.4a) show the same depletion in the Fe^{2+} and Fe^{3+} cations. For the four chromitite layer types, the Cr# variation differs greatly. For most samples, the Cr cation values do not vary much with changing Cr#, whereas strong enrichment trends for Al are observed. It is therefore this variation in Al and not Cr that is controlling the Cr#.





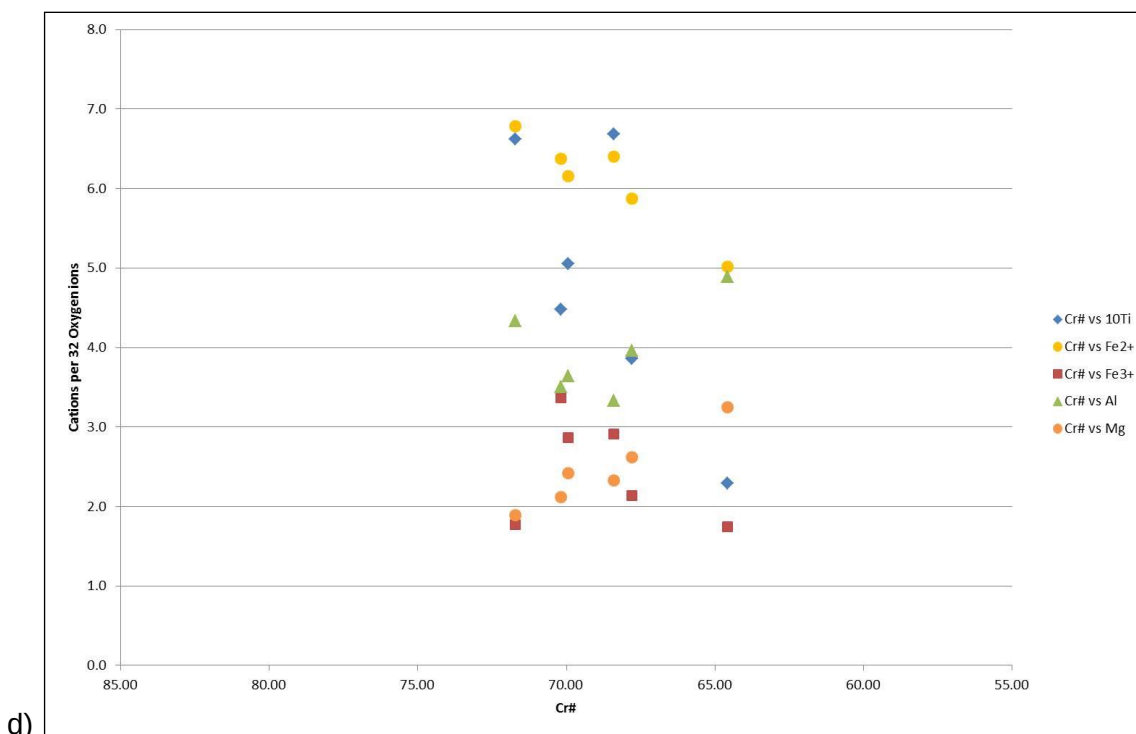


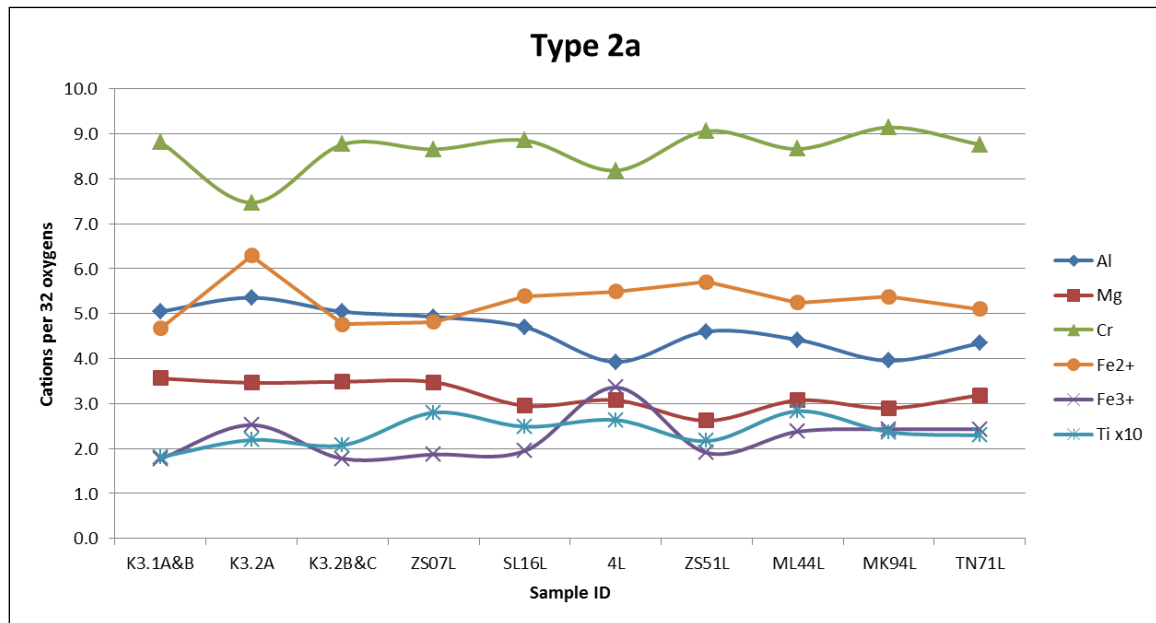
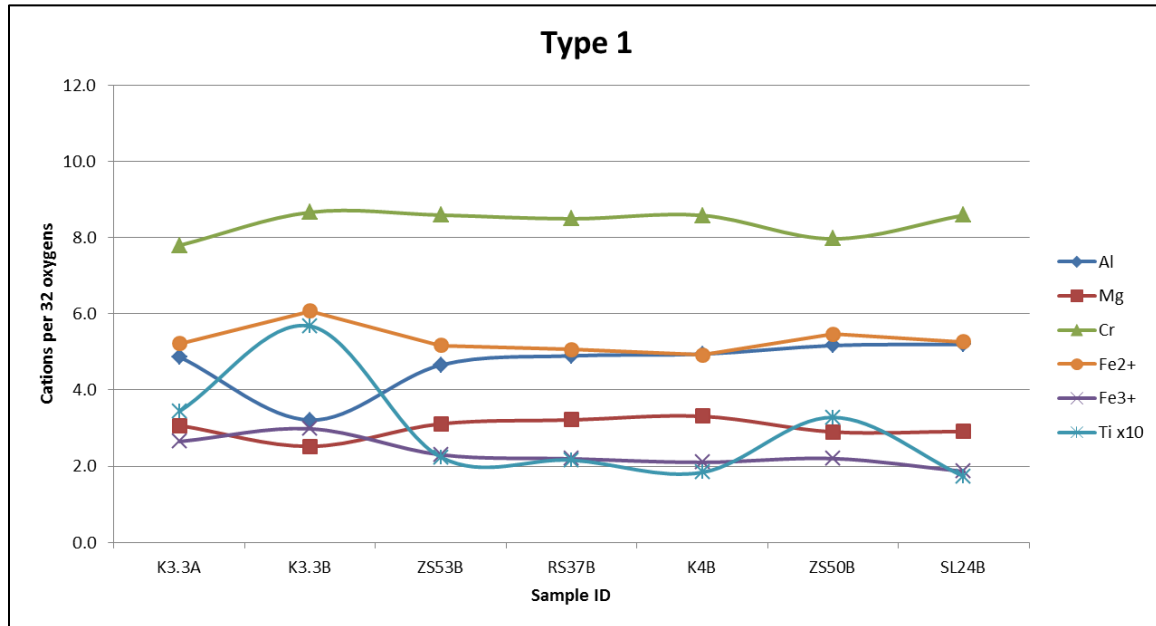
Figure 5.2.6.4 Plots showing cations per 32 oxygen ions of Ti x10, Fe²⁺, Fe³⁺, Al and Cr for the Type 3 chromitite layers (a), the Type 2a chromitite layers (b), the Type 2b chromitite layers (c) and the Type 1 chromitite layers (d) versus Cr#.

5.2.7 Lateral variation in Compositions

All chromitite layers were sorted by X-coordinate, in a west to east direction along strike, to test whether the compositions of chromitite layers can be correlated across facies (Figure 5.2.7.1). The sample locations are shown in Figure 3.1.1.

Type 3 (Figure 5.2.7.1) and Type 1 (Figure 5.2.7.1) chromitite layers show comparable values across the west to east profile with minor fluctuations observed for Fe³⁺. Type 2 (Figure 5.2.7.1) chromitite layers show a large variation across the west to east profile. The Cr and Ti cations remain relatively constant; Al, Mg and Fe³⁺ cations show undulations particularly in sample 4L for Type 2a and K4L for Type 2b with zones of

stability in the immediate west and east of the profile. The compositions at the west and east ends of these sections are essentially the same which shows that there is no significant lateral trend in composition.



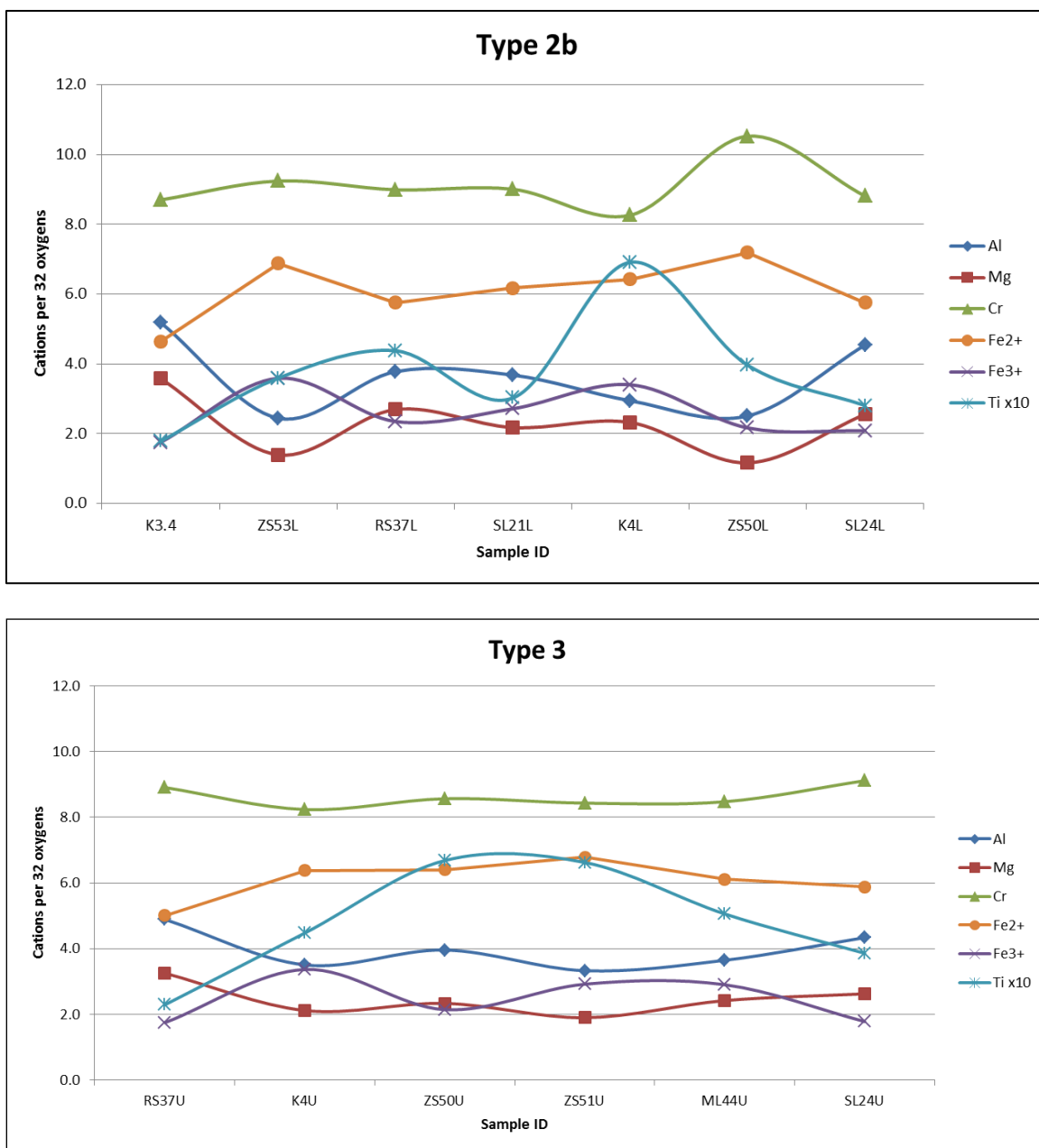
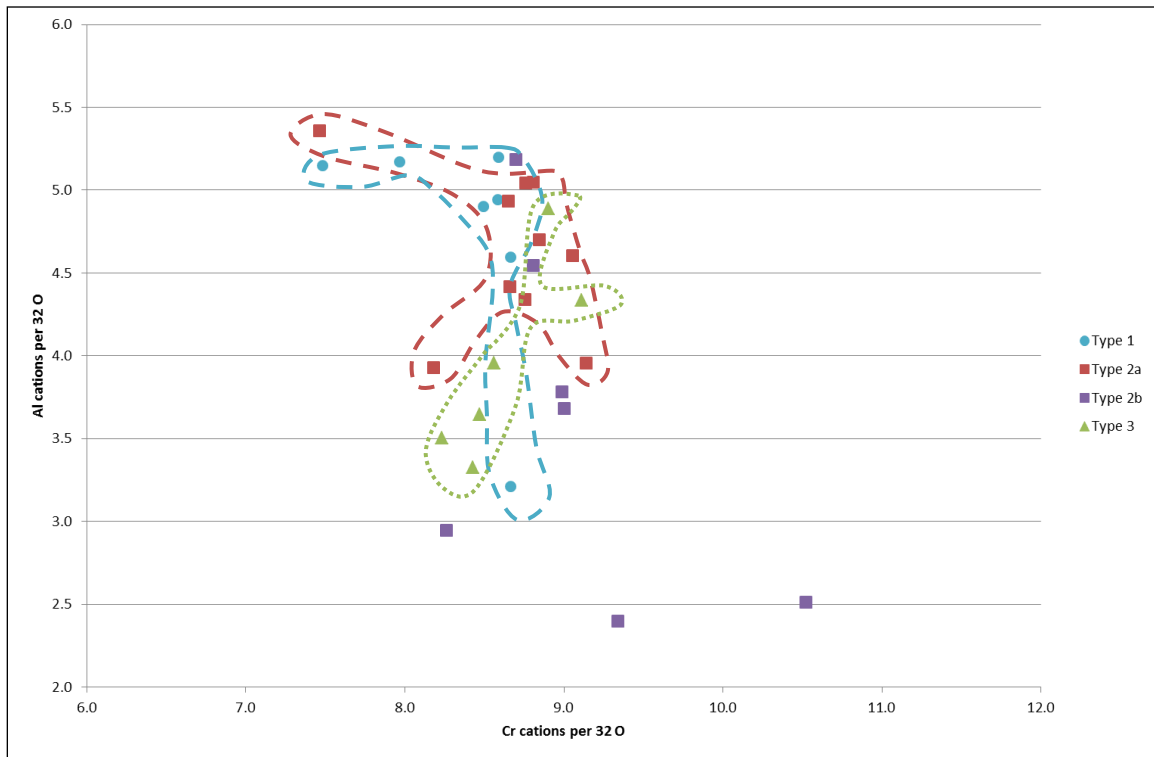


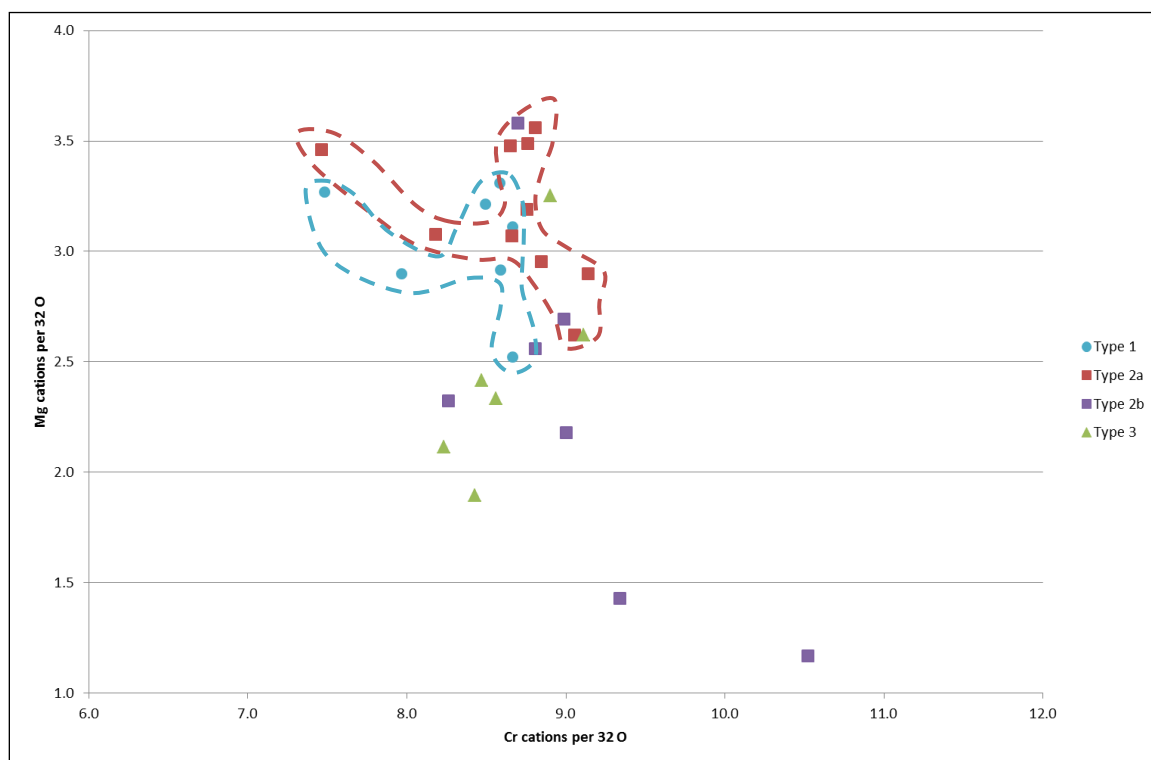
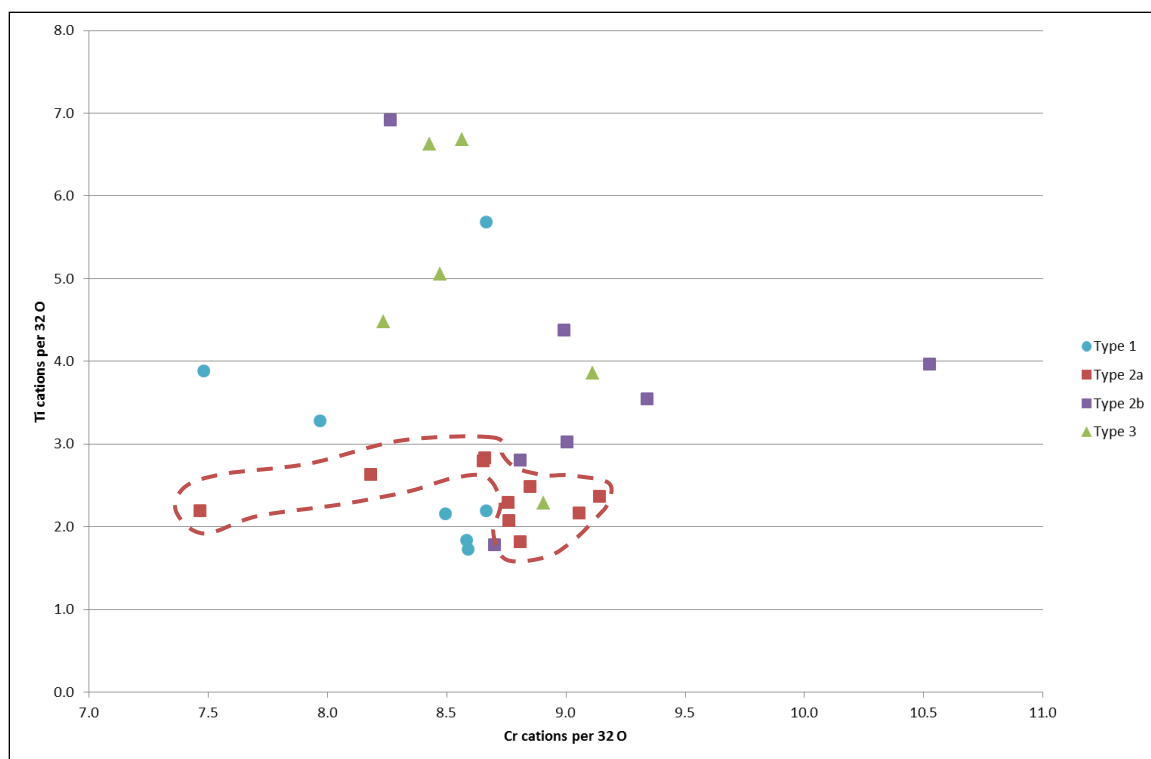
Figure 5.2.7.1 Plots showing west to east profiles of cations per 32 oxygen ions of Al, Mg, Cr, Fe^{2+} , Fe^{3+} and Ti x10 for all four chromitite layers.

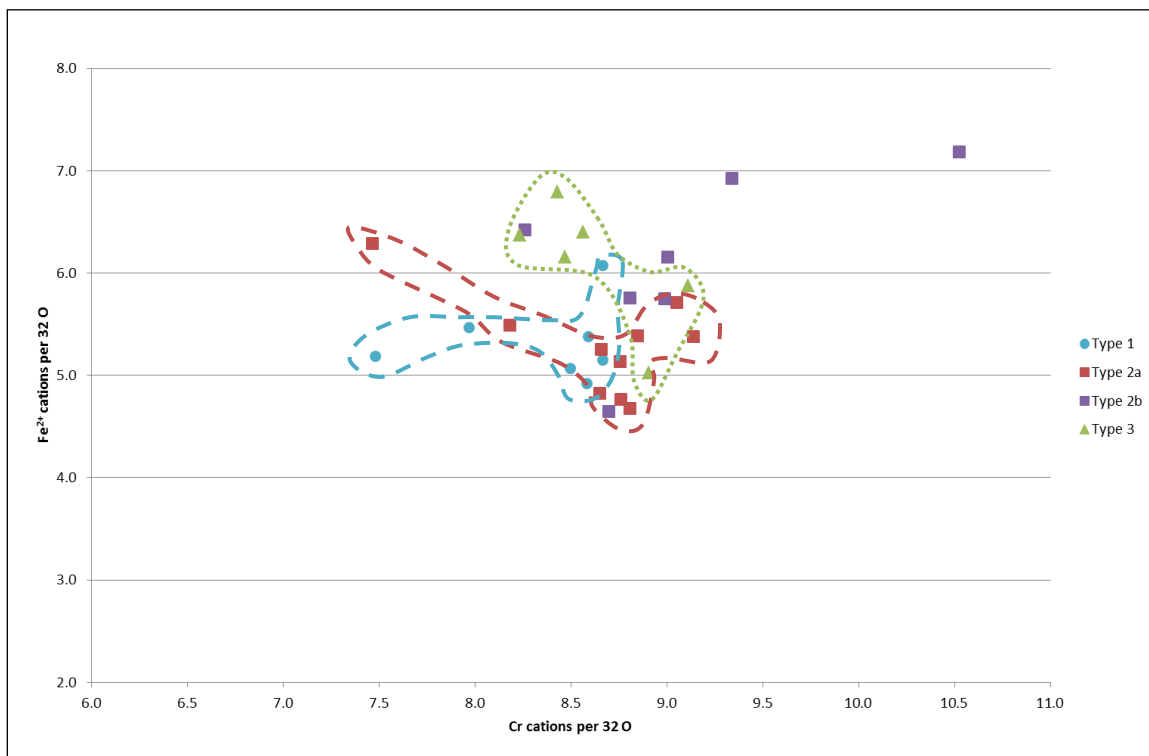
5.2.8 Cation Composition Trends

Various cation plots were constructed to test for any trends or groupings that may occur. In Figure 5.2.8.1, the Cr versus Al and Cr versus Mg cation plots show some clustering

of data, in particular for types 1 and 2a chromitite layers. Type 3 chromitite layers possibly have too few data to make any meaningful comparison. Type 1 and 2a chromitite layers appear to be constrained more than Type 3 chromitite layers in the Cr versus Ti cation plot, but no obvious trends are noted in this figure. For the Cr versus Fe^{2+} all three chromitite layers are tightly constrained for both cations. The trend in the Fe^{3+} cation plot is generally flat with slight depletion. In all plots it is clear that no change to the Cr cation have taken place.

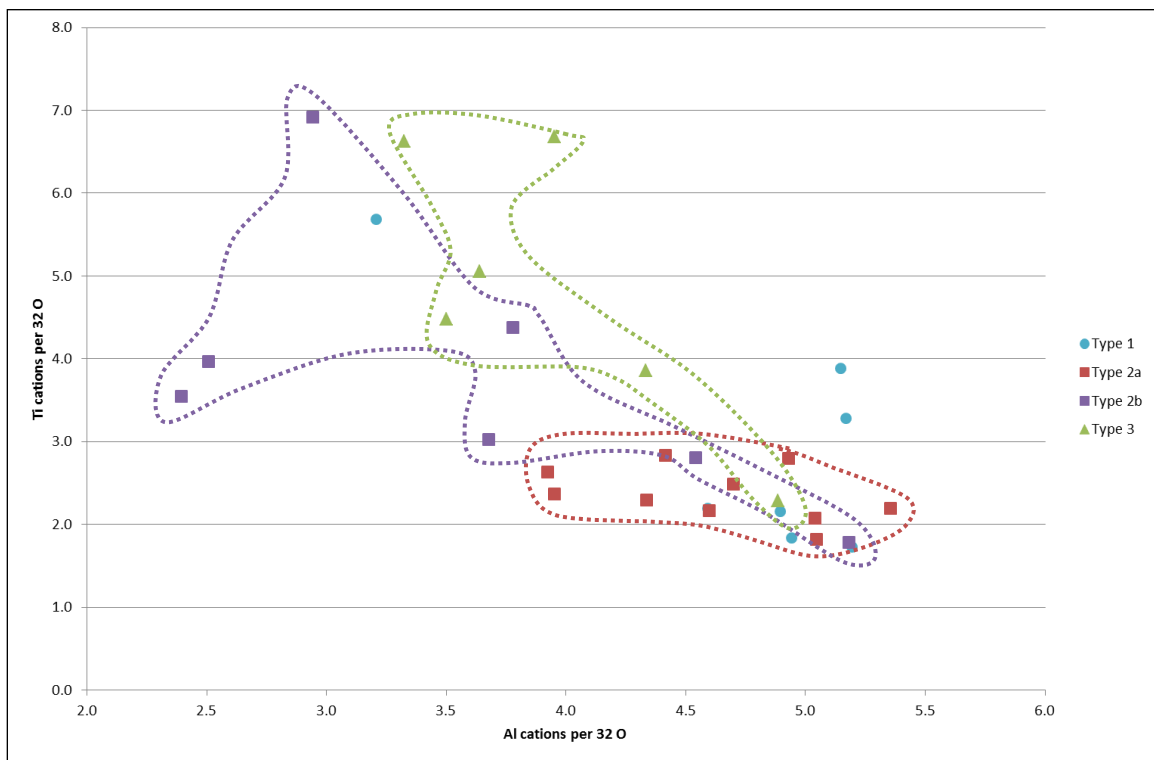






a) Cr versus Al, b) Cr versus Ti, c) Cr vs Mg, d) Cr versus Fe^{2+} , e) Cr versus Fe^{3+} . Lines were roughly constructed around points to show trends and groupings observed.

In Figure 5.2.8.2 some noticeable trends are observed. The Al versus Ti plot shows a definite negative trend, which is particularly noticeable for the Type 2a and 2b chromitite layers. The Al versus Fe^{3+} plot shows a similar negative trend to the Ti plot, similarly for the Types 2a and 2b chromitite layers. The Fe^{3+} versus Ti plot displays a slightly positive trend with the Type 3 chromitite layers showing the most enrichment in both cations and Type 2a being the least enriched.



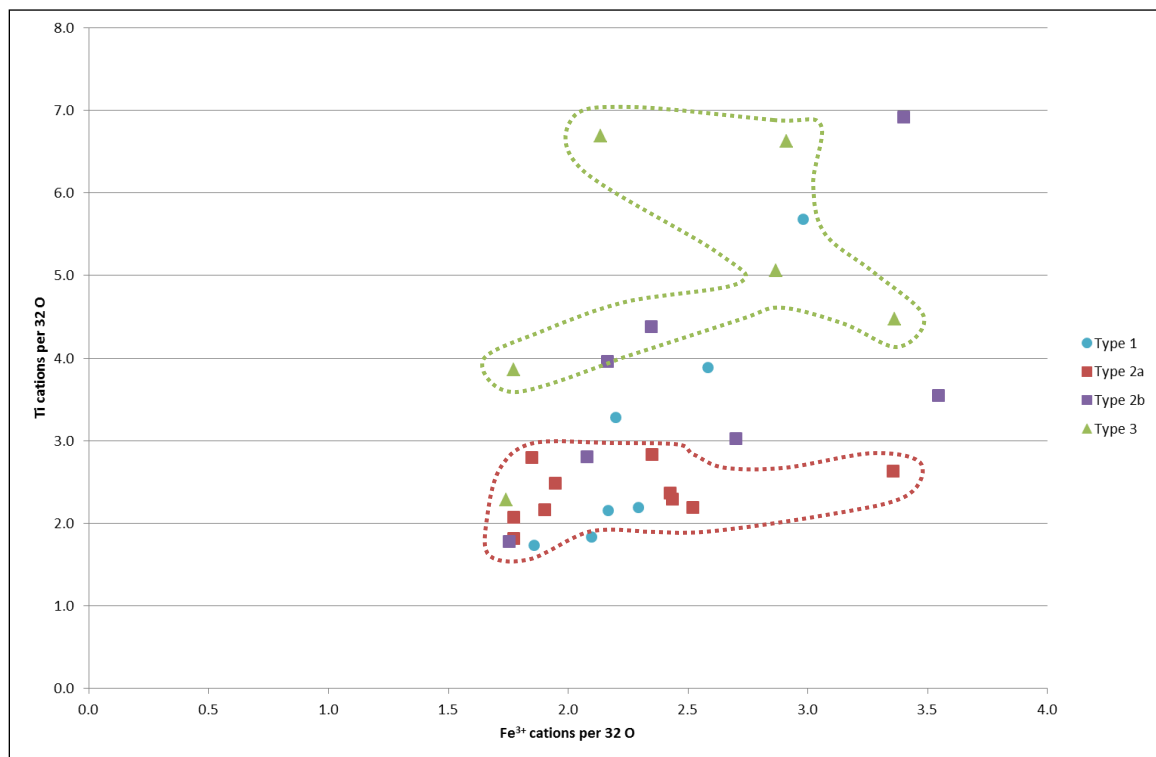
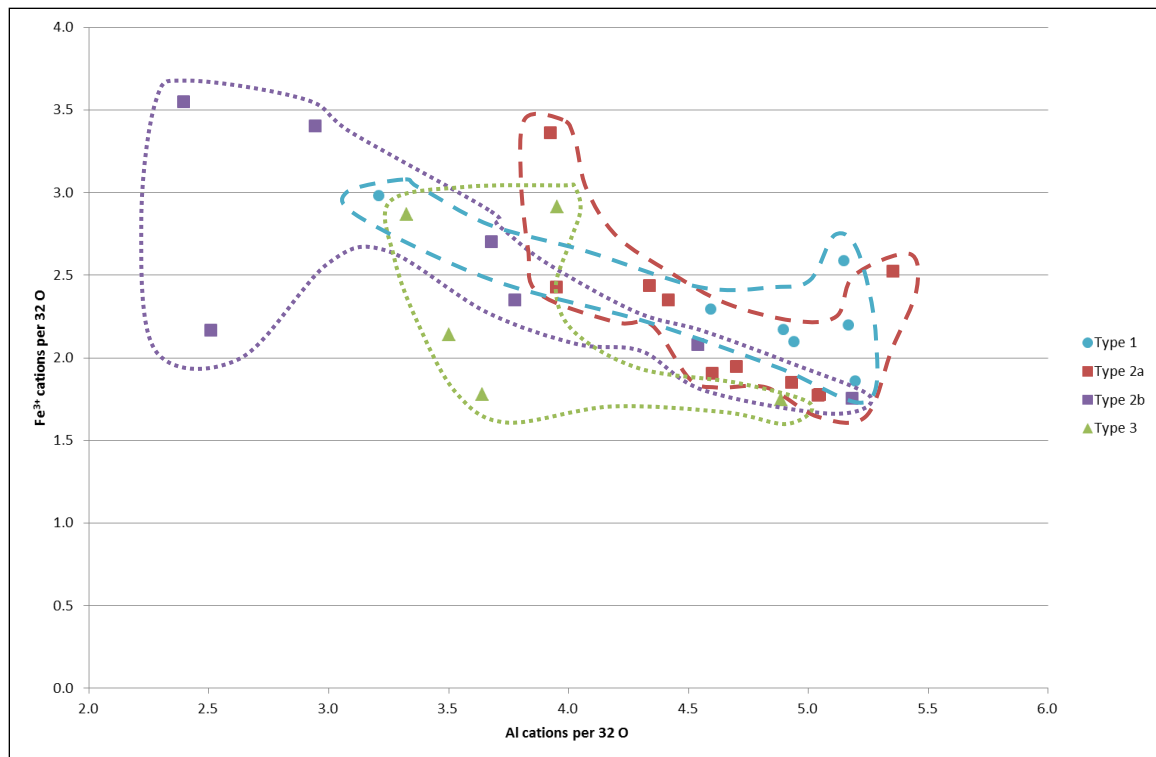


Figure 5.2.8.2 Cation value ratios for all four chromitite layer types for

a) Al versus Ti, f) Al versus Fe^{3+} and g) Fe^{3+} versus Ti. Lines were roughly constructed around points to show trends and groupings observed.

5.2.9 Chromite Populations

Chromite grains from Type 1 and 2a chromitite layers have Mg# ranging from 30 to 45 and 21 to 44 respectively, with Cr# from for Type 1 ranging from 59 to 70 and Type 2a from 56 to 75 (Figure 5.2.9.1). These chromitite layers display the least variable Cr# and Mg# and due to this are more clustered than Types 2b and 3. Type 2b chromite grains have Mg# and Cr# ranging from 10 to 44 and 61 to 83, respectively (Figure 5.2.9.1). These chromite grains display the most variability and range of values for both variables. Chromite grains from Type 3 chromitite layers have Mg# and Cr# ranging from 15 to 45 and 60 to 75, respectively (Figure 5.2.9.1). Compositions of this type chromitite layer display similar variability to that of Type 2b layers but show a tighter constrained Cr# range.

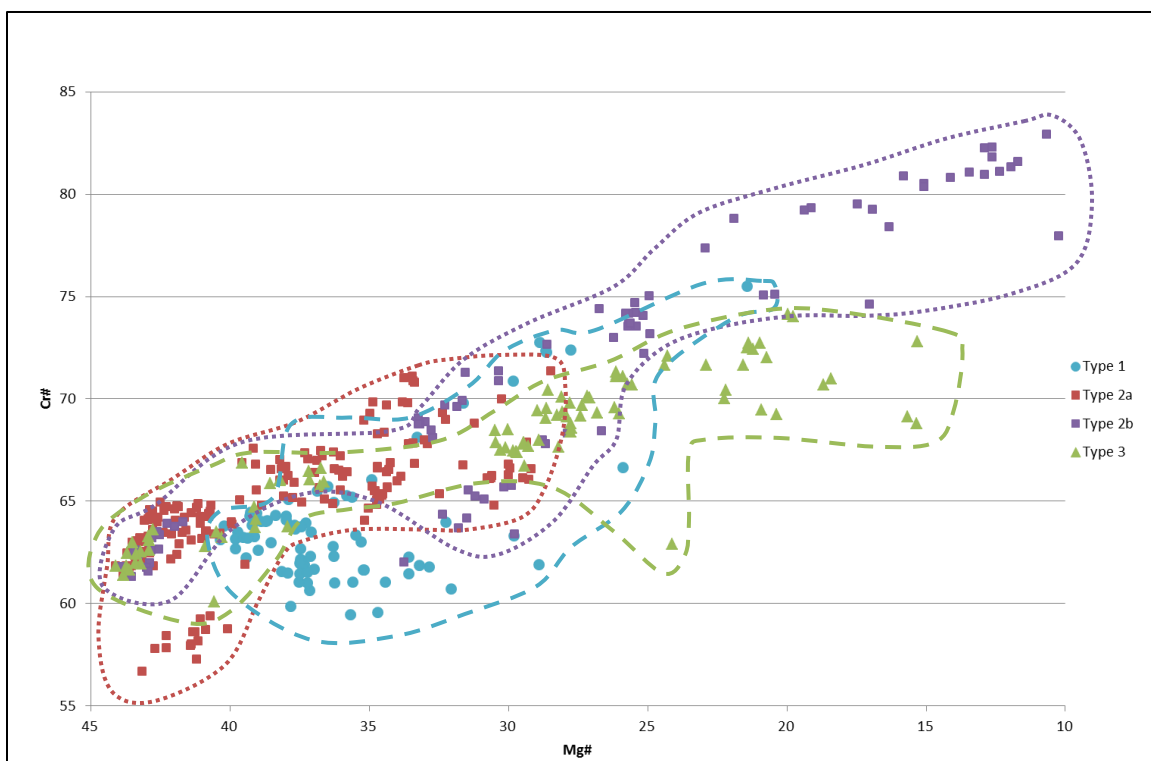


Figure 5.2.9.1 Plot of Cr# versus Mg# of all analysed chromite grains for the four chromitite layer types. Lines were roughly constructed around points to show potential trends and groupings.

Figure 5.2.9.1 was simplified to represent averages of all analyses in individual profiles. Figure 5.2.9.2 shows some grouping of values for the Type 1 and Type 2a chromitite layers at higher Mg# and lower Cr# than with Types 2b and 3 chromitites. Types 2b and 3 show overlap across all other chromitite types and therefore do not show any distinct populations. The groupings of mineral chemistry are not similar enough to be able to define discrete groups absolutely based on these criteria.

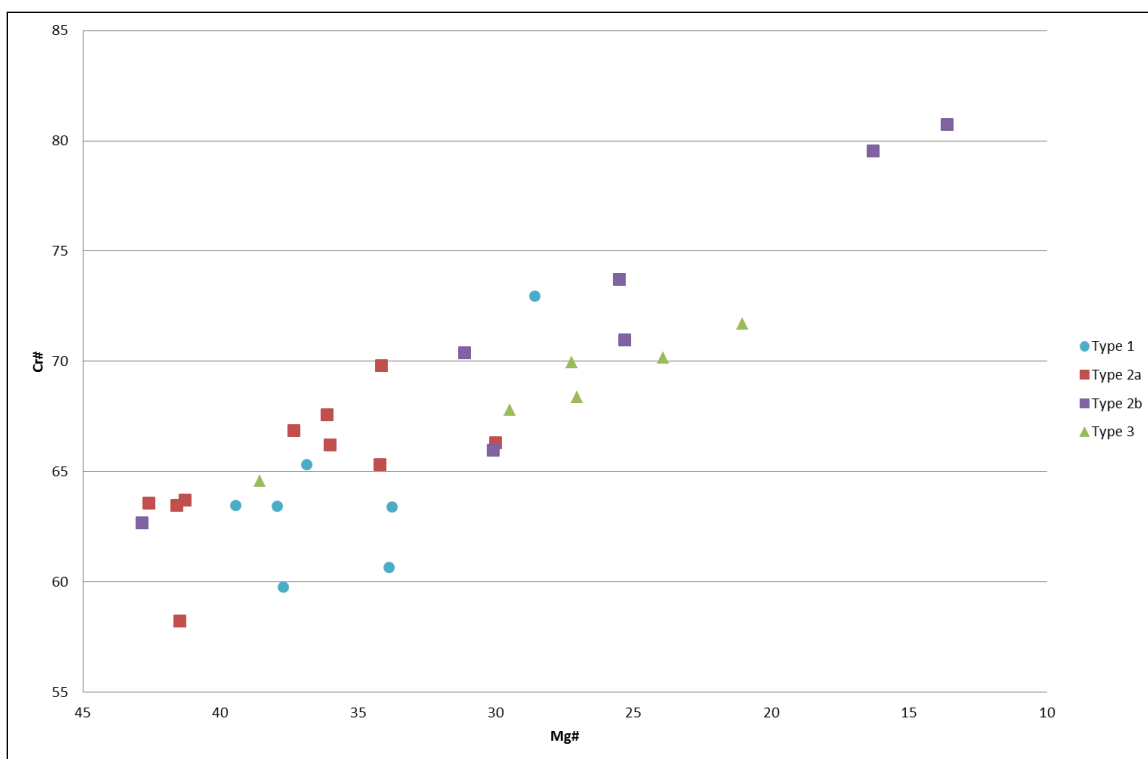


Figure 5.2.9.2 Plot of Cr# versus Mg# showing averages of all analyses in individual profiles for all four chromitite layer types.

5.2.10 Modal Abundance of chromite

The chromitite layers have a broad range of chromite percentages of between 14 and 80%. The modal abundance of chromite was plotted against Cr#, Mg# and Al to examine any possible effect related to the proportion of chromite. No clear trends are observed in Figures 5.2.10.1, 2, & 3 and this shows that proportion of chromite has no effect on the chromite compositions. Those layers with chromite percentages of less than 40% would be more disseminated and those closer to 80% would be more massive chromitite layers (closely packed grains).

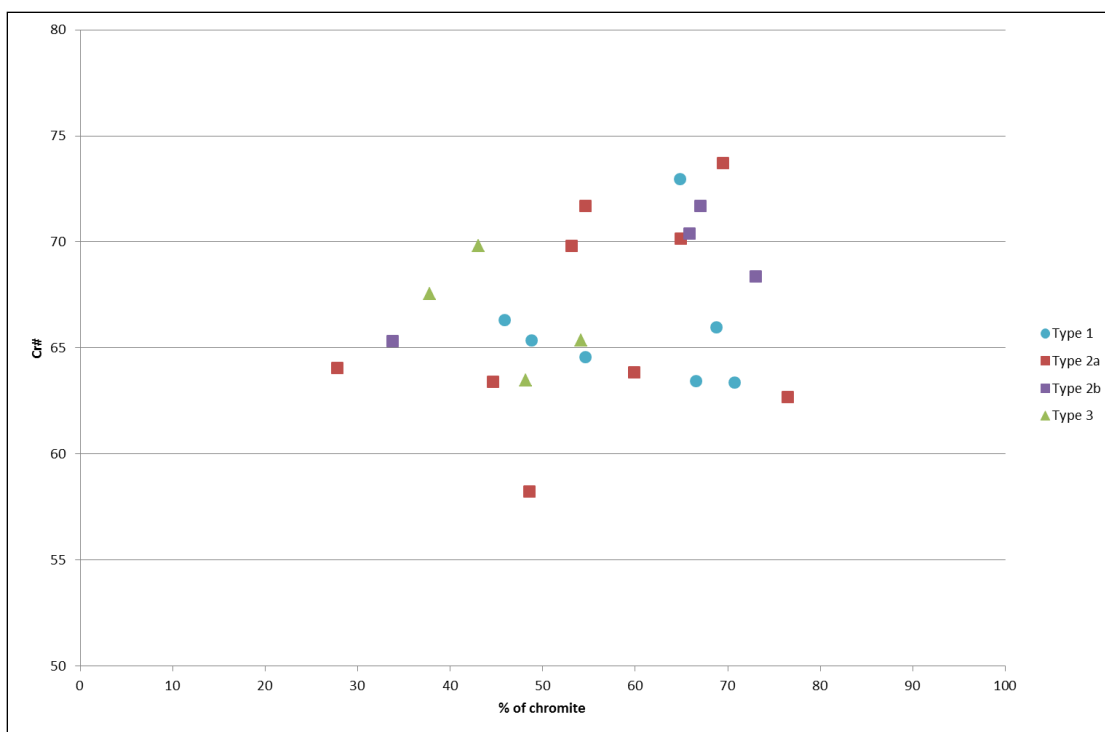


Figure 5.2.10.1 Plot showing % of chromite versus Cr# of averages of analysed chromite grains for all four chromitite layer types.

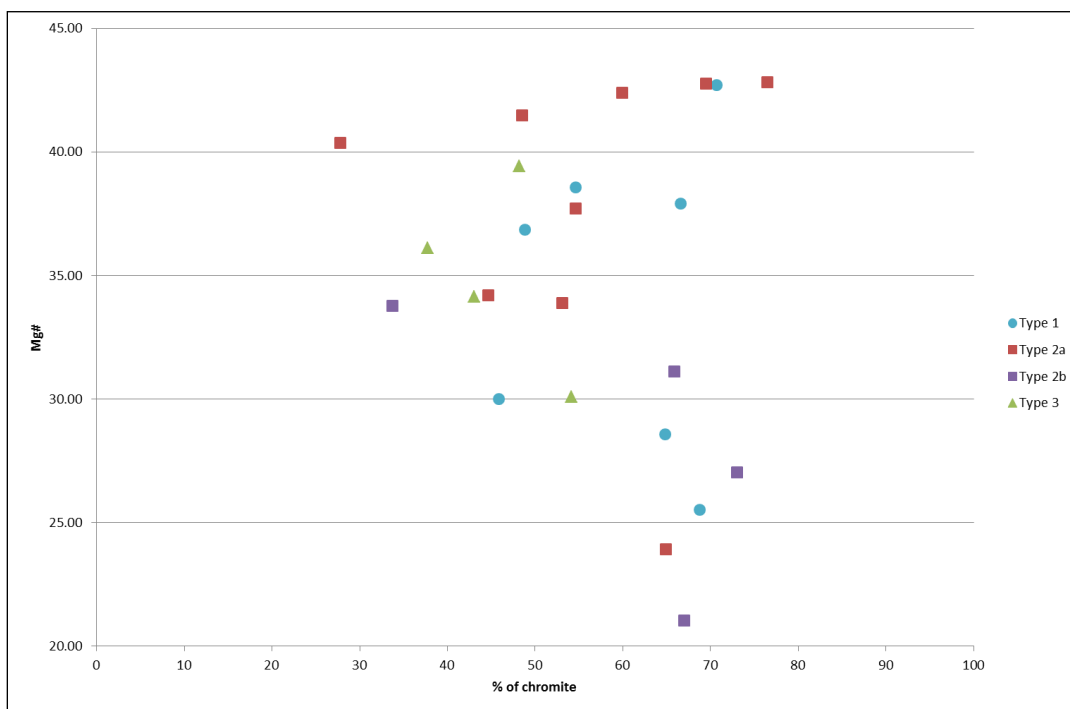


Figure 5.2.10.2 Plot showing % of chromite versus Mg# of averages of analysed chromite grains for all four chromitite layer types.

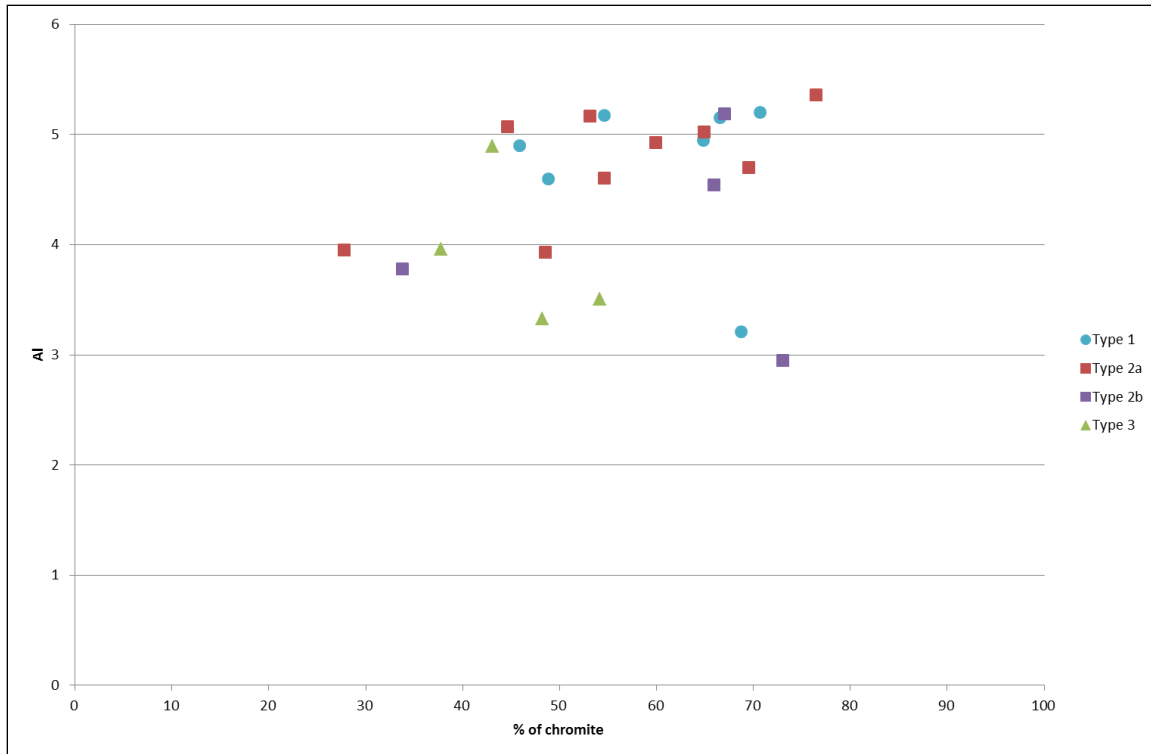


Figure 5.2.10.3 Plot showing % of chromite versus Al cations of averages of analysed chromite grains for all four chromitite layer types.

5.2.11 Proportions of trivalent cations

Figure 5.2.11.1 is a ternary data plot that represents all samples taken at Marikana as well as data from other similar studies as described in chapter 1. In terms of trivalent ions, all chromite grains show very little variation in the proportion of Fe^{3+} and the data are clustered together. Due to limited solid solution between aluminates and ferrites, very few examples between Al and Fe^{3+} at low values of Cr exist (Mattioli & Wood 1988, Nell & Wood 1989, Sack & Ghiorso 1991).

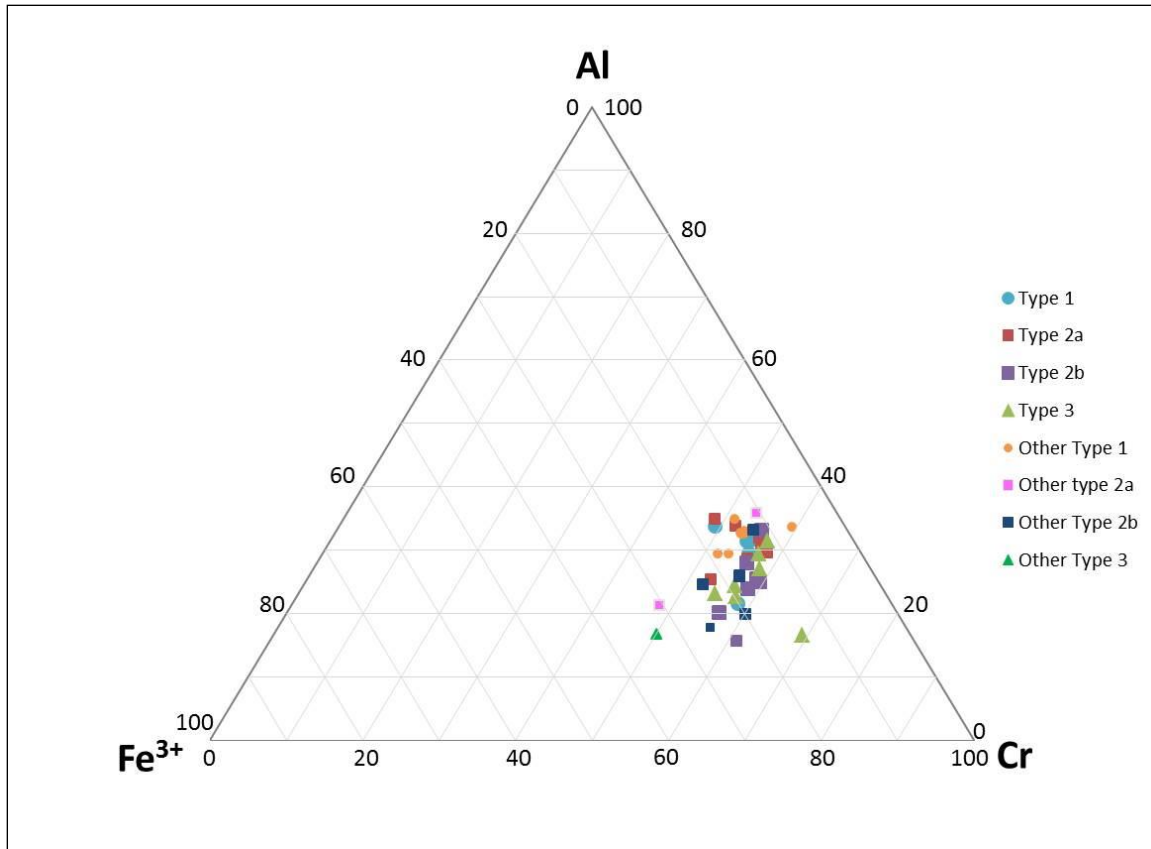


Figure 5.2.11.1 Ternary plot showing trivalent cations, Cr, Al and Fe^{3+} of the chromites at Marikana and similar studies on Merensky chromites. Comparative data are from Brynard et al. (1976) , Eales & Reynolds (1986), Kinloch & Peyerl (1990), Li et al. (2005), Vukmanovic et al. (2013) and Cawthorn (unpublished) from Impala Platinum mine.

Figure 5.2.11.2 is a ternary data plot that represents all samples taken at Marikana as well as data from other similar studies as described in chapter 1. The plot shows that there is very little variation in the proportion of Ti in all samples, with no clear trend of enrichment in Ti. A few exceptions are observed where samples from Type 3 chromitite layers show some Ti enrichment.

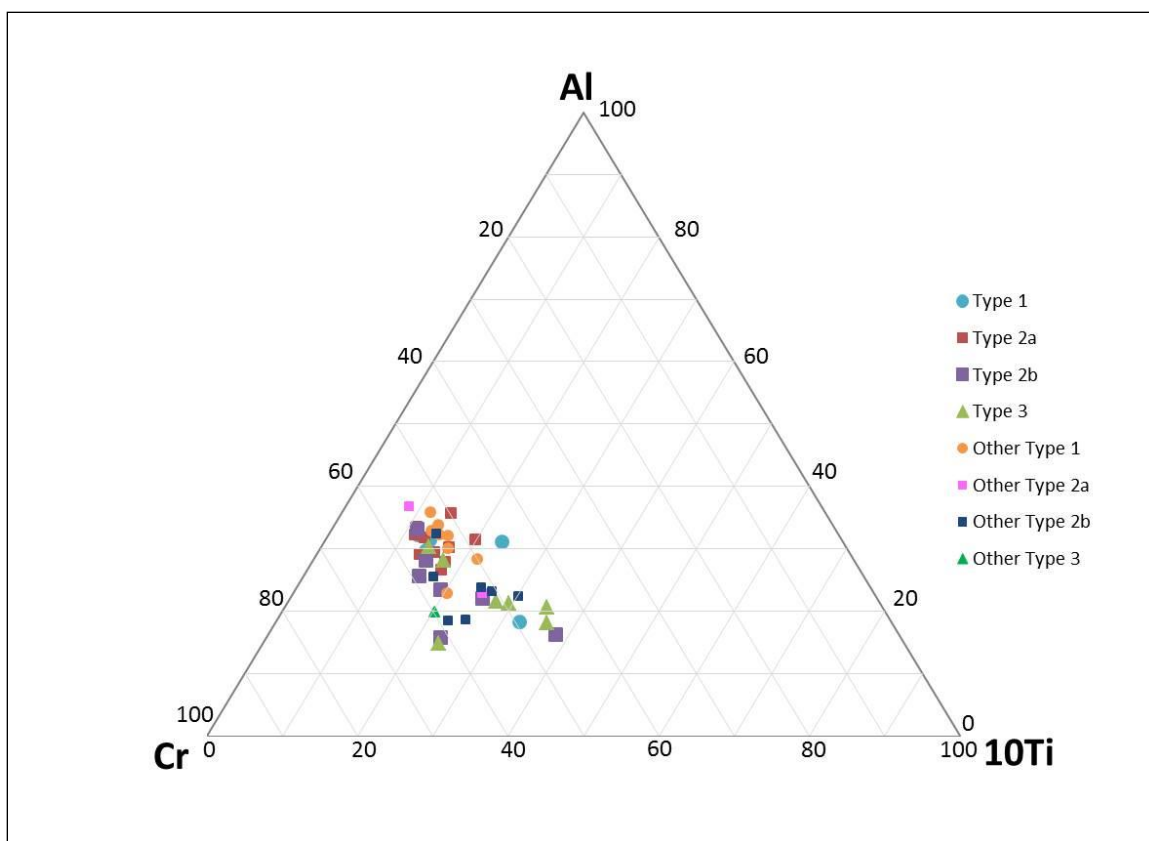


Figure 5.2.11.2 Ternary plot showing trivalent cations, Cr, Al and 10xTi of the chromites at Marikana and similar studies on Merensky chromites. Comparative data are from Brynard et al. (1976) , Eales & Reynolds (1986), Kinloch & Peyerl (1990), Li et al. (2005), Vukmanovic et al. (2013) and Cawthorn (unpublished) from Impala Platinum mine.

CHAPTER SIX - DISCUSSION

6.1 Introduction

The Merensky Reef is one of several PGE-bearing layers the Upper Critical Zone of the Bushveld Complex. The Merensky Reef displays significant variations in its thickness and continuity of individual layers in comparison to the UG2 and Platreef. Viljoen (1999) commented that regionally the Merensky Reef does not represent a consistent well defined layer. He notes that the regional variations in the characteristics of the Merensky Reef are important in the understanding of the nature and origin of this layer. Despite being mined for many decades and many models being proposed, there is still little consensus on the origin and formation of the Merensky Reef.

Irvine (1965, 1967) recognized that spinels are valuable petrogenic indicators as their composition is sensitive to the environment in which they form, particularly the composition of their parent magma. Chromite is a useful indicator of magmatic conditions at the time of crystallization due to its stability under a range of geological conditions (Roeder, 1994). Eales (2000) also noted that chromite is highly reactive and equilibrates rapidly with their environment.

The results of the mineral chemistry and interpretation of the field observations from underground exposures are discussed in detail.

6.1.1 Comparison from other studies on Merensky chromitites

As discussed in Chapter 1.3, various other studies have produced mineral chemistry values for Merensky Reef chromitite layers, specific to the Western Bushveld Complex. It is of value to plot the comparative studies and the data from this study and note whether any similarities or differences occur in what is thought to be chromitite layers formed within the same time frames and potentially from the same magma injections. Other studies were presented by Brynard et al. (1976) , Eales & Reynolds (1986), Kinloch & Peyerl (1990), Li et al. (2005), Vukmanovic et al. (2013) and Cawthorn (unpublished) from Impala Platinum mine.

In Figure 6.1.1.1, Cr# and Mg# compositions were plotted for the data in this study as well as from the comparative studies. As observed in the data from this study, there is a strong inverse relationship between these two element ratios. The range of the Cr# compositions is between 60 and 80, with the Mg# having a wider range of between 10 and 45.

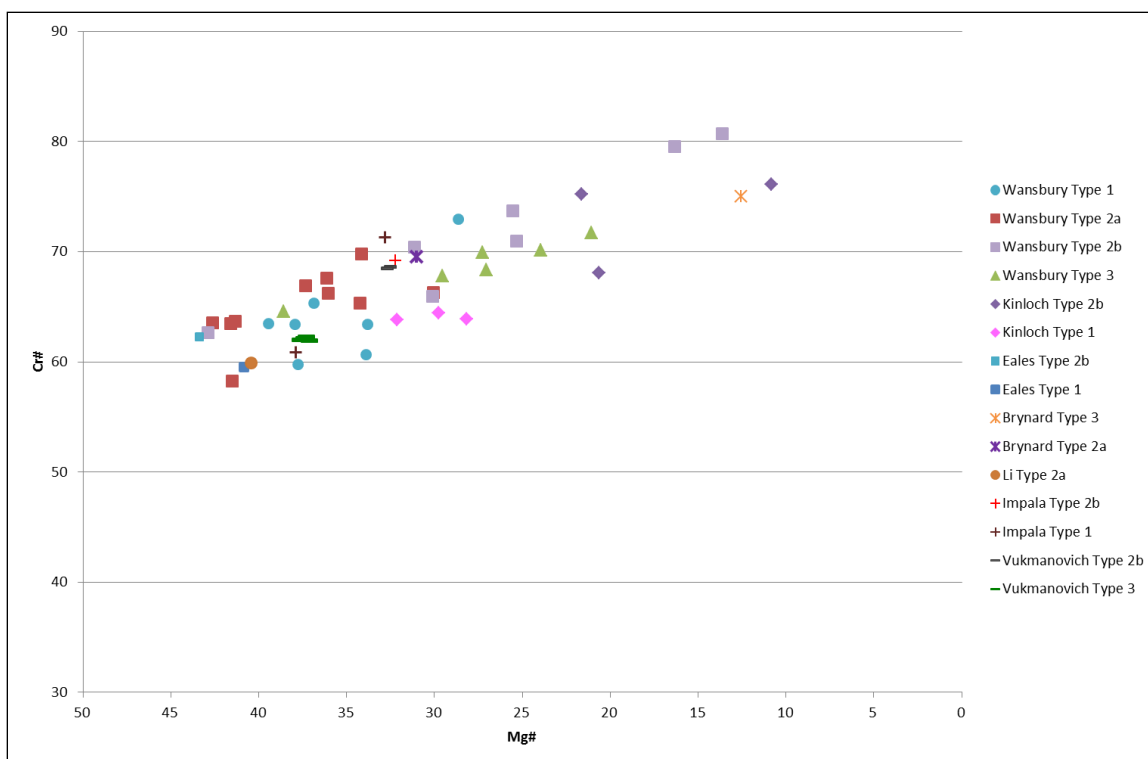


Figure 6.1.1.1 Plot of average Cr# and Mg# values for chromite grains from all chromitite layer types. Comparative data are from Brynard et al. (1976) , Eales & Reynolds (1986), Kinloch & Peyerl (1990), Li et al. (2005), Vukmanovic et al. (2013) and Cawthorn (unpublished) from Impala Platinum mine.

Individual cation contents for all data are plotted against Cr# (Figure 6.1.1.2) and Mg# (Figure 6.1.1.3). As the Mg# decreases, most notably the Al cation value decreases and the Cr cation values remain constant. With an increase in Cr# there is a strong decrease in Al and Mg. No clusters of data from the same chromitite layers are observed. The most notable outliers are the 4 samples at low Mg# values of less than 20. They include 2 samples of Type 2b chromitites from this study, a Type 2b samples from the Kinloch & Peyerl (1990) study and the Type 3 sample from the Brynard et al. (1976) study. The samples from this study are ZS50 and ZS53. These samples are thought to be outliers due to the low percentage of chromite for these layers, 14 and 16% respectively. Modal

percentages were only presented by Li et al. (2005) as 70% chromite. Shelembe (2006) noted 37 to 62% of chromite for her study and Vukmanovic et al. (2013) mention that their study's layers contain approximately 50 to 55% chromite. The Kinloch & Peyerl (1990) outlier is from their potholed reef and the low Mg# may be due to some reef disturbance. The reason for the anomalous values from Brynard et al. (1976) is not known.

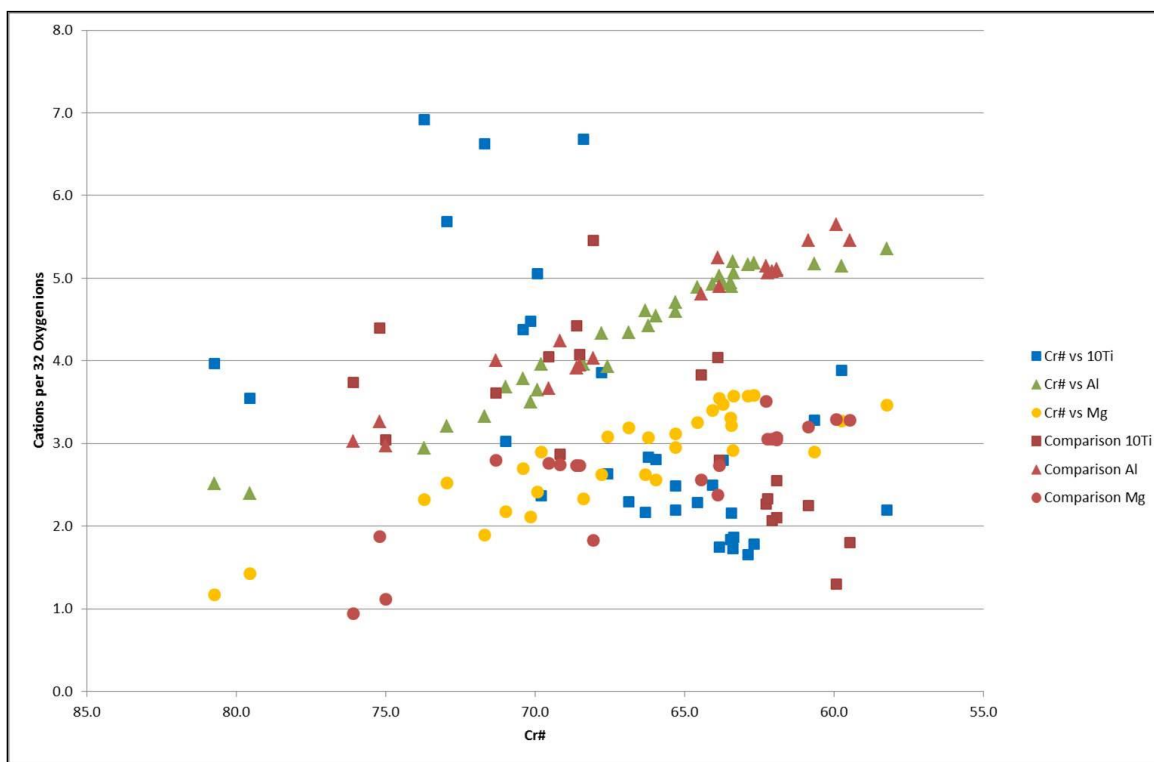


Figure 6.1.1.2 Plot of cation concentrations of Ti x10, Al and Mg from all chromitite layer types versus Cr#. Comparative data are from Brynard et al. (1976) , Eales & Reynolds (1986), Kinloch & Peyerl (1990), Li et al. (2005), Vukmanovic et al. (2013) and Cawthorn (unpublished) from Impala Platinum mine.

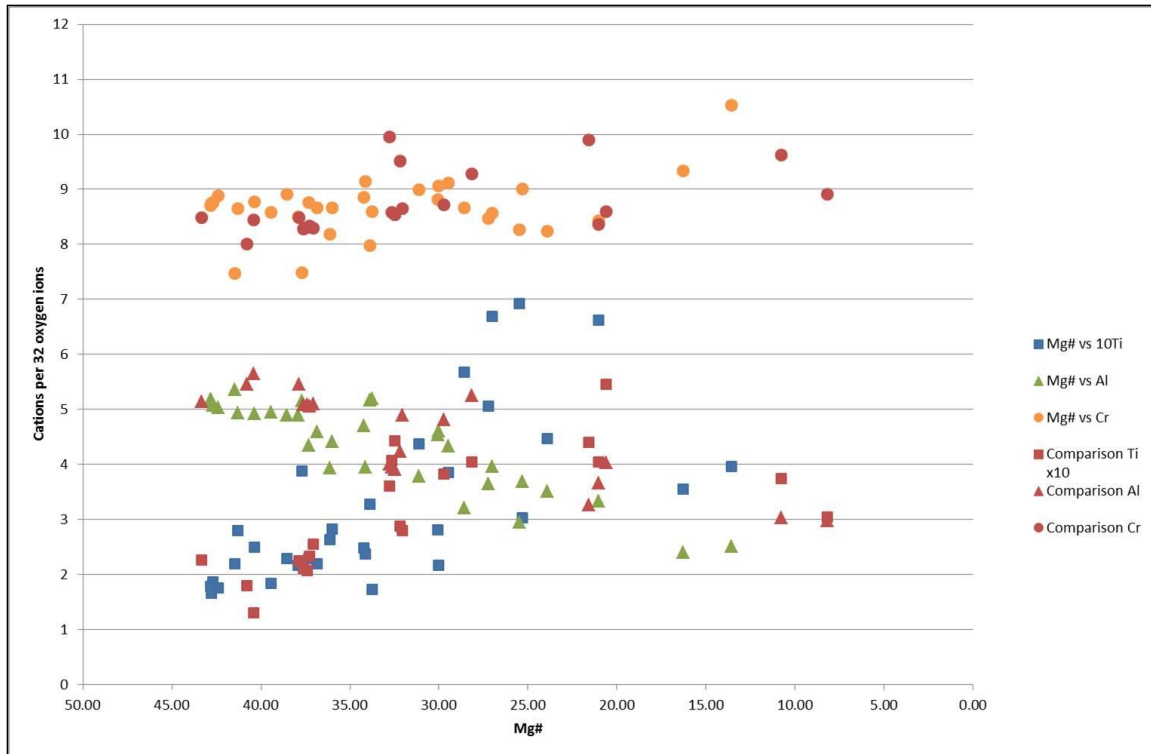


Figure 6.1.1.3 Plot of cation concentrations of Ti x10, Al and Cr from all chromitite layer types versus Mg#. Comparative data are from Brynard et al. (1976), Eales & Reynolds (1986), Kinloch & Peyerl (1990), Li et al. (2005), Vukmanovic et al. (2013) and Cawthorn (unpublished) from Impala Platinum mine.

The Cr# (Figure 6.1.1.4) and Mg# (Figure 6.1.1.5) were plotted according to a qualitative height from the footwall contact upwards. The aim of these plots was to test for any consistent compositional patterns in the vertical profiles of the chromitite layers. In Figure 6.1.1.4 the Cr# generally increases with height from Type 1 to 2b and then reverses to a lower Cr# from Type 2b to Type 3. Although the Cr# compositions overlap, tie lines were used in samples where more than one chromitite layer was sampled in order to see whether this Type 3 reversal is consistent. Three samples out of four show this reversal trend and the other two continue on the trend of increasing Cr# with height.

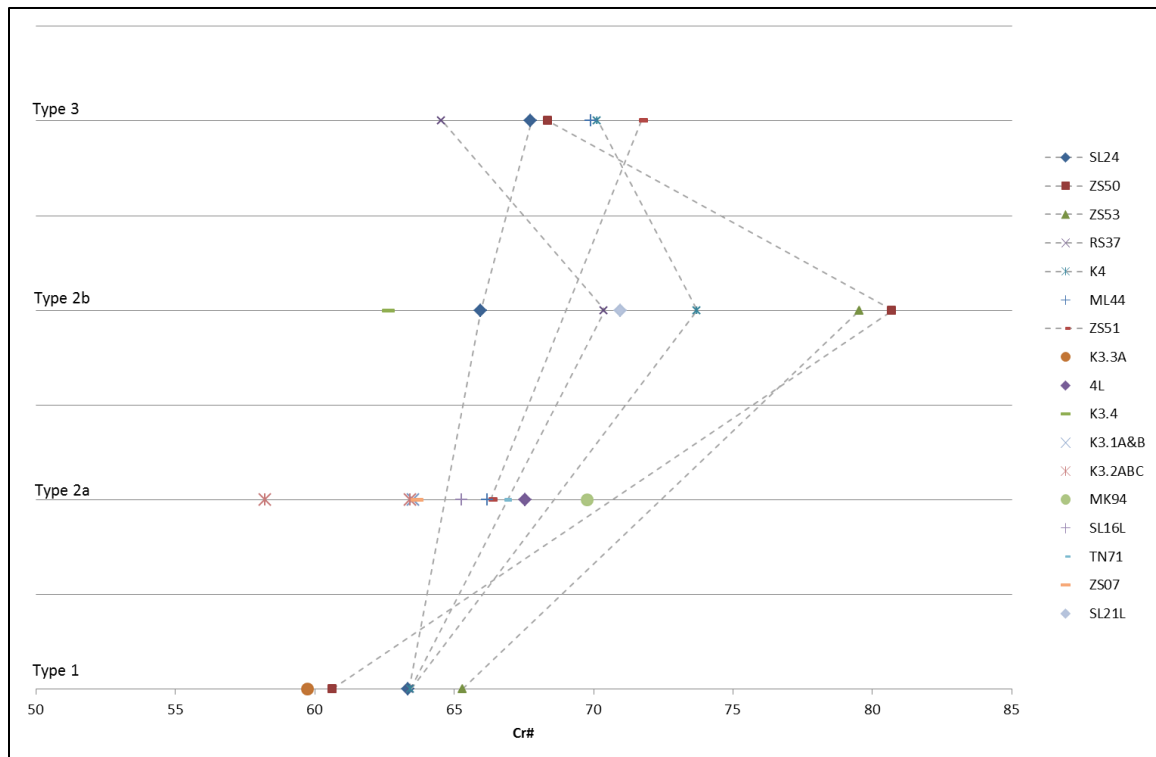


Figure 6.1.1.4 Plot of Cr# versus height of chromitite layer types based on a qualitative height from the footwall contact upwards.

In Figure 6.1.1.5 the Mg# decreases with height from Type 1 to 2b and then reverse to a higher Mg# from Type 2b to Type 3 in two samples out of four. This reversal is more pronounced than in Figure 6.1.1.4.

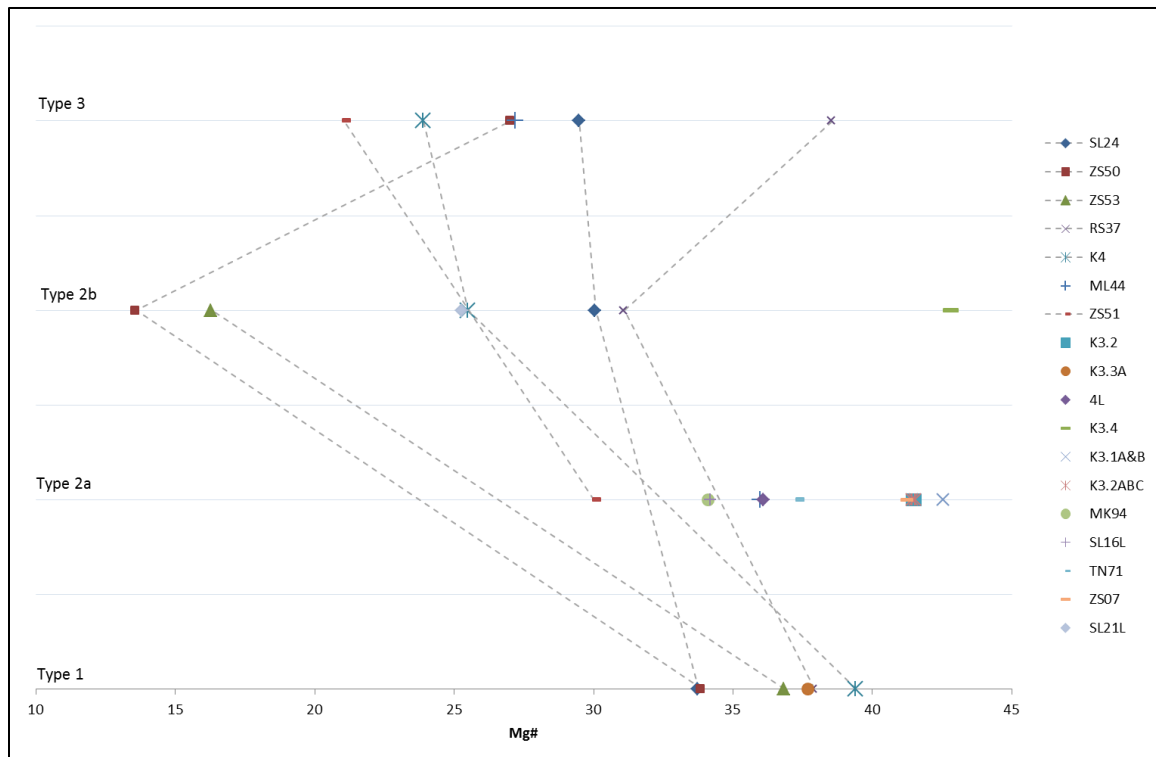


Figure 6.1.1.5 Plot of Mg# versus height of chromitite layer types based on a mock height from the footwall contact upwards.

Vukmanovic et al. (2013) found that their lower chromitite layer, equivalent to Type 2b, showed higher Mg# and lower Cr# than their upper layer, which is equivalent to Type 3. The reason they give for this difference is their upper layer is thought to contain grains that have undergone more extensive reaction with trapped liquid than the lower layer. In comparison to Vukmanovic et al. (2013), chromite concentrations show no consistent pattern to make a definitive conclusion of chromite compositions by height for the Type 2b layers.

6.1.2 Lateral variation

The lateral variation in composition can be investigated at two different scales, the first over tens of centimetres and the other over tens of kilometres (and including chromite compositional data from other studies on Merensky chromitites). Five samples were taken from an exposure underground at Lonmin's K3 Vertical Shaft (Figure 6.1.2.1). This exposure is within a transition zone between two facies, namely the Thin (left on Figure 6.1.2.1) and Brakspruit (right on Figure 6.1.2.1) facies types. Samples were taken where one chromitite layer (K3.1a&b) changes laterally into two chromitite layers (K3.4 & K3.3a) with an internal parting of pegmatoidal pyroxenite. K3.3b was a chromitite layer sampled within the pegmatoidal pyroxenite which is not consistently developed and was therefore not used for comparison. The thicknesses of the layers expressed as the vertical height in Figure 6.1.2.2 as measured by the EMPA, are approximate measurements that were converted from microns to millimetres. In the cases of K3.1a&b and K3.2b&c, these layers were analysed individually and combined thickness of the two split layers represent the total thickness of the single layers. Thicknesses of layer K3.1a&b measure 10mm, K3.2a 2.7mm, K3.2b&c 20mm, K3.3a 2.9mm and K3.4 8.5mm.

The average cation compositions (number of cations per 32 oxygens) of these five samples are shown in Figure 6.1.2.1, and all analyses are plotted as a function of height in Figure 6.1.2.2. They illustrate the differences between the lower Type 1 (K3.3a) and upper Type 2b (K3.4) chromitite layer of the Brakspruit Facies, and allow for a comparison with the single layer (K3.1a&b) of the Thin Facies. It is important to note that all vertical profiles for each layer are very uniform in composition. K3.3a and K3.4 have different Cr cation contents of 7.8 and 8.7 respectively, indicating that these two layers

can be distinguished geochemically. At the section where these two layers almost meet K3.2a and K3.2b+c have values of 7.5 and 8.8 demonstrating the horizontal uniformity of this layer over a short distance. A vertical line is drawn on all profiles at 8.4 cations of Cr to emphasize this distinction. It is then possible to test if layer K3.1a&b matches either or both of the two distinct layers. Its Cr content is 8.8 indicating correlation with the upper layer, with no evidence for the preservation of the lower layer. The matrix to K3.1a&b is plagioclase, similar to that for K3.2a and K3.3a, whereas that for K3.2b+c and K3.4 is pyroxene. Hence, differences or similarities in chromite composition cannot be attributed to influence by the host phase. The plots for Fe^{3+} , Fe^{2+} , TiX10, Mg and Al also show progressively less differences between the lower and upper chromitite layer although not always as diagnostic as for Cr, but in all cases the single Type 2a layer in K3.1a&b correlates much more closely with the upper Type 2b layer. The vertical lines drawn on all profiles for all cations emphasize this correlation. It can therefore be concluded that the lower Type 1 layer on the right of Figure 6.1.2.1 does not continue to the left, but that the upper Type 2b layer is continuous. The probable interpretation is that deposition of the lower Type 1 chromitite and the pegmatoidal pyroxenite was terminated by an erosive event that removed them along some sections of the reef, but not along others. Crystallization resumed with the deposition of the second chromitite layer that formed the single layer for what is called Thin Facies.

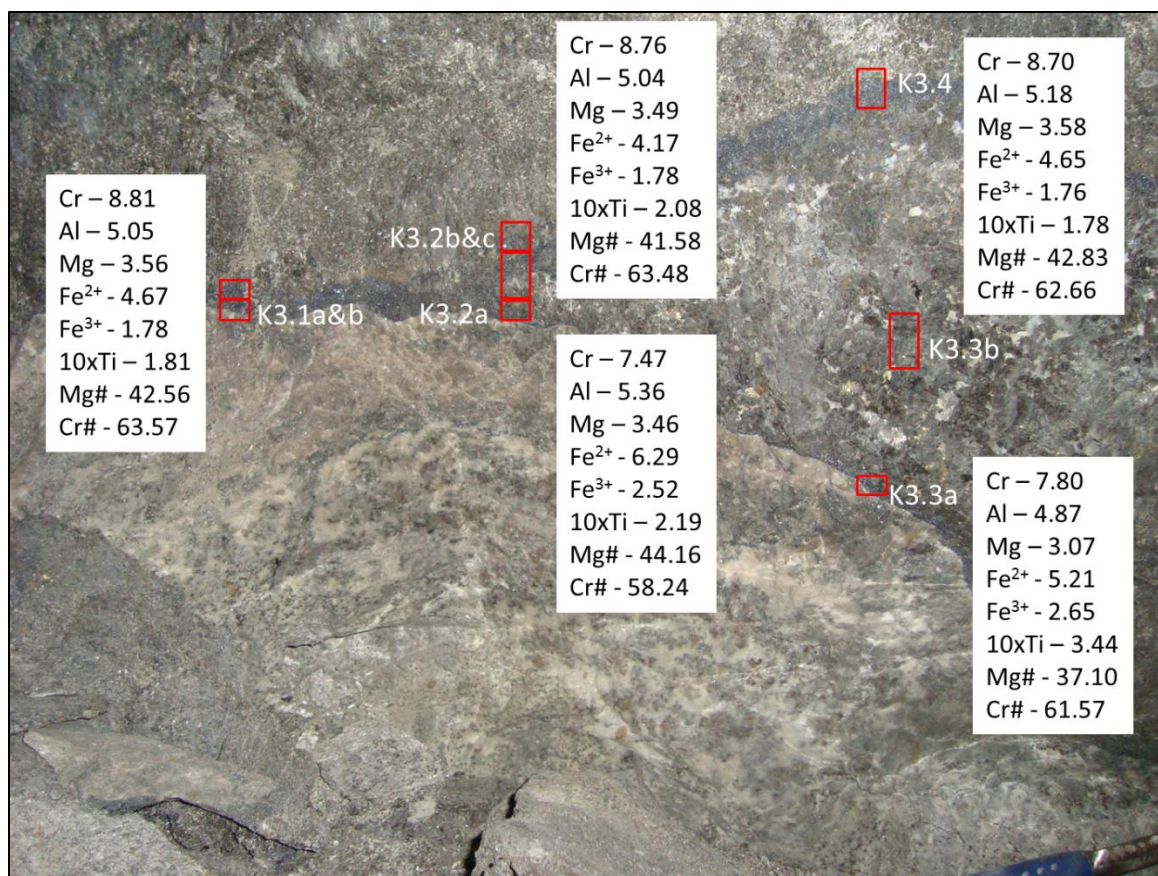
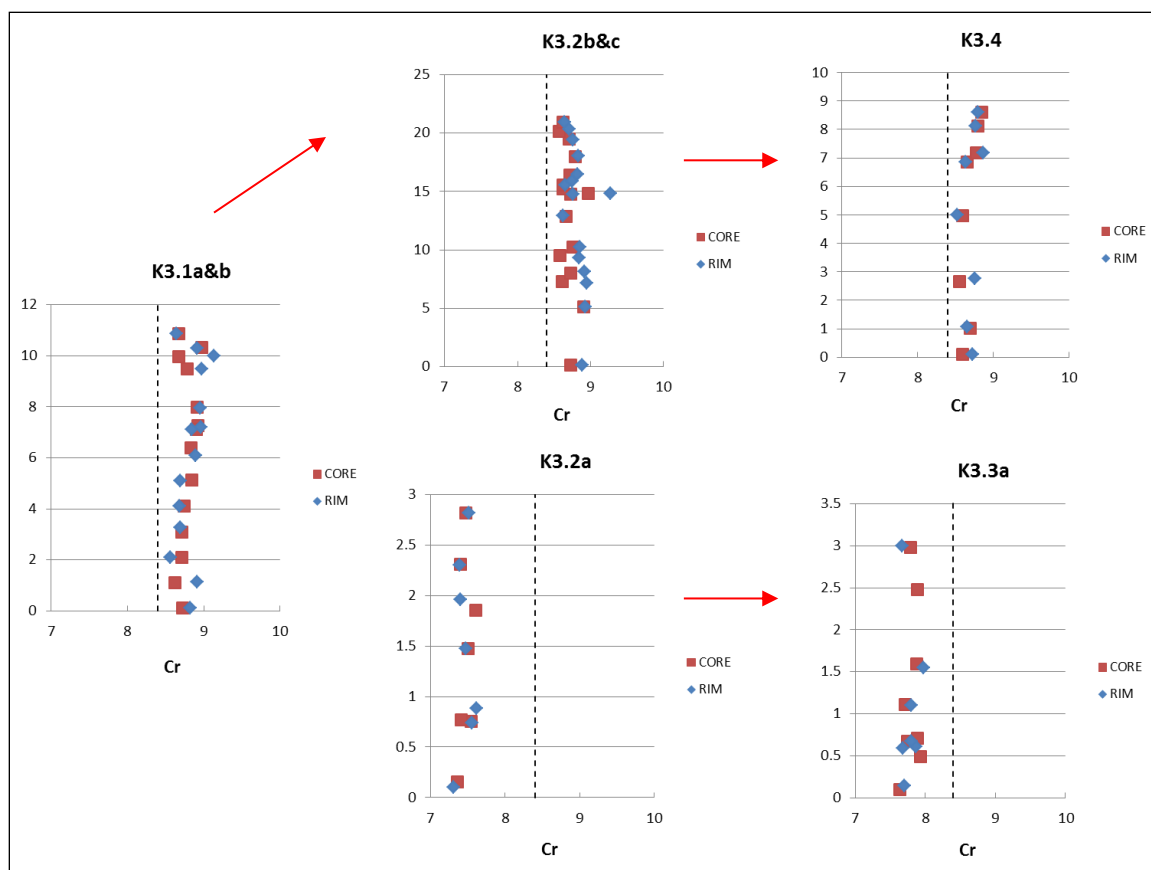
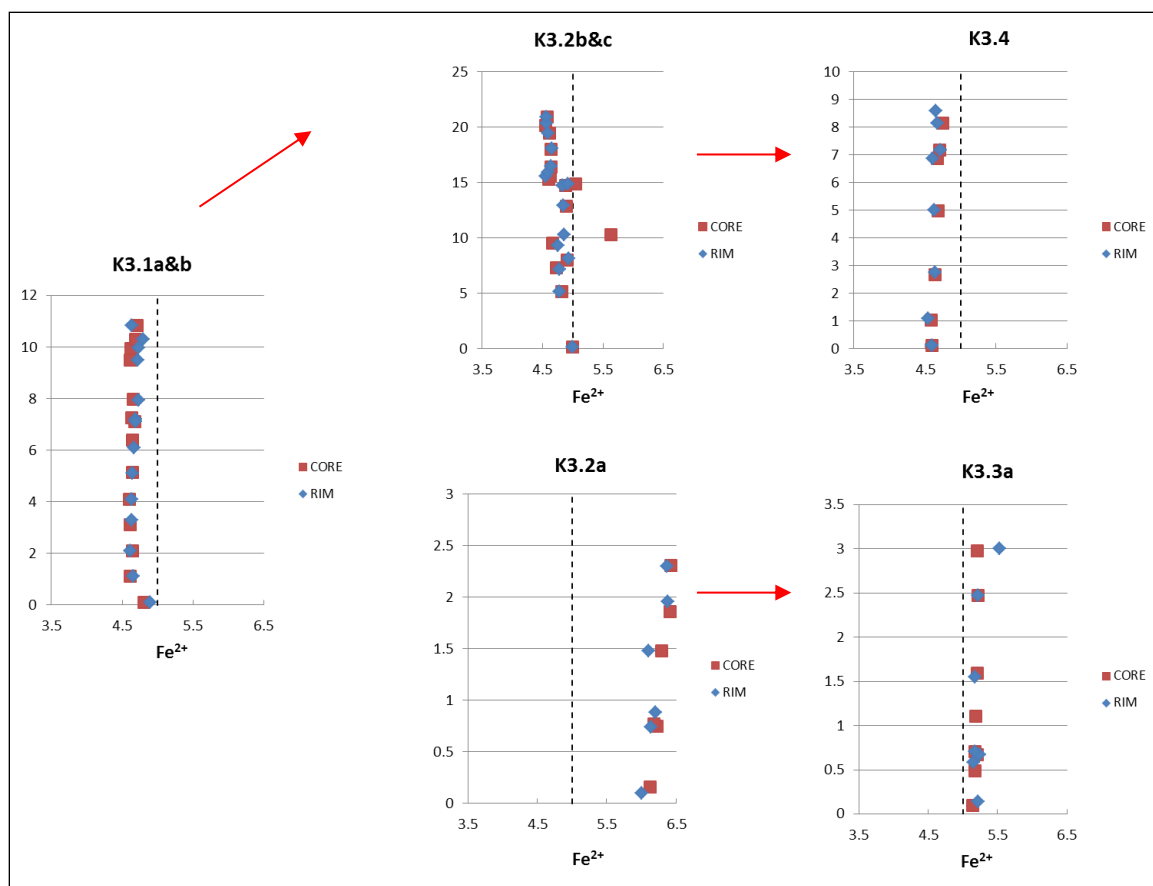
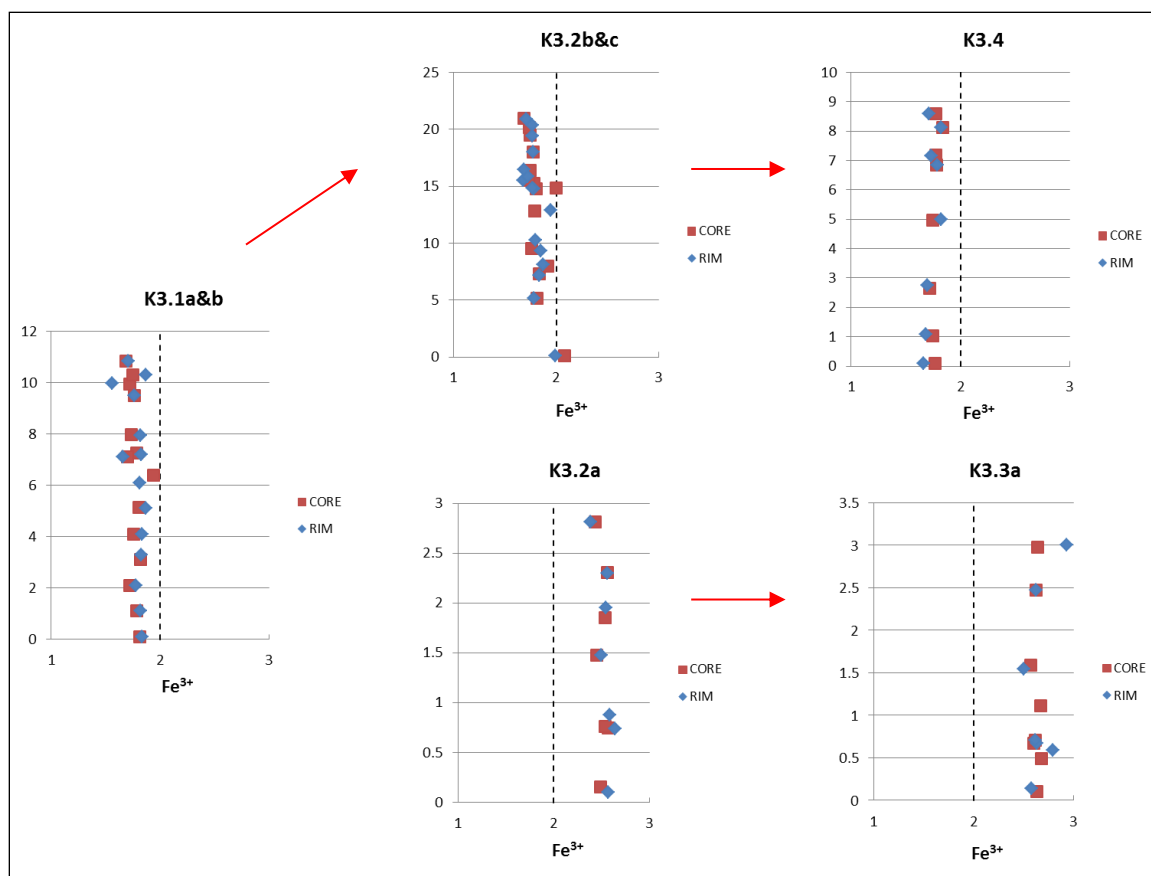
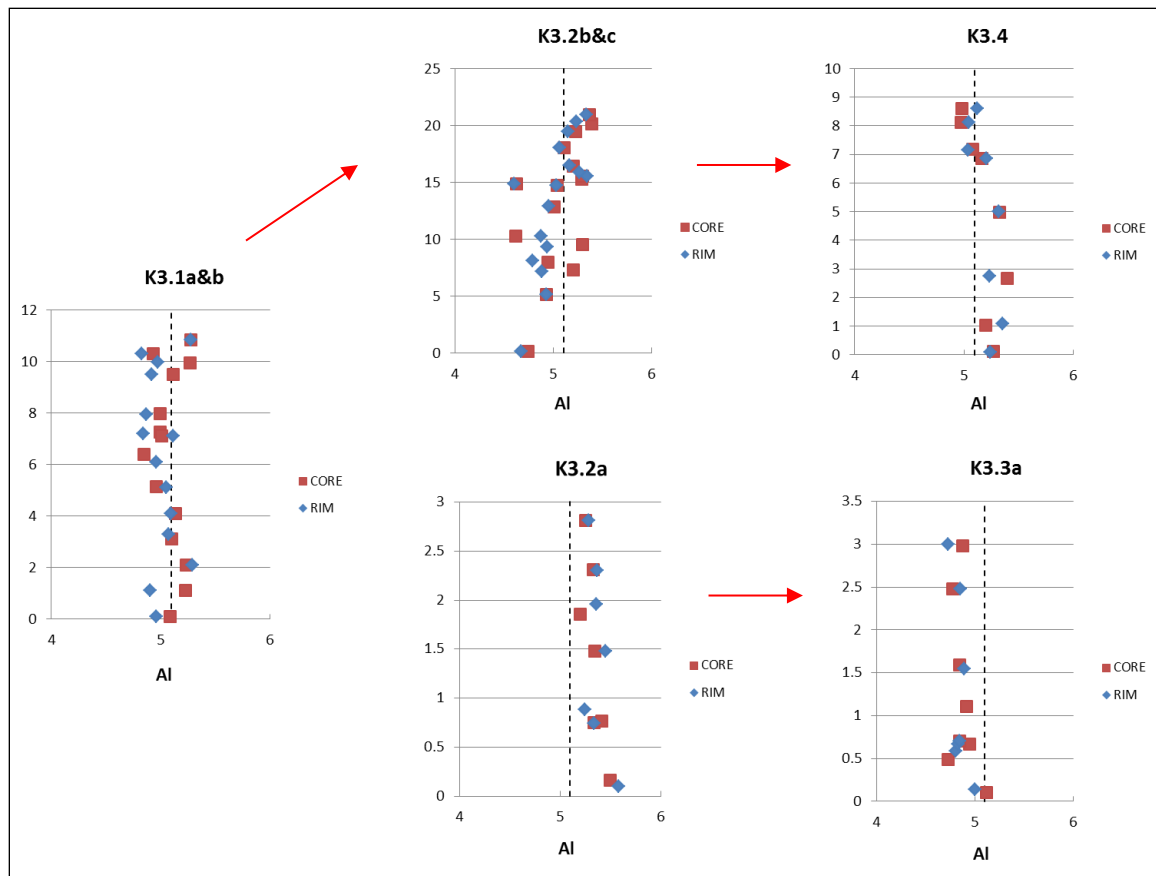


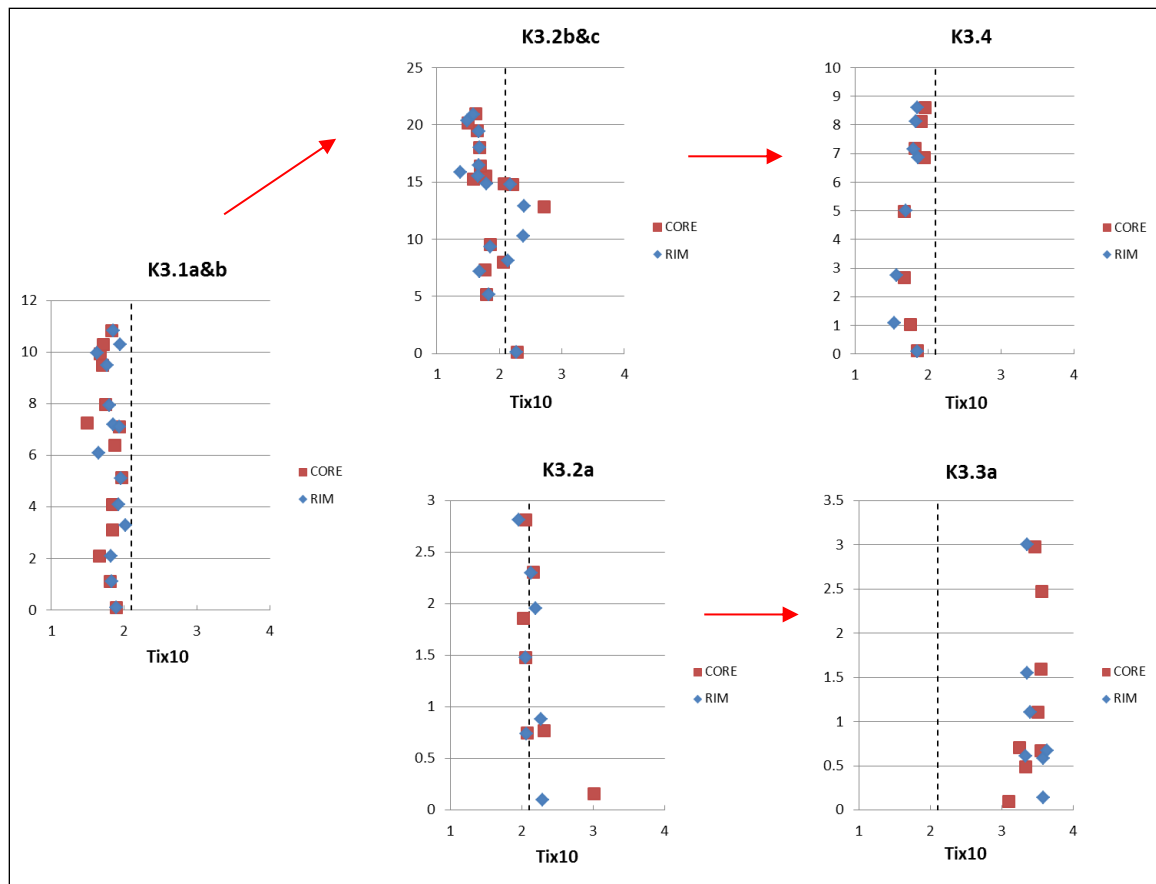
Figure 6.1.2.1 Photograph showing sampled locations in the K3 example and average cation compositions in order to demonstrate that the Type 1 layer of K3.3a on the right of the photo does not continue on the left and that the Type 2a and Type 2b are continuous.











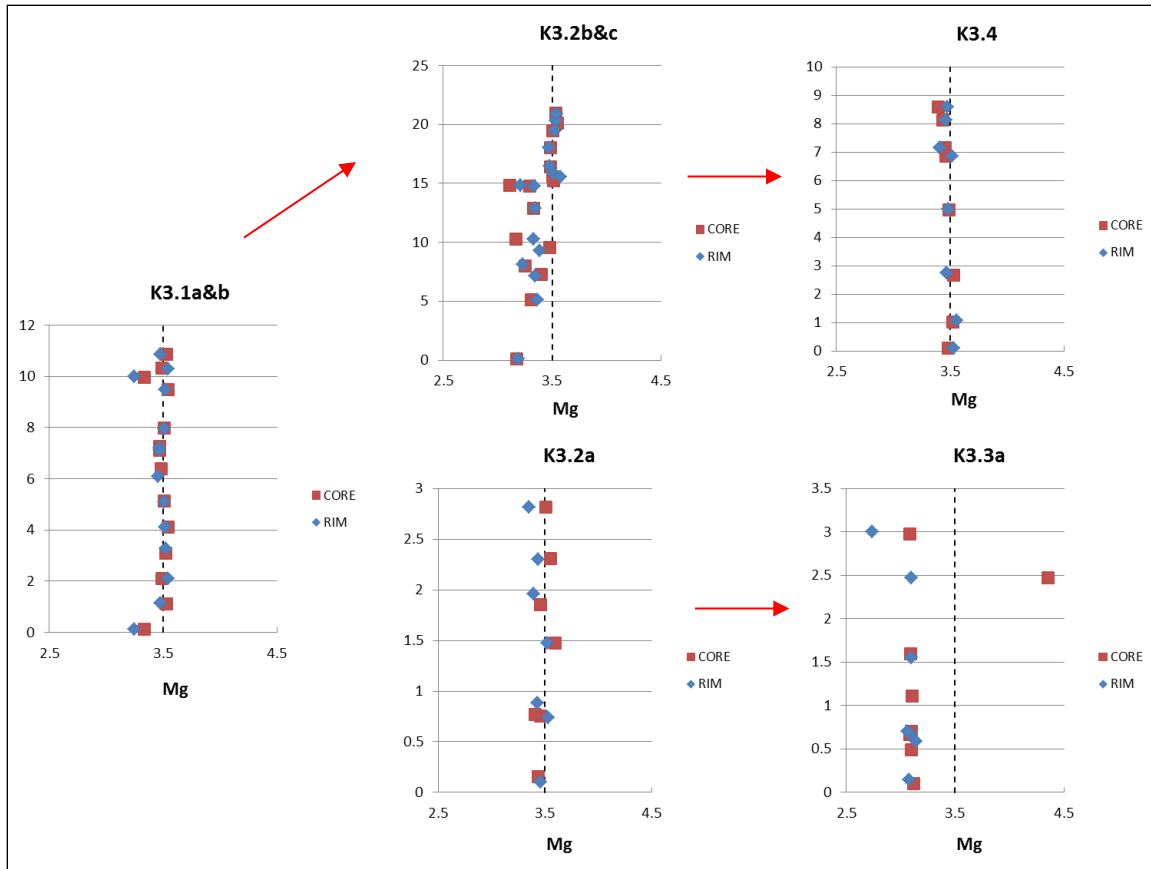
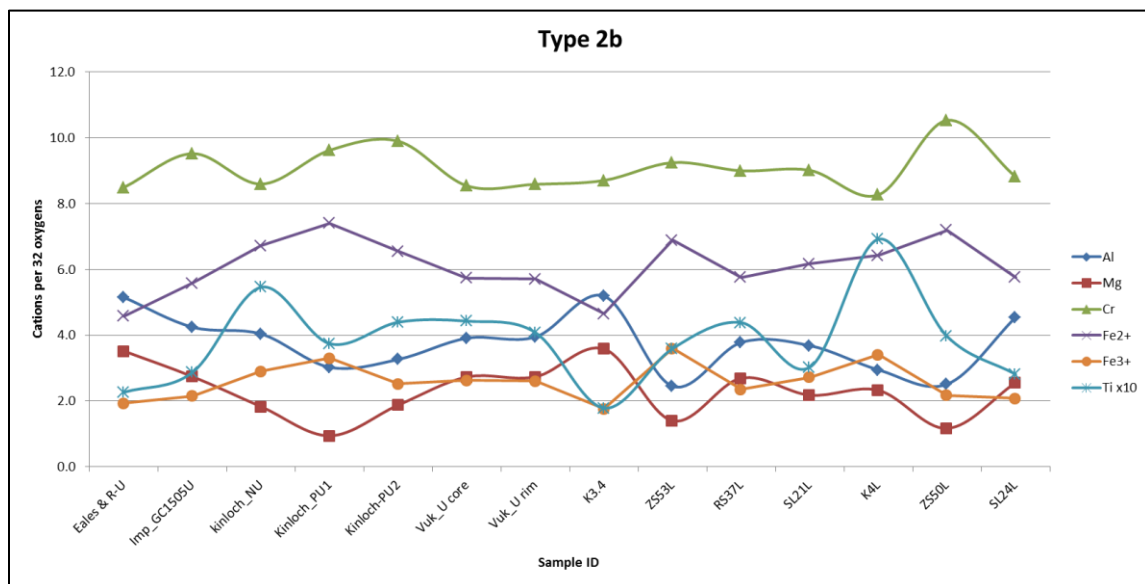
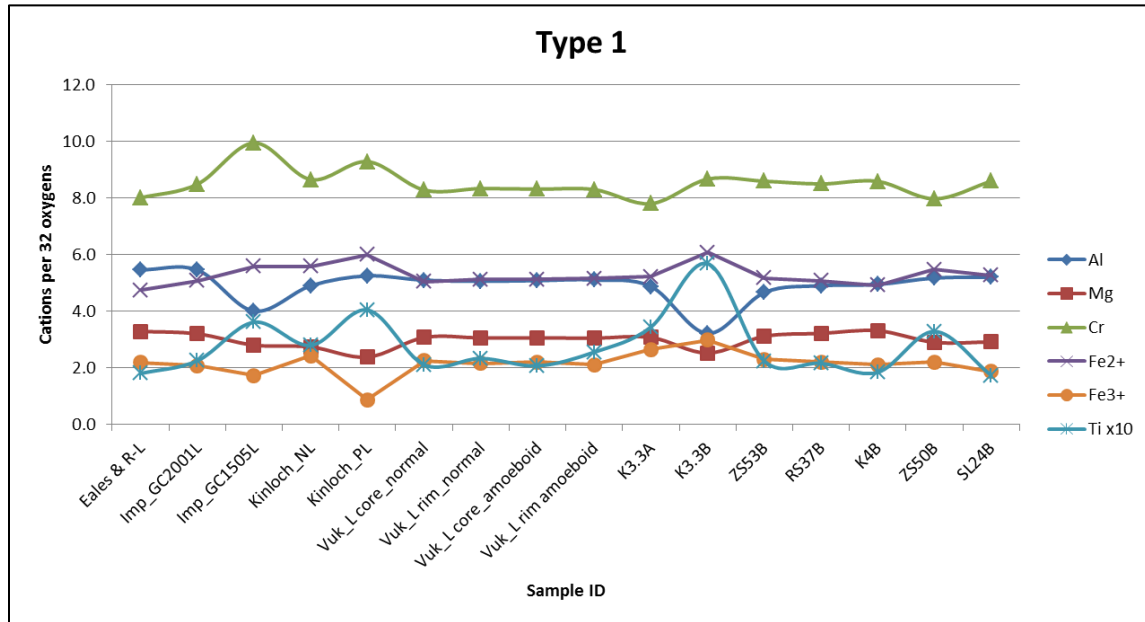


Figure 6.1.2.2 Plots showing cation contents of Cr, Fe²⁺, Fe³⁺, Al, Ti_{x10} and Mg studying possible correlation between samples and ultimately chromitite layers. Correlations are indicated using red arrows. The vertical scales are in mm as measured under the EMPA.

On a large scale (+/- 90km along strike), the variations in the chromite compositions of the few types of layers can be investigated. All comparative study cation data were plotted from west to east for all chromitite layer types across the Western Bushveld (Figure 6.1.2.3). The data for Type 3 and 2a chromitite layers show comparative values across the west to east profile with very few undulations observed. The data for the Type 1 and 2b chromitite layers show a few changes in the Ti values but display relatively stable patterns for the other cations. These differences in Ti values are due to their low concentrations and appear more exaggerated. Overall some lateral variability across the

study area or even beyond (to the west) was observed, however this variability is not regular or persistent.



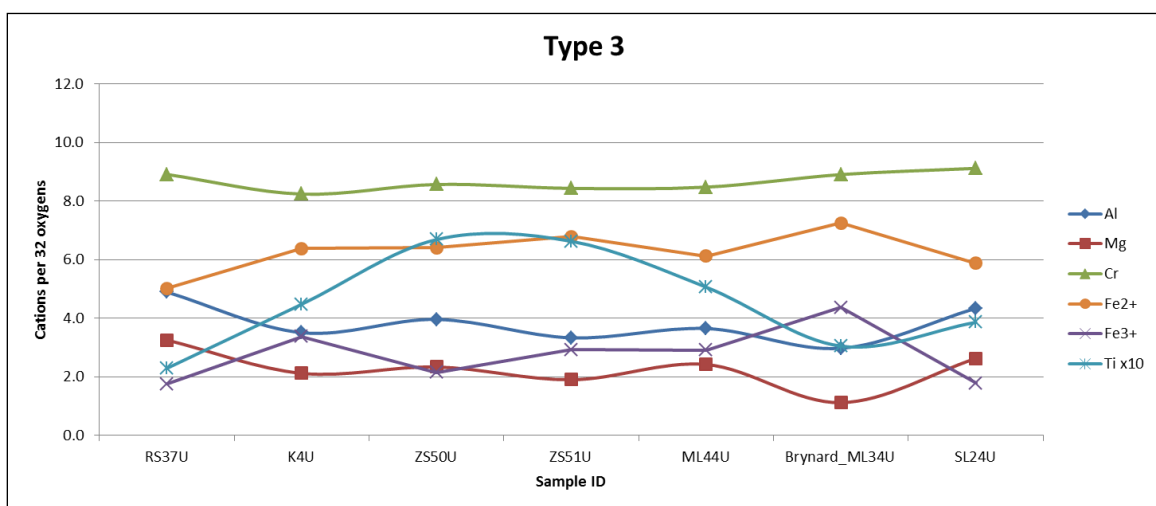
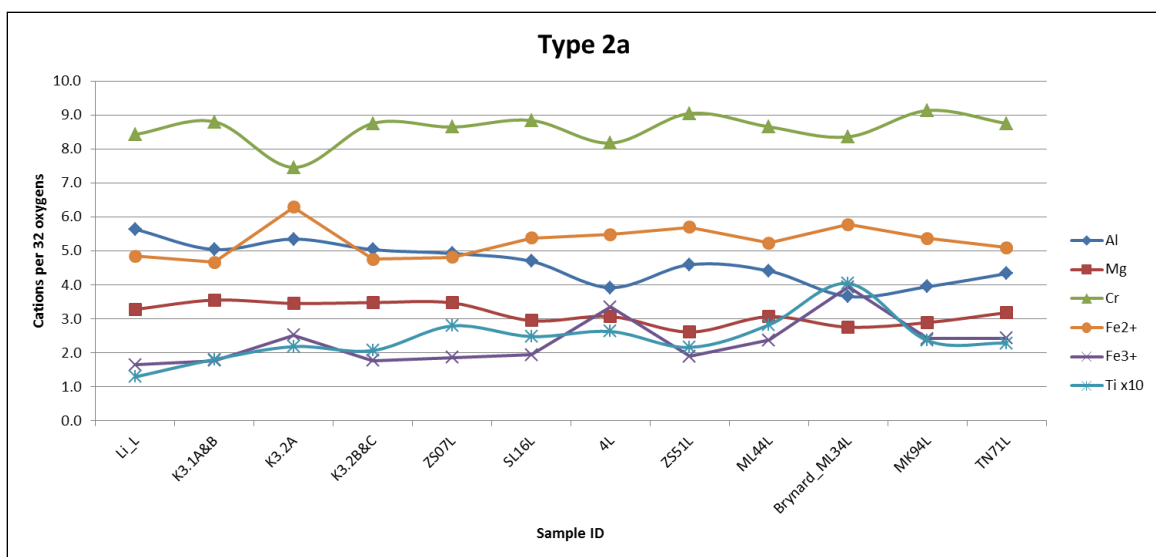


Figure 6.1.2.3 West to east plots of cation compositions of Al, Mg, Cr, Fe²⁺, Fe³⁺ and Ti x10 from Type 1, 2a, 2b and 3 chromitite layers versus comparative study data. Comparative data are from Brynard et al. (1976) , Eales & Reynolds (1986), Kinloch & Peyerl (1990), Li et al. (2005), Vukmanovic et al. (2013) and Cawthorn (unpublished) from Impala Platinum mine. Fe compositions were calculated using stoichiometry where not available for comparative studies. The total distance for this profile is ~ 90km, but samples are not uniformly distributed.

The data in Figure 6.1.2.3 divide into two parts. Samples in the east from K3.3 to SL24 are from this study and the samples to the west are from several different studies.

Overall it is noted that the comparative study data do not differ much in chemical composition and plot within the same ranges as the data from this study. It is also noted that, the Fe^{2+} , Fe^{3+} and Ti compositions are variable and this is attributed to post cumulus changes that occur. Many overlaps between all studies are noted, in particular the Li et al. (2005) and Eales & Reynolds (1986) data.

6.2 Compositional variation and trends

The data are presented as a single analysis for each layer. There are four issues to be addressed to justify this decision;

1. Homogeneity from core to rim.

From the vertical sections in Figure 5.2.1.1, it was concluded that the chromite compositions and cation concentrations between core and rim analyses for all chromitite layers did not show zoning.

2. Uniformity of composition regardless of grain size.

Figure 5.2.3.1 revealed that the chemical compositions between large and smaller grain sizes (100 μ to 1000 μ) had limited differences and it was concluded that grain size is independent of composition.

3. The effect of enclosing silicate grains.

Chromite grains from this study are commonly associated with plagioclase and orthopyroxene minerals. A small number of samples were investigated for systematic differences in chemical composition. No variation patterns or trends were observed in Figure 5.2.4.1, it has been established that no major compositional differences occur between chromite grains hosted by different minerals. A similar conclusion has been observed by Shelembe (2006).

4. Uniformity with height.

The vertical sections in Figure 5.2.1.1 show chemical homogeneity across each chromitite layer. Due to this homogeneity, the average values within each layer were used to represent the chromite composition for each vertical profile.

6.2.1 Zoning and grain size

Hatton and von Gruenewaldt (1985) tested for zoning and effect of grain size on composition. They concluded that the grains were found to be largely unzoned and that the composition from grain to grain in a sample remained constant regardless of grain size. Roeder and Campbell (1985) also found that chromite size within any one silicate host did not affect the composition of the chromite. Similarly, Brynard et al. (1985) found that there is little difference in composition between chromite grains occurring in different silicates.

Li et al. (2005) found that no chemical zoning was observed in their inclusion-free chromites. In contrast, their inclusion-bearing chromites were chemically zoned but that this was attributed to post-entrapment chemical exchange between the inclusions and host chromites resulting in a Ti-Mg exchange. Vukmanovic et al. (2013) found that both their idiomorphic and amoeboidal grains showed little or no zonation from core to rim as seen in Figure 5.2.5.1.

From the few samples tested in this study as seen in Figure 5.2.4.1 and the findings by Shelembe (2006), this study reaches the same conclusion, in that independent of grain size, little variation in chemical composition of the grains occurs.

The chromite grains in a single layer have constant chemical mineral composition independent of the associated footwall and hangingwall layer, and nature of the enclosing host mineral (plagioclase and pyroxene) within the layer.

6.2.2 Compositional trends

Hatton and von Gruenewaldt (1985) investigated three chromitite layers and compared the sub solidus behavior of chromite in olivine and orthopyroxene hosts. Two of the layers are massive chromitites and one layer disseminated. Only observations in the pyroxenite host will be discussed. They observe a decreasing Cr# with cooling and a decreasing Mg#, which they term trend A in their study. Hatton and von Gruenewaldt (1985) equate this trend to reequilibration of chromite with adjacent silicates. They suggest that the chromite would deviate from its original composition by the degree of reaction between orthopyroxene and chromite. Given that in this study it has been established that the chromite compositions are independent of their host silicate, it is suggested that this effect is not important.

Barnes & Roeder (2001) identified what they term the Cr-Al trend in the extremely large dataset on which their study was based as seen in Figure 6.2.2.1. They explain that this trend shows an overall tendency towards increasing Cr# with increasing Fe# as defined by $\text{Fe}^{2+} / (\text{Fe}^{2+} + \text{Mg})$. They note that this trend was first recognized by Irvine (1967). They note that the Cr-Al trend is prevalent in rocks that have equilibrated over a range of pressures.

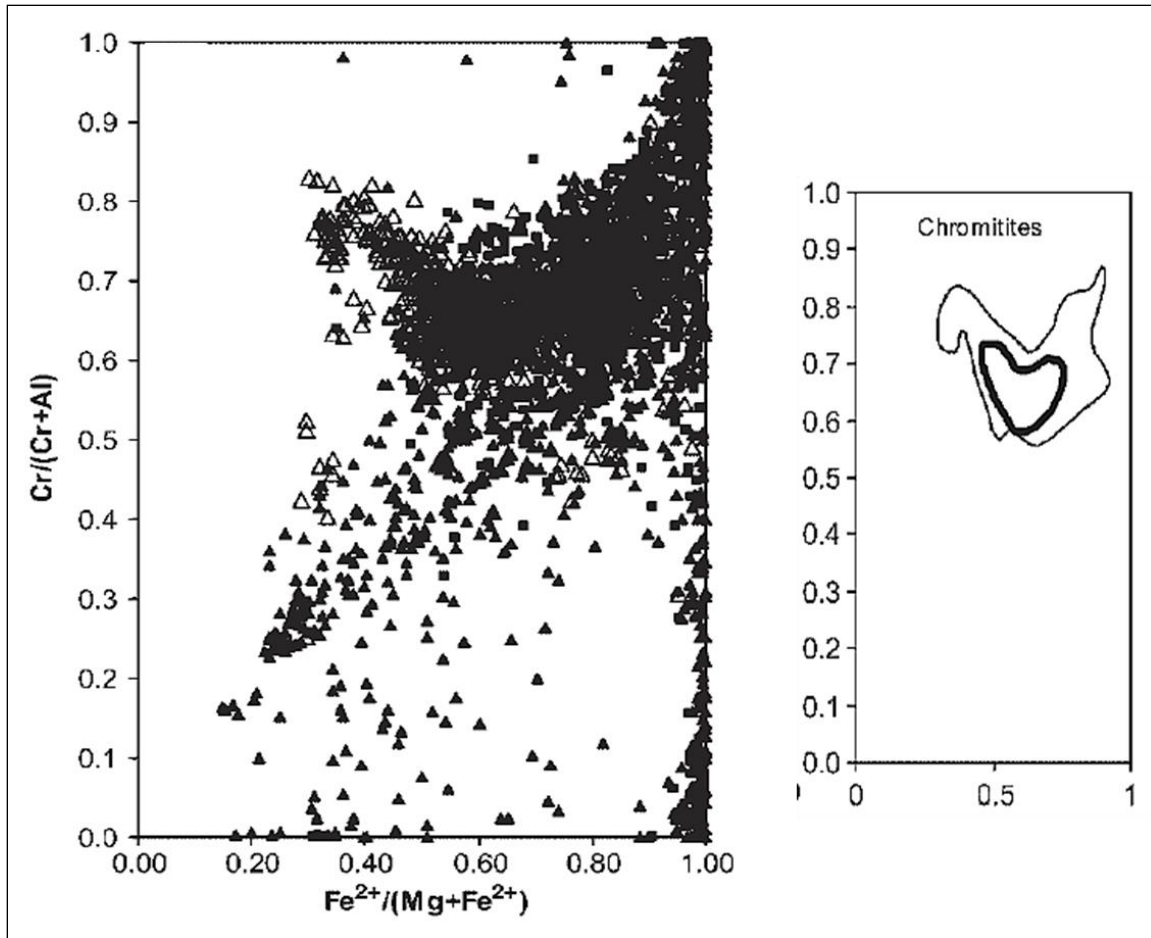


Figure 6.2.2.1 Plot of Cr# versus $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ for samples within continental mafic intrusions after Barnes & Roeder (2001).

The data from this study in Figure 6.2.2.2 corresponds well with this Cr-Al trend described by Barnes & Roeder (2001) and plot in the field of their maximum concentration in Figure 6.2.2.1. No significant differences occur between the different chromitite layer types.

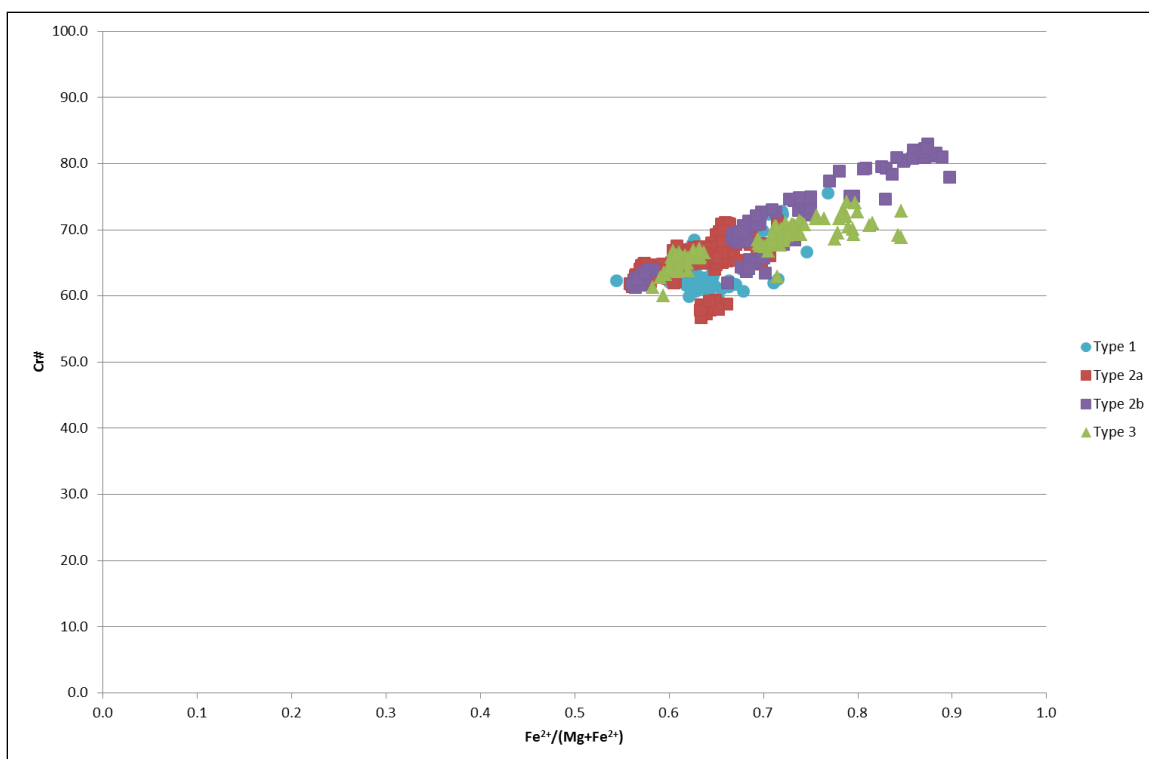


Figure 6.2.2.2 Plot of Cr# versus $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ of all chromite samples.

Barnes & Roeder (2001) identified a second trend in their spinel data which they term the Fe-Ti trend. This trend shows an increase in Fe# as seen in Figure 6.2.2.3. They attribute this trend to the evolution of compositions during fractional crystallization of olivine or pyroxene from the host magma which increases the Fe/Mg ratio and the Ti content of the melt. They comment that previous authors (Henderson, 1975; Henderson & Wood, 1981; Roeder & Campbell, 1985; Scowen et al., 1991) found that in many cases this trend is accentuated by the reaction of spinels in orthocumulate rocks with evolving trapped intercumulus magma. Their data show that chromitites are clustered at low Fe^{3+} contents with a less extensive development of a Fe-Ti trend compared to the category as a whole. They explain this observation to be due to chromite being less susceptible to trapped liquid reactions when the proportion of chromite to liquid in the

rock is high. They therefore conclude that the compositional field of chromitites matches compositions of primary liquidus chromites.

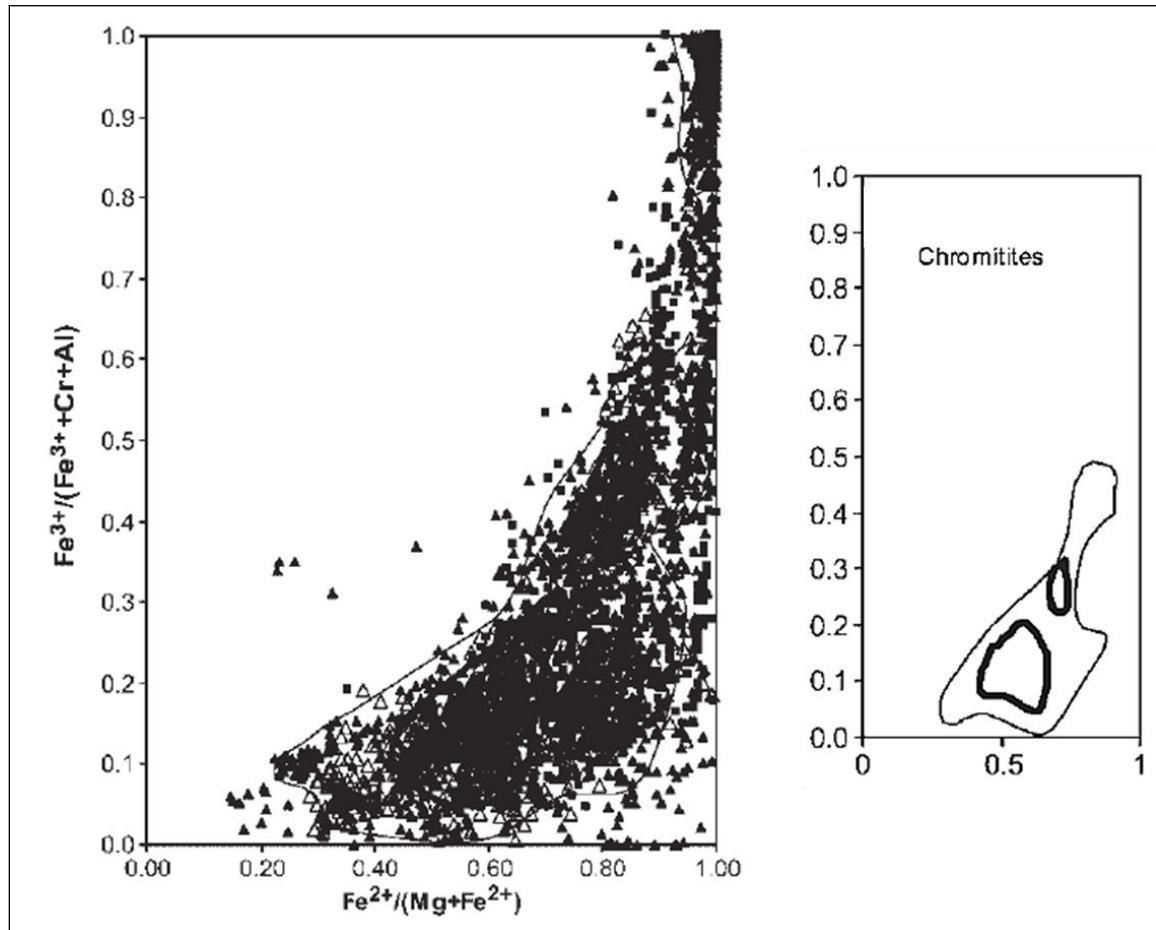


Figure 6.2.2.3 Plot of $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Cr}+\text{Al})$ versus $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ for samples within continental mafic intrusions after Barnes & Roeder (2001).

Roeder & Reynolds (1991) note that their experimental studies show that chromites that have crystallized early from basaltic magmas generally have $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Cr}+\text{Al})$ values below 0.15. In this study, comparable low values of $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Cr}+\text{Al})$ are found (Figure 6.2.2.4) but have a wider range of between 0.06 and 0.25. This wider range corresponds to Roeder & Reynold's (1991) maximum concentration as seen in Figure 6.2.2.3. Types

2b and 3 suggest a trend to higher Fe# but at similar Fe^{2+} to the Types 1 and 2a. This may indicate that the samples in the field of lower values of Fe^{3+} are compositions of chromite close to primary liquid composition and that the values above 0.15 may be due to reaction with intercumulus liquid and subsequent evolution and change in composition of the chromite as the magma slowly cools. However, the present data do not extend to the higher values noted in Figure 6.2.2.3 and so the residual magma may not have evolved as far as in the many of the other examples in their database.

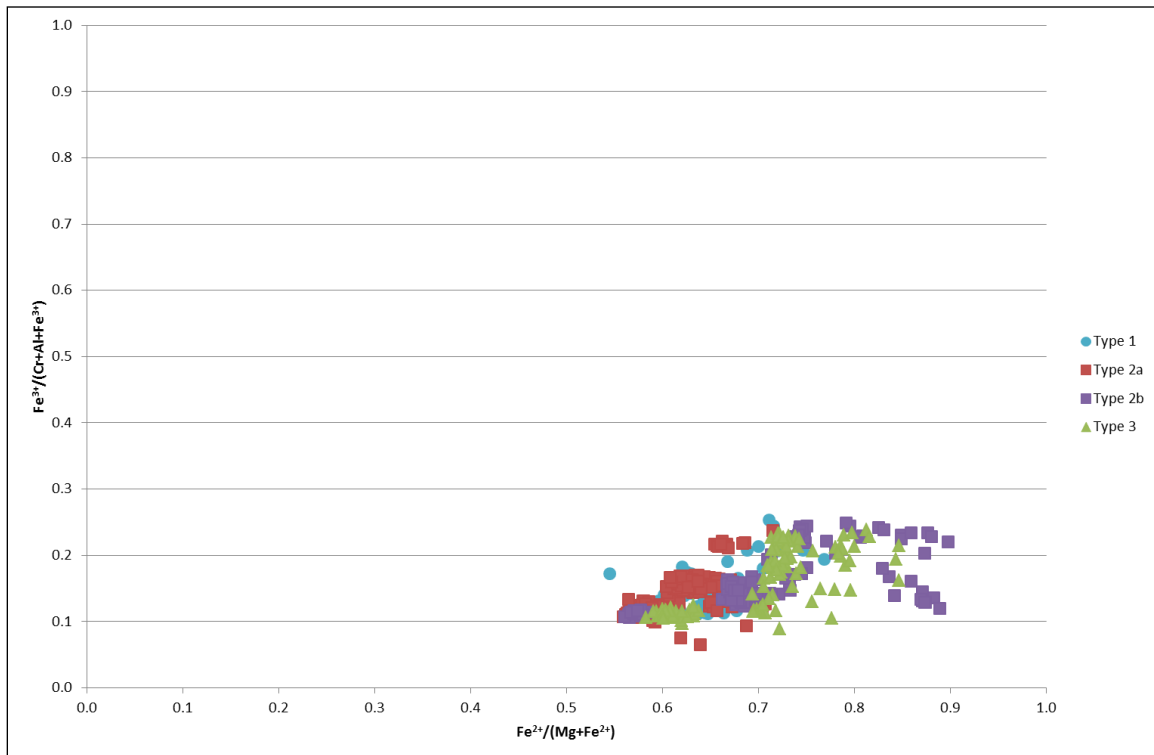


Figure 6.2.2.4 Plot of $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Cr}+\text{Al})$ versus $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ of all chromite samples. Fe-Ti trend shown is after Barnes & Roeder (2001).

Naldrett et al. (2009) focused their study on 19 chromitite horizons from the LG-1 to the UMG-2. In contrast to this study, all their samples collected were of massive chromitite in order to ensure results as close to original cumulus composition as possible. Naldrett et

al. (2009) describe Trend A in their data, the same trend as identified by Irvine (1967); Hatton and von Gruenewaldt (1985) and Barnes & Roeder (2001). The negative slopes of Trend A are interpreted as stages where input of new magma overrode the effect of fractional crystallization and the positive slope of Trend B results from fractional crystallization of orthopyroxene. Figure 6.2.2.5 shows the Bushveld data of massive chromitites from Naldrett et al. (2009) and compositions of disseminated Merensky chromitites on the western Bushveld Complex and the data from this study. The ellipses include all of Naldrett et al.'s (2009) analysed points and group together data from both trends in specific chromitite layers. The different groups of chromitites form in different stages of variation in Mg#. From this study, Types 2b and 3 are hosted by orthopyroxene, so some greater degree of reaction between chromite and orthopyroxene may have occurred compared to Types 1 and 2a.

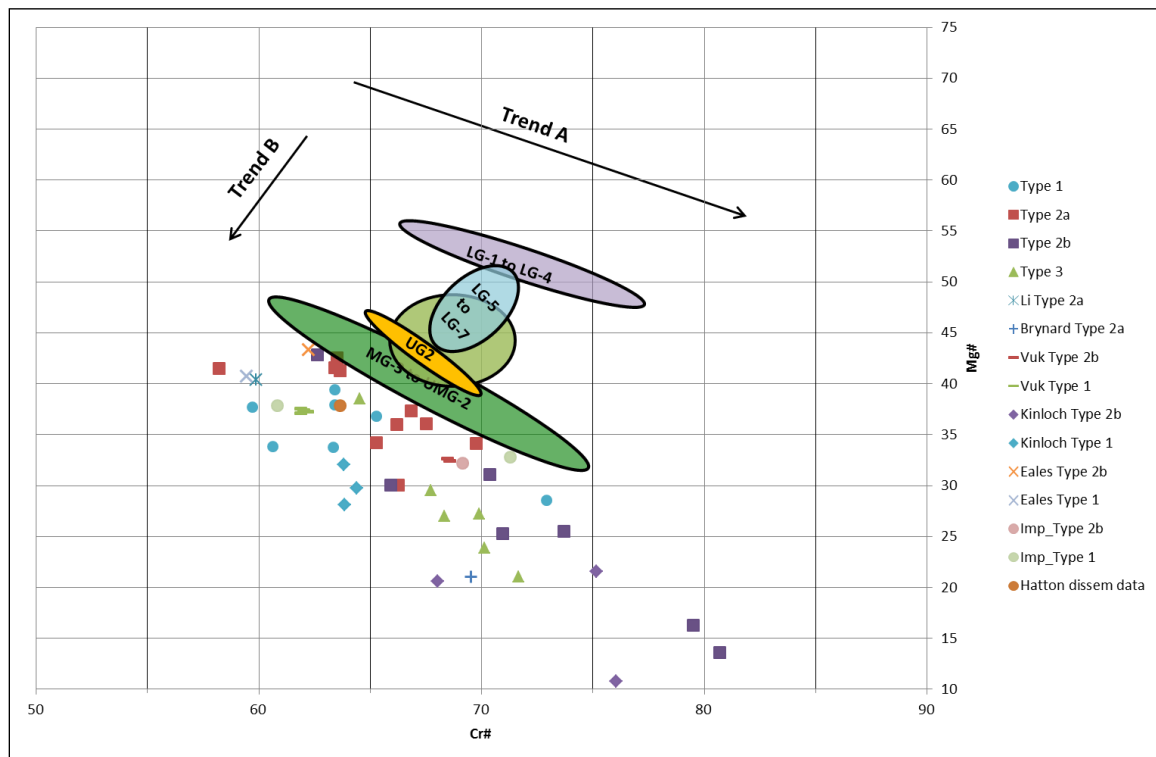


Figure 6.2.2.5 Plot of Mg# versus Cr# for chromite from massive chromitites (ellipses) and chromite from the disseminated Merensky chromitites after Naldrett et al. (2011).

Although the layers from Naldrett et al. (2011) are massive in contrast to the layers from this study with variable amounts of chromite, it is interesting to note that the behaviour of the chromite compositions show some similarities. The average compositions of the chromitite layers in this study show considerable variations. The Mg# ranges from 14 to 44% and Cr# ranges from 55 to 80%, and there is a strong Trend A as seen in Figure 6.2.2.5. The chromites from this study show a Trend A direction, similar to the MG-3 to UMG-2 trends in terms of composition but at a slightly lower Mg#. Naldrett et al. (2011) note that the MG-3 to UMG-2 Trend A, where the data from this study plot, is marked by the first appearance of cumulus plagioclase in the Critical Zone which buffered the crystallization of pyroxene and activity of Al_2O_3 in the magma and terminated trend B. Fractionation of chromite during this stage was dominant and they note that any trends in chromite composition above this level are dominated by Trend A.

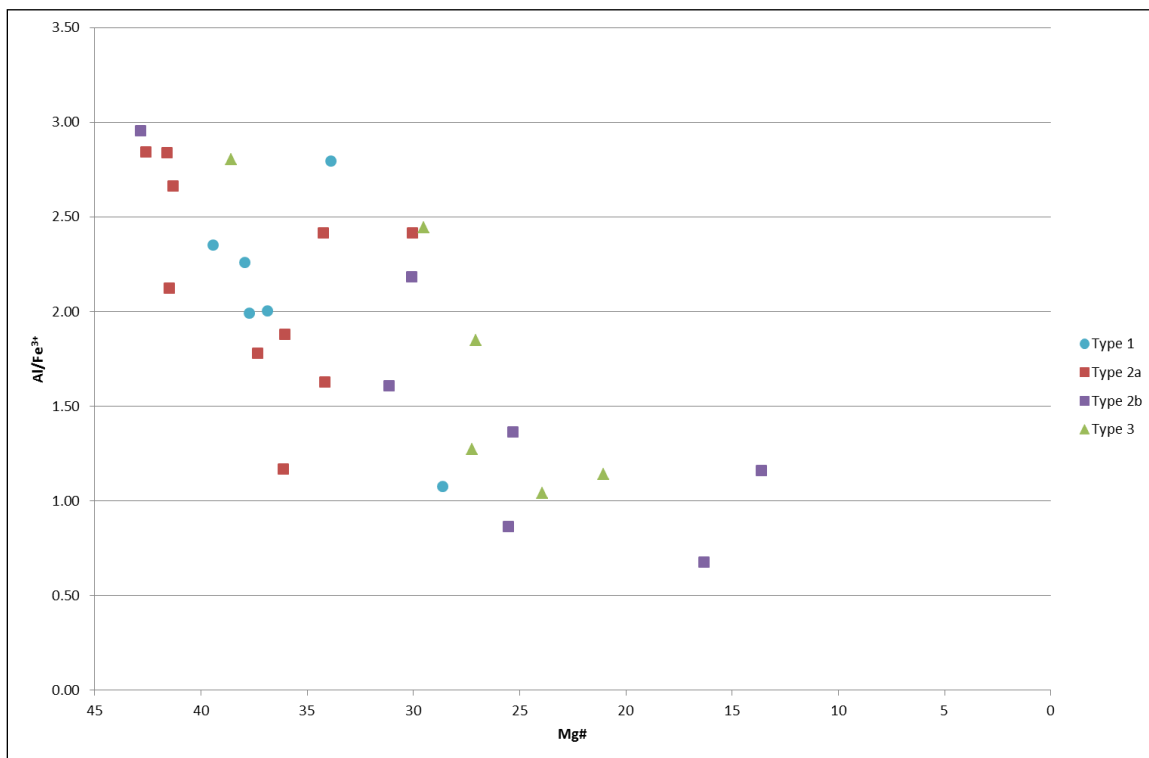
6.3 Post cumulus processes

6.3.1 Reequilibration of chromite grains

Roeder and Campbell (1985) mention that the only sub solidus reequilibration in chromite composition is the redistribution of magnesium and ferrous iron between chromite and the host silicate (Cameron, 1975; Clark, 1978; Wilson 1982). Kruger & Marsh (1985) note that after the crystallization at the liquidus stage of the Merensky Cyclic Unit, that compaction occurred which subsequently caused the expulsion of interstitial liquid from the footwall cumulates. They envisage that the primocrysts could have reacted with the coexisting interstitial liquid in situ and the example that they give is the case in which the orthopyroxene would have reequilibrated with the liquid to more iron-rich compositions.

The Roeder & Campbell (1985) study on the Jimberlana intrusion in Western Australia focuses on the reaction between chromite and the intercumulus liquid as well as the relationship between chromite and its enclosing silicate phase. Roeder & Campbell (1985) state that the compositional complexity of chromite would result from local conditions on a millimeter scale within the intercumulus liquid. They note that, if for example, bronzite did not nucleate in the vicinity with chromite that the chromite would react with the liquid and become richer in Fe and Ti as heat was removed. The trends observed in their chromite compositions show most notably an increase of Fe^{3+} with decreasing Al and Cr and a slight increase in the Cr: Al ratio. They conclude that compositional complexity is due to fractional crystallization and that in the case of large intrusive complexes such as the Bushveld Complex, slow cooling allows intercumulus liquid a greater opportunity to equilibrate with the early minerals, destroying the early magmatic history by reaction and recrystallization.

a)



b)

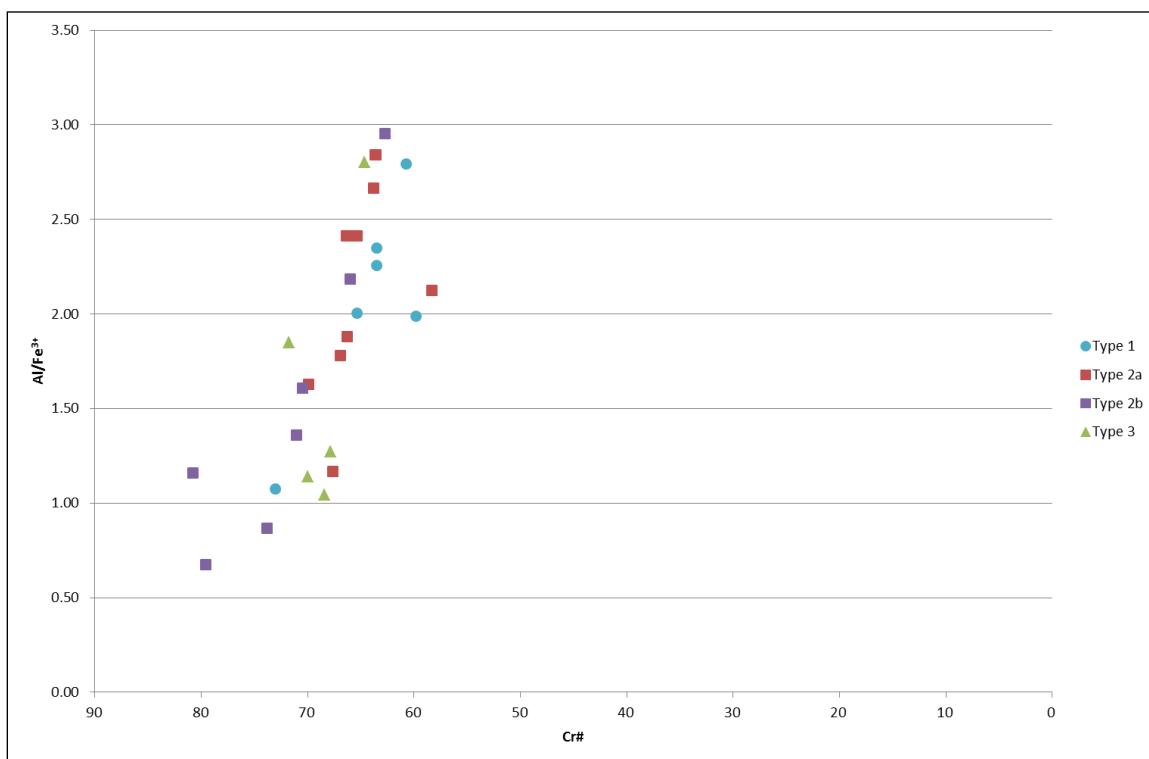


Figure 6.3.1.1 a) Mg# versus Al/Fe^{3+} ratio and b) Cr# versus Al/Fe^{3+} ratio of analysed chromite grains for all types of chromite layers.

The cation plots in Figures 5.2.6.1&2 as well as the west to east profiles in Figure 5.2.7.1 and the Cr cation versus other cations plots shown as ratios in Figure 5.2.8.1 all show that the Cr cation content stays constant throughout. The ternary plot in Figure 5.2.9.5 shows that the Cr remains constant at relatively low Fe^{3+} contents. It is therefore only useful to focus on the Al and Fe^{3+} compositions. This is because Cr, Al and Fe^{3+} occupy the trivalent site and if Cr remains constant, then the only variables are Al and Fe^{3+} . Therefore reaction of chromite with iron-rich liquid causes an increase in Fe^{3+} . Interchange of Fe^{2+} for Mg would also cause a decrease in the Mg# in chromite. In Figures 6.3.1.1a and b, the Al/Fe^{3+} ratio reflects the relative proportions of these two elements showing the same observation that Roeder & Campbell (1985) noted when compared to Mg# and Cr#. All chromitite layer types follow the same main trend. Two close parallel trends are observed for Types 1 and 2a (hosted by plagioclase) and Types 2b and 3 (hosted by pyroxene). There is a minor difference in value between the two groupings with Types 1 and 2a having higher Mg# and a higher Al/Fe^{3+} ratio than Types 2b and 3. It is thought that this difference is possibly due to some reaction with different interstitial minerals.

The near constant Cr cation content for all chromitite layers implies that all chromite along the length of the layer had the same primary Cr content and that changes to composition brought about by trapped liquid had little effect on the Cr cation content. Irvine (1967) shows that the degree of sub solidus reequilibration is correlated with the modal amount of chromite in the sample. Barnes & Roeder (2001) describe this as the buffering effect; this is due to chromite being less susceptible to trapped liquid reaction

effects when the grain to liquid ratio is high. The modal proportion of chromite in the different chromitite layers in this study ranges from 14 to 77%. It is thought that the layers with less percentage chromite would create less localized buffering effect and it would be expected that these grains would be more susceptible to compositional changes. However Figures 5.2.9.3, 4 & 5 show that there is no correlation between proportion of chromite and composition, as no trends are observed when plotted against Cr#, Mg# and Al. This could indicate that regardless of the percentage of chromite present, that it is possible that either (i) all layers have undergone post-cumulus processes and reequilibrated to some degree or (ii) that all grains are near primary composition. Here, the latter is considered to be highly unlikely. Chistyakova et al. (2015) discuss the main processes of postcumulus modification of chromite and note that they are either by reaction of chromite with interstitial melt or involve subsolidus reaction between chromite and silicates. They note that abundant chromite acts as a buffer during reaction with intercumulus liquids and that the effect is therefore minimal, particularly for massive chromitite. Studying the vertical cation compositions of Cr in Figure 5.2.1.1, samples 50L and 53L which have the lowest percentage of chromite of 14 and 16% respectively, show small variations in Cr contents compared to the constant Cr cation content of the other layers which have greater percentages of chromite. This could be due to what Chistyakova et al. (2015) attribute to modification of the primary composition of disseminated chromite with trapped melt. Chistyakova et al. (2015) do however ignore the need for a fall in temperature in order for reaction to take place with the interstitial liquid and this issue still needs to be resolved.

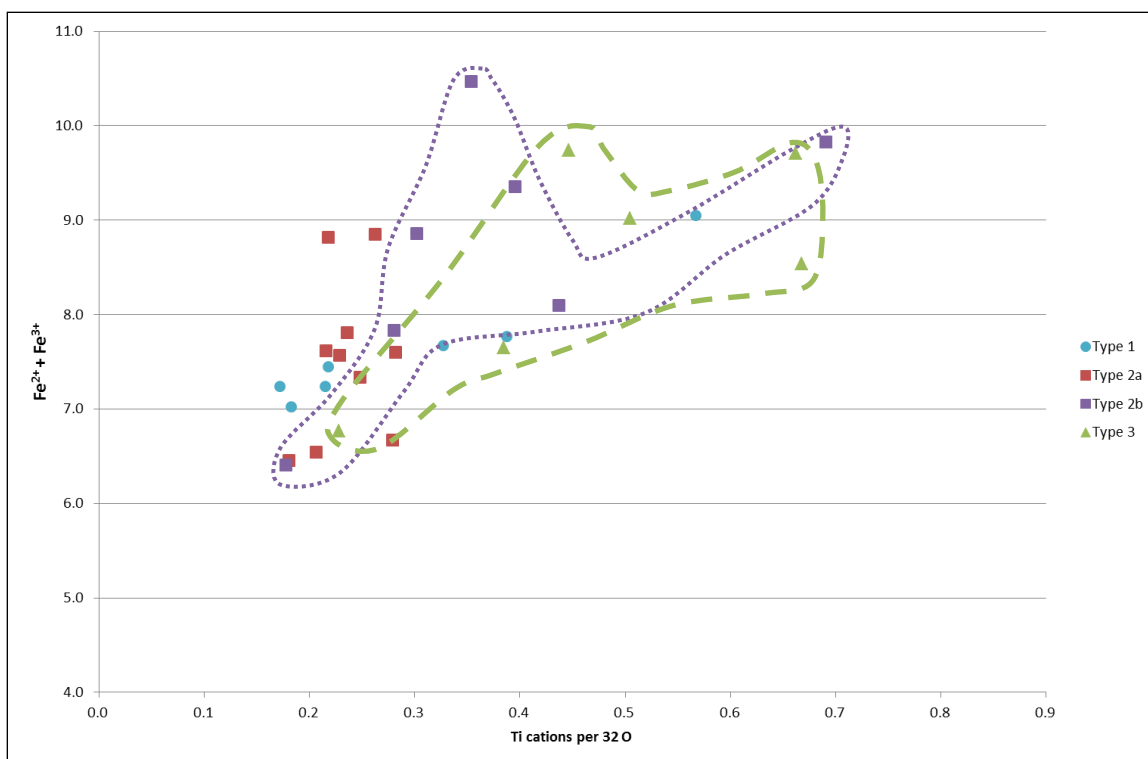


Figure 6.3.1.2 Total Fe versus Ti for all types of chromite layers.

In Figure 6.3.1.2, the Type 2b and 3 chromitite layers show slightly more enrichment in both Ti cations and total Fe than the lower Type 1 and Type 2a chromitite layers. Roeder and Campbell (1985) also concluded that their data showed a positive correlation between total Fe and Ti. Yudovskaya et al (2015) note that increasing Fe^{3+} in chromite enhances the tendency of Ti to partition into chromite and Figure 6.3.1.2 shows that the chromite grains from this study are in agreement with this. The ternary plot in Figure 5.2.9.6 shows no clear trend of enrichment in Ti or Fe^{3+} , although the Type 3 chromitite layer values plot at the highest values of Ti, in a range of 14 to 36 $\text{Ti} \times 10$ cations, compared to the other layer types. The Ti enrichment in chromite from Yudovskaya et al.'s (2015) study in the Uitkomst Complex in South Africa is considered to be a primary feature and not due to subsolidus reequilibration. However in this study, no significant sources of contamination are thought to provide Ti as in their study and it is suggested

that reaction with trapped liquid on cooling has resulted in some Ti enrichment, in particular for the Type 3 chromitites.

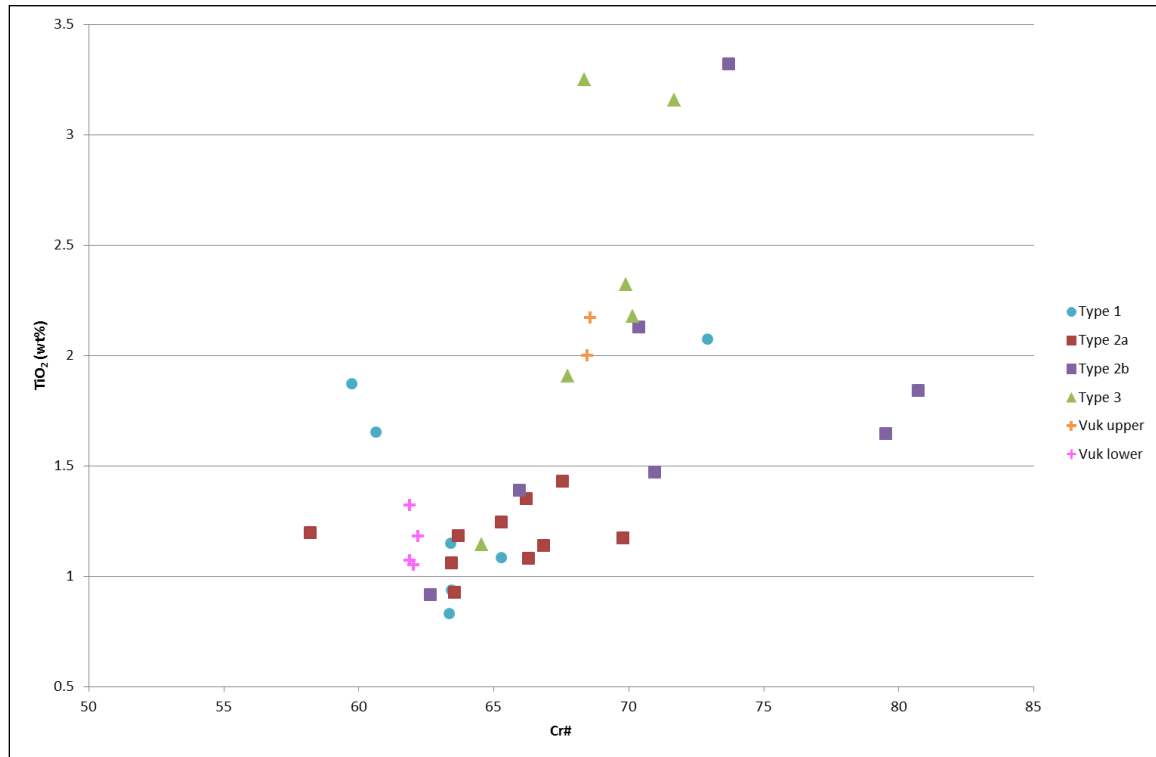


Figure 6.3.1.3 Cr# versus TiO₂ wt% for all types of chromite layers and showing comparative data from Vukmanovic et al. (2013).

Figure 6.3.1.3 shows the TiO₂ wt% data from this study in comparison to the data from Vukmanovic et al. (2013). Vukmanovic et al. (2013) noted that their lower chromitite grains show lower values of Cr#, Ti and Fe than the grains from the upper chromitite layer. The TiO₂ data from this study plot in similar concentrations and are thus in agreement with this statement. The Type 1 and Type 2a chromitite layers show less enrichment in Ti with values being below 1.5wt% TiO₂ than the Type 2b and Type 3 layers which display TiO₂ wt% values of above 1.5. Vukmanovic et al. (2013) attribute

this trend to the upper chromitite having more extensive reaction with trapped liquid than the lower layer.

In Figure 6.3.1.4, after Roeder (1994), the possible compositions of spinels are displayed, of which chromite is of particular interest in this study. He comments that it is the composition of the melt that determines the composition of chromite. The arrows in the figure show expected chromite compositions resulting from the co-crystallization of melt and olivine (OL), plagioclase (PL) and pyroxene (PY). The data from this study plot within the red oval, which fits into the fractionation fields of both pyroxene and plagioclase (pre-supposing they are primary compositions). A hypothetical process of reequilibration by interstitial liquid for the data from this study could be that at the higher temperature (approximately 1200 degrees Celsius as shown experimentally by Roeder (1994) and indicated by “a” in Figure 6.3.1.4) the cation compositions were closer to primary magmatic composition and as the magma cooled and co crystallization was taking place with either plagioclase or pyroxene, the compositions were reequilibrated by the interstitial liquid. At the lowest temperature (less than 1100 degrees Celsius and indicated by b on Figure 6.3.1.4) the cation compositions are the most altered.

Chromitite layers Types 1 and 2a are hosted almost entirely by plagioclase and Types 2b and 3 are hosted almost entirely by pyroxene. The averages, standard deviations and relative standard deviations for all samples for all cations were calculated in order to study the variation in values between samples (Appendix A). It was found that across the layer, the compositions are relatively homogenous regardless of the host silicate, as well as cases where grains are in contact with both plagioclase and pyroxene. It was found that there is little difference in the average compositions between these two groups. For all comparative figures of Mg# versus Cr#, Ti and Fe^{2+} and Al, no separate trends for

plagioclase and pyroxene hosted grains are observed (Figure 5.2.6.2; 5.2.6.4; 5.2.8.1; 5.2.8.2; 5.2.9.2; 5.2.11.1 and 5.2.11.2). If reequilibration occurred with the silicates, then different trends would be expected. The two explanations for this observation are both plagioclase and pyroxene are in constant proportion to one another, or the changes are due to intercumulus liquid. It is unlikely that the former scenario is true and it is the authors opinion that reequilibration by liquid has most likely occurred. From this evidence it can be inferred that the reaction between chromite and either plagioclase or pyroxene is minimal.

Roeder (1994) noted that the chromites in his dataset of chromite spinel and magnetite compositions from a wide range of geological environments commonly have high Cr# and a low $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ value as shown in Figure 6.3.1.5. Roeder (1994) notes that most massive chromitites have this low $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ value due to the large amount of chromite relative to the amount of silicate and therefore don't envisage that subsolidus equilibration has taken place. Roeder (1994) infers that these compositions may be close to that produced at magmatic temperatures. He further concluded that disseminated grains in low concentration increase their $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ value during slow cooling, by equilibration with coexisting silicates and thus don't reflect a magmatic composition.

Hatton and von Gruenewaldt (1985) found that subsolidus reequilibrium extensively alters chromite compositions and that the parameter controlling the degree of reequilibration is the ratio of area of chromite in contact with a silicate versus the volume of chromite in the layer. They observe that it is the disseminated chromites where the proportion of chromite in contact with the silicate is high, that subsolidus diffusion proceeds to low temperatures and is extensive and that in the chromitite layers, that

subsolidus diffusion is not as extensive. In contrast to Hatton and von Gruenewaldt's (1985) conclusion, Cameron (1975) note that analyses of chromite and coexisting olivine or bronzite in various textural associations indicate that equilibration in the postcumulus and subsolidus phases exist but that these do not cause the main variation in composition of chromite, these changes occur in the cumulus stage.

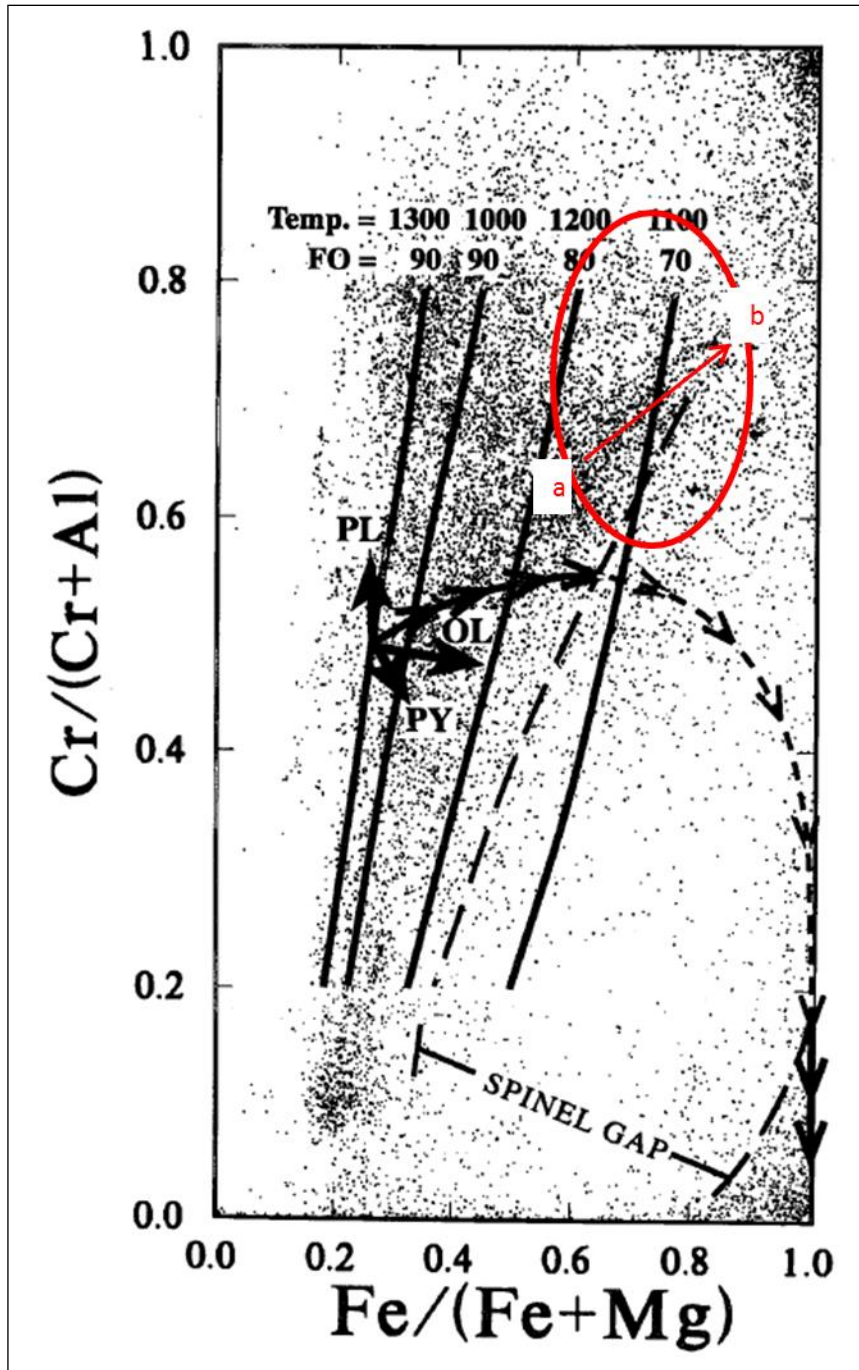


Figure 6.3.1.4 Plot of $\text{Cr}/(\text{Cr}+\text{Al})$ versus $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ of all samples in the database after Roeder (1994) which may be expected by the co-crystallization from a basaltic melt of chromite and plagioclase, pyroxene and olivine (not discussed here). The data range from this study is within the red oval and the hypothetical process of reequilibration by interstitial liquid is shown by the red arrow from a to b.

The data range from this study in the red oval in Figure 6.3.1.5 is in agreement with Roeder's (1994) finding that this is the range that low concentrations of chromite grains would plot in. The $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ values range between 0.54 and 0.89. Disseminated chromites are known to be different in chemistry from layered chromites because their chance of reacting with late stage fluids is greater (Eales & Reynolds, 1986). In comparison to massive chromitites, these $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ values are relatively high which could indicate that these are not the original magmatic compositions and that changes have occurred on cooling.

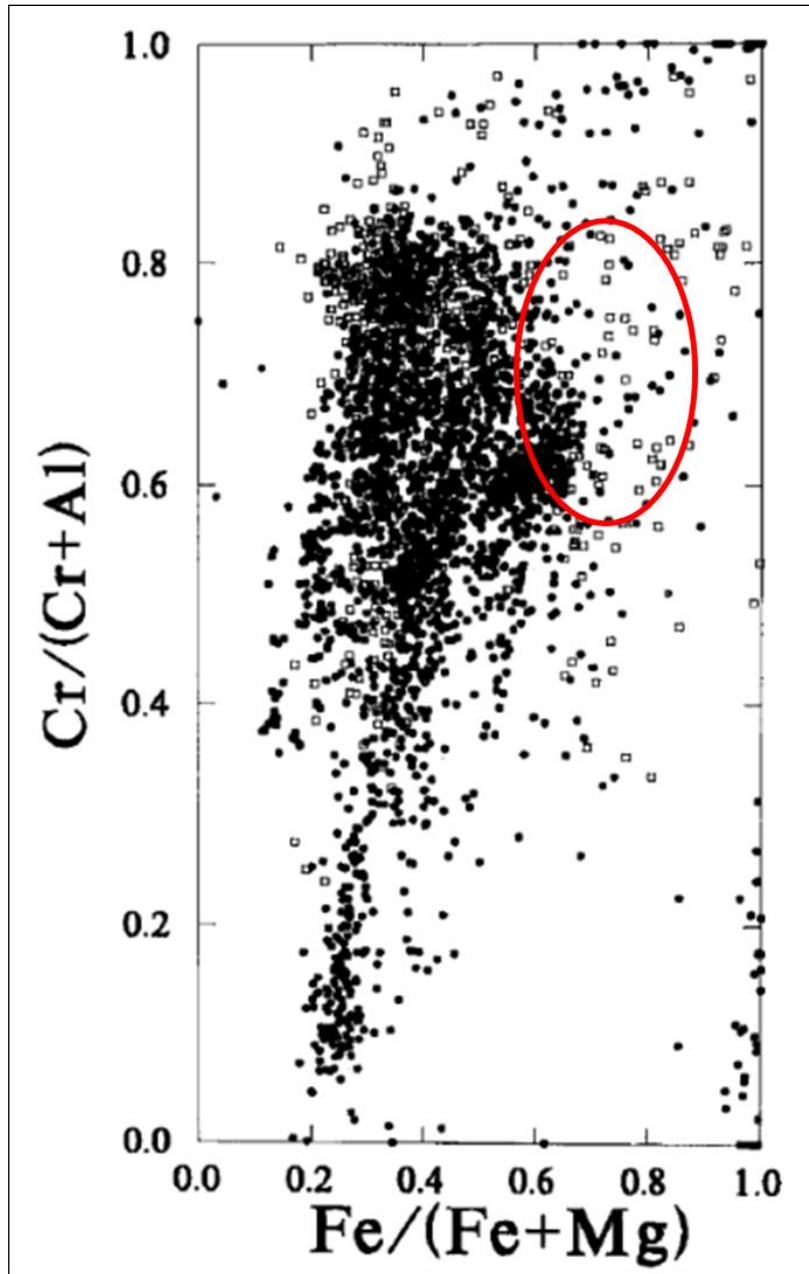


Figure 6.3.1.5 Plot of Cr# versus Mg# from ophiolites (solid dots) and chromitites (open squares) after Roeder (1994). The study data range is indicated by the red oval which is where Roeder (1994) note that disseminated chromitite data plotting.

To summarise the findings relating to Cr compositions as discussed above;

1. On a local scale ($\pm 30\text{m}$), mineral chemistry was used to correlate chromitite layers laterally. On a large scale ($\pm 90\text{km}$), no lateral variability across the Marikana Operations or even beyond (to the west) was observed.
2. No zoning was observed between core and rim pairs of chromite grains and it was concluded that grain size have no effect on chromite composition, similarly chromitite layers were found to be vertically homogenous.
3. No separate trends were observed for plagioclase and pyroxene hosted chromite grains and it was concluded that the reaction between chromite and either plagioclase or pyroxene was minimal.
4. The chromite grains from this study showed a strong Trend A which is attributed to the dominant fractionation of chromite.
5. The chromite grains have relatively high values of $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ which could indicate that these are not the original magmatic compositions and that changes have occurred on cooling.
6. The near constant Cr cation content for all chromitite layers would suggest that all chromite along the length of the chromitite layer had similar, if not the same primary Cr content and that compositional changes brought about by trapped liquid had little effect on the Cr cation content.
7. It was noted that when the proportion of chromite to liquid in the rock is high, that chromite will be less susceptible to trapped liquid reactions. It was however found that regardless of the percentage of chromite present, that it is possible that all layers have undergone post-cumulus processes. Slow cooling of the Bushveld Complex allowed intercumulus liquid a greater opportunity to equilibrate with the early minerals, destroying the early magmatic history by reaction and recrystallization.

6.4 Depositional models

This previous discussion focussed on the chromite compositions. It is then necessary to comment on the formation of the Merensky unit with its variable number of chromitite layers.

6.4.1 Existing models

Various deposition models have been presented for the emplacement of the Merensky Reef. Only those that are applicable to this study will be discussed here. As summarised by Latypov et al. (2015) they include one of the earliest and most widely accepted magma mixing model (Figure 6.4.1.1a) proposed by Campbell et al. (1983) and Naldrett et al. (1987). This model proposes the mixing of new and resident magma followed by gravitational settling of chromite and /or dense sulphide melt onto the temporary magma chamber floor. Scoon & Tieglar (1994) proposed a variation to the magma mixing model (Figure 6.4.1.1b) and favoured the lateral mixing of primitive and resident magma over distances of more than 150km in order to achieve high silicate magma to sulphide melt ratios (R-factor). Naldrett et al. (2011) reached a similar conclusion that the Merensky Reef was produced by settling of chromite and sulphide droplets from a mixed magma. They note that some chromite may have crystallised in the magma conduit and introduced as a bottom load in the intruding magma and most crystallised in situ, probably as a bottom growth. While Latypov et al. (2015) acknowledge that mixing of magma is inevitable when denser magma is intruded into a chamber (Campbell & Turner, 1989), they favour mixing in a basal layer. This is due to evidence for erosion of footwall rocks and the magma needed to be in direct contact with the floor cumulates.

Cawthorn (2011) considers it unlikely that instantaneous and efficient mixing took place on such a lateral and vertical scale.

Kinnaird et al. (2002) proposed that chromite was produced by crustal contamination of the magma (Figure 6.4.1.1c). They envisaged that new magma erupted along weaknesses in the crust into the chamber and that should there be enough upward movement of magma, both roof fragments and entrained material were melted and are the source of this contamination. Both the primitive and resident magma were contaminated with a silica-rich component and this induced chromite saturation and associated crystallization of PGM. It is widely accepted that contamination of the magma occurs as the magma is intruded into the chamber. However, Seabrook et al. (2005) argued that the variations in Sr isotope ratios do not result from the mixing of magmas and that the processes are more complicated. Seabrooke et al. (2005) suggest that the pyroxenites of the Merensky Reef contain variable proportions of plagioclase. They note that the proportions of the cumulus and intercumulus plagioclase are variable, which explain the variable Sr isotope ratios of the Bushveld Complex. In cases where no cumulus plagioclase is present, they explain that upward infiltration of residual liquid took place, assigning Sr isotope ratios of Critical zone signature. They explain that in cases where some plagioclase is cumulus, it originated from the overlying Critical zone magma and sank with orthopyroxene. They comment that either or both of these processes might occur to produce the Sr isotope values in the pyroxenite. Hutchinson et al. (2015) suggest that this model would indicate that the roof of the complex was essentially floating on the mafic magmas. They report however that Irvine (1977) rejected the idea that silica addition would lead to chromite precipitation due to the large amounts of siliceous rocks required for this process.

Cawthorn (2005, 2011) proposed a pressure mechanism induced crystallization of sulphide /chromite (Figure 6.4.1.1d) where an increase in pressure in the resident melt caused the injection of new magma. The increased pressure causes the formation of an immiscible sulphide melt and/or chromite in the resident melt which settled and accumulated on the chamber floor. While settling, PGE was scavenged by either chromite or sulphide liquid. Maier et al. (2013) note that the change in pressure would affect the entire intrusion simultaneously and thus could explain the lateral continuity of the reefs, however they comment that this model is difficult to test as the proposed pressure changes would most likely not result in significant compositional differences. Hutchinson et al. (2015) note that the limitation of this model is the difficulty in explaining the variability in number, thickness and positions of the chromitite layers.

Willmore et al. (2000) proposed a fluid induced sulphide saturation model (Figure 6.4.1.1e). In their model, interstitial fluids migrate upward from the footwall into the magma chamber. As the fluid moves it collects sulphur and PGE from the footwall and the fluid becomes sulphur bearing. Mixing of this sulphide bearing fluid and silicate magma would induce sulphur saturation and PGE collection. Latypov et al.(2015) argue that if the footwall cumulates were nearly solid a few metres below the floor of the magma chamber, then transfer of interstitial melts or fluids from the underlying cumulates is unlikely and they thus infer that post-cumulus processes cannot be regarded as principal agents in the formation of the PGE deposits. Willmore et al. (2000) do not comment on the mechanism for deposition of chromite and this model can therefore not be tested based on the results from this study.

Mitchell & Scoon (2007) and Kruger (2010) proposed that a sill-like emplacement of magma rich in sulphur and PGE, was injected into pre-existing cumulates (Figure

6.4.1.1f). The argument that Cawthorn (2011) made against these emplacement models was why the injections occurred exactly along the contact between two different rock types, especially over an area of 30 000 km² with such uniform thickness.

Hutchinson et al. (2015) proposed the emplacement of chromite and sulphide-rich pulses of new magma from a staging chamber. They suggest that the new magma carried suspended chromite crystals, sulphide droplets and PGM (Figure 6.4.1.1g) and argue for sustained, high energy, lateral injections of magma. They attribute the number and positions of layers to be as a result of thermo-mechanical erosion together with deposition of layers in response to successive magma influxes. The limitation of this model is again the problem of lateral continuity and as argued above by Cawthorn (2011) how these lateral injections of magma were able to create layers of such uniform thickness across the Bushveld Complex.

Vukmanovic et al. (2013) proposed a model for the crystallization and compaction of the Merensky Reef based on microstructural observations, chemical compositions and crystal size distribution curves. They envisage a three phase process. During the first phase, the lower chromitite layer formed by rapid crystallization in a thermal boundary layer between hot incoming magma and a cooler eroded crystal pile beneath. Initial crystallization formed primary dendritic chromite morphologies, followed by textural maturation during solidification and compaction. They note that the similar chemistry for the two populations of lower chromitite grains imply a two-stage crystallisation event. They described the second stage as being the input of a new magma responsible for the formation of the upper chromitite layer and modification of dendrites in the lower layer. They comment that the upper chromitite layer was emplaced on a hotter substrate with no supercooling, and therefore no dendrites formed. The third phase they proposed was

the cooling of the magmatic column resulting in the mobilisation of intercumulus melt and the formation of compaction-related deformation. As with all other models proposing in situ crystallization of chromite, a major problem as noted by Yudovskaya et al. (2015) is how a significant thickness of chromitite can form without crystallization of concurrent orthopyroxene or olivine.

Based on cross-sections by Viljoen (1999), Latypov et al. (2013) concluded that the chromitites in the Merensky Cyclic Unit follow the undulations in the footwall with constant thicknesses. Hutchinson et al. (2015) challenges Latypov et al.'s (2013) conclusion by drawing on Naldrett et al.'s (2009) comment that these conclusions are based on cross-sections and not field observations. Latypov et al. (2015) further attempt to back up their conclusions, by presenting examples of field observations from across the Bushveld Complex. Latypov et al. (2015) show from their study of field evidence as proposed by Cawthorn et al. (2002), that the Merensky Reef formed by several events of magma replenishment as a basal layer to the chamber. Cawthorn et al. (2002) comment that either recrystallization or erosion of the immediate unconsolidated footwall occurred due to the addition of new magma to the chamber. They note as proposed by Campbell (1986), that where the footwall is plagioclase-rich, erosion may take place and that an ultramafic layer is more likely to resist erosion and reconstitution dominates in this case. They recognized that the erosional unconformity at the base of the Merensky Cyclic Unit represented a break in cumulate accumulation. Kruger and Marsh (1982) demonstrated a Sr isotopic break which they attributed to the addition of magma different to that of the resident magma. Latypov et al. (2015) note that various authors have proposed that a hot olivine-rich saturated magma melted the plagioclase-rich footwall and caused dissolution of pyroxenite and chromite that crystallized from previous magma flows as the magma cooled (Cawthorn, 1999; Mitchell & Scoon, 2007). This Latypov et al. (2015)

proposes was followed by in situ crystallization of chromite onto the magma-cumulate interface and not gravitational settling as proposed by other authors.

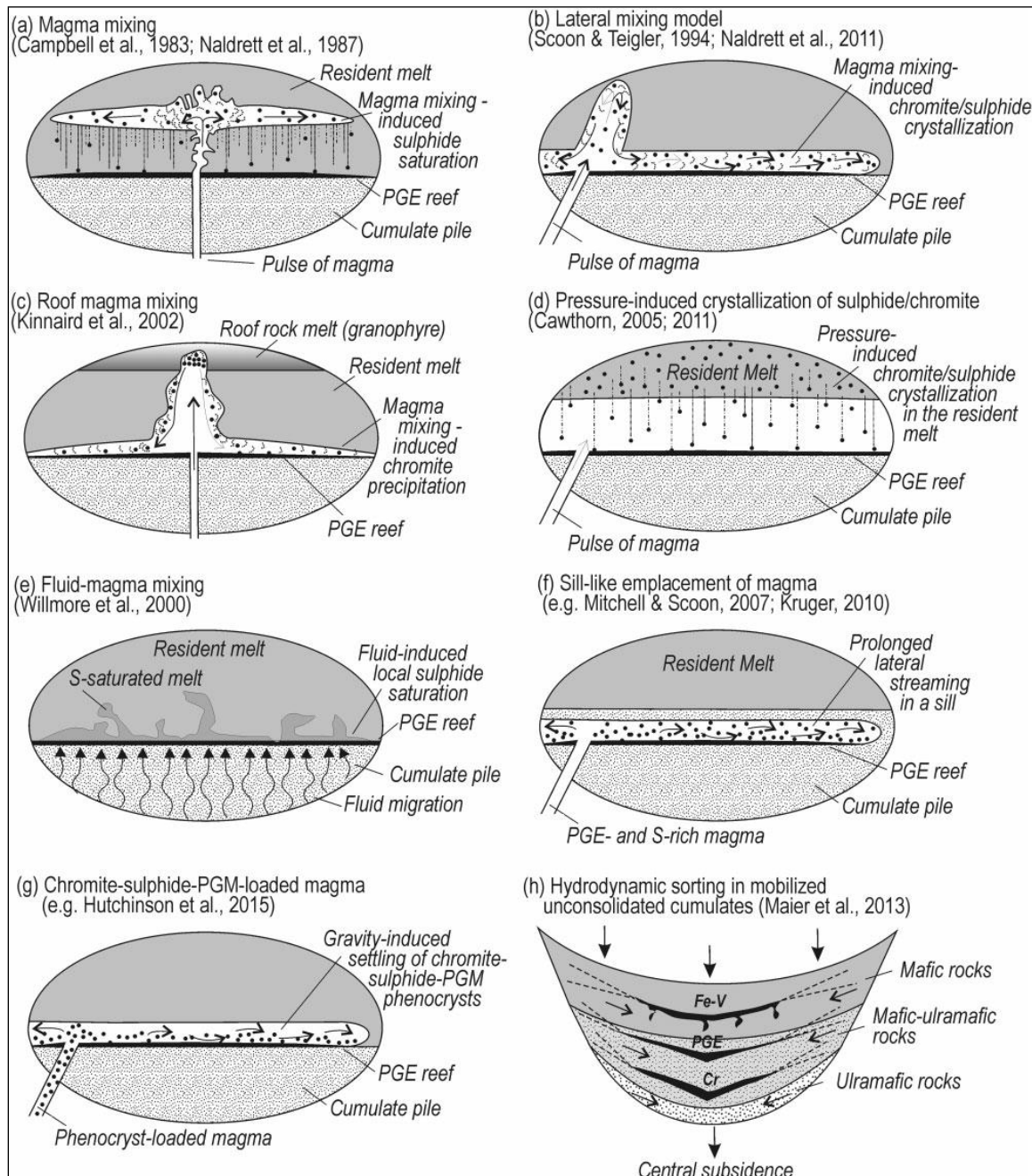


Figure 6.4.1.1 Sketches illustrating some of the most popular hypotheses for the origin of the Merensky Reef (Latypov et al. 2015).

6.4.2 Preferred Depositional model

6.4.2.1 Evidence from field observations

The field observations detailed in Chapter 2.4 highlight a few processes which could point to the formation of the Merensky Reef and Merensky Cyclic Unit at Marikana.

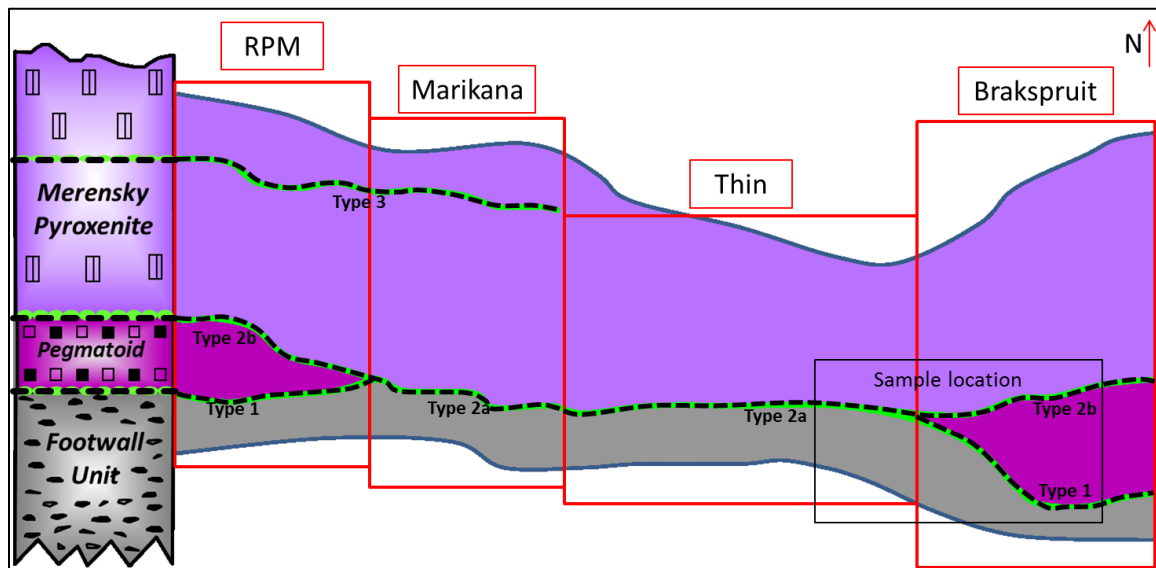


Figure 6.4.2.1.1 Sketch showing the lateral facies changes that can be observed within a stope of approximately 30m strike length at K3 Vertical Shaft, Marikana. (Sketch courtesy of Samantha Plumb).

Figure 5.1.1 shows a photo of the area at K3 Vertical Shaft where a facies transition was observed. The location is shown in Figure 6.4.2.1.1 with an interpretation of facies changes that are observed in a stope of 30m strike length. In order to construct the evolution of this package, an attempt was made to laterally correlate the chromitite layers to determine to which chromitite in a three-chromitite or two-chromitite facies does the single chromitite facies equate. It was concluded from the mineral chemistry that within the sample location indicated in Figure 6.4.2.1.1, the single Type 2a chromitite

layer of the Thin facies and the top two samples within the transition zone correspond with the Type 2b chromitite layer in the Brakspruit facies (Figure 6.1.2.1). There was no chemical evidence for continuation of the bottom layer in the Brakspruit facies with the layer at the base of the Thin facies. In the sketch it is assumed that the Type 3 chromitite layer of the RPM and Marikana facies correlate laterally. Although chemically no obvious groupings were found for any of the layer types, there are some overlaps and similarities, particularly for Type 3 and the compositions may have originally been similar but they have subsequently undergone post cumulus reequilibration causing compositional changes. The most likely correlation of layers between the RPM and Marikana facies in Figure 6.4.2.1.1 is that the Type 2b layer from the RPM facies continues as the Type 2a layer of the Marikana facies and there is no continuation of the Type 1 layer of the RPM. An important observation from this correlation attempt is that the lateral variations require regions of partial or complete erosion in order to correlate layers. This will be explored further below.

6.4.2.2 Preferred Depositional Model Description

The contact between the Type 1 chromitite layers and the footwall anorthosite is consistently sharp and in many cases may be undulating and truncate down into the footwall (Figures 2.4.1, 2.4.5, 2.4.6 & 2.4.7). This provides evidence that this contact is in fact erosional and forms an unconformity. Campbell et al. (1983) argues that the addition of hotter, undifferentiated magma could lead to erosion and a hiatus in silicate accumulation. Cawthorn (1996) suggested that the magma added at the stratigraphic point of the Merensky Reef, was more evolved than the resident magma and that this could lead to supersaturation and interrupted crystallization. Kruger & Marsh (1985) also recognised that it was the higher temperature, turbulent mixing, and gravitational

readjustment produced by the injection new magma chamber that produced the unconformity and the dimpled basal contact of the Merensky Cyclic Unit. Cawthorn et al. (2002) attribute this unconformity to the addition of hot, plagioclase-undersaturated magma that eroded the footwall, forming a new temporary floor of the magma chamber. They note that localised, deeper erosion of the footwall produced the undulating footwall and small potholes. This process could therefore explain the undulating and truncating nature of the first chromitite layer observed. Cawthorn et al. (2002) suggest that the PGE mineralization straddles the chromitite layer and penetrates into its footwall. This is consistent with localized occurrences of footwall mineralization observed and sampled at Marikana. Latypov et al. (2015) mention that it was mixing that superheated the magma, allowing it to melt the footwall. Alternatively Cawthorn & Boerst (2006) attribute the superheating of the magma to be due to the addition of superheated magma into the chamber or a release in pressure in the magma chamber.

Cawthorn et al. (2002) proposed a sequence of events leading to the formation of the Merensky Cyclic Unit (Figure 6.4.2.2.1.). They note that a succession of norites and anorthosites form the footwall rocks. With the addition of a plagioclase-undersaturated magma, the floor rocks were eroded. This was followed by crystallization of a thin chromitite layer and an unknown thickness of either pyroxenite or hartzburgite. Further injection of magma produced a second erosional event and Cawthorn et al. (2002) suggest that either the pyroxenite was completely removed in places or that pegmatitic pyroxenite formed. A second chromitite and pyroxenite were deposited on top of either the pegmatitic pyroxenite or the anorthosite footwall. In the Cawthorn et al. (2002) model, details were only given for the formation of two chromitite layers. Cawthorn (2011) envisaged that there may have been up to three events of these rhythmic units producing up to three chromitite layers in the package. He comments that these

erosional events would produce different variations from a thin to a thick reef package and would explain variations in chromitite layer sequences preserved and the absence of others. He explains that each new influx of magma would deposit a chromitite layer followed by pyroxenite and that should the magma have been superheated, then the layer of pyroxenite was recrystallized to a pegmatitic pyroxenite. Cawthorn and Boerst (2006) suggest that the pegmatitic pyroxenite formed by addition of superheated magma which caused the magma above the pyroxene crystal mush to become superheated. They explain that it was at this interface that the pegmatitic texture was formed and some dissolution also occurred. They propose that once the pegmatitic pyroxenite had formed, crystallization resumed and formed the overlying pyroxenite with a basal chromitite.

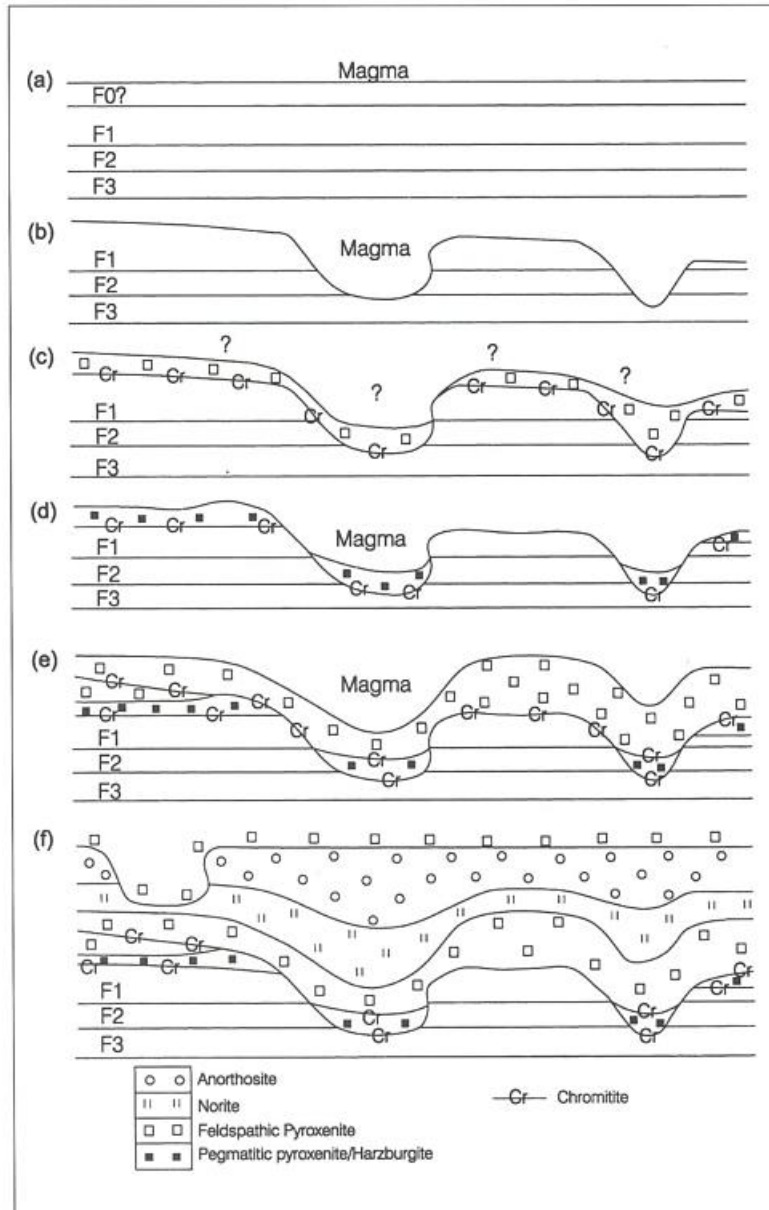


Figure 6.4.2.1 Schematic model for the formation of shallow potholes and the Merensky Cyclic Unit (Cawthorn et al. 2002).

In Figure 6.4.2.1.1, the sequence of events could have been as follows; superheated magma melts the floor. The superheated magma assumed by Latypov et al. (2015) to be saturated in chromite and sulphide, cools to its liquidus temperature. The first phase to crystallize is chromite, followed by olivine or orthopyroxene in the case of this study. The

next emplacement event took place and the magma would either completely or partially erode existing chromite and pyroxenite layers. In the case of the Brakspruit and RPM facies, possibly the Type 1 chromitite layer was deposited first as this is in contact with the footwall anorthosite and was followed by pyroxenite. Some of the overlying pyroxenite and in some areas the chromitite layer was removed, the superheated magma may then have caused recrystallization of the pyroxenite to pegmatoidal pyroxenite in the case of the RPM and Brakspruit facies. It was this magma that deposited the second chromitite layer, the Type 2b layer from the Brakspruit and RPM facies and the Type 2a layers of the Marikana and Thin facies. The average thickness at Marikana for the pegmatoidal pyroxenite unit between the Type 1 and 2b chromitite layers is 40cm and is only found to the west of the Marikana Operations in the Karee area. The third event may not have been as turbulent and erosional and a thicker pyroxenitic unit was preserved. The average thickness of the pyroxenite between the 2a/2b and 3 chromitite layers is 75cm and can reach a maximum of 2.2m in some places. As Cawthorn et al. (2002) pointed out; the difference in the distance between the upper and lower chromitite layers is attributed to the magma responsible for the Merensky Cyclic Unit variably eroding the pyroxenite of the Pre-Merensky unit. On cooling a third chromitite layer and pyroxenite was deposited. The Type 3 chromitite layer is only preserved to the west of the Marikana Operations. The only facies observed to the east is the Eastplats facies. Here the pyroxenite from the Type 2a chromitite layer is up to 12m thick. Latypov et al. (2015) conclude that either the basal layer of the final event and the overlying resident melt mixed to form magma that crystallized the hangingwall, or as Cawthorn (1999) suggests that the hangingwall rocks formed post the Merensky by magma not saturated in chromite and sulphide.

CHAPTER SEVEN – CONCLUSION

7.1 Conclusion

The transitions between the Merensky Reef facies at Marikana are poorly understood and a large part of the uncertainty involves the chromitite layers and whether they can be correlated between facies or whether they merge or are discontinuous as the facies types change. The samples in this study presented four compositionally distinct chromitite layers with no compositional trends or groupings observed both laterally or across each layer. On a local scale ($\pm 30\text{cm}$ along strike), in the case of the underground example at K3 Vertical Shaft, the mineral chemistry showed lateral continuation of the upper chromitite layer with no evidence for preservation of the lower level. On a regional scale ($\pm 90\text{km}$ along strike), no lateral variability across the study area or to the west across the Western Bushveld Complex was observed.

The preferred deposition model for the formation of the Merensky Cyclic unit at Marikana is envisaged to be due to the emplacement of several pulses of superheated magma. These events are supported by the occurrence of several chromitite layers within the sequence (Cawthorn 2011). It is envisaged that up to three rhythmic events produced up to three or more chromitite layers in the package and that these erosional events produced different reef package variations. Each new influx of magma deposited a chromitite layer followed by pyroxenite and potentially a pegmatitic pyroxenite. These erosional events would produce different variations in the Merensky Reef package and would explain why in some cases chromitite layer sequences have been preserved and the absence of others. In all cases the layer has a sharp contact with the immediate footwall and in some cases truncates the footwall in an unconformity.

No chromite compositional trends similarities were observed for chromitite layers hosted by the same silicate mineral; no compositional zoning between cores and rims of grains was observed and similarly no vertical composition differences were observed where grains were in contact with different silicate minerals. Due to the varying percentage of chromite per layer, it is not likely that the chromite grains created a buffer to any reequilibration from occurring. The near constant Cr cation throughout all chromitite layers implies that no reequilibration of the Cr cation took place and that trapped liquid had little effect on the Cr cation content. The chromite grains from this study showed a strong Trend A which is attributed to the reequilibration of chromite. The chromite grains have relatively high values of $Fe^{2+}/(Fe^{2+}+Mg)$ which implies that these are not the original magmatic compositions and that changes have occurred on cooling. The evidence presented here shows that it is post cumulus processes that have changed the primary chromite compositions of the chromitite layers.

The author therefore concludes that reequilibration has occurred due to reaction with trapped intercumulus liquid and little to no reaction with the host silicates of plagioclase and pyroxene. It is envisaged that the slow cooling of the Bushveld Complex allowed intercumulus liquid a greater opportunity to equilibrate with the early minerals, destroying the early magmatic history by reaction and recrystallization. Evidence of this slow cooling is shown in slight enrichment trends in Ti and Fe^{3+} cations.

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APPENDIX A
CHROMITE MINERAL CHEMISTRY DATA

53L

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	2.95	6.73	0.04	41.44	44.34	0.8	0.02	2.07	0.39	0.06	0.3	0.19	99.33
rim 1	2.93	6.88	0.15	41.92	43.84	0.77	0.04	1.78	0.33	0.06	0.26	0.18	99.13
core 3	2.36	6.61	0.08	42.25	45	0.74	0.02	1.28	0.35	0.05	0.13	0.18	99.04
rim 3	2.27	6.55	0.09	42.47	44.6	0.77	0	1.29	0.35	0.04	0.16	0.17	98.76
core 4	3.77	7.3	0.1	41.78	43.3	0.72	0	1.79	0.3	0.03	0.26	0.16	99.5
rim 4	3.82	7.35	0.11	41.74	43	0.72	0.04	1.82	0.29	0.05	0.26	0.18	99.37
core 5	4	8.63	0.1	38.77	43.66	0.64	0.01	1.67	0.35	0.07	0.37	0.18	98.43
rim 5	4.09	8.6	0.11	38.57	43.91	0.63	0	1.69	0.33	0.04	0.37	0.16	98.5
core 6	3.42	7.07	0.13	40.88	44.41	0.64	0	1.79	0.33	0.06	0.27	0.15	99.16
rim 6	3.29	7.2	0.14	41.02	44.2	0.63	0	1.61	0.28	0.05	0.25	0.16	98.83

53L

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	15.04	80.51	7.10	3.49	4.45	2.26	9.36	1.26	0.85	0.23	10.58	0.65
rim 1	15.05	80.34	7.05	3.43	3.83	2.32	9.48	1.25	0.85	0.23	10.49	0.68
core 3	12.33	81.09	7.18	3.62	2.76	2.24	9.59	1.01	0.88	0.23	10.80	0.62
rim 3	11.91	81.31	7.22	3.53	2.80	2.23	9.68	0.98	0.88	0.23	10.75	0.63
core 4	19.09	79.34	6.72	3.49	3.80	2.43	9.32	1.59	0.81	0.23	10.21	0.70
rim 4	19.35	79.21	6.71	3.45	3.87	2.45	9.33	1.61	0.81	0.23	10.16	0.71
core 5	20.39	75.09	6.59	3.74	3.55	2.88	8.67	1.69	0.80	0.24	10.33	0.77
rim 5	20.79	75.05	6.56	3.81	3.59	2.86	8.61	1.72	0.79	0.25	10.37	0.75
core 6	17.44	79.50	6.86	3.69	3.82	2.37	9.18	1.45	0.83	0.24	10.54	0.64
rim 6	16.88	79.26	6.88	3.65	3.45	2.42	9.24	1.40	0.83	0.24	10.53	0.66

53B

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 2	7.85	15.7	0.07	41.27	33.07	0.34	0.01	1.04	0.23	0.07	0.26	0.12	100.02
core 3	7.5	14.9	0.08	41.16	34.13	0.38	0.01	1.07	0.29	0.05	0.22	0.13	99.92
rim 3	7.38	14.58	0.08	40.82	33.98	0.35	0.01	1.23	0.21	0.05	0.25	0.12	99.08
core 4	7.17	14.23	0.05	41.26	34.63	0.39	0.01	1.11	0.28	0.04	0.26	0.15	99.57
rim 4	7.29	14.38	0.06	40.16	34.72	0.39	0.01	1.17	0.31	0.05	0.27	0.13	98.95
core 5	7.88	15.38	0.06	41.24	33.2	0.35	0.01	1.02	0.27	0.04	0.24	0.11	99.82
rim 5	7.85	15.04	0.08	41.77	32.73	0.34	0.02	1.09	0.25	0.05	0.24	0.12	99.58
core 6	7.83	15.43	0.07	40.26	33.77	0.36	0.02	1.16	0.2	0.04	0.26	0.11	99.5
rim 6	7.73	15.25	0.1	40.28	33.66	0.37	0.01	1.23	0.21	0.05	0.27	0.12	99.27
rim 7 opx	7.53	14.54	0.09	41.55	33.73	0.35	0.01	1.1	0.23	0.04	0.24	0.15	99.56

rim 7 plag	7.62	14.73	0.09	41.7	33.28	0.36	0.02	1.12	0.24	0.05	0.22	0.13	99.56
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53B

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 2	37.66	63.81	5.08	2.17	2.05	4.86	8.56	3.07	0.62	0.14	7.25	2.24
core 3	36.24	64.95	5.20	2.34	2.13	4.64	8.60	2.95	0.64	0.15	7.54	1.98
rim 3	35.79	65.26	5.27	2.31	2.47	4.58	8.61	2.94	0.64	0.15	7.58	1.98
core 4	34.89	66.05	5.31	2.40	2.22	4.47	8.69	2.85	0.65	0.15	7.71	1.86
rim 4	35.60	65.20	5.26	2.50	2.35	4.53	8.49	2.91	0.64	0.16	7.76	1.81
core 5	37.96	64.27	5.05	2.25	2.02	4.77	8.58	3.09	0.62	0.14	7.30	2.12
rim 5	37.88	65.07	5.07	2.16	2.17	4.68	8.72	3.09	0.62	0.14	7.23	2.17
core 6	37.62	63.64	5.11	2.34	2.30	4.80	8.40	3.08	0.62	0.15	7.45	2.05
rim 6	37.24	63.92	5.15	2.31	2.45	4.76	8.44	3.05	0.63	0.15	7.46	2.06
rim 7 opx	36.47	65.72	5.19	2.29	2.20	4.55	8.72	2.98	0.64	0.15	7.48	1.98
rim 7 plag	36.85	65.51	5.16	2.21	2.23	4.60	8.74	3.01	0.63	0.14	7.37	2.08

K4U

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	5.5	11.02	0.15	37.54	42.22	0.6	0.09	2.82	0.34	0.01	0.42	0.21	100.91
rim 1	5.43	10.66	0.2	39.1	41.88	0.63	0	2.63	0.32	0.08	0.29	0.17	101.39
core 2	5.9	11.34	0.14	37.73	41.39	0.55	0.03	2.07	0.4	0.05	0.33	0.12	100.06
rim 2	5.85	11.17	0.1	37.31	42.45	0.59	0.07	2.58	0.45	0.08	0.39	0.07	101.11

K4U

core 3	5.5	10.85	0.17	36.5	41.6	0.62	0	2.62	0.4	0.08	0.42	0.11	98.88
rim 3	5.77	11.35	0.25	37.29	42.39	0.58	0.07	2.17	0.23	0.02	0.29	0.18	100.58
core 4	3.72	10.51	0.17	37.75	44.76	0.55	0	1.5	0.33	0.04	0.34	0.2	99.89
rim 4	3.16	11.61	0.77	38.74	43.1	0.54	0.02	1.87	0.23	0.07	0.22	0.27	100.6
core 5	3.07	11.56	0.25	38.01	44.58	0.67	0.03	1.55	0.32	0.05	0.26	0.26	100.6
rim 5	5.45	10.4	0.2	38.36	42.62	0.57	0	2.56	0.33	0.07	0.34	0.18	101.06
core 6	5.38	10.42	0.17	38.2	41.85	0.59	0	2.36	0.26	0.03	0.29	0.16	99.73
rim 6	5.36	10.17	0.31	37.72	41.87	0.66	0.02	2.55	0.38	0	0.35	0.21	99.58
core 7	4.97	10.51	0.19	40.44	41.45	0.56	0	1.86	0.24	0.07	0.25	0.09	100.63
rim 7	3.61	10.46	0.13	38.15	43.57	0.59	0.02	1.34	0.33	0.05	0.24	0.16	98.63

K4U

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺	
core 1	26.15	69.56	6.28	3.29	5.75	3.52	8.04	2.22	0.74	0.22	9.56	1.07	
rim 1	25.85	71.10	6.28	3.18	5.34	3.39	8.35	2.19	0.74	0.21	9.46	1.07	
core 2	28.64	69.06	5.95	3.44	4.22	3.62	8.09	2.39	0.71	0.23	9.38	1.05	
rim 2	27.87	69.14	6.07	3.47	5.22	3.54	7.94	2.35	0.72	0.23	9.55	1.02	
core 3	26.79	69.29	6.19	3.41	5.44	3.53	7.97	2.26	0.73	0.23	9.60	1.03	
rim 3	27.74	68.79	6.06	3.52	4.42	3.62	7.98	2.33	0.72	0.23	9.59	1.03	
core 4	18.66	70.67	6.70	3.67	3.13	3.43	8.27	1.54	0.81	0.24	10.37	0.94	
rim 4	15.65	69.12	7.03	2.95	3.90	3.79	8.48	1.30	0.84	0.19	9.98	1.29	
core 5	15.32	68.81	6.98	3.30	3.22	3.76	8.29	1.26	0.85	0.21	10.29	1.14	
rim 5	26.07	71.22	6.24	3.41	5.22	3.32	8.22	2.20	0.74	0.23	9.66	0.97	
core 6	26.11	71.09	6.23	3.37	4.87	3.37	8.29	2.20	0.74	0.22	9.60	1.00	
rim 6	26.10	71.33	6.24	3.41	5.29	3.30	8.22	2.20	0.74	0.23	9.65	0.97	
core 7	24.26	72.08	6.31	3.14	3.81	3.38	8.72	2.02	0.76	0.21	9.45	1.08	
rim 7	18.39	70.99	6.70	3.52	2.83	3.46	8.46	1.51	0.82	0.23	10.21	0.98	

K4L

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	5.33	9.07	0.15	37.57	42.56	0.73	0	3.51	0.31	0.05	0.28	0.12	99.68
rim 1	5.38	9.07	0.09	37.85	42.33	0.69	0	3.4	0.26	0.05	0.28	0.11	99.5
core 2	5.44	9.52	0.12	38.31	42.06	0.73	0	2.85	0.25	0.05	0.27	0.12	99.71
rim 2	5.17	10.05	0.1	38.93	41.86	0.71	0	2.42	0.28	0.06	0.25	0.1	99.93
core 3	5.38	9.14	0.1	37.83	42.37	0.7	0.02	3.46	0.32	0.05	0.28	0.13	99.77
rim 3	5.27	8.97	0.08	38.19	42.31	0.7	0	3.42	0.29	0.06	0.29	0.14	99.7
core 4	5.37	9.02	0.09	37.34	42.64	0.7	0.01	3.4	0.29	0.04	0.29	0.14	99.35

K4L

rim 4	5.35	8.92	0.08	37.26	43.07	0.74	0.02	3.31	0.27	0.05	0.3	0.1	99.48
core 5	5.19	8.32	0.11	37.25	43.02	0.72	0	3.59	0.36	0.05	0.29	0.13	99.04
rim 5	5.32	8.7	0.11	37.31	42.82	0.72	0.01	3.56	0.29	0.04	0.28	0.13	99.29
core 6	5.38	8.76	0.07	37.52	42.67	0.72	0.01	3.56	0.32	0.06	0.29	0.12	99.48
rim 6	5.37	8.87	0.1	37.95	42.08	0.71	0	3.38	0.34	0.05	0.28	0.12	99.26

K4L

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺	
core 1	25.37	73.54	6.46	3.37	7.30	2.95	8.21	2.20	0.75	0.23	9.84	0.88	
rim 1	25.65	73.68	6.43	3.35	7.07	2.96	8.27	2.22	0.74	0.23	9.78	0.88	
core 2	26.18	72.97	6.30	3.39	5.90	3.09	8.34	2.23	0.74	0.23	9.68	0.91	
rim 2	25.10	72.21	6.32	3.29	5.00	3.25	8.45	2.12	0.75	0.22	9.61	0.99	
core 3	25.60	73.52	6.43	3.34	7.18	2.97	8.25	2.21	0.74	0.23	9.77	0.89	
rim 3	25.13	74.07	6.47	3.31	7.11	2.92	8.35	2.17	0.75	0.23	9.78	0.88	
core 4	25.67	73.52	6.42	3.45	7.09	2.95	8.18	2.22	0.74	0.24	9.88	0.85	
rim 4	25.60	73.70	6.42	3.55	6.89	2.91	8.16	2.21	0.74	0.24	9.97	0.82	
core 5	24.92	75.02	6.51	3.53	7.54	2.74	8.22	2.16	0.75	0.24	10.04	0.78	
rim 5	25.39	74.21	6.47	3.47	7.44	2.85	8.19	2.20	0.75	0.24	9.94	0.82	
core 6	25.64	74.18	6.45	3.44	7.42	2.86	8.22	2.22	0.74	0.24	9.88	0.83	
rim 6	25.76	74.16	6.40	3.36	7.06	2.90	8.33	2.22	0.74	0.23	9.76	0.86	

K4B

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	8.33	16.52	0.13	41.37	32.03	0.33	0	0.89	0.25	0.06	0.16	0.16	100.23
rim 1	8.23	16.43	0.12	40.34	32.95	0.32	0.03	0.93	0.27	0.04	0.14	0.1	99.89
core 2	8.3	16.21	0.14	41.68	32.12	0.29	0.02	0.92	0.3	0.03	0.12	0.12	100.24
rim 2	8.34	16.16	0.12	41.3	32.65	0.36	0.01	0.93	0.26	0.04	0.12	0.09	100.39
core 3	8.42	16.37	0.15	41.77	31.69	0.33	0	0.84	0.28	0.05	0.13	0.13	100.17
rim 3	8.27	16.36	0.13	41.94	31.89	0.33	0	0.86	0.24	0.03	0.13	0.13	100.29
core 4	8.16	15.57	0.13	42.1	32.03	0.35	0	0.96	0.25	0.05	0.15	0.09	99.84
rim 4	8.18	15.7	0.15	42.12	31.99	0.37	0.02	0.97	0.3	0.06	0.13	0.09	100.07
core 5	8.24	16.17	0.15	41.37	32.61	0.32	0	0.95	0.28	0.05	0.16	0.15	100.44
rim 5	8.08	15.81	0.1	41.94	31.92	0.35	0.08	0.98	0.29	0.07	0.14	0.11	99.86
core 6	8.17	15.81	0.12	41.57	32.35	0.36	0.02	0.99	0.25	0.04	0.16	0.12	99.95
rim 6	8.07	15.81	0.14	41.93	32.09	0.32	0.01	1.01	0.23	0.06	0.13	0.09	99.87

K4B

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	39.79	62.69	4.89	2.08	1.74	5.07	8.51	3.23	0.60	0.13	6.97	2.44
rim 1	39.40	62.22	4.92	2.26	1.82	5.05	8.32	3.20	0.61	0.14	7.19	2.23
core 2	39.68	63.30	4.89	2.09	1.80	4.97	8.58	3.22	0.60	0.13	6.99	2.38
rim 2	39.77	63.16	4.89	2.20	1.82	4.95	8.49	3.23	0.60	0.14	7.09	2.25
core 3	40.31	63.12	4.84	2.06	1.64	5.02	8.59	3.27	0.60	0.13	6.89	2.44
rim 3	39.51	63.23	4.91	2.02	1.68	5.01	8.62	3.21	0.60	0.13	6.93	2.48
core 4	39.22	64.46	4.94	2.08	1.89	4.81	8.73	3.19	0.61	0.13	7.02	2.32
rim 4	39.27	64.28	4.93	2.06	1.91	4.84	8.71	3.19	0.61	0.13	7.00	2.35
core 5	39.33	63.19	4.93	2.16	1.86	4.96	8.51	3.20	0.61	0.14	7.09	2.29
rim 5	38.86	64.02	4.97	2.03	1.93	4.89	8.70	3.16	0.61	0.13	7.00	2.41
core 6	39.17	63.82	4.95	2.13	1.95	4.88	8.60	3.19	0.61	0.14	7.08	2.29
rim 6	38.69	64.02	5.00	2.03	1.99	4.88	8.69	3.15	0.61	0.13	7.03	2.40

16L

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	6.74	14.79	0.15	41.56	34.2	0.45	0	1.47	0.24	0.05	0.19	0.12	99.96
rim 1	6.53	14.2	0.13	42.51	34.24	0.45	0	1.4	0.31	0.06	0.19	0.11	100.13
core 2	7.09	15.05	0.14	42.32	32.53	0.43	0.02	1.19	0.34	0.04	0.19	0.14	99.49
rim 2	7.03	14.72	0.13	42.52	32.83	0.43	0	1.38	0.28	0.06	0.21	0.1	99.7
core 3	7.2	14.84	0.13	42.01	33.2	0.44	0.01	1.32	0.3	0.05	0.19	0.1	99.81
rim 3	7.24	14.94	0.13	42.28	33.14	0.42	0.05	1.34	0.28	0.05	0.21	0.13	100.19
core 4	7.18	15.23	0.13	42.31	32.94	0.41	0	1.24	0.31	0.06	0.18	0.1	100.09
rim 4	7.18	15.27	0.16	42.35	32.63	0.4	0.07	1.19	0.28	0.06	0.18	0.11	99.88
core 5	7.22	15.25	0.11	41.58	33.01	0.41	0	1.19	0.31	0.05	0.2	0.12	99.45
rim 5	7.15	15.17	0.12	41.66	32.97	0.39	0.02	1.24	0.36	0.04	0.2	0.09	99.41
core 6	7.27	15.82	0.1	42.04	32.63	0.35	0.01	1.01	0.29	0.06	0.18	0.14	99.9
rim 6	7.11	15.28	0.11	43.5	32.53	0.35	0.01	0.98	0.26	0.06	0.16	0.12	100.47

16L

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	32.43	65.34	5.57	2.04	2.94	4.64	8.74	2.67	0.68	0.13	7.60	2.28
rim 1	34.48	65.35	5.35	1.89	2.38	4.72	8.91	2.60	0.67	0.12	7.24	2.50
core 2	34.75	65.51	5.35	2.02	2.63	4.64	8.81	2.81	0.66	0.13	7.37	2.30
rim 2	34.58	65.08	5.35	1.93	2.46	4.74	8.84	2.79	0.66	0.12	7.28	2.46
core 3	35.00	64.65	5.31	2.02	2.38	4.77	8.73	2.85	0.65	0.13	7.33	2.36
rim 3	35.13	64.06	5.28	1.92	2.00	4.92	8.77	2.85	0.65	0.12	7.19	2.57

16L

core 4	31.61	66.76	5.62	2.02	2.81	4.46	8.96	2.83	0.67	0.13	7.63	2.21
rim 4	33.96	65.96	5.42	1.88	2.76	4.62	8.95	2.84	0.66	0.12	7.31	2.45
core 5	34.78	65.50	5.35	1.97	2.66	4.66	8.84	2.86	0.65	0.13	7.32	2.36
rim 5	34.69	65.04	5.34	1.89	2.37	4.77	8.87	2.83	0.65	0.12	7.23	2.53
core 6	34.70	64.82	5.33	1.99	2.48	4.75	8.76	2.86	0.65	0.13	7.33	2.38
rim 6	34.30	65.63	5.35	1.81	1.94	4.74	9.06	2.79	0.66	0.12	7.16	2.61

51U

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	4.51	9.65	0.11	37.92	41.79	0.66	0	3.91	0.31	0.03	0.24	0.17	99.31
rim 1	4.64	10.77	0.11	38.22	40.75	0.66	0.01	3.4	0.27	0.04	0.24	0.18	99.28
core 2	4.51	9.83	0.1	37.02	42.47	0.71	0	3.64	0.23	0.04	0.28	0.18	99.01
rim 2	4.41	9.7	0.11	38.01	41.94	0.7	0	3.46	0.23	0.04	0.23	0.19	99.02
core 3	4.39	9.34	0.11	37.12	42.75	0.7	0.01	3.84	0.26	0.04	0.26	0.14	98.96
rim 3	4.48	9.41	0.12	37.38	42.61	0.73	0	3.81	0.3	0.04	0.24	0.18	99.31
core 4	4.28	9.85	0.1	37.82	42.47	0.73	0.01	3.18	0.26	0.04	0.22	0.16	99.12
rim 4	4.56	11.04	0.11	38.45	40.81	0.7	0.05	2.64	0.28	0.06	0.21	0.17	99.07
core 5	4.07	8.82	0.11	37.68	43.55	0.77	0	3.04	0.3	0.04	0.3	0.17	98.86
rim 5	4.02	8.78	0.11	37.29	43.64	0.81	0	3.06	0.3	0.05	0.3	0.15	98.53
core 6	4.21	12.06	0.39	40.9	38.12	0.56	0.23	1.98	0.31	0.06	0.25	0.25	99.32
rim 6	4.11	12.25	0.09	41.07	38.39	0.56	0.01	1.91	0.28	0.06	0.25	0.22	99.2

51U

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	21.40	72.50	6.87	2.85	8.19	3.17	8.35	1.87	0.79	0.20	9.73	1.11
rim 1	21.54	71.64	6.83	3.07	7.64	3.23	8.17	1.92	0.78	0.21	9.91	1.05
core 2	20.94	72.72	6.92	3.09	8.08	3.08	8.21	1.88	0.79	0.21	10.00	1.00
rim 2	20.69	72.03	6.83	3.08	6.67	3.24	8.34	1.84	0.79	0.21	9.91	1.05
core 3	19.94	74.13	6.86	3.39	6.44	2.93	8.39	1.83	0.79	0.23	10.26	0.86
rim 3	20.89	69.47	6.60	2.25	4.13	3.95	8.98	1.86	0.78	0.15	8.85	1.75
core 4	22.15	70.42	6.73	2.70	7.08	3.51	8.37	1.78	0.79	0.19	9.43	1.30
rim 4	21.17	72.44	6.84	2.96	7.27	3.19	8.39	1.89	0.78	0.20	9.79	1.08
core 5	21.34	72.71	6.87	3.07	7.99	3.09	8.24	1.71	0.80	0.21	9.93	1.01
rim 5	22.22	70.03	6.60	2.86	5.51	3.61	8.43	1.70	0.80	0.19	9.46	1.26
core 6	19.76	74.02	6.89	3.43	6.51	2.93	8.34	1.74	0.80	0.23	10.32	0.85
rim 6	20.33	69.22	6.64	2.24	3.97	3.99	8.98	1.69	0.80	0.15	8.87	1.79

51L													
Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	6	14.65	0.08	42.47	34.73	0.38	0	1.12	0.24	0.06	0.15	0.13	100
rim 1	6.04	14.7	0.07	42.75	34.48	0.38	0.01	1.06	0.26	0.06	0.14	0.12	100.08
core 2	6.13	14.63	0.11	42.86	34.07	0.36	0	1.06	0.27	0.04	0.15	0.12	99.8
rim 2	5.98	14.04	0.11	44.17	33.77	0.35	0	1.02	0.25	0.04	0.14	0.11	99.98
core 3	6.3	15.46	0.07	42.42	34.25	0.34	0	1.03	0.26	0.04	0.14	0.14	100.45
rim 3	5.98	14.71	0.09	43.64	33.95	0.33	0.01	1.01	0.27	0.04	0.14	0.11	100.26
4core	6.14	14.46	0.08	43.38	34.02	0.36	0	1.05	0.29	0.05	0.16	0.13	100.13
rim 4	6.12	14.45	0.08	42.99	34.16	0.36	0.04	1.09	0.29	0.05	0.14	0.09	99.85
core 5	6.34	14.73	0.1	42.85	34.16	0.36	0.01	1.13	0.24	0.04	0.15	0.12	100.24
rim 5	6.31	14.67	0.07	42.69	34.45	0.36	0.02	1.15	0.25	0.05	0.15	0.14	100.31
core 6	6.32	14.76	0.09	42.91	34.11	0.37	0	1.12	0.25	0.06	0.14	0.11	100.24
rim 6	6.28	14.62	0.08	42.72	34.13	0.35	0.04	1.14	0.27	0.04	0.14	0.12	99.94

51L													
Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺	
core 1	29.24	66.04	5.78	1.97	2.25	4.61	8.97	2.39	0.71	0.13	7.75	2.34	
rim 1	29.97	66.28	5.71	1.91	2.13	4.61	9.06	2.40	0.70	0.12	7.61	2.42	
core 2	30.48	64.80	5.66	1.91	2.05	4.82	8.87	2.44	0.70	0.12	7.57	2.53	
rim 2	29.98	66.80	5.70	1.88	2.11	4.55	9.15	2.39	0.70	0.12	7.59	2.41	
core 3	30.74	66.12	5.66	1.93	2.26	4.61	9.00	2.48	0.70	0.12	7.59	2.39	
rim 3	30.65	66.10	5.66	1.91	2.24	4.62	9.02	2.37	0.70	0.12	7.58	2.42	
4core	29.46	66.11	5.75	1.94	2.13	4.62	9.02	2.44	0.70	0.12	7.69	2.39	
rim 4	29.31	67.85	5.76	1.80	2.06	4.43	9.35	2.44	0.70	0.12	7.56	2.46	
core 5	29.16	66.56	5.77	1.79	2.02	4.62	9.19	2.51	0.70	0.11	7.56	2.58	
rim 5	29.92	66.62	5.71	1.92	2.19	4.55	9.09	2.50	0.70	0.12	7.64	2.37	
core 6	30.58	66.13	5.67	1.98	2.30	4.59	8.97	2.50	0.69	0.13	7.65	2.32	
rim 6	30.57	66.22	5.67	1.94	2.29	4.60	9.01	2.50	0.69	0.12	7.61	2.37	

24U													
Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	5.9	13.32	0.1	42.97	33.24	0.42	0.01	3.08	0.22	0.05	0.15	0.17	99.64
rim 1	6.13	13.88	0.14	42.83	34.17	0.46	0.02	1.6	0.22	0.05	0.2	0.12	99.83
core 2	5.83	13.79	0.09	42.99	34.45	0.42	0	1.76	0.26	0.05	0.19	0.13	99.95
rim 2	6.03	13.91	0.13	43.46	33.73	0.42	0.02	1.54	0.26	0.05	0.17	0.13	99.87
core 3	6.16	13.85	0.11	42.69	33.86	0.43	0	1.92	0.29	0.05	0.18	0.13	99.69
rim 3	6.21	13.88	0.11	42.87	34.01	0.44	0.01	1.89	0.26	0.07	0.19	0.12	100.06

24U

core 4	6.27	13.78	0.08	42.86	34.08	0.43	0	1.9	0.27	0.05	0.22	0.15	100.07
rim 4	6.31	13.96	0.08	43.22	33.77	0.43	0.03	1.78	0.22	0.05	0.2	0.14	100.2
core 5	6.34	13.61	0.11	42.84	33.85	0.45	0	1.99	0.26	0.05	0.21	0.15	99.87
rim 5	6.3	13.39	0.08	43.36	33.43	0.41	0.1	1.83	0.24	0.04	0.2	0.13	99.52
core 6	5.92	13.37	0.06	42.3	35.15	0.45	0.02	1.56	0.25	0.05	0.22	0.16	99.5
rim 6	6.13	13.48	0.06	42.32	34.67	0.44	0	2.03	0.26	0.05	0.23	0.16	99.84

24U

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺	
core 1	27.73	68.40	6.20	1.32	6.26	4.24	9.19	2.38	0.72	0.09	7.51	3.22	
rim 1	29.68	67.43	5.82	1.86	3.23	4.40	9.10	2.46	0.70	0.12	7.68	2.37	
core 2	28.16	67.65	5.96	1.78	3.56	4.37	9.14	2.34	0.72	0.12	7.74	2.45	
rim 2	29.27	67.70	5.84	1.74	3.11	4.40	9.23	2.42	0.71	0.11	7.58	2.53	
core 3	29.67	67.40	5.85	1.76	3.88	4.39	9.08	2.47	0.70	0.12	7.61	2.50	
rim 3	29.80	67.45	5.84	1.78	3.81	4.38	9.08	2.48	0.70	0.12	7.62	2.47	
core 4	30.08	67.60	5.82	1.81	3.83	4.35	9.07	2.50	0.70	0.12	7.63	2.40	
rim 4	30.26	67.50	5.79	1.75	3.58	4.40	9.13	2.51	0.70	0.11	7.55	2.51	
core 5	30.42	67.86	5.81	1.79	4.02	4.31	9.09	2.54	0.70	0.12	7.60	2.40	
rim 5	30.46	68.48	5.78	1.75	3.71	4.26	9.25	2.53	0.70	0.11	7.54	2.43	
core 6	28.88	67.97	5.88	2.07	3.17	4.26	9.04	2.39	0.71	0.13	7.94	2.06	
rim 6	29.44	67.80	5.89	1.90	4.11	4.27	9.00	2.46	0.71	0.13	7.80	2.25	

24L

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	6.72	15.54	0.11	41.82	33.91	0.35	0	1.21	0.23	0.06	0.17	0.14	100.27
rim 1	6.52	15.04	0.12	42.64	34.02	0.33	0	1.18	0.2	0.06	0.16	0.14	100.41
core 2	6.38	14.74	0.09	41.23	34.44	0.39	0.01	1.24	0.27	0.05	0.18	0.15	99.16
rim 2	6.3	14.87	0.09	41.31	34.45	0.36	0.01	1.16	0.27	0.06	0.18	0.14	99.2
core 3	6.54	15.72	0.07	41.11	34.05	0.35	0	1.04	0.16	0.05	0.19	0.12	99.41
rim 3	6.46	15.49	0.08	41.37	34.1	0.35	0	1.01	0.19	0.04	0.19	0.16	99.46
core 4	6.18	14.36	0.07	41.09	35.25	0.39	0.01	1.59	0.17	0.04	0.21	0.12	99.48
rim 4	6.25	14.45	0.06	41.22	35.24	0.39	0.01	1.61	0.25	0.04	0.22	0.13	99.88
core 5	5.86	13.1	0.06	41.49	35.49	0.42	0	1.64	0.25	0.07	0.23	0.14	98.76
core 6	5.71	13.03	0.06	41.87	35.96	0.43	0.01	1.72	0.27	0.06	0.22	0.13	99.47
rim 5	5.8	13.19	0.09	41.38	35.23	0.44	0.01	1.56	0.27	0.07	0.23	0.15	98.41
rim 6	5.42	12.82	0.06	41.39	36.52	0.42	0.01	1.7	0.3	0.04	0.24	0.15	99.08

24L

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	32.32	64.35	5.54	1.95	2.40	4.84	8.73	2.65	0.68	0.13	7.49	2.49
rim 1	31.42	65.54	5.62	1.91	2.35	4.69	8.92	2.57	0.69	0.12	7.53	2.45
core 2	31.17	65.23	5.64	2.09	2.50	4.66	8.75	2.55	0.69	0.13	7.73	2.23
rim 2	30.82	65.08	5.65	2.07	2.34	4.70	8.76	2.52	0.69	0.13	7.72	2.27
core 3	31.76	63.69	5.58	2.00	2.08	4.93	8.65	2.60	0.68	0.13	7.58	2.47
rim 3	31.47	64.18	5.59	2.01	2.03	4.87	8.72	2.57	0.69	0.13	7.60	2.42
core 4	29.85	65.75	5.81	2.10	3.21	4.54	8.72	2.47	0.70	0.14	7.91	2.16
rim 4	30.11	65.68	5.78	2.09	3.24	4.55	8.71	2.49	0.70	0.14	7.87	2.17
core 5	28.75	68.00	5.90	2.18	3.36	4.21	8.94	2.38	0.71	0.14	8.08	1.93
core 6	28.63	67.79	5.98	2.17	3.51	4.16	8.97	2.31	0.72	0.14	8.15	1.92
rim 5	27.83	68.31	5.89	2.16	3.21	4.25	8.95	2.36	0.71	0.14	8.05	1.97
rim 6	26.62	68.41	6.08	2.25	3.49	4.12	8.93	2.20	0.73	0.15	8.33	1.83

24B

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	6.92	16.85	0.07	41.47	32.48	0.32	0.01	0.82	0.22	0.04	0.17	0.15	99.5
rim 1	6.59	15.91	0.06	42.15	32.97	0.31	0.05	0.81	0.25	0.06	0.17	0.14	99.46
core 2	7.5	16.64	0.1	41.86	31.56	0.3	0.01	0.85	0.22	0.05	0.16	0.13	99.38
rim 2	7.31	16.39	0.09	42.21	31.77	0.31	0.04	0.83	0.24	0.06	0.15	0.09	99.49
core 3	7.5	16.92	0.06	41.68	31.48	0.29	0	0.83	0.2	0.07	0.15	0.12	99.3
rim 3	7.3	16.59	0.07	42.11	31.87	0.3	0.02	0.87	0.22	0.06	0.17	0.11	99.68
core 5	7.53	17.4	0.07	40.59	32.46	0.32	0	0.79	0.2	0.05	0.16	0.14	99.7
rim 5	7.29	17.04	0.1	40.79	32.57	0.31	0	0.86	0.18	0.05	0.17	0.11	99.47
core 6	7.31	16.73	0.06	40.09	33.37	0.35	0	1.04	0.26	0.05	0.19	0.14	99.6
rim 6	7.38	16.95	0.08	39.6	33.26	0.36	0.02	1.03	0.24	0.04	0.19	0.12	99.26
rim 1 plag	6.66	15.98	0.17	42.55	32.74	0.31	0.05	0.83	0.22	0.04	0.17	0.12	99.85
rim 2 plag	6.67	15.58	0.14	42.05	33.27	0.3	0.09	0.86	0.23	0.05	0.17	0.13	99.54
rim 3 plag	6.54	15.48	0.12	42.56	33.02	0.3	0.09	0.8	0.23	0.05	0.16	0.16	99.53
rim 1 opx	6.66	15.66	0.12	43.48	32.46	0.3	0.03	0.61	0.22	0.04	0.13	0.1	99.81
rim 2 opx	6.45	15.46	0.14	41.14	34.36	0.3	0.02	0.8	0.22	0.04	0.18	0.12	99.23
rim 3 opx	6.43	14.87	0.13	43.28	33.3	0.27	0.02	0.78	0.25	0.05	0.18	0.13	99.7
rim 4 opx	6.21	14.27	0.15	43.55	33.51	0.29	0.01	0.74	0.24	0.06	0.16	0.1	99.3
core 2	6.88	16.55	0.14	41.68	32.63	0.31	0	0.78	0.18	0.04	0.17	0.12	99.48
core 3	6.84	16.8	0.13	41.96	32.45	0.32	0.01	0.84	0.2	0.04	0.19	0.13	99.91

24B

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	33.57	62.28	5.39	1.78	1.63	5.24	8.65	2.72	0.66	0.11	7.17	2.95
rim 1	32.22	63.99	5.49	1.83	1.62	4.98	8.86	2.61	0.68	0.12	7.33	2.72
core 2	36.28	62.79	5.17	1.78	1.68	5.17	8.72	2.95	0.64	0.11	6.95	2.91
rim 2	35.45	63.34	5.24	1.77	1.65	5.10	8.80	2.88	0.65	0.11	7.01	2.88
core 3	36.24	62.30	5.18	1.75	1.64	5.25	8.67	2.94	0.64	0.11	6.93	3.00
rim 3	35.25	63.00	5.26	1.75	1.72	5.14	8.76	2.86	0.65	0.11	7.01	2.94
core 5	36.21	61.01	5.17	1.93	1.55	5.37	8.40	2.94	0.64	0.12	7.10	2.79
rim 5	35.17	61.62	5.27	1.89	1.70	5.28	8.48	2.86	0.65	0.12	7.16	2.79
core 6	35.19	61.65	5.28	2.06	2.06	5.19	8.34	2.87	0.65	0.13	7.34	2.52
rim 6	35.57	61.05	5.25	2.08	2.04	5.26	8.25	2.90	0.64	0.13	7.33	2.54
rim 1 plag	32.41	64.11	5.49	1.77	1.65	4.99	8.91	2.63	0.68	0.11	7.25	2.83
rim 2 plag	32.58	64.42	5.48	1.92	1.72	4.89	8.85	2.65	0.67	0.12	7.40	2.54
rim 3 plag	32.05	64.84	5.51	1.85	1.60	4.86	8.97	2.60	0.68	0.12	7.36	2.63
rim 1 opx	32.60	65.07	5.44	1.75	1.22	4.89	9.11	2.63	0.67	0.11	7.19	2.79
rim 2 opx	31.66	64.10	5.54	2.13	1.61	4.87	8.69	2.57	0.68	0.14	7.67	2.29
rim 3 opx	31.57	66.13	5.54	1.88	1.57	4.68	9.13	2.56	0.68	0.12	7.43	2.48
rim 4 opx	30.74	67.18	5.61	1.92	1.50	4.52	9.26	2.49	0.69	0.12	7.53	2.35
core 2	33.43	62.82	5.40	1.81	1.55	5.16	8.72	2.71	0.67	0.12	7.22	2.85
core 3	33.08	62.62	5.44	1.71	1.66	5.22	8.74	2.69	0.67	0.11	7.15	3.05

94L

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	7.14	12.75	0.09	42.82	34.42	0.34	0	1.2	0.3	0.04	0.15	0.11	99.38
rim 1	7.09	12.65	0.09	43.61	33.81	0.33	0.1	1.12	0.32	0.05	0.15	0.14	99.48
core 2	7.01	12.59	0.09	43.14	34.74	0.35	0	1.13	0.31	0.05	0.15	0.11	99.67
rim 2	7.16	13.08	0.1	43.28	33.89	0.35	0.06	0.99	0.33	0.03	0.14	0.13	99.53
core 3	6.81	11.96	0.09	43.87	34.89	0.34	0	1.17	0.27	0.06	0.15	0.14	99.75
rim 3	6.85	11.94	0.08	43.62	34.85	0.35	0.01	1.16	0.31	0.04	0.15	0.11	99.48
core 4	6.82	11.99	0.08	43.45	35.03	0.36	0	1.28	0.28	0.05	0.15	0.11	99.61
rim 4	6.8	12.05	0.08	43.56	34.81	0.35	0.01	1.27	0.3	0.07	0.15	0.14	99.57
core 5	6.86	12.4	0.11	42.78	35.24	0.36	0.01	1.06	0.27	0.05	0.17	0.14	99.44
rim 5	6.86	12.41	0.11	42.74	35.24	0.35	0.03	1.24	0.26	0.06	0.16	0.14	99.6
core 6	7.11	13.05	0.06	41.84	35.3	0.37	0	1.23	0.31	0.06	0.16	0.13	99.62
rim 6	7.05	13.03	0.07	41.93	35.22	0.34	0.01	1.22	0.3	0.05	0.17	0.14	99.53

94L

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	34.94	69.26	5.32	2.40	2.42	4.03	9.08	2.86	0.65	0.15	7.72	1.68
rim 1	34.33	69.68	5.36	2.43	2.28	3.98	9.14	2.84	0.65	0.16	7.78	1.64
core 2	33.41	71.10	5.44	2.40	2.37	3.79	9.33	2.80	0.66	0.15	7.85	1.58
rim 2	33.40	70.85	5.46	2.43	2.59	3.80	9.25	2.86	0.66	0.16	7.89	1.57
core 3	33.77	69.83	5.40	2.53	2.15	3.93	9.11	2.73	0.66	0.16	7.93	1.55
rim 3	34.66	68.26	5.34	2.55	2.47	4.11	8.85	2.75	0.66	0.16	7.89	1.61
core 4	34.83	69.81	5.31	2.28	2.26	4.01	9.26	2.74	0.66	0.15	7.59	1.76
rim 4	35.17	68.94	5.27	2.32	1.99	4.13	9.16	2.73	0.66	0.15	7.58	1.78
core 5	33.71	71.02	5.41	2.44	2.35	3.79	9.30	2.75	0.66	0.16	7.85	1.55
rim 5	33.35	70.80	5.46	2.38	2.57	3.83	9.28	2.75	0.66	0.15	7.84	1.61
core 6	33.57	69.79	5.44	2.48	2.51	3.93	9.09	2.83	0.66	0.16	7.92	1.59
rim 6	34.41	68.34	5.36	2.52	2.46	4.11	8.88	2.81	0.66	0.16	7.88	1.63

4L

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	6.35	11.51	0.02	42.75	35.54	0.43	0	1.65	0.28	0.05	0.32	0.14	99.03
rim 1	6.78	12.4	0.03	43.1	34.42	0.44	0.02	1.69	0.25	0.06	0.32	0.13	99.65
core 2	7.5	13.42	0.03	42.18	33.28	0.38	0	1.49	0.28	0.05	0.28	0.13	99.01
rim 2	7.4	13.35	0.05	42.25	33.5	0.37	0.08	1.44	0.29	0.06	0.28	0.14	99.2
core 3	7.85	14.83	0.01	41.57	33.19	0.37	0	1.33	0.22	0.06	0.3	0.13	99.85
rim 3	7.66	14.39	0.03	42.01	33.25	0.34	0	1.35	0.23	0.06	0.3	0.11	99.73
core 4	7.74	14.2	0.02	41.84	32.91	0.37	0	1.4	0.27	0.05	0.3	0.12	99.23
rim 4	7.74	14.07	0.04	41.86	32.36	0.36	0.07	1.38	0.31	0.05	0.29	0.13	98.66
core 5	7.74	14.62	0.02	41.69	33.06	0.35	0.01	1.21	0.26	0.05	0.3	0.13	99.44
rim 5	7.73	13.92	0.04	41.55	32.48	0.35	0.05	1.36	0.28	0.05	0.29	0.12	98.22
core 6	7.27	12.85	0.02	43.24	33.68	0.38	0.01	1.47	0.24	0.04	0.28	0.12	99.59
core 7	7.75	14.11	0.05	42.42	33.19	0.36	0	1.35	0.25	0.05	0.3	0.13	99.96
core 8	7.56	13.64	0.03	42.81	33.22	0.36	0.01	1.35	0.24	0.05	0.29	0.13	99.68
core 9	7.23	12.97	0.03	42.96	33.64	0.37	0	1.5	0.26	0.04	0.28	0.11	99.39
core 10	7.55	14.05	0.03	42.22	33.38	0.36	0	1.49	0.25	0.06	0.3	0.13	99.83

4L

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	28.44	71.36	5.90	3.65	3.08	3.36	8.38	2.35	0.72	0.24	9.55	0.92
rim 1	30.21	69.99	5.77	3.35	3.14	3.61	8.41	2.66	0.68	0.22	9.11	1.08
core 2	33.40	67.83	5.47	3.38	2.75	3.88	8.18	2.50	0.69	0.22	8.86	1.15

4L

rim 2	32.97	67.98	5.50	3.42	2.66	3.86	8.19	2.80	0.66	0.22	8.92	1.13
core 3	34.52	65.28	5.37	3.35	2.42	4.23	7.94	2.74	0.66	0.22	8.71	1.26
rim 3	33.84	66.20	5.43	3.32	2.47	4.12	8.07	2.75	0.66	0.21	8.74	1.24
core 4	34.35	66.40	5.39	3.32	2.57	4.09	8.07	2.71	0.67	0.21	8.71	1.23
rim 4	34.67	66.62	5.35	3.26	2.55	4.08	8.14	2.65	0.67	0.21	8.61	1.25
core 5	34.32	65.67	5.37	3.37	2.21	4.19	8.01	2.83	0.65	0.22	8.73	1.24
rim 5	34.68	66.69	5.35	3.35	2.52	4.04	8.10	2.74	0.66	0.22	8.70	1.21
core 6	32.34	69.30	5.56	3.36	2.71	3.71	8.39	2.77	0.67	0.22	8.92	1.11
core 7	34.20	66.85	5.39	3.34	2.46	4.03	8.13	2.82	0.66	0.22	8.73	1.21
core 8	33.55	67.80	5.45	3.32	2.48	3.92	8.26	2.84	0.66	0.21	8.77	1.18
core 9	32.22	68.96	5.58	3.34	2.77	3.76	8.35	2.80	0.67	0.22	8.92	1.12
core 10	33.35	66.84	5.48	3.29	2.73	4.03	8.13	2.84	0.66	0.21	8.77	1.23

21L

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1 plag	1.97	7.83	0.15	41.27	45.08	0.63	0	1.53	0.36	0.05	0.23	0.26	99.35
core 2 plag	4.6	8.02	0.14	40.87	41.86	0.42	0.01	2.26	0.33	0.06	0.33	0.16	99.06
core 3 plag	4.36	7.74	0.11	42.87	40.9	0.53	0	1.97	0.29	0.06	0.28	0.17	99.29
core 4 pyx	7.01	16.66	0.09	40.54	34.07	0.35	0	0.94	0.25	0.05	0.27	0.16	100.41
core 5	6.7	13.56	0.09	43.1	34.48	0.34	0	1.08	0.25	0.04	0.19	0.19	100.03
core 6 pyx	6.09	15.74	0.11	40.63	35.47	0.35	0	0.85	0.25	0.06	0.25	0.19	99.99
core 7 plag	5.01	10.35	0.08	42.04	38.98	0.4	0.01	1.68	0.3	0.06	0.19	0.17	99.26

21L

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	10.19	77.95	7.40	3.37	3.29	2.64	9.33	0.84	0.90	0.22	10.78	0.78
core 2	22.90	77.37	6.48	3.34	4.77	2.65	9.06	1.92	0.77	0.22	9.81	0.79
core 3	21.88	78.79	6.52	3.08	4.16	2.56	9.52	1.83	0.78	0.20	9.61	0.83
core 4	33.70	62.01	5.39	2.08	1.85	5.15	8.40	2.74	0.66	0.13	7.47	2.48
core 5	32.68	68.07	5.49	2.20	2.17	4.27	9.10	2.67	0.67	0.14	7.70	1.94
core 6	29.76	63.39	5.70	2.18	1.70	4.93	8.54	2.41	0.70	0.14	7.89	2.26
core 7	24.89	73.15	6.22	2.77	3.49	3.36	9.17	2.06	0.75	0.18	8.99	1.21

50B

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	6.79	15.92	0.11	38.35	35.18	0.37	0	1.46	0.29	0.07	0.19	0.12	98.85
core 2	7.07	16.54	0.11	39.28	34.6	0.37	0	1.55	0.25	0.06	0.18	0.15	100.16

50B

core 3	6.75	15.58	0.09	35.88	36.62	0.43	0	2.43	0.29	0.05	0.24	0.16	98.53
core 4	7.38	17.33	0.1	38.04	34.8	0.38	0	1.69	0.26	0.05	0.2	0.16	100.4
core 5	7.52	17.61	0.13	38.47	33.67	0.36	0	1.42	0.25	0.05	0.19	0.14	99.81
core 6	7.18	16.83	0.1	39.32	33.72	0.32	0	1.36	0.3	0.06	0.18	0.16	99.54

50B

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	32.83	61.77	5.53	2.32	2.93	5.01	8.09	2.70	0.67	0.15	7.85	2.16
core 2	33.55	61.44	5.48	2.11	3.06	5.12	8.16	2.77	0.66	0.14	7.60	2.42
core 3	32.04	60.71	5.73	2.49	4.90	4.93	7.61	2.70	0.68	0.17	8.21	1.98
core 4	34.66	59.56	5.41	2.18	3.31	5.32	7.84	2.87	0.65	0.14	7.58	2.45
core 5	35.64	59.44	5.29	2.06	2.79	5.43	7.95	2.93	0.64	0.13	7.36	2.63
core 6	34.38	61.05	5.38	2.04	2.70	5.23	8.19	2.82	0.66	0.13	7.43	2.56

50L

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	2.8	7.04	0.07	44.14	40.38	1.01	0	2.77	0.31	0.07	0.19	0.21	98.99
core 2	3.28	7.93	0.05	42.89	40.49	0.98	0	2.82	0.27	0.07	0.25	0.2	99.24
core 3	3.46	9.24	0.08	40.48	41.41	0.84	0	2.92	0.28	0.07	0.28	0.19	99.23
core 4	3.06	7.47	0.06	47.06	38.05	0.92	0	1.61	0.31	0.07	0.12	0.21	98.93
core 5	2.52	6.75	0.08	46.61	39.56	1.04	0	2.16	0.29	0.06	0.16	0.24	99.48
core 6	2.24	7.29	0.06	48.08	38.97	0.96	0	1.29	0.3	0.08	0.12	0.31	99.67
core 7	2.46	7.64	0.08	48.41	38.24	0.88	0.01	1.03	0.31	0.07	0.11	0.26	99.49
rim 7	2.53	7.65	0.1	48.82	36.88	0.85	0.26	0.89	0.33	0.06	0.09	0.27	98.74
rim 6	2.02	6.76	0.1	48.91	38.55	0.89	0	1.23	0.34	0.07	0.1	0.31	99.29
core 7	2.44	7.09	0.06	47.46	38.65	0.96	0	1.81	0.34	0.09	0.15	0.32	99.37
rim 7	2.43	6.93	0.09	47.98	38.22	0.93	0.01	1.72	0.34	0.07	0.14	0.33	99.19

50L

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	14.08	80.79	7.32	2.38	5.99	2.39	10.03	1.20	0.86	0.16	9.71	1.00
core 2	16.30	78.39	7.15	2.48	6.04	2.66	9.65	1.39	0.84	0.17	9.63	1.07
core 3	17.01	74.61	7.10	2.66	6.19	3.07	9.03	1.45	0.83	0.18	9.76	1.15
core 4	15.79	80.87	6.97	2.14	3.47	2.52	10.65	1.31	0.84	0.14	9.10	1.18
core 5	12.86	82.25	7.32	2.19	4.67	2.29	10.59	1.08	0.87	0.15	9.51	1.04
core 6	11.66	81.56	7.25	2.09	2.78	2.46	10.89	0.96	0.88	0.14	9.34	1.18
core 7	12.87	80.95	7.10	2.04	2.21	2.57	10.94	1.05	0.87	0.13	9.14	1.26

50L													
rim 7	13.42	81.06	7.02	1.87	1.93	2.60	11.14	0.87	0.89	0.12	8.90	1.39	
rim 6	10.63	82.92	7.31	1.99	2.67	2.30	11.17	1.05	0.87	0.13	9.31	1.15	
core 7	12.59	81.79	7.26	2.03	3.91	2.40	10.79	1.09	0.87	0.13	9.29	1.19	
rim 7	12.60	82.28	7.25	1.96	3.73	2.35	10.93	1.04	0.87	0.13	9.21	1.20	
50U													
Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	3.08	10.2	0.07	40.71	40.67	0.68	0	2.62	0.34	0.05	0.17	0.15	98.76
core 2	6.24	12.76	0.06	38.16	37.42	0.65	0	3.19	0.28	0.04	0.26	0.14	99.2
core 3 sulphide	6.18	12.56	0.06	39.57	36.38	0.64	0.01	2.88	0.27	0.04	0.18	0.14	98.9
rim 3 sulphide	6.23	12.73	0.07	41.27	35.36	0.62	0.01	2.28	0.26	0.04	0.23	0.14	99.24
core 4	4.98	15.09	0.05	38.13	37.34	0.5	0	2.12	0.3	0.07	0.27	0.21	99.06
core 5	4.7	10.96	0.08	41.29	37.83	0.57	0	2.73	0.3	0.04	0.24	0.17	98.9
core 6	6.39	11.55	0.06	37.59	35.84	0.56	0	6.91	0.27	0.05	0.2	0.13	99.55
50U													
Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺	
core 1	15.29	72.81	7.18	2.41	5.56	3.39	9.08	1.30	0.85	0.16	9.59	1.41	
core 2	29.40	66.74	6.06	2.43	6.51	4.08	8.19	2.52	0.71	0.17	8.49	1.68	
core 3 sulphide	29.43	67.88	6.02	2.27	5.90	4.03	8.52	2.51	0.71	0.15	8.28	1.78	
rim 3 sulphide	29.99	68.50	5.89	2.14	4.66	4.07	8.86	2.59	0.69	0.14	8.02	1.90	
core 4	24.09	62.90	6.35	2.12	4.33	4.83	8.18	2.52	0.72	0.14	8.47	2.27	
core 5	22.87	71.65	6.56	2.22	5.70	3.58	9.06	2.02	0.76	0.15	8.77	1.62	
core 6	27.71	68.59	6.76	1.39	14.13	3.70	8.08	1.94	0.78	0.11	8.15	2.67	
K3.1a													
Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	8.94	16.24	0.01	43.26	29.41	0.31	0	0.76	0.19	0.03	0.17	0.11	99.45
rim 1	8.88	15.73	0.02	43.43	29.82	0.31	0.03	0.94	0.2	0.03	0.19	0.09	99.67
core 2	8.94	16.26	0.02	43.24	29.32	0.31	0	0.89	0.2	0.05	0.16	0.12	99.51
rim 2	8.69	15.72	0.06	43.07	29.82	0.31	0	0.91	0.21	0.05	0.18	0.11	99.12
core 3	9.03	16.64	0.01	42.59	29.27	0.31	0	0.87	0.21	0.04	0.15	0.11	99.25
rim 3	8.69	15.84	0.05	43.1	29.44	0.31	0.08	0.89	0.21	0.05	0.17	0.1	98.91
core 4	8.8	15.97	0.01	43.31	29.39	0.32	0	0.87	0.22	0.05	0.17	0.11	99.21
rim 4	8.5	15.52	0.04	42.71	30.17	0.3	0.1	0.98	0.25	0.04	0.18	0.1	98.9
core 5	9.1	17.32	0.01	42.47	29.38	0.32	0	0.86	0.18	0.03	0.15	0.13	99.97
rim 5	8.65	16.03	0.03	43.85	28.55	0.32	0.02	0.82	0.17	0.06	0.14	0.11	98.76

K3.1a

core 6	8.88	17.3	0.02	42.37	29.57	0.32	0	0.94	0.19	0.03	0.13	0.09	99.86
rim 6	9.12	17.3	0.05	42.25	29.29	0.32	0.07	0.95	0.17	0.05	0.14	0.11	99.82

K3.1a

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺	
core 1	42.89	64.12	4.63	1.78	1.49	1.49	4.99	8.92	3.47	0.57	0.11	6.41	2.80
rim 1	42.46	64.94	4.68	1.82	1.85	4.84	8.97	3.47	0.57	0.12	6.51	2.65	
core 2	42.75	64.08	4.66	1.74	1.75	5.00	8.92	3.51	0.57	0.11	6.39	2.88	
rim 2	41.86	64.76	4.73	1.82	1.80	4.87	8.95	3.51	0.57	0.12	6.55	2.67	
core 3	43.21	63.19	4.61	1.77	1.71	5.11	8.78	3.54	0.57	0.11	6.38	2.90	
rim 3	41.96	64.61	4.72	1.76	1.76	4.91	8.97	3.51	0.57	0.11	6.48	2.79	
core 4	42.32	64.53	4.69	1.75	1.71	4.93	8.97	3.49	0.57	0.11	6.44	2.81	
rim 4	41.11	64.86	4.79	1.87	1.95	4.83	8.92	3.55	0.57	0.12	6.66	2.59	
core 5	43.11	62.19	4.62	1.72	1.67	5.27	8.67	3.34	0.58	0.11	6.34	3.07	
rim 5	41.82	64.73	4.73	1.56	1.63	4.98	9.13	3.25	0.59	0.10	6.29	3.19	
core 6	42.09	62.16	4.71	1.68	1.83	5.28	8.67	3.53	0.57	0.11	6.40	3.13	
rim 6	43.19	62.10	4.63	1.71	1.85	5.28	8.64	3.48	0.57	0.11	6.34	3.09	

K3.1b

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	9.03	16.5	0.01	43.71	29.6	0.32	0	1	0.21	0.04	0.22	0.08	100.7
rim 1	9.03	16.85	0.05	43.42	29.49	0.33	0	1	0.15	0.04	0.19	0.11	100.65
core 2	9.1	16.29	0.01	43.26	29.84	0.31	0.01	1.01	0.22	0.04	0.17	0.11	100.38
rim 2	9.13	16.64	0.04	42.62	30.2	0.32	0.08	1.01	0.21	0.05	0.17	0.09	100.55
core 3	9.25	16.98	0.01	43.08	29.62	0.32	0.01	0.95	0.19	0.05	0.19	0.12	100.75
rim 3	9.14	16.77	0.03	42.57	30.03	0.31	0.07	0.99	0.18	0.04	0.19	0.11	100.43
core 4	9.09	17.27	0.02	42.82	29.62	0.32	0	0.86	0.14	0.04	0.15	0.12	100.44
rim 4	9.26	17.48	0.05	42.18	29.75	0.33	0.08	0.94	0.13	0.03	0.17	0.1	100.49
core 5	8.64	16.67	0.03	42.6	30.59	0.32	0	0.97	0.22	0.04	0.12	0.1	100.29
rim 5	8.3	16.05	0.06	42.51	30.67	0.32	0.06	0.96	0.23	0.04	0.13	0.11	99.43
core 6	9.17	17.18	0.02	42.24	29.62	0.32	0	0.93	0.19	0.05	0.17	0.12	100.01
rim 6	8.94	15.95	0.05	43.19	29.7	0.31	0.04	0.93	0.2	0.05	0.15	0.1	99.62
core 7	9.17	16.79	0.01	42.73	29.86	0.31	0	0.95	0.2	0.04	0.19	0.1	100.35
rim 7	9.17	16.7	0.04	42.65	29.98	0.32	0.01	1.04	0.18	0.05	0.17	0.12	100.41
core 8	8.82	15.52	0	42.19	29.75	0.3	0	0.94	0.26	0.04	0.16	0.11	98.08
rim 8	8.88	16.14	0.03	43.13	29.69	0.31	0	0.84	0.21	0.04	0.11	0.11	99.49

K3.1b

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	42.57	63.99	4.68	1.70	1.94	5.01	8.90	3.47	0.57	0.11	6.38	2.95
rim 1	42.49	63.35	4.69	1.66	1.94	5.11	8.84	3.47	0.58	0.11	6.35	3.09
core 2	43.03	64.05	4.64	1.81	1.96	4.96	8.84	3.51	0.57	0.12	6.45	2.75
rim 2	43.05	63.21	4.64	1.87	1.96	5.06	8.69	3.51	0.57	0.12	6.51	2.71
core 3	43.48	62.99	4.60	1.75	1.83	5.14	8.74	3.54	0.57	0.11	6.36	2.93
rim 3	43.11	63.00	4.64	1.84	1.92	5.10	8.68	3.51	0.57	0.12	6.48	2.78
core 4	42.85	62.45	4.65	1.72	1.66	5.24	8.71	3.49	0.57	0.11	6.37	3.04
rim 4	43.49	61.81	4.61	1.78	1.82	5.29	8.57	3.55	0.57	0.11	6.39	2.97
core 5	40.97	63.16	4.81	1.82	1.89	5.09	8.72	3.34	0.59	0.12	6.62	2.80
rim 5	39.90	63.99	4.89	1.84	1.89	4.96	8.82	3.25	0.60	0.12	6.73	2.70
core 6	43.38	62.26	4.61	1.79	1.81	5.23	8.62	3.53	0.57	0.11	6.39	2.93
rim 6	42.74	64.50	4.66	1.82	1.83	4.91	8.91	3.48	0.57	0.12	6.48	2.70
core 7	43.30	63.06	4.62	1.82	1.84	5.10	8.71	3.52	0.57	0.12	6.44	2.80
rim 7	43.19	63.14	4.64	1.83	2.02	5.08	8.70	3.53	0.57	0.12	6.46	2.78
core 8	42.85	64.58	4.65	1.94	1.87	4.85	8.84	3.48	0.57	0.12	6.59	2.49
rim 8	42.55	64.19	4.67	1.81	1.65	4.96	8.90	3.45	0.57	0.12	6.48	2.74

K3.2a

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	9.13	18.11	0.02	38.43	32.37	0.28	0	1.11	0.22	0.05	0.25	0.1	100.08
rim 1	9.24	18.11	0.05	38.4	31.7	0.29	0.01	1.05	0.22	0.06	0.24	0.1	99.47
core 2	9.78	18.96	0.1	38.73	30.52	0.32	0.01	1.27	0.21	0.05	0.24	0.1	100.29
rim 2	9.49	18.63	0.1	39.32	30.2	0.31	0.03	1.13	0.19	0.05	0.23	0.12	99.8
core 3	9.57	19.22	0.08	38.4	30.2	0.32	0	1.65	0.21	0.04	0.24	0.1	100.03
rim 3	10.05	19.72	0.1	38.48	29.89	0.33	0.02	1.27	0.21	0.04	0.24	0.11	100.46
core 4	9.69	18.59	0.08	38.92	30.87	0.29	0	1.12	0.26	0.03	0.23	0.09	100.18
rim 4	9.92	19.25	0.09	39.3	30.38	0.29	0.01	1.14	0.19	0.03	0.23	0.1	100.94
core 5	9.47	18.57	0.03	38.47	31.57	0.3	0	1.18	0.21	0.05	0.25	0.11	100.21
rim 5	9.51	18.68	0.05	38.37	31.27	0.29	0	1.16	0.22	0.04	0.26	0.11	99.97
core 6	9.32	18.08	0.05	39.41	31.4	0.29	0	1.1	0.23	0.05	0.27	0.1	100.3
rim 6	9.54	18.71	0.05	38.54	31.38	0.29	0	1.2	0.23	0.03	0.26	0.09	100.31
core 7	9.5	18.68	0.04	39.39	30.71	0.31	0	1.14	0.23	0.03	0.24	0.08	100.36
rim 7	9.44	18.3	0.06	39.61	30.48	0.31	0.01	1.24	0.21	0.05	0.23	0.11	100.04

K3.2a

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	40.05	58.74	6.66	2.43	2.06	5.25	7.48	3.51	0.66	0.16	9.09	2.16
rim 1	40.84	58.72	6.56	2.39	1.96	5.28	7.52	3.35	0.66	0.16	8.95	2.21
core 2	42.26	57.81	6.18	2.54	2.31	5.41	7.42	3.41	0.64	0.17	8.72	2.13
rim 2	41.30	58.61	6.14	2.64	2.07	5.34	7.55	3.53	0.63	0.17	8.78	2.02
core 3	41.17	57.27	6.12	2.48	3.01	5.49	7.36	3.44	0.64	0.16	8.61	2.21
rim 3	43.13	56.69	6.00	2.57	2.29	5.58	7.31	3.46	0.63	0.17	8.57	2.18
core 4	42.26	58.41	6.30	2.45	2.05	5.34	7.50	3.60	0.64	0.16	8.74	2.18
rim 4	42.67	57.80	6.11	2.50	2.06	5.45	7.47	3.52	0.63	0.16	8.61	2.18
core 5	41.11	58.15	6.43	2.56	2.16	5.33	7.40	3.56	0.64	0.17	8.99	2.08
rim 5	41.38	57.95	6.37	2.56	2.13	5.37	7.39	3.44	0.65	0.17	8.93	2.10
core 6	40.69	59.39	6.41	2.53	2.02	5.20	7.61	3.46	0.65	0.17	8.94	2.05
rim 6	41.36	58.02	6.38	2.54	2.19	5.36	7.40	3.39	0.65	0.17	8.92	2.11
core 7	41.21	58.58	6.22	2.56	2.08	5.33	7.55	3.46	0.64	0.17	8.79	2.08
rim 7	41.03	59.22	6.20	2.58	2.27	5.25	7.62	3.43	0.64	0.17	8.78	2.03

K3.2b

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	8.11	15.32	0.01	42.05	32.29	0.31	0	1.16	0.27	0.05	0.21	0.11	99.89
rim 1	8.13	15.06	0.04	42.69	31.73	0.31	0.04	1.15	0.23	0.06	0.2	0.1	99.73
core 2	8.49	16.4	0.02	42.38	30.69	0.32	0	1.13	0.21	0.04	0.22	0.11	100.01
rim 2	8.6	16.4	0.05	42.62	30.43	0.31	0	1.11	0.23	0.04	0.23	0.1	100.13
core 3	8.5	16.01	0.03	43.12	30.35	0.31	0.01	0.91	0.23	0.05	0.2	0.12	99.83
rim 3	8.65	16.02	0.04	43.25	30.04	0.3	0.01	0.93	0.2	0.04	0.19	0.12	99.81
core 4	8.36	16.07	0.03	42.33	31.27	0.31	0	1.05	0.25	0.05	0.17	0.12	100
rim 4	8.24	15.44	0.05	42.85	30.92	0.3	0.04	1.08	0.26	0.06	0.18	0.11	99.53
core 5	8.11	14.94	0.03	42.32	29.95	0.29	0.01	4.31	0.25	0.04	0.16	0.11	100.53
rim 5	8.51	15.76	0.04	42.7	30.33	0.32	0.01	1.21	0.25	0.05	0.2	0.12	99.49
core 6	8.59	16.32	0.01	42.09	30.7	0.31	0	1.39	0.23	0.05	0.22	0.11	100.01
rim 6	8.57	16.06	0.03	41.66	31.04	0.31	0	1.22	0.24	0.05	0.23	0.11	99.53
core 7	9	17.35	0.02	41.89	29.64	0.3	0	0.95	0.22	0.05	0.2	0.12	99.74
rim 7	8.68	16	0.03	42.76	30.19	0.28	0.02	0.94	0.22	0.04	0.2	0.11	99.48
core 8	8.82	17.04	0.03	42.11	30.32	0.3	0	0.91	0.22	0.04	0.2	0.11	100.08
rim 8	8.61	15.91	0.03	43.45	30.37	0.29	0.01	0.86	0.22	0.04	0.19	0.11	100.1

K3.2b

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	38.83	64.80	5.00	2.08	2.29	4.74	8.72	3.17	0.61	0.13	7.08	2.27
rim 1	39.01	65.54	4.99	1.99	2.28	4.67	8.88	3.19	0.61	0.13	6.98	2.34
core 2	40.31	63.42	4.88	1.80	2.21	5.03	8.72	3.30	0.60	0.12	6.68	2.80
rim 2	40.82	63.55	4.83	1.78	2.17	5.02	8.76	3.33	0.59	0.11	6.61	2.82
core 3	40.72	64.37	4.82	1.81	1.79	4.93	8.90	3.31	0.59	0.12	6.63	2.72
rim 3	41.36	64.43	4.77	1.78	1.83	4.93	8.92	3.37	0.59	0.11	6.55	2.77
core 4	39.89	63.86	4.90	1.92	2.06	4.94	8.73	3.25	0.60	0.12	6.82	2.58
rim 4	39.62	65.06	4.92	1.87	2.14	4.79	8.91	3.23	0.60	0.12	6.80	2.55
core 5	36.01	65.52	5.63	0.93	8.49	4.61	8.76	3.17	0.64	0.07	6.56	4.96
rim 5	40.67	64.51	4.86	1.80	2.39	4.87	8.86	3.33	0.59	0.12	6.65	2.71
core 6	40.54	63.37	4.89	1.79	2.72	5.01	8.66	3.33	0.59	0.12	6.68	2.80
rim 6	40.84	63.51	4.84	1.95	2.40	4.95	8.62	3.34	0.59	0.13	6.79	2.54
core 7	42.71	61.83	4.66	1.76	1.85	5.30	8.58	3.48	0.57	0.11	6.42	3.02
rim 7	41.61	64.19	4.75	1.85	1.85	4.93	8.84	3.39	0.58	0.12	6.60	2.66
core 8	41.86	62.37	4.73	1.83	1.77	5.20	8.62	3.40	0.58	0.12	6.56	2.84
rim 8	41.17	64.69	4.78	1.83	1.68	4.88	8.95	3.34	0.59	0.12	6.61	2.66

K3.2c

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	7.94	14.91	0.01	43.15	32.01	0.32	0	1.05	0.26	0.05	0.23	0.14	100.08
rim 1	8.2	14.86	0.05	44.68	30.42	0.32	0.08	0.91	0.26	0.04	0.21	0.14	100.16
core 2	9.24	17.74	0.05	42.52	29.2	0.3	0	0.84	0.23	0.05	0.21	0.1	100.48
rim 2	9.25	17.63	0.04	42.56	29.19	0.29	0	0.82	0.24	0.05	0.2	0.12	100.4
core 3	9.15	17.24	0.02	42.86	29.58	0.3	0	0.85	0.22	0.05	0.2	0.12	100.56
rim 3	9.19	16.95	0.04	43	29.54	0.28	0.06	0.86	0.23	0.04	0.2	0.09	100.48
core 4	9.06	16.79	0.02	43.09	29.72	0.29	0	0.87	0.24	0.04	0.18	0.11	100.4
rim 4	8.97	16.54	0.05	43.06	29.6	0.28	0.08	0.86	0.23	0.04	0.18	0.12	100.01
core 5	9.1	17.2	0.01	42.92	29.75	0.29	0	0.88	0.22	0.03	0.19	0.11	100.69
rim 5	9.07	17.01	0.04	43.36	29.38	0.29	0	0.86	0.23	0.05	0.18	0.11	100.58
core 6	9.15	17.47	0.01	42.39	29.52	0.29	0	0.92	0.23	0.05	0.18	0.12	100.32
rim 6	9.37	17.69	0.04	42.73	29.05	0.3	0	0.86	0.21	0.03	0.16	0.1	100.54
core 7	9.29	17.85	0.02	42.31	29.38	0.28	0	0.78	0.23	0.04	0.22	0.1	100.51
rim 7	9.23	17.28	0.03	42.82	29.44	0.29	0	0.77	0.23	0.04	0.2	0.09	100.44
core 8	9.19	17.47	0.01	42.47	29.72	0.3	0	0.82	0.22	0.05	0.19	0.12	100.56
rim 8	9.14	17.36	0.05	42.98	29.29	0.28	0.04	0.71	0.23	0.05	0.16	0.1	100.41

K3.2c

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	38.18	66.00	5.04	2.00	2.08	4.62	8.97	3.11	0.62	0.13	7.03	2.31
rim 1	39.52	66.85	4.91	1.77	1.80	4.60	9.28	3.21	0.60	0.11	6.68	2.60
core 2	43.57	61.65	4.58	1.69	1.62	5.36	8.63	3.53	0.56	0.11	6.26	3.18
rim 2	43.70	61.82	4.56	1.70	1.58	5.34	8.64	3.54	0.56	0.11	6.27	3.13
core 3	43.19	62.52	4.61	1.74	1.64	5.22	8.71	3.51	0.57	0.11	6.35	3.00
rim 3	43.46	62.99	4.59	1.77	1.67	5.14	8.75	3.53	0.57	0.11	6.36	2.91
core 4	42.92	63.26	4.63	1.77	1.69	5.10	8.79	3.48	0.57	0.11	6.41	2.88
rim 4	42.75	63.59	4.65	1.77	1.68	5.06	8.83	3.47	0.57	0.11	6.42	2.85
core 5	42.88	62.60	4.64	1.74	1.70	5.20	8.71	3.48	0.57	0.11	6.38	2.98
rim 5	42.88	63.10	4.64	1.68	1.66	5.16	8.82	3.48	0.57	0.11	6.32	3.06
core 6	43.17	61.94	4.62	1.73	1.78	5.30	8.62	3.51	0.57	0.11	6.35	3.06
rim 6	44.06	61.84	4.54	1.68	1.66	5.34	8.65	3.58	0.56	0.11	6.22	3.18
core 7	43.80	61.39	4.55	1.74	1.50	5.39	8.57	3.55	0.56	0.11	6.29	3.10
rim 7	43.68	62.44	4.56	1.76	1.49	5.24	8.70	3.54	0.56	0.11	6.33	2.97
core 8	43.35	61.99	4.59	1.78	1.58	5.28	8.62	3.52	0.57	0.11	6.38	2.97
rim 8	43.35	62.42	4.58	1.72	1.37	5.26	8.74	3.51	0.57	0.11	6.30	3.06

K3.3a

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	8.01	16.63	0.01	36.96	35.56	0.34	0.01	1.58	0.25	0.05	0.29	0.12	99.8
rim 1	7.86	16.14	0.04	37.08	35.5	0.32	0.02	1.81	0.25	0.04	0.3	0.13	99.5
core 2	7.9	16.01	0.02	37.37	35.63	0.34	0	1.8	0.25	0.04	0.28	0.12	99.75
rim 2	7.8	15.58	0.03	37.37	35.67	0.34	0.04	1.83	0.25	0.03	0.28	0.12	99.36
core 3	7.92	15.85	0.02	37.05	35.7	0.33	0	1.77	0.26	0.05	0.29	0.12	99.36
rim 3	7.86	15.67	0.04	37.26	35.27	0.32	0.01	1.71	0.28	0.05	0.27	0.13	98.88
core 4	7.87	15.59	0.03	37.75	35.24	0.34	0.01	1.79	0.26	0.04	0.26	0.12	99.3
rim 4	7.86	15.57	0.04	38.12	34.74	0.33	0.06	1.69	0.27	0.05	0.26	0.12	99.11
core 5	7.79	15.29	0.03	37.68	35.44	0.34	0	1.79	0.27	0.06	0.26	0.11	99.07
core 6	6.68	14.57	2.5	35.23	36.73	0.3	0.02	1.62	0.29	0.05	0.28	0.15	98.43
rim 6	7.78	15	0.02	37.54	35.16	0.32	0	1.66	0.25	0.04	0.27	0.1	98.15
core 7	7.89	15.26	0.03	36.33	35.56	0.33	0.04	1.78	0.26	0.06	0.32	0.1	97.97
rim 7	7.89	15.61	0.01	37.87	35.36	0.35	0	1.64	0.22	0.04	0.3	0.1	99.41
core 8	7.84	15.44	0.02	37.52	35.23	0.36	0.04	1.67	0.25	0.04	0.31	0.1	98.83

K3.3a

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	37.78	59.85	5.14	2.63	3.10	5.12	7.63	3.12	0.62	0.17	7.76	1.95
rim 1	37.10	60.65	5.22	2.58	3.58	5.00	7.71	3.08	0.63	0.17	7.80	1.94
core 2	37.21	61.03	5.21	2.60	3.55	4.95	7.75	3.09	0.63	0.17	7.81	1.91
rim 2	36.94	61.67	5.24	2.63	3.63	4.85	7.80	3.07	0.63	0.17	7.87	1.84
core 3	37.48	61.06	5.19	2.67	3.50	4.92	7.71	3.11	0.63	0.17	7.86	1.84
rim 3	37.48	61.47	5.18	2.63	3.41	4.89	7.80	3.10	0.63	0.17	7.81	1.86
core 4	37.30	61.90	5.20	2.57	3.55	4.85	7.87	3.10	0.63	0.17	7.77	1.89
rim 4	37.45	62.16	5.18	2.50	3.36	4.85	7.97	3.10	0.63	0.16	7.68	1.94
core 5	37.07	62.31	5.22	2.62	3.57	4.77	7.89	4.35	0.55	0.17	7.85	1.82
rim 5	37.19	61.52	5.21	2.64	3.47	4.87	7.79	3.08	0.63	0.17	7.85	1.85
core 6	33.17	61.86	5.53	2.93	3.36	4.73	7.67	2.74	0.67	0.19	8.46	1.61
rim 6	37.45	62.67	5.18	2.68	3.34	4.72	7.93	3.10	0.63	0.17	7.85	1.77
core 7	37.90	61.50	5.15	2.79	3.58	4.81	7.68	3.15	0.62	0.18	7.95	1.72
rim 7	37.45	61.94	5.18	2.61	3.25	4.85	7.89	3.10	0.63	0.17	7.79	1.86
core 8	37.46	61.98	5.18	2.64	3.33	4.83	7.87	3.10	0.63	0.17	7.81	1.83

K3.3b

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1 pyx	5.97	10.37	0.03	41.26	37.66	0.44	0	2.59	0.29	0.06	0.3	0.13	99.08
core 2 plag	5.98	10.41	0.02	40.58	39.07	0.47	0	2.64	0.27	0.05	0.34	0.13	99.96
core 3 plag	5.98	9.93	0.01	38.62	39.9	0.57	0.01	3.14	0.29	0.05	0.32	0.12	98.93
core 4 pyx	5.79	10.04	0.02	39.23	40.82	0.61	0	2.71	0.24	0.05	0.32	0.12	99.94
core 5 pyx	4.34	8.46	0.03	38.84	43.7	0.6	0	2.51	0.31	0.06	0.38	0.17	99.41
core 6 plag	6.87	13.17	0.02	41.97	35.22	0.37	0	1.48	0.27	0.05	0.27	0.16	99.85
core 7 pyx	6.51	12.18	0.03	41.96	36.1	0.37	0	1.74	0.29	0.04	0.28	0.15	99.64
rim 8 pyx	5.16	14.22	0.02	42.35	35.95	0.38	0.04	0.58	0.28	0.06	0.23	0.2	99.47

K3.3b

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1 pyx	28.86	72.75	6.29	3.06	5.95	2.80	8.95	2.44	0.72	0.21	9.35	0.92
core 2 plag	28.63	72.34	6.27	3.14	5.66	2.84	8.89	2.43	0.72	0.21	9.42	0.90
core 3 plag	28.62	72.29	5.89	2.69	5.41	3.53	8.69	2.46	0.71	0.18	8.58	1.31
core 4 pyx	27.74	72.38	5.78	2.79	4.62	3.73	8.56	2.36	0.71	0.18	8.56	1.34
core 5 pyx	21.40	75.49	6.02	2.88	5.87	3.33	8.62	1.81	0.77	0.19	8.90	1.15
core 6 plag	33.26	68.13	6.05	3.08	5.84	3.30	8.45	2.74	0.69	0.21	9.13	1.07
core 7 pyx	31.59	69.80	6.13	3.15	6.10	3.04	8.59	2.62	0.70	0.21	9.27	0.97
rim 8 pyx	25.86	66.64	6.15	3.08	5.99	3.13	8.60	2.08	0.75	0.21	9.23	1.02

K3.4

Sample	MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
core 1	8.74	16.24	0.04	42.97	30	0.29	0.01	1	0.23	0.04	0.2	0.09	99.86
rim 1	9	16.77	0.04	42.9	29.37	0.3	0	0.95	0.24	0.04	0.21	0.11	99.93
core 2	9.17	17.72	0.05	41.87	29.21	0.29	0	0.86	0.21	0.05	0.19	0.11	99.73
rim 2	8.97	17.11	0.04	42.69	29.2	0.29	0.07	0.8	0.22	0.04	0.17	0.11	99.71
core 3	9.05	17.31	0.03	42.08	29.73	0.3	0.01	0.95	0.24	0.04	0.2	0.11	100.05
rim 3	9.15	17.18	0.03	42.66	28.98	0.31	0.03	0.95	0.24	0.05	0.19	0.1	99.86
core 4	9.1	16.98	0.03	42.36	29.25	0.29	0	0.9	0.22	0.05	0.2	0.12	99.52
rim 4	9.27	17.67	0.03	42.57	28.99	0.28	0.04	0.79	0.23	0.05	0.18	0.11	100.2
core 5	9.06	17.49	0.02	42.08	29.54	0.29	0	0.86	0.19	0.05	0.19	0.11	99.89
rim 5	9.03	17.43	0.02	41.64	29.86	0.29	0.05	0.87	0.23	0.04	0.21	0.12	99.78
core 6	9	16.98	0.04	42.43	29.95	0.3	0	1	0.23	0.04	0.21	0.13	100.3
rim 6	9.17	17.16	0.05	42.43	29.76	0.3	0.01	0.96	0.25	0.05	0.2	0.11	100.43
core 7	8.93	16.62	0.02	42.79	29.74	0.29	0	0.93	0.23	0.04	0.2	0.11	99.9
rim 7	8.8	16.45	0.02	43.13	29.68	0.3	0.02	0.92	0.23	0.04	0.21	0.12	99.92
core 8	8.84	16.2	0.02	42.72	30.03	0.29	0	0.97	0.24	0.05	0.21	0.11	99.69
rim 8	8.98	16.55	0.01	42.88	30.04	0.3	0	0.94	0.23	0.04	0.22	0.11	100.29

K3.4

Sample	Mg#	Cr#	Fe ²⁺	Fe ³⁺	Ti	Al	Cr	Mg	Fe ²⁺ /(Mg+Fe ²⁺)	Fe ³⁺ /(Cr+Al+Fe ³⁺)	Fe ²⁺ +Fe ³⁺	Al/Fe ³⁺
core 1	41.66	63.96	4.75	1.78	1.96	4.98	8.85	3.39	0.58	0.11	6.53	2.80
rim 1	42.78	63.18	4.65	1.71	1.85	5.12	8.79	3.48	0.57	0.11	6.37	2.99
core 2	43.49	61.32	4.59	1.72	1.67	5.40	8.55	3.53	0.57	0.11	6.31	3.14
rim 2	42.80	62.60	4.64	1.70	1.56	5.23	8.76	3.47	0.57	0.11	6.33	3.08
core 3	42.85	61.99	4.65	1.77	1.85	5.27	8.59	3.48	0.57	0.11	6.42	2.98
rim 3	43.40	62.49	4.60	1.66	1.85	5.24	8.73	3.53	0.57	0.11	6.27	3.15
core 4	43.36	62.60	4.60	1.75	1.76	5.20	8.70	3.52	0.57	0.11	6.35	2.97
rim 4	43.86	61.78	4.55	1.68	1.53	5.36	8.66	3.55	0.56	0.11	6.23	3.18
core 5	42.95	61.74	4.64	1.74	1.67	5.33	8.60	3.49	0.57	0.11	6.38	3.05
rim 5	42.91	61.58	4.64	1.82	1.69	5.32	8.52	3.48	0.57	0.12	6.46	2.91
core 6	42.54	62.63	4.68	1.78	1.94	5.17	8.66	3.46	0.57	0.11	6.46	2.90
rim 6	43.27	62.39	4.61	1.79	1.86	5.20	8.63	3.52	0.57	0.11	6.40	2.91
core 7	42.49	63.33	4.68	1.77	1.82	5.08	8.78	3.45	0.58	0.11	6.45	2.86
rim 7	41.96	63.75	4.72	1.73	1.80	5.04	8.87	3.41	0.58	0.11	6.45	2.91
core 8	42.21	63.89	4.70	1.84	1.90	4.98	8.80	3.43	0.58	0.12	6.54	2.70
rim 8	42.57	63.48	4.67	1.82	1.83	5.04	8.77	3.46	0.57	0.12	6.49	2.77

Type	Sample ID	Cr			Al			Mg			Fe ²⁺		
		AVE	STD DEV	RSD	AVE	STD DEV	RSD	AVE	STD DEV	RSD	AVE	STD DEV	RSD
1	SL24B	8.59	0.20	2.33	5.20	0.10	1.96	2.85	0.10	3.54	5.27	0.10	1.84
1	50B	7.97	0.20	2.54	5.17	0.17	3.36	2.80	0.08	3.03	5.47	0.14	2.49
1	ZS53B	8.67	0.21	2.37	4.60	0.18	3.94	3.00	0.07	2.45	5.15	0.09	1.69
1	RS37B	8.44	0.42	4.95	4.92	0.22	4.47	3.10	0.20	6.34	5.07	0.28	5.48
1	K4B	8.59	0.11	1.32	4.94	0.08	1.62	3.20	0.03	0.94	4.92	0.04	0.82
1	K3.3A	7.80	0.10	1.29	4.87	0.10	2.02	3.16	0.33	10.49	5.21	0.09	1.68
1	K3.3B	8.67	0.16	1.84	3.21	0.30	9.45	2.39	0.25	10.50	6.07	0.17	2.74
2a	4L	8.18	0.14	1.70	3.93	0.23	5.80	2.72	0.13	4.91	5.49	0.15	2.80
2a	MK94L	9.14	0.15	1.64	3.95	0.12	3.10	2.79	0.05	1.73	5.38	0.06	1.13
2a	SL16L	8.85	0.10	1.09	4.70	0.11	2.27	2.80	0.08	2.80	5.38	0.10	1.83
2a	ZS51L	9.06	0.12	1.34	4.60	0.08	1.80	2.45	0.05	1.98	5.71	0.04	0.76
2a	K3.1A	8.88	0.14	1.63	5.02	0.16	3.24	3.47	0.09	2.46	4.68	0.05	1.12
2a	K3.1B	8.76	0.10	1.16	5.07	0.12	2.34	3.48	0.08	2.20	4.67	0.07	1.59
2a	K3.2A	7.47	0.09	1.20	5.36	0.10	1.84	3.47	0.07	1.88	6.29	0.18	2.86
2a	K3.2B	8.78	0.12	1.33	4.92	0.17	3.46	3.31	0.08	2.53	4.89	0.21	4.28
2a	K3.2C	8.75	0.17	1.91	5.16	0.23	4.42	3.47	0.12	3.51	4.64	0.13	2.82
2a	ZS07L	8.66	0.16	1.80	4.95	0.10	2.02	3.37	0.07	2.16	4.82	0.14	2.90
2a	ML44L	8.69	0.12	1.33	4.40	0.17	3.82	2.96	0.10	3.48	5.24	0.20	3.73
2a	TN71L	8.76	0.08	0.97	4.36	0.07	1.54	3.07	0.08	2.52	5.10	0.10	1.96
2b	K4L	8.27	0.08	1.01	2.95	0.12	4.16	2.20	0.03	1.45	6.42	0.06	0.91
2b	53L	9.34	0.38	4.08	2.40	0.23	9.64	1.34	0.26	19.17	6.92	0.23	3.27
2b	24L	8.81	0.11	1.28	4.54	0.28	6.11	2.47	0.13	5.13	5.76	0.17	2.94
2b	K3.4	8.70	0.10	1.18	5.18	0.13	2.47	3.48	0.04	1.24	4.65	0.05	1.08
2b	ZS50L	10.53	0.65	6.15	2.51	0.21	8.47	1.14	0.17	15.31	7.19	0.12	1.66
2b	SL21L	9.02	0.38	4.16	3.65	1.04	28.45	2.07	0.60	29.02	6.17	0.66	10.65
2b	RS37L	9.02	0.21	2.28	3.76	0.33	8.82	2.59	0.16	6.34	5.76	0.24	4.18
3	ZS50U	8.57	0.40	4.66	3.96	0.43	10.96	2.20	0.44	20.14	6.40	0.43	6.70
3	51U	8.43	0.26	3.02	3.33	0.35	10.39	1.81	0.08	4.26	6.79	0.11	1.64
3	K4U	8.24	0.22	2.62	3.50	0.15	4.20	2.00	0.39	19.54	6.38	0.33	5.14
3	24U	9.12	0.07	0.78	4.34	0.06	1.39	2.46	0.06	2.52	5.87	0.11	1.85
3	ML44U	8.50	0.19	2.25	3.65	0.15	4.11	2.31	0.07	2.83	6.12	0.21	3.41
3	RS37U	8.96	0.20	2.20	4.84	0.26	5.28	3.16	0.11	3.51	5.01	0.14	2.72

Type	Sample ID	Fe ³⁺			Ti			Mg#			Cr#		
		AVE	STD DEV	RSD	AVE	STD DEV	RSD	AVE	STD DEV	RSD	AVE	STD DEV	RSD
1	SL24B	1.86	0.12	6.33	1.73	0.17	9.60	35.12	1.22	3.48	62.30	0.94	1.50
1	50B	2.20	0.16	7.10	3.28	0.75	22.88	33.85	1.19	3.53	60.66	0.89	1.46
1	ZS53B	2.29	0.09	3.95	2.19	0.17	7.85	36.84	0.93	2.52	65.35	1.37	2.10
1	RS37B	2.19	0.45	20.54	2.22	0.88	39.73	38.02	2.69	7.07	63.18	0.75	1.19
1	K4B	2.10	0.07	3.39	1.84	0.10	5.59	39.42	0.42	1.06	63.46	0.64	1.01
1	K3.3A	2.65	0.10	3.64	3.44	0.14	4.16	37.10	1.08	2.91	61.57	0.68	1.11
1	K3.3B	2.98	0.16	5.40	5.68	0.45	7.88	28.55	3.06	10.72	70.40	3.36	4.77
2a	4L	3.36	0.08	2.50	2.63	0.24	8.92	33.14	1.70	5.14	67.59	1.64	2.42
2a	MK94L	2.43	0.08	3.24	2.37	0.17	7.14	34.13	0.64	1.87	69.81	0.95	1.36
2a	SL16L	1.95	0.07	3.49	2.49	0.29	11.65	34.20	1.03	3.02	65.31	0.65	0.99
2a	ZS51L	1.91	0.06	2.92	2.17	0.09	4.35	30.00	0.57	1.91	66.30	0.66	1.00
2a	K3.1A	1.75	0.08	4.31	1.75	0.11	6.57	42.40	0.63	1.48	63.86	1.08	1.70
2a	K3.1B	1.80	0.07	3.67	1.86	0.10	5.24	42.68	0.92	2.16	63.36	0.78	1.23
2a	K3.2A	2.52	0.06	2.56	2.19	0.25	11.42	41.46	0.80	1.93	58.24	0.70	1.20
2a	K3.2B	1.80	0.24	13.36	2.49	1.57	63.03	40.37	1.49	3.69	64.06	1.00	1.56
2a	K3.2C	1.75	0.07	4.06	1.66	0.15	9.03	42.78	1.54	3.61	62.90	1.47	2.33
2a	ZS07L	1.87	0.20	10.64	2.58	1.04	40.16	41.20	1.06	2.58	63.64	0.77	1.21
2a	ML44L	2.38	0.22	9.44	2.69	1.23	45.95	36.09	1.57	4.35	66.39	1.08	1.63
2a	TN71L	2.43	0.10	4.04	2.26	0.25	11.00	37.57	1.01	2.68	66.77	0.43	0.64
2b	K4L	3.40	0.08	2.36	6.92	0.70	10.17	25.50	0.33	1.28	73.73	0.67	0.91
2b	53L	3.55	0.17	4.89	3.55	0.45	12.71	16.25	3.06	18.82	79.54	2.21	2.78
2b	24L	2.08	0.10	4.66	2.81	0.55	19.45	30.06	1.69	5.61	66.00	1.62	2.46
2b	K3.4	1.76	0.05	2.87	1.78	0.12	6.87	42.82	0.57	1.32	62.67	0.83	1.32
2b	ZS50L	2.17	0.23	10.72	3.96	1.49	37.60	13.62	1.90	13.94	80.68	2.22	2.76
2b	SL21L	2.72	0.52	19.20	3.06	1.10	35.91	25.14	7.47	29.72	71.54	6.54	9.14
2b	RS37L	2.35	0.21	9.09	4.38	0.82	18.69	31.06	2.21	7.11	70.63	2.04	2.88
3	ZS50U	2.14	0.33	15.24	6.68	3.12	46.65	25.54	4.91	19.23	68.44	3.01	4.40
3	51U	2.92	0.36	12.36	6.62	1.37	20.73	21.03	0.74	3.54	71.78	1.59	2.21
3	K4U	3.36	0.18	5.23	4.48	0.93	20.85	23.83	4.50	18.90	70.16	1.10	1.57
3	24U	1.78	0.16	9.24	3.86	0.79	20.48	29.49	0.83	2.80	67.77	0.34	0.51
3	ML44U	2.90	0.37	12.90	4.76	1.75	36.77	27.41	1.05	3.83	69.98	0.67	0.96
3	RS37U	1.74	0.10	5.58	2.28	0.39	16.96	38.71	1.43	3.70	64.93	1.66	2.56

APPENDIX B
ELECTRON MICROPROBE SETTINGS

Electron microprobe analysis of major and trace element concentrations were performed at the Spectrau laboratory, the Central Analytical Facility of the Faculty of Science, University of Johannesburg. The major element compositions of the chromite grains were analysed with a CAMECA SX100 electron microscope at standard operating conditions of a 20 Kv accelerating voltage with a 40 nA beam current and a beam diameter of 5 μm . Counting times of 40s for Ti and 20s for all other elements were recorded. Detection limits for Cr, Fe and V were set at 400ppm and for other elements at 200ppm.

The surfaces of the polished sections were coated with a thin layer of carbon and loaded into the electron microprobe analyser (EMPA) equipped with the Windows-based SAMx operating system and interface software. EMPA was used to analyse the chromite grains for Mg, Al, Si, Cr, Fe, V, Ca, Ti, Mn, Co, and Zn. Minor elements such as Si, Ca, Co, Zn and V are not reported in tables of analyses because they occur in small amounts in the chromite grains. Si content was determined to ensure that the beam had not overlapped onto a silicate phase.

The instrument calibrations were done internally by Dr Christian Reinke using chromite standards. The standard used to ensure integrity of the data was the Chro-MA1 standard and Table 1 below details the measured values of this standard. 14 different measurements of this standard were taken during analysis for comparison and are shown in Table 1 below. The data shows that the values are comparable and the data is reliable and can be used for further analysis.

Table 1: Standards measured during electron microprobe analysis.

		MgO	Al ₂ O ₃	SiO ₂	Cr ₂ O ₃	FeO	V ₂ O ₃	CaO	TiO ₂	MnO	CoO	NiO	ZnO	Total
Chro-MA1 Standard		5.47	8.51		30.69	21.01			0.56	0.24		0.19	0.11	
Chromite	1	9.47	16.64	0.01	44.67	27.41	0.33	0	0.91	0.21	0.04	0.18	0.11	99.99
FeCr ₂ O ₄	2	9.55	16.89	0.03	44.37	27.35	0.33	0	0.88	0.2	0.05	0.19	0.11	99.95
	3	9.57	16.87	0.03	44.7	27.34	0.33	0	0.8	0.22	0.03	0.19	0.12	100.2
	4	9.45	16.55	0.05	44.71	27.47	0.33	0	0.92	0.23	0.04	0.2	0.11	100.06
	5	9.58	16.42	0.14	44.62	27.4	0.36	0.02	0.88	0.27	0.06	0.18	0.12	100.05
	6	9.4	15.93	0.03	44.89	27.44	0.34	0	0.91	0.27	0.05	0.19	0.11	99.56
	7	9.42	16.5	0.02	45	27.49	0.36	0	0.92	0.24	0.06	0.18	0.13	100.33
	8	9.55	16.62	0.02	44.57	27.47	0.35	0	0.88	0.2	0.04	0.18	0.11	100
	9	9.4	16.2	0.03	44.62	27.48	0.34	0	0.94	0.26	0.04	0.17	0.11	99.59
	10	9.4	15.92	0.03	44.7	27.56	0.32	0	0.91	0.21	0.03	0.18	0.12	99.39
	11	9.55	16.54	0.05	44.82	27.47	0.32	0	0.91	0.2	0.04	0.19	0.1	100.18
	12	9.58	16.94	0.03	44.58	27.43	0.34	0	0.9	0.21	0.04	0.18	0.12	100.34
	13	9.22	15.66	0.03	44.54	27.22	0.33	0.01	0.91	0.23	0.03	0.19	0.1	98.46
	14	9.4	16.2	0.03	44.62	27.48	0.34	0	0.94	0.26	0.04	0.17	0.11	99.59