# ARCHEAN METAMORPHOSED ULTRAMAFIC ROCKS AND CHROMITITES FROM THE BEARTOOTH MOUNTAINS, MONTANA, USA: INSIGHTS INTO MANTLE GEOCHEMISTRY AND TECTONICS

A Thesis

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# Abstract

Metamorphosed ultramafic rocks and associated chromitite pods in the eastern Beartooth Mountains, Montana (USA) provide a window into the tectonic evolution of the Archean northern Wyoming Province. Meta-ultramafic rocks occur with a variety of metasupracrustal rocks as xenoliths in an extensive 2.8 Ga suite of TTG (meta)plutonic rocks. The origin of the ultramafic rocks is obscured by an upper amphibolite-to-greenschist facies overprint. Major element analyses (XRF, wt. %) of meta-ultramafic host rocks show $SiO_2$ from 40.53-50.37, MgO from 15.33-45.25, $TiO_2$ from 0.07-0.62, $Al_2O_3$ from 1.25-10.62, and $Fe_2O_3$(t) from 8.06-14.54. Total alkali contents ($Na_2O$+$K_2O$) range from 0.06-3.78 wt.% and plot in the picro-basalt and basalt fields on a TAS diagram and gabbro and peridot-gabbro fields on the plutonic equivalent TAS diagram. Major oxide whole-rock analyses for meta-ultramafic host rocks plot within boninitic and komatiitic fields based on their high MgO and low $TiO_2$ values. Cr contents of non-chromitites are high (1500-6500 ppm). Primitive mantle normalized spider diagrams show arc characteristics, e.g., enrichments and depletions in LILE, a positive lead anomaly, and negative HFSE anomalies.

In contrast, chromitite pods (ultramafic rocks with >75% chromite) contain chromite grains that retain their igneous chemistry and textures. Pull-apart textures, relatively large (>1 mm) to massive anhedral chromite, and poorly developed/tectonically disrupted chromite nodules are inconsistent with derivation from a layered mafic intrusion. Major and trace element analyses of chromites by electron microprobe show chromites have minor compositional zoning with the rims being slightly enriched in Mg and Al at the expense of Cr and $Fe^{2+}$. Chromites have Cr/(Cr+Al) from 0.69-0.83 and Mg/(Mg+$Fe^{2+}$) from 0.11-0.56, consistent with derivation from an ophiolite sequence or layered mafic intrusion. Low $TiO_2$ concentrations of chromite

from meta-chromitites are inconsistent with derivation from a layered mafic intrusion. Melts calculated to be in equilibrium with chromite are boninitic in character.

In conclusion, the boninitic/ophiolitic/arc geochemical signature of the meta-chromites and meta-ultramafic rocks suggest that they formed in the forearc of an early subduction setting. These rocks were intercalated with a variety of lithologies during an episode of plate convergence that preceded the 2.8 Ga TTG plutonism.

# Chapter 1. Introduction

Ultramafic rocks develop in a variety of tectonically significant geologic settings including in the mantle, in subduction-zones, and in layered mafic intrusions. Most investigations of mantle and subduction-zone setting ultramafic rocks focus on post-Archean occurrences that are exposed in ophiolite sequences (e.g., Boudier and Coleman, 1981; Coleman, 1981; Harper, 1984; Varga and Moore, 1985; Boudier et al., 1996; Li, 1997; Pagé et al., 2008). However, ultramafic rocks are also found tectonically intermixed in Archean terranes and the tectonic environment in which they formed is debatable (e.g., Ahmed et al., 2001; Kusky et al., 2001; Furnes et al., 2007; Yellappa et al., 2012; Szilas et al., 2015; Santosh et al., 2016; Guice et al., 2020; Huang et al., 2021). Interpreting Archean ultramafic rocks is challenging because their original chemistry and structural features may be masked by metamorphism and tectonic mixing (Evans, 1977). Among the mineral constituents of ultramafic rocks, chromite has proved useful as a petrogenetic indicator of the original igneous host because it is typically geochemically resilient to low-grade metamorphism, preserving its pre-metamorphic geochemical signature. Thus, chromite chemistry has been used for identification of the tectonic environment in which it formed (Irvine, 1965; Barnes and Roeder, 2001). Consequently, it is important to investigate Archean ultramafic rocks and their extant chromites to provide insights into aspects of Archean tectonic processes.

Archean ultramafic rocks and chromitite pods occur in the eastern Beartooth Mountains of Montana and Wyoming, USA (James, 1946). These rocks are important to study because they contain information about the tectonic environment in which they formed and constrains interpretations regarding the style of tectonics operational in the Beartooth Mountains during the

Archean. Chromitites and their enclosing ultramafic rocks are found as pods and lenses in the 2.8 Ga tonalite-trondhjemite-granodiorite (TTG) rocks of the Beartooth Mountains of Montana and Wyoming, USA (James, 1946; Henry et al. 1982). Although the ultramafic rocks are variably serpentinized and affected by upper-amphibolite facies metamorphism resulting in chromite exsolution in those rocks in which chromite is an accessory mineral, chromite in chromitites may maintain chemical signatures of their parent magma (Loferski and Lipin 1983; Loferski, 1986; Robinson and Henry, 2016). Robinson and Henry (2016) determined the conditions for metamorphic episodes recorded in the ultramafic and associated lithologies through geothermobarometry, phase equilibrium modeling, and construction of mineral association-diagrams. M1 was determined to occur at 750-800 °C and 6-8 kbar, M2 occurred at 600-700 °C and 5-7 kbar, M3 occurred at 400-450 °C and <5 kbar. These pressures and temperature conditions are similar to those recorded in other lithologies in the eastern Beartooths (e.g. metasupracrustal rocks; Henry et al., 1982).

Previous studies of the chromitites and chromite-bearing rocks of the eastern Beartooth Mountains suggest several possible modes of origin. James (1946) interpreted the ultramafic rocks as a tectonically emplaced alpine-type body because of their lenticular form mixed with metasedimentary and metavolcanic lithologies. He suggested that the ultramafics are not part of a layered igneous complex because the amount of chromite present in chromitite pods does not correlate with the size of the ultramafic body. Skinner (1969) focused on the serpentinite and hornblende-rich ultramafic rocks of the Highline Trails area and interprets these rocks as a dismembered ultramafic-mafic intrusion consisting of interlayered metamorphosed picrites and troctolites. He suggested that they might be related to the Stillwater Complex, but Loferski (1986) dismissed his suggestion because the Stillwater Complex is at least one hundred million

years younger. Loferski (1986) interprets the meta-ultramafic rocks and meta-chromitites as a dismembered layered igneous intrusion because of the chemical differences of the ultramafic bodies, their Archean age and the fine-grained nature and chain-texture of the chromite. Additionally, chromite chemistry which falls within the layered mafic intrusion field in tectonic discrimination diagrams.

This research aims to test the hypotheses of James (1946), Skinner (1969), and Loferski (1986) to explain the origin of these meta-ultramafic rocks and meta-chromitites. These data may then expand the possible tectonic scenarios that were operative in the Archean. These hypotheses will be tested with chromite tectonic environment discrimination diagrams; mineral chemistry of chromite, olivine, apatite, and phlogopite; and whole rock geochemistry of these meta-ultramafic rocks.

# Chapter 2. Background

## 2.1. Geologic Setting

The eastern Beartooth Mountains are in the northern portion of the Wyoming Province, a craton in North America and one of the Archean blocks or proto-continents that make up Laurentia (fig. 1). The craton formed at ~4.0 Ga and grew until 2.5 Ga developing a thick tectosphere which prevented it from deforming during its incorporation into Laurentia (Mueller and Frost, 2006). Paleoproterozoic orogens surround the province, but their effects are generally limited to its margins (fig. 1). The province remained undeformed until the Cretaceous when Eocene-Laramide and Sevier style-tectonism fractured the basement causing uplift and exposure of ~ 10 km of the province's basement (Mogk et al., 2022).

The Wyoming Province is divided into three subprovinces based on their lithologies and ages: The Beartooth-Bighorn Magmatic Zone (BBMZ), Montana Metasedimentary Terrane (MMT), and the Southern Accreted Terranes (SAT, fig. 1). Each subprovince records a different aspect of the Wyoming Province's evolution throughout the Archean (Mogk et al., 1992; Mueller and Frost, 2006, Mogk et al. 2020). Based on highly radiogenic isotopic Pb signatures, the MMT and BBMZ were part of the same geochemical provenance before 3.6 Ga but have different geologic histories from 3.6 Ga until 2.7-2.5 Ga (Mogk et al., 1992; Mueller et al., 1998). The SAT do not share these highly radiogenic Pb signatures and are interpreted as Neoarchean crustal additions to the southern Wyoming Province accreted during subduction (Chamberlain et al., 2003). The MMT is composed of 3.3-3.5 Ga TTG gneisses intercalated with younger metasedimentary rocks (Mogk et al., 1992). The BBMZ is dominated by 2.8 Ga tonalite-trondhjemite-granodiorite (TTG) plutonic and metaplutonic rocks, but also contains enclaves of

older metamorphic rocks including >3.0 Ga metasupracrustal rocks that are tectonically intercalated with 3.5 – 3.1 Ga TTG gneisses (Henry et al., 1982; Mueller et al., 1992, 2014; Mueller and Wooden, 2012). The SAT is composed of late Archean metasupracrustal rocks that are intruded by granitic plutons (Chamberlain et al., 2003).

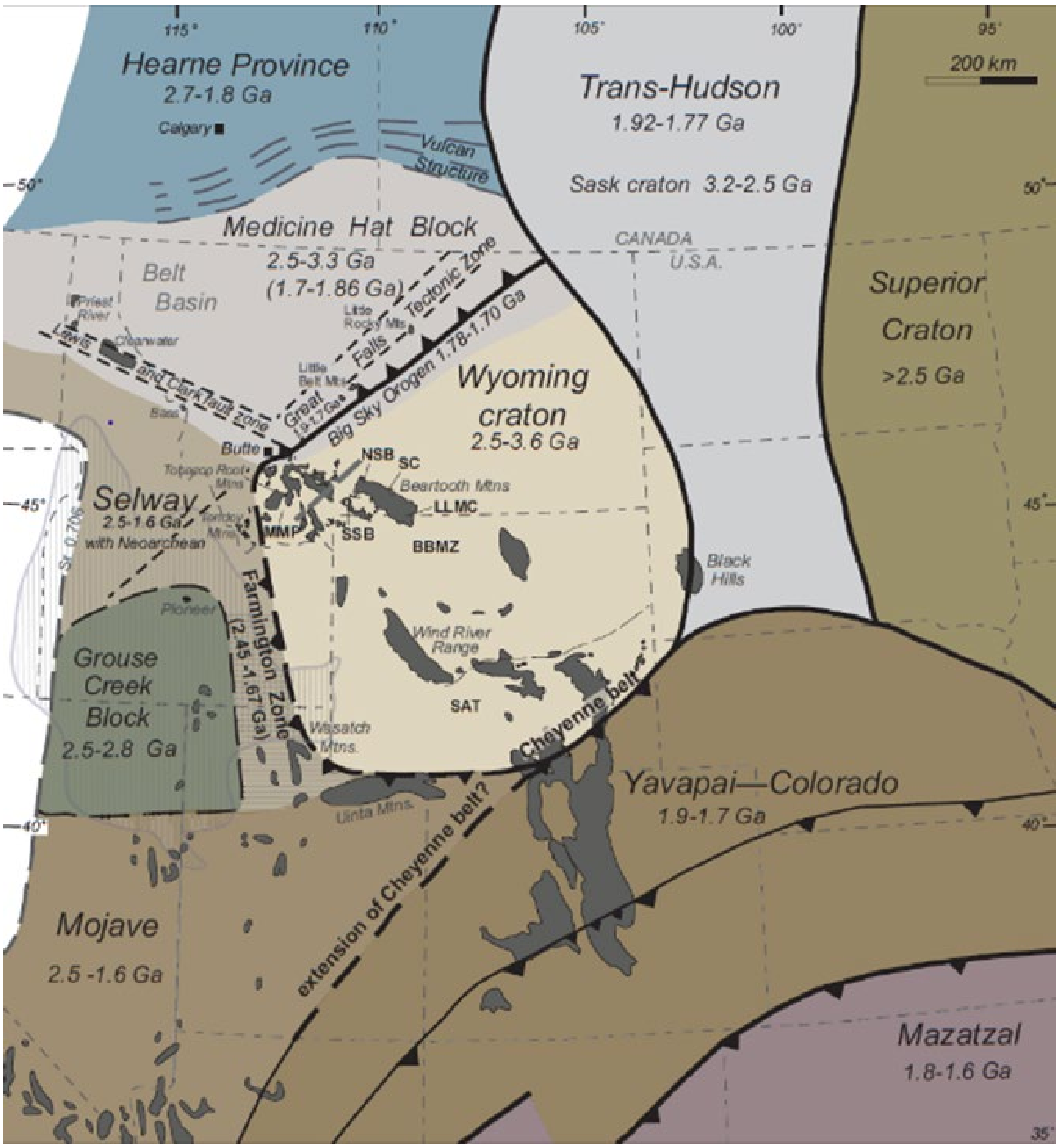



Figure 1. A map of the Wyoming Craton and surrounding belts. NSB, North Snowy Block; SC, Stillwater Complex; MMP, Montana Metasedimentary Terrane; SSB, South Snowy Block; LLMC, Long Lake Magmatic Complex; BBMZ, Beartooth Bighorn Magmatic Zone; SAT, Southern Accreted Terranes. Modified from Mogk et al. (2020).

The chromite-bearing rocks of this research are from the eastern Beartooth Mountains, part of the BBMZ. The Beartooth Mountains are divided into four blocks based on ages and lithologies: the Beartooth Plateau Block, the Stillwater Block, the North Snowy Block, and the South Snowy Block (fig. 2). These blocks record different aspects of crustal formation.

The Beartooth Plateau Block (BPB) is dominated by the Long Lake Magmatic Complex (LLMC), a ~2.8 Ga suite of amphibolite- or upper amphibolite-facies metaplutonic felsic gneisses derived from a variety TTG igneous rocks. TTG rock protoliths range from granodiorite to trondhjemite to granite, many with adakitic affinity, suggesting their derivation in a continental-arc (Mueller et al., 1983, 2010). Other evidence for the LLMCs development in a continental arc includes isotopic and major and trace element data that are identical to those that develop in modern arc settings (Mueller et al., 2014). The LLMC includes xenoliths of metasupracrustal rocks, tectonically juxtaposed with 3.1-3.5 Ga TTG gneisses (Henry et al., 1982). Metasupracrustals include quartzite, pelitic schist, banded iron formation, metabasite, and minor ultramafic rocks (James, 1946; Henry et al., 1982; Mueller et al., 1998). The protoliths of the metasedimentary rocks are stable platform sedimentary material which formed during a period of tectonic quiescence between 3.1 Ga and 2.9 Ga (James, 1946; Henry et al., 1982; Mogk et al. 2020).

The Stillwater Block (SB) is dominated by the 2.71 Ga mafic-ultramafic layered igneous Stillwater Complex and its contact metasedimentary aureole (DePaolo and Wasserburg, 1979). Rhythmic layering of the Stillwater Complex suggests that it was intruded horizontally during a period of tectonic quiescence in an extensional environment (McCallum, 1996; McCallum et al., 1980; Raedeke and McCallum, 1984). The Stillwater Block was emplaced against the Beartooth Block ~2.70 Ga based on cross-cutting relationships (Page and Zientek, 1985, Premo et al.,

1990). Its contact aureole contains metasedimentary units that record metamorphic conditions of 2-3 kbar and 500-600 °C, pressures much lower than those that the adjacent rocks in the BPB experienced during regional metamorphism, indicating that orogeny had ceased by the time that it was emplaced (Geissman and Mogk, 1986). The SB is now tilted steeply to vertically and overturned in some areas because of Laramide faulting as well as Precambrian tilting based on the unconformably overlying horizontal Cambrian sediments (Mogk et al., 2020).

The North Snowy Block (NSB) consists of six Archean-aged metasedimentary and meta-igneous units that are tectonically juxtaposed and separated by myolinitic shear zones (Mogk et al., 1988, 2020). Each unit preserves unique metamorphic grades and fabrics (Mogk et al., 1988, 2020). The oldest unit is a 3.5-3.6 Ga TTG gneiss-amphibolite complex, and the youngest unit is a 2.55 Ga leucogranitic sill (Mogk et al., 1988). The leucogranitic sill is interpreted to reflect the last major Archean deformation event in the NSB (Mogk et al., 2020). Another tectonically significant unit is the ~3.2 Ga Pine Creek Nappe which, because of its tectonic similarity to modern Alpine nappes, is interpreted as one of the oldest examples of horizontal tectonics typically associated with modern-style plate tectonics (Mogk et al., 1988). The NSB was emplaced onto the BPB ~2.55 Ga based on ages of shear zones and cross-cutting dikes (Henry personal communication, 2022).

The South Snowy Block (SSB) consists of a series of Mesoarchean undeformed plutons that are intrusive into the Jardine Metasedimentary Sequence (JMS) and the Slough Creek Block (SCB) which is thrust over the JMS at the Yellowstone River Shear Zone (fig.2). The JMS is composed of phyllites, biotite schists, quartzites, metaconglomerates, and banded iron formations. Relict sedimentary features preserved in these rocks such as compositional layering and graded bedding, low-angle cross-stratification, rip-up clasts, channel scour deposits, and

partial Bouma sequences suggest their deposition in turbidity currents (Mogk, 1988). The JMS is metamorphosed to relatively low grades compared to other metasediments in the Wyoming Province, the peak metamorphic conditions reaching ~3.8 kbar and 550 °C (Mogk et al., 2020). The JMS rocks also differ from other metasediments in the Wyoming Province in that they have no detrital zircons of 2.8 Ga, so they cannot have been derived from the Beartooth massif (Goldstein et al., 2011). Instead, detrital zircons of the JMS have a maximum age frequency at ~3.2 and 3.0 and a minimum age of 2.9 Ga (Mogk et al., 2020). The ~2.8 Ga plutons that intrude the JMS are granitic with associated granodioritic to dioritic sheets. The SCB is mainly composed of the 2.8 Ga Slough Creek Batholith and 3.2 Ga suite of felsic-intermediate gneisses which are similar to those of the BPB (Mogk et al., 2012 and Mueller et al., 2014). The batholith ranges in composition from dioritic to granitic with TTG affinities (Mogk et al., 2012; Mueller et al., 2014). The Slough Creek Batholith and the 2.8 Ga plutons in the JMS are both interpreted to be upper and middle crustal equivalents of the LLMC intruding at 12 km and 24 km depth, respectively (Mogk et al., 2012; Mueller et al., 2014).

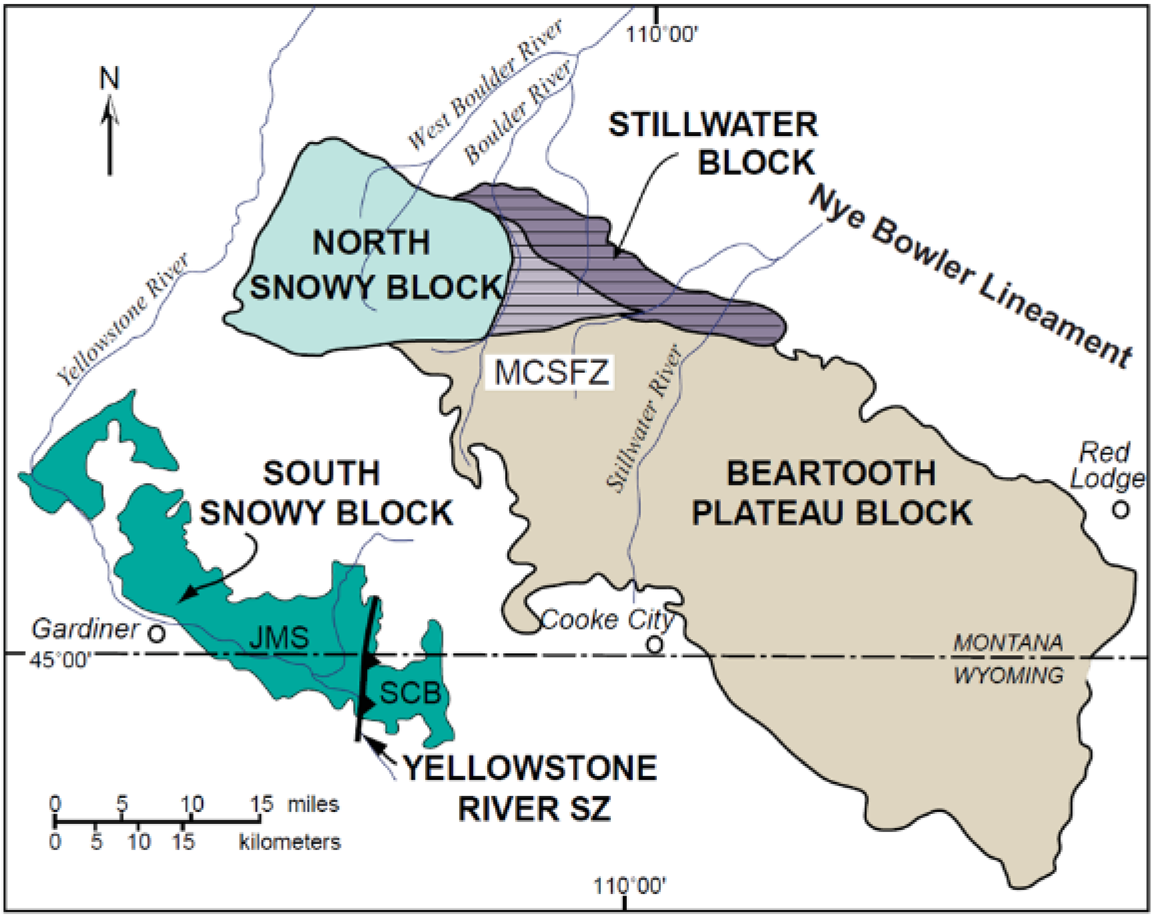



Figure 2. Map of the four blocks making up the Archean rocks of the Beartooth Mountains: The Beartooth Plateau Block, the North Snowy Block, the South Snowy Block, and the Stillwater Block (Mogk et al., 2020). The Stillwater Block is represented by horizontal lines and is divided into a lighter shade which represents the Stillwater Contact Aureole and a darker shade which represents the Stillwater Complex. MCSFZ, Mill Creek Stillwater Fault Zone, JMS, Jardine Metasedimentary Suite; SCB, Slough Creek Block.

## 2.2. Occurrence of the Meta-ultramafic Rocks and Meta-chromitites

The focus of this study is the Archean meta-ultramafic rocks and chromitite pods found in the eastern Beartooth Mountains. Meta-ultramafic rocks are mainly serpentinite (> 80% serpentine minerals) with rare relict olivine, but assemblages of prograde magnesio-hornblende and enstatite also occur as a product of upper-amphibolite to granulite facies metamorphism (James, 1946; Loferski, 1986). Chromitite pods tend to have chromite with octahedral morphologies within a matrix of serpentine, chlorite, and talc with variable amounts of

phlogopite, olivine, diopside, tremolite, magnesio-hornblende, magnetite, plagioclase, and pyrite (James, 1946; Loferski, 1986). Where serpentinite is in contact with chromitite pods it is common for the serpentine to alter to Cr-diopside and/or Cr-tremolite (James, 1946).

Meta-ultramafics and their enclosed chromitite pods occur with metasupracrustals as roof pendants in the LLMC. The roof pendants follow a northeastern trend (fig. 3), they are roughly perpendicular with the northwestern trending antiformal-synformal structure of the Beartooth Mountains (James, 1946). The meta-ultramafics are most prominent in the axes of synformal folds (James, 1946). Contacts between the meta-ultramafic rocks and metasupracrustal rocks tend to be obscured by soil and vegetation, but are sheared where present (James, 1946). Not all ultramafic bodies contain chromitite pods, but in those that do chromitite pods are randomly distributed, sheared, rolled, and broken up (James, 1946). The largest meta-ultramafic bodies are ~700 m long and ~70 m wide and occur with amphibolite and quartzite metasupracrustals while smaller bodies, only a few meters in diameter occur with the banded iron formation and massive quartzites (James, 1946). All meta-ultramafics occur on the Hellroaring, Line Creek, and Silver Run Plateaus at an elevation of no less than 2700 m (James, 1946).

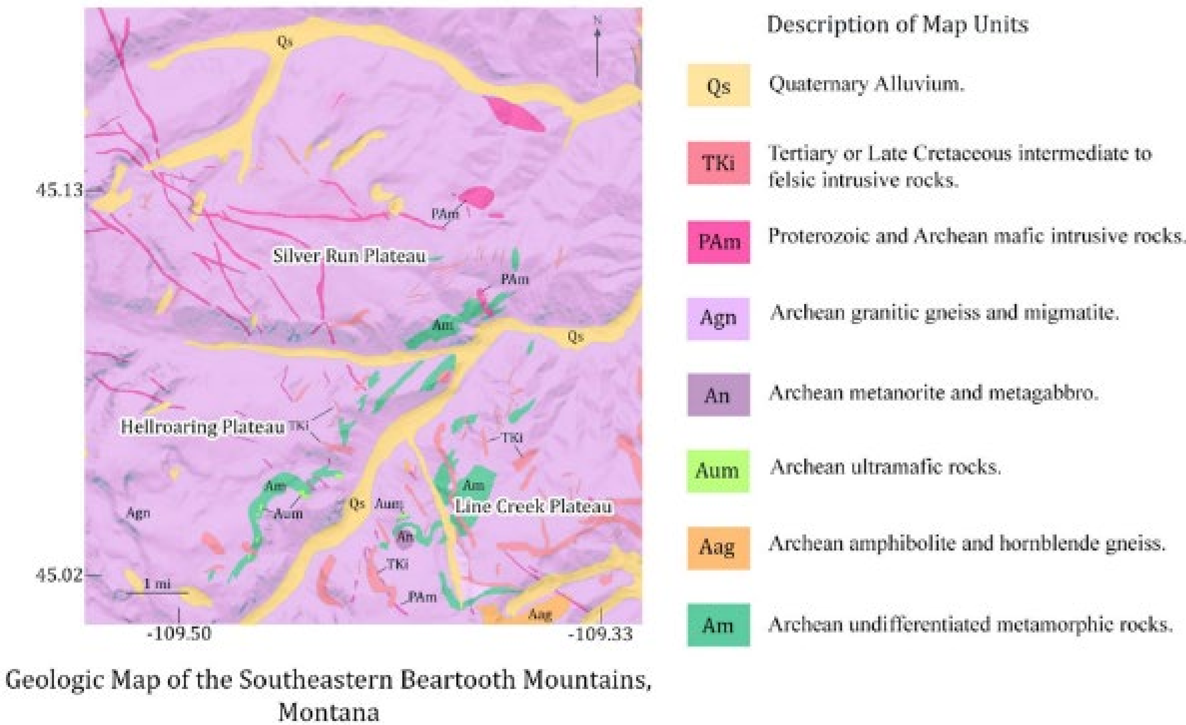



Figure 3. A geologic map of the eastern Beartooth Mountains adapted from B.S Van Gosen, et al. (2000) and Mueller et al. (1992).

The Hellroaring Plateau contains the largest number of ultramafic bodies that host chromite ore (James, 1946). Meta-ultramafic rocks occur in the southern portion of the plateau mainly between amphibolite and micaceous-quartzite layers (James, 1946). Chromitite pods occur in 6 locations on the Hellroaring Plateau and were mined during World War II at the Pick, Shovel, Drill, North Star, Gallon Jug 1, Gallon Jug 2, and Gallon Jug 4 Mines (fig. 4 and 5, James, 1946).

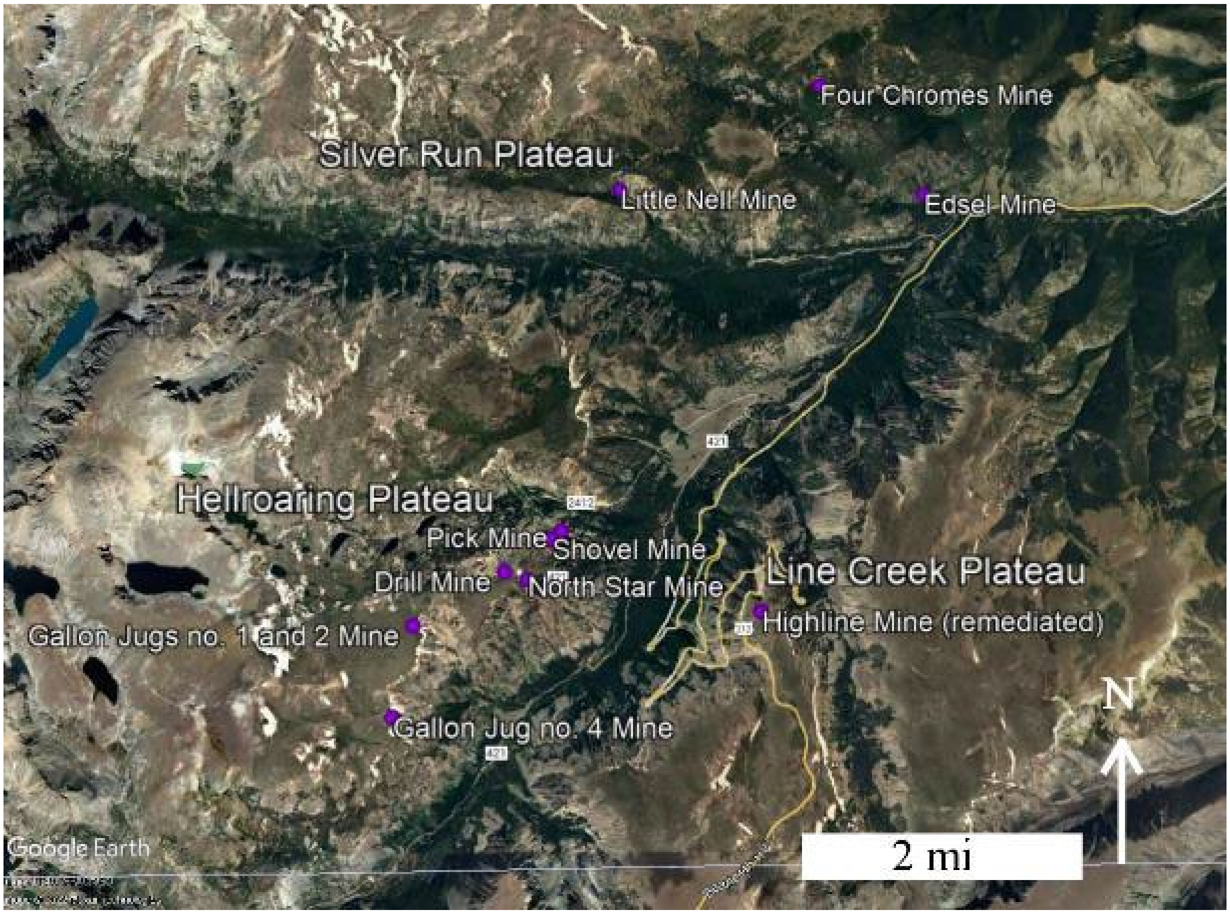



Figure 4. A map of the eastern Beartooth Mountains showing the locations of chromite mines that were active during World War II.

On the Line Creek Plateau chromitite pods occur in a single 300 m long ~70 m wide ultramafic lens (James, 1946). The interbedded micaceous-quartzite and amphibolite that are associated with ultramafics on the Hellroaring Plateau are absent on the Line Creek Plateau (James, 1946). On the southern side of the Line Creek Plateau in the Highline Trail Lakes area, there are a series of eighteen ultramafic lenses following a northeast trend (Skinner, 1969). The Highline Trail meta-ultramafic rocks consist of serpentinites commonly interlayered with hornblende-orthopyroxene rocks and do not contain chromitite pods (Skinner, 1969).

Figure 5. Photograph of the remnants of the Pick Mine. Photo credit: Darrell Henry 2021.

On the Silver Run Plateau chromitite pods are found in the Little Nell, Edsel, and Four Chromes Mines. The metasupracrustal rocks are almost completely absent, but serpentinite lenses remain (James, 1946). Chromite from the Four Chromes Mine is the only chromite in the Beartooths noted to have poorly developed nodular structure (James, 1946).

# Chapter 3. Methods

## 3.1. Sample Classification and Petrography

Thirty-four samples representative of the lithologies of the ultramafic-to-mafic rocks and chromitites of the eastern Beartooth Mountains (MT/WY) were chosen for this study. They are curated at Louisiana State University (LSU) and are part of the collections of Drs. Darrell Henry and David Mogk. Location and year collected as well as an ordered sample number make up the sample names (i.e., QC81-28 was collected from Quad Creek in 1981). Samples that are part of Dr. David Mogk's collection include his initials (e.g., 93DM-36), all others are part of Dr. Darrell Henry's collection.

Traditional optical petrographic methods were used to identify the mineralogy and mineral modes of each sample. Reflected-light petrography was used to identify oxides and sulfides, and exsolution or zoning that is present in chromite in some samples. Photomicrographs of each sample were taken in plane-polarized, cross-polarized, and reflected light and were important to determine analytical targets for electron microprobe analysis.

## 3.2. Electron Microprobe Analysis (EMPA)

Chromite, olivine, phlogopite, and apatite mineral chemistry of select samples was analyzed using the JEOL JXA 8230 electron microprobe in the Chevron Geomaterials Characterization Lab at LSU. The following operating conditions were used in the analyses: accelerating voltage of 15 kV; probe current of 40 nA; a beam diameter of 1-2 µm for chromite, 5 µm for olivine, and 10 µm for apatite and phlogopite; and counting times of 20 - 30 s on peak and 10 – 15 s on background. Well characterized natural and synthetic standards were used and

run simultaneously with the samples from this study to indicate their reproducibility (Tables 1 and 2). Standard Deviation

Table 1. Elements, Standards, and Detection Limits for EMP Analysis of Phlogopite, Olivine, and Chromite.

| Element | Standard for Phlogopite Analysis | Detection Limit (wt. % oxide) | Standard for Olivine Analysis | Detection Limit (wt. % oxide) | Standard for Chromite Analysis | Detection Limit (wt. % oxide) |
|---|---|---|---|---|---|---|
| **F** | Toronto Fluorite | 0.0577 | N/A | N/A | N/A | N/A |
| **Na** | Amelia Albite | 0.0111 | N/A | N/A | N/A | N/A |
| **Mg** | San Carlos Olivine | 0.0101 | San Carlos Olivine | 0.0116 | USNM Chromite | 0.0102 |
| **Al** | Toronto Almandine | 0.0017 | Toronto Almandine | 0.0085 | USNM Chromite | 0.0095 |
| **Si** | Toronto Almandine | 0.0171 | San Carlos Olivine | 0.015 | USNM Diopside | 0.0106 |
| **Cl** | Toronto Tugtupite | 0.0035 | N/A | N/A | N/A | N/A |
| **K** | USNM Microcline | 0.0047 | N/A | N/A | N/A | N/A |
| **Ca** | USNM Diopside | 0.0044 | USNM Diopside | 0.0045 | N/A | N/A |
| **Ti** | Toronto Rutile | 0.0255 | Toronto Rutile | 0.028 | USNM Ilmenite | 0.0092 |
| **V** | N/A | N/A | N/A | N/A | Geller pure V | 0.008 |
| **Cr** | USNM Chromite | 0.0162 | N/A | N/A | USNM Chromite | 0.0161 |
| **Mn** | Toronto Rhodonite | 0.0152 | Toronto Rhodonite | 0.0096 | USNM Ilmenite | 0.0161 |
| **Fe** | Toronto Almandine | 0.0182 | San Carlos Olivine | 0.0213 | USNM Ilmenite | 0.0163 |
| **Ni** | N/A | N/A | Ni-Diopside Glass | 0.016 | Geller pure Ni | 0.0108 |
| **Zn** | N/A | N/A | N/A | N/A | USNM Gahnite | 0.0175 |
| **Ba** | Toronto Barite | 0.0121 | N/A | N/A | N/A | N/A |

Si measured in chromite is below the detection limit.

Table 2. Elements, Standards, and Detection Limits used for EMP Analysis of Apatite.

| Element | Standard for Apatite Analysis | Detection Limit (wt. % element) |
|---|---|---|
| **F** | Durango Apatite | 0.0798 |
| **Na** | Amelia Albite | 0.0174 |
| **Mg** | Diopside | 0.012 |
| **Si** | Diopside | 0.0237 |
| **P** | Durango Apatite | 0.0268 |
| **S** | Toronto Celestite | 0.0102 |
| **Cl** | Toronto Tugtupite | 0.0754 |
| **Ca** | Durango Apatite | 0.0169 |
| **Mn** | Toronto Rhodonite | 0.0249 |
| **Fe** | San Carlos Olivine | 0.0268 |
| **Sr** | Toronto Celestite | 0.0027 |
| **Y** | Glass REE3 | 0.0028 |
| **La** | USNM LaPO4 | 0.0033 |
| **Ce** | USNM CePO4 | 0.0031 |
| **Nd** | USNM NdPO4 | 0.0032 |

Major elements analyzed in chromite are Mg, Fe, Cr, and Al; minor elements analyzed in chromite are Mn, Ti, Ca, Si, Ni, Zn, and V. Major elements analyzed in olivine are Si, Mg, and Fe; minor elements analyzed in olivine are Mn and Ni; trace elements measured in olivine are Ca, Ti, and Al. Major elements analyzed in phlogopite are Si, Fe, Mg, Al, Ti, and K; minor elements analyzed in phlogopite are Ca, Na, Ba, F, and Cl; the trace element measured in phlogopite is Cr. Major elements analyzed in apatite are Ca, P, and F; minor elements analyzed in apatite are Si, Sr, Ce, Nd, S, and Cl; trace elements analyzed in apatite are Fe, Mg, Na, Y, and La.

Table 3. Chromite Error Analysis Using Chromite Standard Cmt1436 as a Secondary Standard.

| | Cmt1436 pt.1 | Cmt1436 pt.2 | Cmt1436 pt.3 | Cmt1436 pt.4 | Cmt1436 pt.5 | Cmt1436 pt.6 | Avg. | Cmt1436 reported | Std. Dev. | % Error |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.184 | 0.174 | 0.253 | 0.278 | 0.309 | 0.298 | 0.249 | 0.25 | 0.058 | -0.267 |
| $TiO_2$ | 0.572 | 0.583 | 0.588 | 0.601 | 0.608 | 0.587 | 0.59 | 0.59 | 0.013 | -0.028 |
| $V_2O_5$ | 0.324 | 0.333 | 0.334 | 0.33 | 0.329 | 0.334 | 0.331 | 0.33 | 0.004 | 0.202 |
| $Al_2O_3$ | 18.671 | 18.552 | 18.442 | 18.392 | 18.455 | 18.465 | 18.496 | 18.38 | 0.1 | 0.632 |
| $Cr_2O_3$ | 41.336 | 41.402 | 41.563 | 41.313 | 41.532 | 41.336 | 41.414 | 41.45 | 0.108 | -0.088 |
| FeO* | 27.416 | 27.507 | 27.387 | 27.346 | 27.476 | 27.383 | 27.419 | 27.4 | 0.061 | 0.07 |
| MnO | 0.185 | 0.202 | 0.187 | 0.21 | 0.21 | 0.207 | 0.2 | 0.2 | 0.011 | 0.083 |
| MgO | 10.12 | 9.983 | 9.973 | 9.967 | 9.927 | 9.989 | 9.993 | 9.99 | 0.066 | 0.032 |
| CaO | 0.094 | 0.09 | 0.05 | 0.081 | 0.08 | 0.086 | 0.08 | 0.08 | 0.016 | 0.208 |
| NiO | 0.155 | 0.139 | 0.155 | 0.151 | 0.149 | 0.154 | 0.151 | 0.15 | 0.006 | 0.333 |
| ZnO | 0.135 | 0.103 | 0.121 | 0.137 | 0.113 | 0.108 | 0.12 | | 0.014 | NA |
| Total | 99.192 | 99.068 | 99.053 | 98.806 | 99.188 | 98.947 | 99.042 | 98.82 | 0.148 | 0.225 |

Table 4. Apatite Error Analysis Using Apatite Standard Toronto Apatite (Tapt) as a Secondary Standard.

| | TApt-001 | TApt-002 | TApt-003 | TApt-004 | TApt pt.5 | TApt-006 | Avg. | Tapt reported | Std. Dev. | % Error |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.188 | 0.133 | 0.156 | 0.325 | 0.21 | 0.192 | 0.201 | 0.2 | 0.0669 | 0.33 |
| FeO | 0 | 0.006 | 0 | 0.008 | 0 | 0 | 0.0023 | | 0.0037 | N/A |
| MnO | 0.039 | 0 | 0 | 0.037 | 0.033 | 0.026 | 0.0225 | | 0.018 | N/A |
| MgO | 0 | 0 | 0 | 0.012 | 0 | 0 | 0.002 | | 0.0049 | N/A |
| CaO | 54.71 | 54.641 | 55.308 | 54.581 | 54.551 | 54.441 | 54.7053 | 54.68 | 0.309 | 0.05 |
| $Na_2O$ | 0.022 | 0 | 0.083 | 0.09 | 0.057 | 0.018 | 0.045 | | 0.0371 | N/A |
| $P_2O_5$ | 40.131 | 39.938 | 39.957 | 39.96 | 40.143 | 40.036 | 40.0275 | 40.04 | 0.0913 | -0.03 |
| SrO | 0.292 | 0.27 | 0.299 | 0.236 | 0.297 | 0.168 | 0.26033 | 0.26 | 0.0511 | 0.13 |
| $Y_2O_3$ | 0 | 0 | 0.034 | 0 | 0 | 0 | 0.00567 | | 0.0139 | N/A |
| $La_2O_3$ | 0.179 | 0 | 0.11 | 0.096 | 0.095 | 0 | 0.08 | 0.08 | 0.0693 | 0 |
| $Ce_2O_3$ | 0.307 | 0.28 | 0.213 | 0.3 | 0.349 | 0.234 | 0.2805 | 0.28 | 0.05 | 0.18 |
| $Nd_2O_3$ | 0.064 | 0.107 | 0.131 | 0.12 | 0.121 | 0.058 | 0.10017 | 0.1 | 0.0313 | 0.17 |
| $SO_3$ | 0.314 | 0.282 | 0.281 | 0.572 | 0.527 | 0.424 | 0.4 | 0.4 | 0.128 | 0 |
| F | 3.662 | 3.349 | 3.459 | 3.505 | 3.496 | 3.275 | 3.45767 | 3.44 | 0.135 | 0.51 |
| Cl | 0.364 | 0.317 | 0.372 | 0.37 | 0.397 | 0.349 | 0.3615 | 0.36 | 0.0268 | 0.42 |

Table 5. Phlogopite Error Analysis Using Biotite Standard Biotite M-1 U. of Oregon, Bernard Evans (M1Bt) as a Secondary Standard.

| | M1Bt-001 | M1Bt-002 | M1Bt-003 | M1Bt-004 | M1Bt-005 | M1Bt-006 | Avg. | M1Bt reported | Std. Dev. | Percent Error |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 34.409 | 34.379 | 34.567 | 34.228 | 34.125 | 34.519 | 34.371 | 34.4 | 0.169 | -0.08 |
| $TiO_2$ | 3.034 | 3.078 | 2.941 | 3.145 | 2.981 | 3.104 | 3.0472 | 3.05 | 0.077 | -0.09 |
| $Al_2O_3$ | 13.315 | 13.265 | 13.324 | 13.324 | 13.236 | 13.471 | 13.323 | 13.3 | 0.081 | 0.17 |
| $Cr_2O_3$ | 0 | 0 | 0.004 | 0 | 0.031 | 0.014 | 0.00817 | | 0.012 | N/A |
| FeO | 30.176 | 30.189 | 30.057 | 30.379 | 30.448 | 30.382 | 30.272 | 30.14 | 0.153 | 0.44 |
| MnO | 0.353 | 0.401 | 0.37 | 0.391 | 0.443 | 0.322 | 0.38 | 0.38 | 0.042 | 0.00 |
| MgO | 4.565 | 4.552 | 4.625 | 4.635 | 4.628 | 4.582 | 4.598 | 4.6 | 0.036 | -0.05 |
| CaO | 0.012 | 0.01 | 0.015 | 0.026 | 0.023 | 0.034 | 0.02 | 0.02 | 0.009 | 0.00 |
| $Na_2O$ | 0.204 | 0.104 | 0.091 | 0.086 | 0.084 | 0.095 | 0.1107 | 0.16 | 0.046 | -30.83 |
| $K_2O$ | 9.18 | 9.386 | 9.426 | 9.437 | 9.392 | 9.404 | 9.3708 | 9.2 | 0.096 | 1.86 |
| BaO | 0.148 | 0.191 | 0.206 | 0.17 | 0.164 | 0.202 | 0.1802 | 0.18 | 0.023 | 0.09 |
| F | 0.294 | 0.336 | 0.38 | 0.465 | 0.377 | 0.377 | 0.372 | 0.37 | 0.057 | 0.41 |
| Cl | 0.359 | 0.376 | 0.373 | 0.362 | 0.377 | 0.379 | 0.371 | 0.37 | 0.008 | 0.27 |

Table 6. Olivine Error Analysis Using Olivine Standard Toronto Olivine (TOl) as a Secondary Standard.

| | TOl-001 | TOl-002 | TOl-003 | TOl-004 | TOl-005 | TOl-006 | Average | TOl reported | Std. Dev. | % Error |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 41.849 | 41.725 | 41.697 | 41.823 | 41.802 | 41.709 | 41.768 | 41.84 | 0.065 | -0.17 |
| $TiO_2$ | 0.017 | 0.004 | 0 | 0.012 | 0 | 0 | 0.0055 | | 0.007 | N/A |
| $Al_2O_3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0.000 | N/A |
| $Cr_2O_3$ | 0 | 0.022 | 0.004 | 0.001 | 0.031 | 0 | 0.00967 | 0.01 | 0.013 | -3.33 |
| FeO | 6.483 | 6.567 | 6.511 | 6.568 | 6.5 | 6.527 | 6.526 | 6.51 | 0.035 | 0.25 |
| MnO | 0.136 | 0.123 | 0.1 | 0.119 | 0.114 | 0.129 | 0.1202 | 0.12 | 0.013 | 0.14 |
| MgO | 51.214 | 51.541 | 51.571 | 51.727 | 51.706 | 51.744 | 51.5834 | 51.57 | 0.200 | 0.03 |
| CaO | 0.021 | 0.018 | 0.019 | 0.028 | 0.015 | 0.021 | 0.0203 | 0.02 | 0.004 | 1.67 |
| NiO | 0.184 | 0.213 | 0.211 | 0.196 | 0.195 | 0.224 | 0.2039 | 0.2 | 0.015 | 1.92 |

Minerals were normalized using Excel spreadsheets developed by Dr. Darrell Henry on the basis of twelve oxygens for chromite, four oxygens for olivine, and 24 anions for phlogopite. $Fe_2O_3$ was calculated using assumed mineral stoichiometry. Additional EMPA data from Dr. Darrell Henry was included. All analytical data are included as tables in the Appendices.

Backscattered electron imaging (BSE) using the JEOL EMP illustrates textural relations and inclusions in chromite as well as serving as a map for the analytical data locations. On average three points were taken per grain unless the mineral exhibited zoning in BSE imaging. Rim-to-rim traverses at ~10 μm spacings of at least one chromite from each chromitite sample were taken to check for zoning that was not identified in BSE imaging.

**3.3 Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS)**

*In situ* LA-ICP-MS of major, minor, and trace elements in chromite was conducted at McGill university (Montreal, Canada) using a New Wave 213 nm Nd-YAD laser coupled to a Thermo Finnigan iCAPQ ICP-MS. Chromite was sampled in troughs of 120 μm width and up to 11 mm in length at 10 Hz repetition rate for the laser pulsing and a fluence of 4.5 $J/cm^2$ after 160 μm wide pre-cleaning of its surface. The primary standard used in LA-ICP-MS was NIST SRM 610 using the preferred values of Jochum et al. (2005) and secondary standards were the in-house synthetic trace-element doped magnetite standards. In house standards are in turn calibrated against NIST SRM 610, 612 and 614, GSC-1G, GSD-1G, GSE-1G, KL2G, BCR-2G, BIR-1G, GOR128, and GOR132.

**3.4. X-Ray Fluorescence (XRF)**

XRF analyses were obtained at the University of Florida to determine the whole-rock geochemistry of select meta-ultramafic samples. Samples were powdered, devolatilized, and

fluxed with lithium borate at a 6:1 ratio to produce glass discs. The discs were analyzed using a tabletop Rigaku Supermini Wavelength Dispersive XRF.

The accuracy of whole-rock data obtained with these methods for ultramafic rocks are subject to the following considerations. Elements are automatically normalized to 100 % by the XRF, but elements that are not typically in high concentrations in most rocks e.g., Cr and Mg, will not be included in the normalization which can bias the results. Also, elements that are in atypical abundances may be skewed because their concentration is not covered by the instrument's calibration, i.e., the elements abundance is outside that of the standards. Finally, ferric and ferrous Fe are estimated assuming that $Fe^{2+}$ is 60% and $Fe^{3+}$ is 30% of the total Fe in the rock based on typical mafic rocks (Mueller, personal communications 2022).

# Chapter 4. Results

## 4.1. Petrography

### 4.1.1. Meta-chromitites

Eleven samples are classified as meta-chromitites (>75% chromite). The matrix of meta-chromitites includes serpentine minerals, phlogopite, chlorite, Cr-rich chlorite, and talc. The matrices of samples 10QCP-728, QC20DM-06, and QC20DM-08 consist mainly of phlogopite (10-15%) with sample 10QCP-728 containing lesser amounts of Cr-rich chlorite (5%) and serpentine (3%). The matrices of samples HP20DM-02, HP20DM-03, HP20DM-04, HP20DM-05, and HP20DM-06 consist mainly of serpentine minerals (5-20%) with lesser amounts of phlogopite (2-5%). The matrix of sample 93DM-36 consists of equal parts talc (5%) and chlorite (5%). The matrix of sample HP20DM-08 consists mainly of chlorite (5%). Olivine, orthopyroxene, clinopyroxene, tremolite, anthophyllite, apatite, and calcite are found as minor minerals in the matrix, each making up less than 5% of its sample. Trace amounts (< 1%) of dolomite, rutile, titanite, millerite, pentlandite, and zircon are also found in the matrix. Mineral names in tables and figures are abbreviated after Whitney and Evans (2010) (table 7). Meta-chromitite modal mineralogy is summarized in table 8.

The texture, morphology, and size of chromite grains in meta-chromitite samples from the Hellroaring Plateau (HP) and Quad Creek (QC) vary. Chromite from HP are mostly subhedral to anhedral whereas chromites from QC are euhedral to subhedral and, on average, smaller (figs. 6 and 7). Samples from HP have two size modes of chromite with the larger size ranging from 0.4 – 1.5 mm and the smaller size ranging from 0.1 – 0.2 mm (e.g., fig. 6d). The smaller-sized chromite tends to cluster in ovoid or vein-like enclaves, in some instances clustering together tightly enough to form a massive adcumulate texture (figs. 6d and 7c). Meta-

chromitites from HP also show pull-apart texture where chromite is fractured by silicate minerals (fig. 6d). Chromite from QC range in size from 0.2 – 0.8 mm and within a given sample have a similar size and distribution.

All meta-chromitite samples have chromite grains containing mineral inclusions (figs. 7a and 8). Inclusions are either ovoid morphology or have negative crystal forms defined by chromite crystallographic planes. Inclusions range from < 1 µm to 100 µm. Because few inclusions are large enough to identify using traditional petrographic methods, inclusions were identified using electron dispersion spectroscopy (EDS).

Table 7. Abbreviations used to Represent Observed Minerals.

| Symbol | Mineral Name | Symbol | Mineral Name |
|---|---|---|---|
| Act | Actinolite | Mhb | Magnesio-hornblende |
| Ath | Anthophyllite | Mlr | Millerite |
| Atg | Antigorite | Mnz | Monazite |
| Ap | Apatite | Ol | Olivine |
| Cal | Calcite | Opx | Orthopyroxene |
| Chl | Chlorite | Pn | Pentlandite |
| Chr | Chromite | Prg | Pargasite |
| Ctl | Chrysotile | Phl | Phlogopite |
| Cum | Cummingtonite | Pl | Plagioclase |
| Di | Diopside | Rt | Rutile |
| Dol | Dolomite | Srp | Serpentine |
| En | Enstatite | Spl | Spinel |
| Fo | Forsterite | Tlc | Talc |
| Hbl | Hornblende | Ttn | Titanite |
| Ilm | Ilmenite | Tr | Tremolite |
| Lz | Lizardite | Zrn | Zircon |
| Mag | Magnetite | | |

Abbreviations after Whitney and Evans (2010).

Table 8. Lithology and Mineral Modes of Meta-Chromitite Samples.

| Sample | Lithology | Ap | Ath | Cal | Chl* | Chr | Di | En | Fo | Mag | Phl | Rt | Srp | Tlc | Ttn | Zrn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10QCP-728 | Phl meta-chromitite with tr vein | | | tr | 5 | 75 | | | | tr | 15 | | 3 | 2 | | |
| 93DM-36 | Chl phl meta-chromitite | | | | 5 | 90 | | | | tr | | | | 5 | | |
| HP20DM-02 | Serpentinized phl meta-chromitite | | | 1 | | 90 | | | | tr | 4 | | 5 | | | |
| HP20DM-03 | Meta-chromitite with serpentinized relict ol | 2 | | 3 | | 85 | | 1 | 2 | tr | 2 | | 5 | | | |
| HP20DM-04 | Serpentinized phl meta-chromitite | | | | | 76 | | | | tr | 4 | | 20 | | | |
| HP20DM-05 | Phl meta-chromitite with serpentinized relict ol | | | | | 80 | | | 5 | tr | 5 | | 10 | | | |
| HP20DM-06 | Serpentinized phl meta-chromitite | | | 2 | | 90 | | | | tr | 3 | | 5 | | | |
| HP20DM-07 | Meta-chromitite with serpentinized relict ol | 2 | | 2 | | 90 | | | 3 | tr | 2 | | 1 | | | |
| HP20DM-08 | Ant Cr-chl meta-chromitite | 3 | 3 | 3 | 5 | 80 | 2 | | | tr | | | 2 | 2 | | |
| QC20DM-06 | Phl meta-chromitite | 1 | 1 | | | 87 | 1 | | | tr | 10 | tr | | | tr | tr |
| QC20DM-08 | Phl meta-chromitite | 4 | | 1 | | 85 | | | | tr | 10 | tr | | | tr | tr |

*Chl includes Cr-chlorite, Cr-chlorite was only analyzed in sample HP20DM-08.

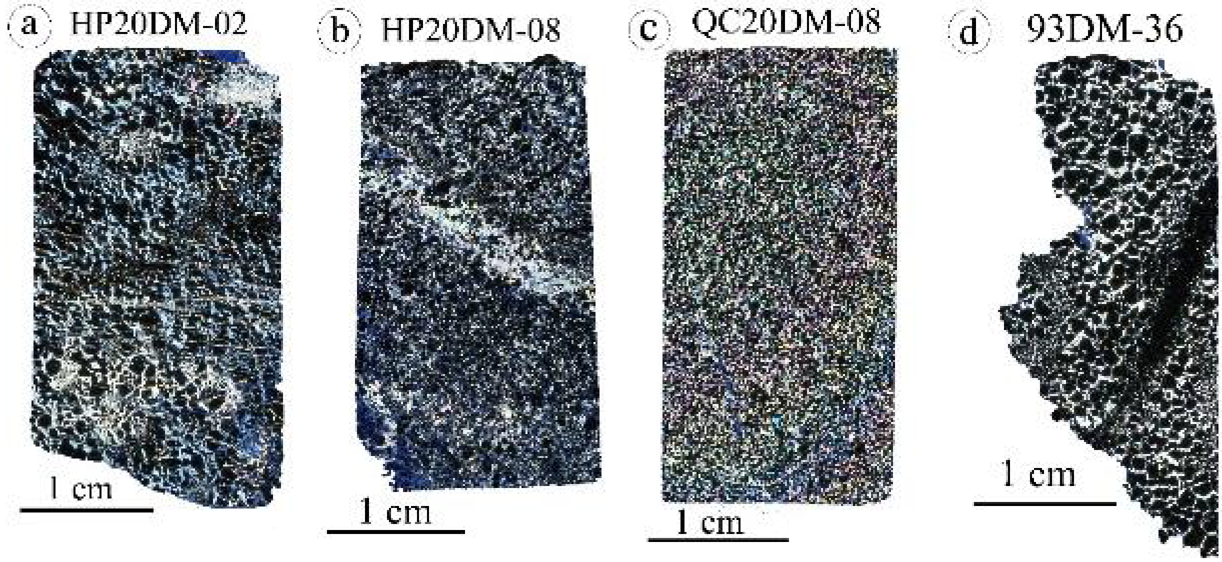



Figure 6. Thin section scans of chromitite samples taken in cross polarized light (XPL) showing the different textures, sizes, and matrix minerals. (a) Meta-chromitite sample HP20DM-02 with serpentine and phlogopite matrix. There are two size modes of subhedral to anhedral chromite with the smaller sized chromite occurring in ovoid clusters. (b) Meta-chromitite sample HP20DM-08 with a Cr-bearing chlorite and anthophyllite matrix. (c) Meta-chromitite sample QC20DM-08 consisting of euhedral chromite in a matrix of phlogopite. Chromite from this QC sample and QC samples in general have smaller and more euhedral chromite than HP samples. (d) HP meta-chromitite sample 93DM-36 with a massive chromite vein running through the sample. Chromite in this sample is in two size modes with the smaller sized chromite occurring in clusters and making up the massive vein. In the bottom right of 93DM-36 chromite shows pull-apart texture where massive chromite fractures are infilled with silicate minerals.

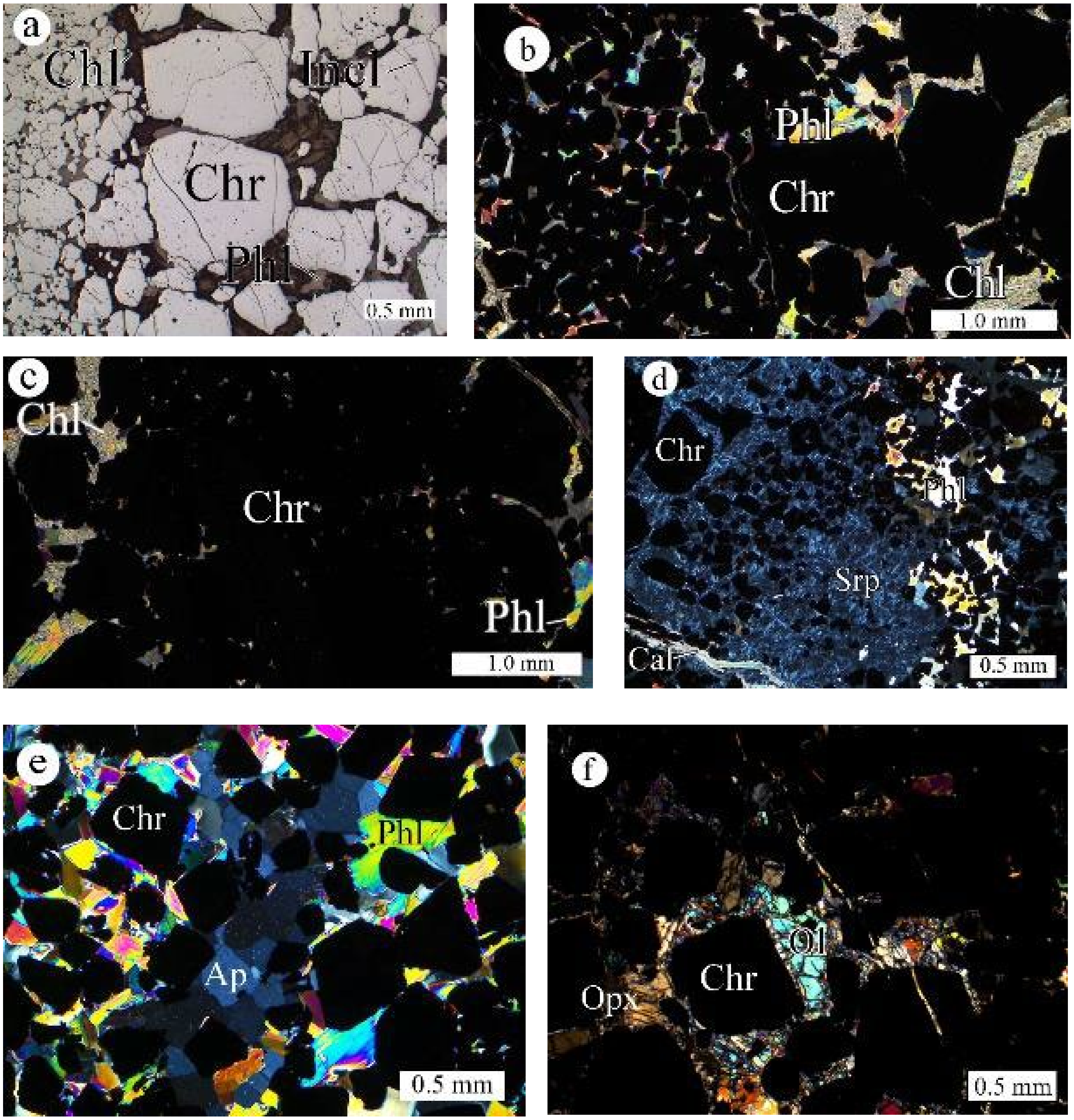



Figure 7. Photomicrographs of meta-chromitite samples showing bimodal sizes of chromite and massive chromite texture. (a) Reflected light photomicrograph of sample 93DM-36 showing numerous unidentified inclusions in chromite. (b) XPL photomicrograph of sample 93DM-36 highlighting the two size modes of chromite. (c) XPL photomicrograph of sample 93DM-36 a meta-chromitite with massive chromite. (d) XPL photomicrograph of sample HP20DM-02 with two sizes of chromite, the smaller of which form ovoid clusters. (e) XPL photomicrograph of sample QC20DM-08 a meta-chromitite with a vein of subhedral apatite in its phlogopite matrix. (f) XPL photomicrograph of sample HP20DM-07 showing relict, intercumulus olivine and orthopyroxene.

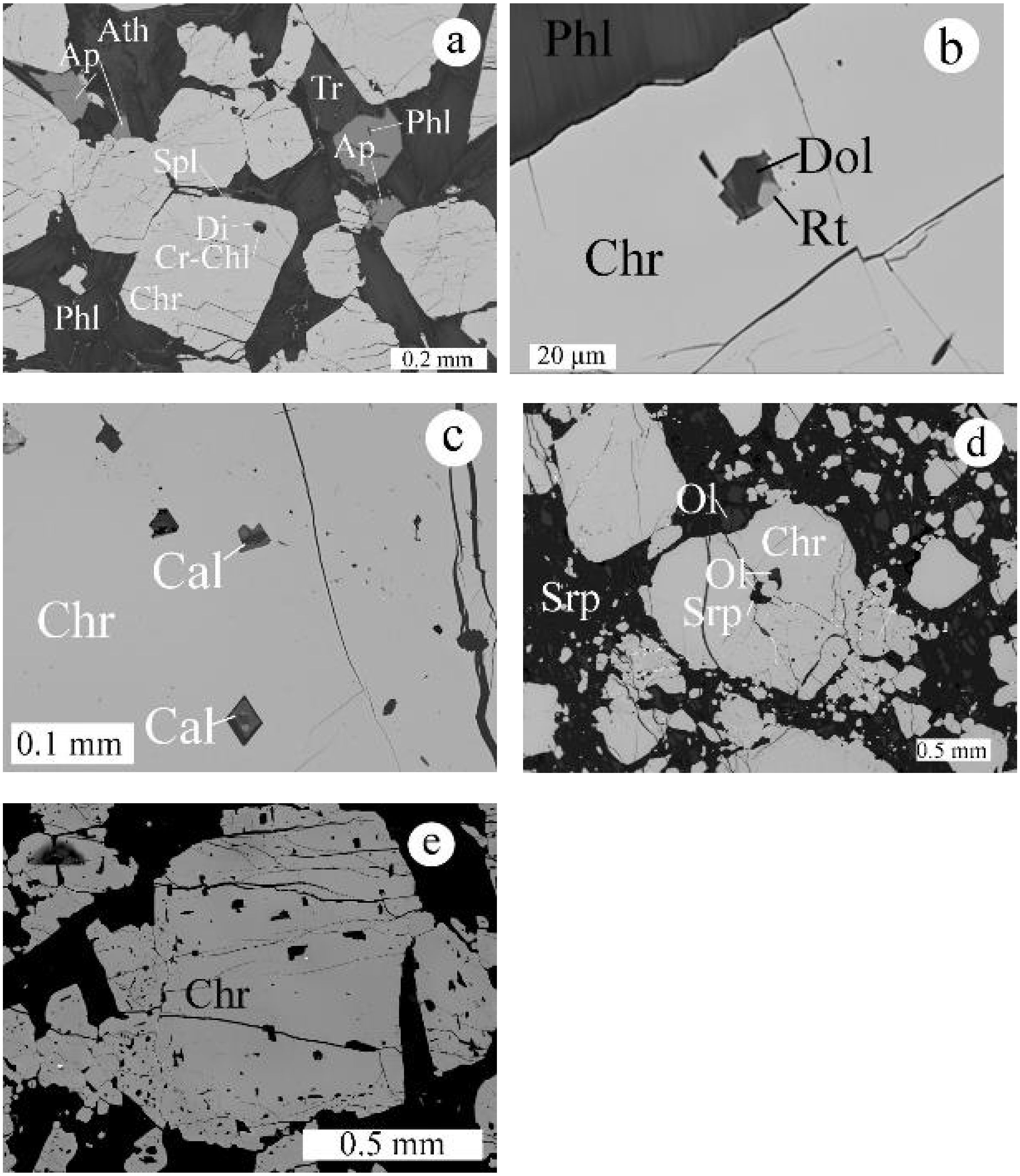



Figure 8. BSE images showing the various mineral inclusions found in chromite from meta-chromitite samples. (a) Euhedral chromite from sample QC20DM-06 with a round inclusion hosting diopside and Cr-chlorite. (b) Sample QC20DM-06 with an angular inclusion containing rutile and dolomite. (c) Sample HP20DM-06 with calcite inclusions exhibiting negative crystal form. (d) Sample HP20DM-03 with globular inclusions hosting olivine and serpentine. (e) Sample HP20DM-02 with inclusions exhibiting negative crystal form that are concentrated around the chromite rim.

### 4.1.2. Meta-ultramafic Rocks

Nineteen samples are classified as meta-ultramafic rocks. These samples are mostly comprised of magnesio-hornblende (60-84%) with a few exceptions. Four meta-ultramafic rocks, HP81-96, HP81-97, QC81-18, and QC93-1 are highly serpentinized (30-60% serpentine), but do not contain sufficient serpentine minerals to be classified as serpentinite (> 75% serpentine). Four meta-ultramafic rocks HP81-95, HR02-49, QC81-19, and RB81-1 are chromite rich (38-65%), but do not contain sufficient chromite to be classified as chromitites (> 75% chromite). Sample CB81-3 contains 45% magnesio-hornblende but is unique from other meta-ultramafics because it contains plagioclase and significant biotite (35%, fig. 9c). Meta-ultramafic lithologies and mineral modes are summarized in table 9.

Table 9. Lithology and Mineral Modes of Meta-Ultramafic Samples.

| Sample | Lithology | Act | Ap | Bt | Cal | Chl | Chr | Cum | Cpx | Opx | Fo | Hbl | Ilm | Mag | Mhb | Phl | Pl | Prg | Srp | Tlc | Tr | Zrn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CB81-3 | Weakly foliated, pl-cum-bt-hbl amphibolitic rock | | tr | 35 | | | | 15 | | | | 45 | tr | | | | 5 | | | | | tr |
| CB81-4 | Opx mhb meta-ultramafic rock | | | 2 | | | 7 | | | 11 | 5 | | | | 75 | | | | | | | |
| CB81-5 | Phl opx mhb meta-ultramafic rock | | | 5 | | | | | | 15 | | | | | 80 | | | | | | | |
| CB81-6 | Opx mhb meta-ultramafic rock | | | | | | 5 | | | 30 | | | | | 65 | | | | | | | |
| HP81-95 | Chr-rich meta-ultramafic | | | | tr | | 50 | | | | 10 | | | | | 10 | | | 30 | | | |
| HP81-96 | Two-spl mhb-rich meta-ultramafic | | | | | | 5 | | | | | | | 3 | 55 | tr | | | 30 | 2 | 5 | |
| HP81-97 | Two-spinel-bearing ol-cpx-opx-mhb meta-ultramafic with meta-ultramafic relicts | | | | | | | | 7 | 15 | 5 | | 2 | 5 | 31 | | | | 35 | | tr | |
| HR02-49 | Tlc-phl-chr metaultramafic | | | | | | 38 | | | | | | | | | 17 | | | 40 | 5 | | |
| QC81-14 | Two-spl-prg-mhb meta-ultramafic with relict ol and opx | 2 | 1 | | | | 5 | | | 24 | 17 | | | | 44 | 5 | | 2 | | | | |
| QC81-18 | Tlc-mag-bearing phl-chl meta-ultramafic with relict ol, opx, chr and spl | | | 8 | | 8 | 1 | | | 16 | 3 | | 1 | 3 | | | | | 60 | | | |
| QC81-19 | Phl-tlc-chr meta-ultramafic with relict chr | | | | | | 65 | | | | | | | | | 13 | | | | 22 | | |
| QC81-21 | Foliated bt meta-ultramafic with relict ol and opx | | | | | | 3 | | | 13 | 5 | | | 2 | 60 | 15 | | | 2 | | | |
| QC81-27 | Two-spl mhb-rich meta-ultramafic | | | | | | 5 | | | | | | | 5 | 80 | | | | 10 | | | |
| QC81-28 | Meta-ultramafic with relict chr trains, opx, and ol | | | | | | 15 | | | 10 | 5 | | | | 60 | | | | 5 | 5 | | |
| QC81-29 | Spl-bearing ol-opx-mhb meta-ultramafic rock | | tr | | | 1 | 3 | | | 5 | 5 | | | 1 | 84 | | | | 1 | tr | | |
| QC93-1 | Mesh-textured meta-ultramafic with relict ol | | | | tr | | | | | 5 | 33 | | | 1 | 5 | 1 | | | 55 | | | |
| RB81-1 | Meta-ultramafic with relict igneous chr | | | | | | 50 | | | | | | | | | 5 | | | | 45 | | |
| RB81-2 | Mhb-rich meta-ultramafic with poikiloblastic opx | | | | | | 5 | | 20 | 10 | 5 | | | | 60 | | | | | | | |
| WC82-12 | Two-spl-bearing mhb-rich meta-ultramafic with significant serpentinization of ol | tr | | | 1 | 3 | | | 1 | | 2 | | | | 67 | | | | 20 | 3 | 3 | tr |

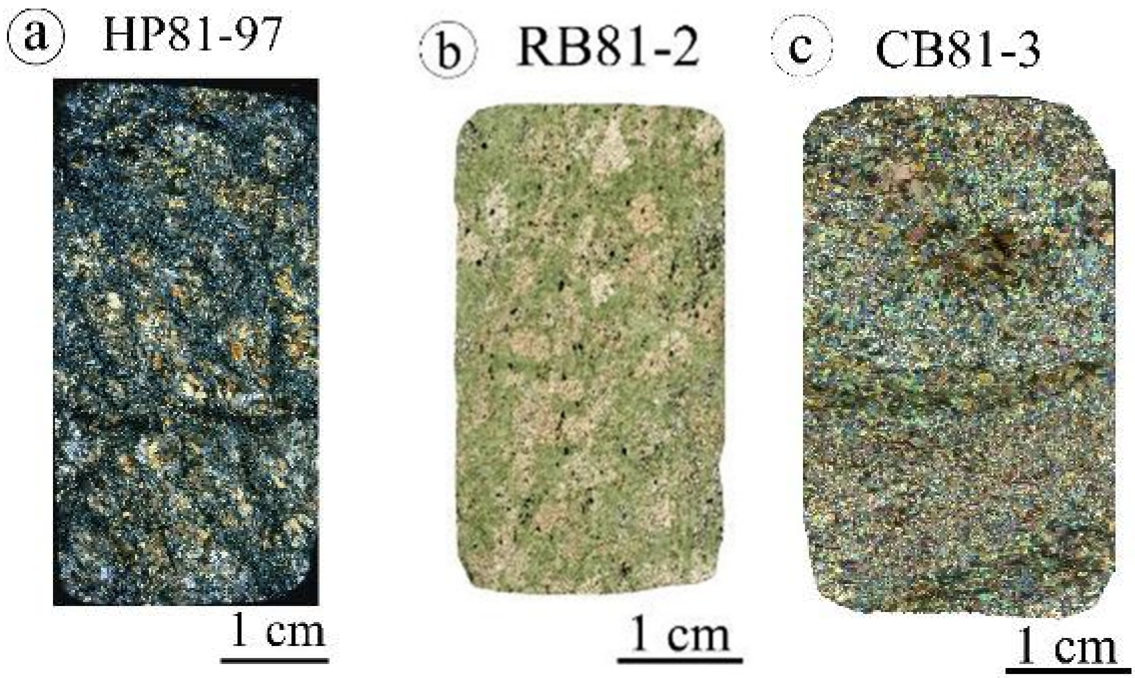



Figure 9. Representative thin section photos of meta-ultramafics. (a) XPL thin section photo of sample HP81-97 a serpentinized meta-ultramafic with augen – like magnesiohornblende rafts. (b) PPL thin section photo of sample RB81-2 a meta-ultramafic rock with orthopyroxene and olivine poikiloblasts. (c) XPL thin section photo of biotite-magnesiohornblende meta-ultramafic sample CB81-3 with foliated layers of biotite.

Silicate minerals in meta-ultramafics do not typically preserve relict igneous textures (Evans, 1977). Magnesio-hornblende in meta-ultramafics is mostly granoblastic but can be found as poikiloblastic grains with inclusions of orthopyroxene. It is common for magnesio-hornblende to be marginally replaced by tremolite and serpentine. In more thoroughly serpentinized samples a combination of granoblastic magnesio-hornblende and orthopyroxene make up augen-like rafts within a massive mesh-textured serpentine matrix (fig. 10a). Orthopyroxene and olivine are common in meta-ultramafics making up to 30% and 33% of a sample, respectively.

Orthopyroxene is commonly poikiloblastic with inclusions of magnesio-hornblende (fig. 9b) it can be altered by talc or serpentine. Phlogopite is another common mineral making up to 15% of

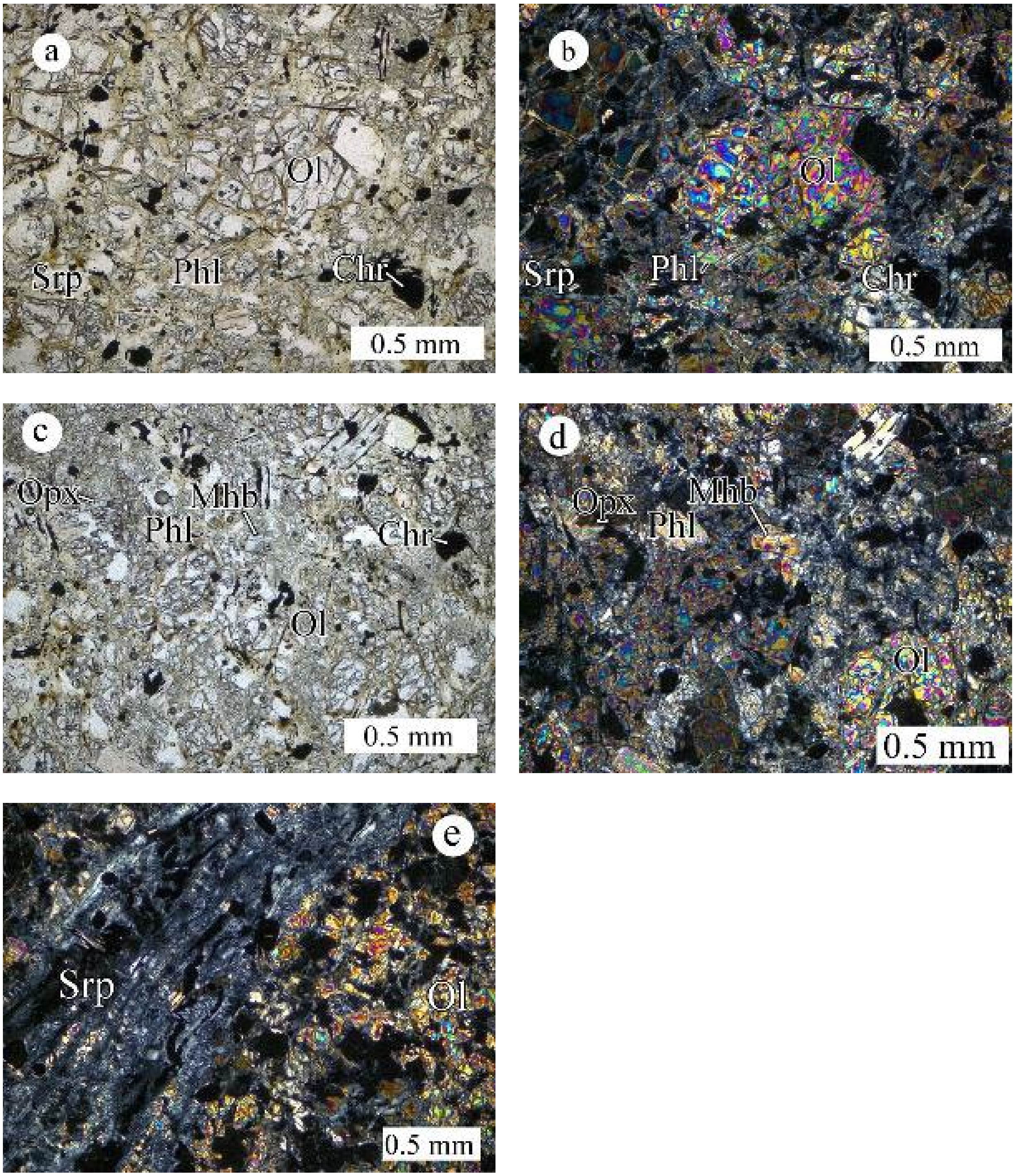



Figure 10. PPL and XPL photomicrographs of sample QC93-1. (a) PPL photomicrograph showing mesh-textured serpentine surrounding relict olivine. (b) the same photomicrograph as (a) in XPL. (c) PPL photomicrograph showing relict orthopyroxene, secondary magnesiohornblende, and phlogopite. (d) XPL photomicrograph of (c). (e) XPL photomicrograph showing a secondary serpentine vein.

a sample. Phlogopite is commonly partially to completely replaced by chlorite. Sample QC93-1 is unique among these samples because it preserves relict igneous olivine in a mesh-textured serpentine matrix (fig. 10).

Chromite is a minor constituent of meta-ultramafic samples CB81-4, CB81-6, HP81-96, QC81-14, QC81-18, QC81-21, QC81-27, QC81-28, QC81-29, and RB81-2 making up 1-15%. Accessory chromite is typically small (~ 0.2 mm), anhedral, and randomly dispersed throughout the sample, except in sample QC81-28 in which subhedral chromite occur in layers between silicate minerals (fig. 11a and b). Accessory chromite in meta-ultramafic samples is commonly exsolved into two or more spinel components. In reflected light the chromite in sample QC81-28 is composed of three exsolved spinels surrounded by a thin, late magnetite rim (fig. 11c). The lighter spinel in reflected light is host for the two other exsolved spinels (fig. 11d). The darker spinel is present as roughly linear blebs that are parallel to the host spinel's crystallographic planes and is more densely distributed towards the rims of grains. The third exsolved spinel is revealed at higher magnification to consist of cross-hatching linear grains parallel to the host's crystallographic planes (fig. 11d). Exsolution in this chromite is comparable to the exsolved chromites from the eastern Beartooth Mountains reported by Loferski and Lipin (1983).

Chromite-rich meta-ultramafic samples HP81-95, HR02-49, QC81-19, and RB81-1 are composed of 38-65% relict igneous chromite. Chromite in these samples is larger than accessory chromite in other meta-ultramafic samples, ranging in size from 0.2-1 mm. Chromite in these samples is subhedral to anhedral and is not exsolved. Matrix minerals for these samples are secondary silicates serpentine, talc, phlogopite, and chlorite. Relict igneous textures are only present in sample HP81-95 where intercumulus olivine makes up 10% of the sample (fig. 12).

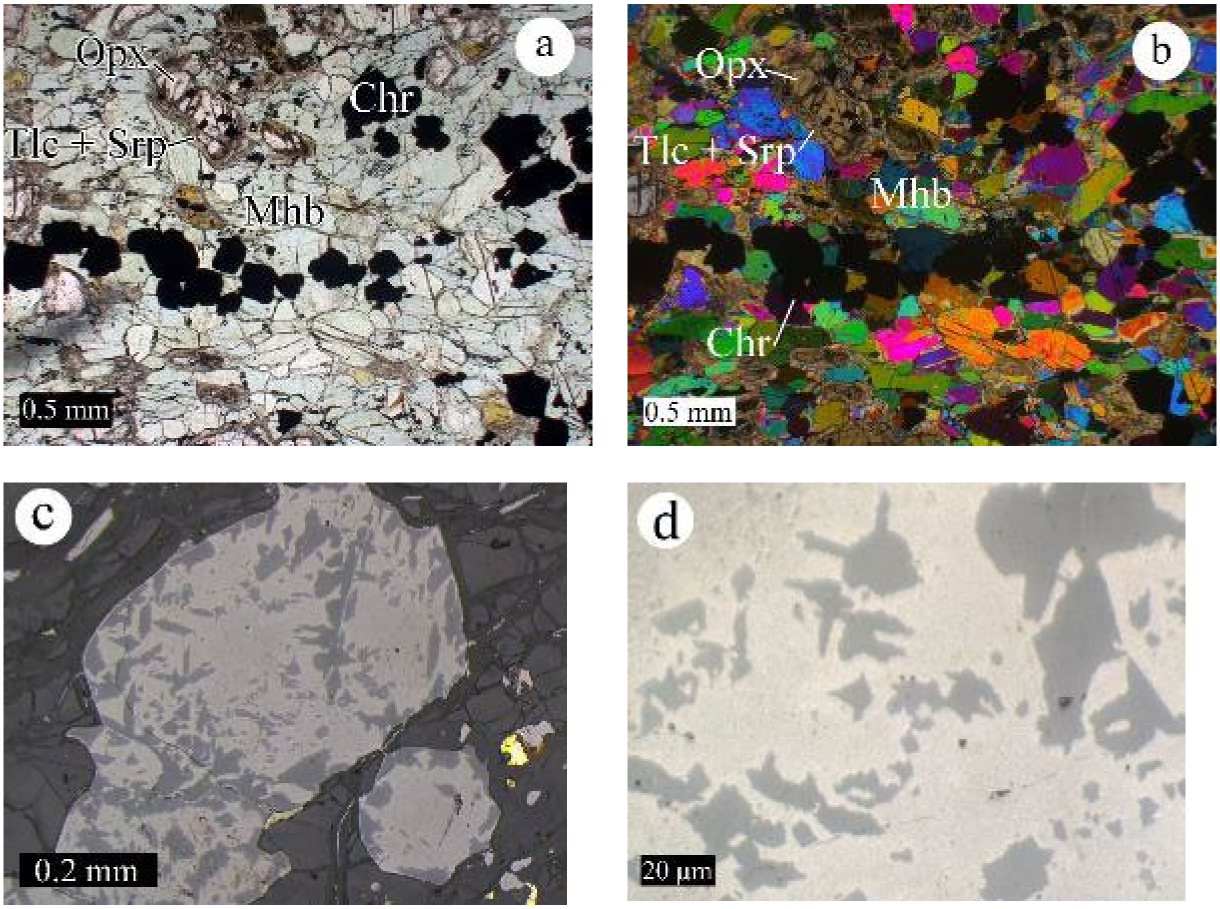



Figure 11. Photomicrographs of chromite from sample QC81-28 showing chromite texture and exsolution features. (a) PPL photomicrograph showing chromite trains of subhedral chromite surrounded by magnesiohornblende. (b) the same photomicrograph as (a) in XPL. (c) Exsolved chromite showing two phases, a darker spinel, roughly parallel to crystallographic planes and a lighter spinel in reflected light. A late magnetite rim surrounds the exsolved spinel. The yellow grain in the matrix is a mixture of chalcopyrite (darker yellow) and pyrite (pale yellow). (d) a close-up image of (c) showing a third exsolved phase, cross-hatched lines bounded by crystallographic planes exsolved from the lighter shade spinel in reflected light. Image credit Darrell Henry.

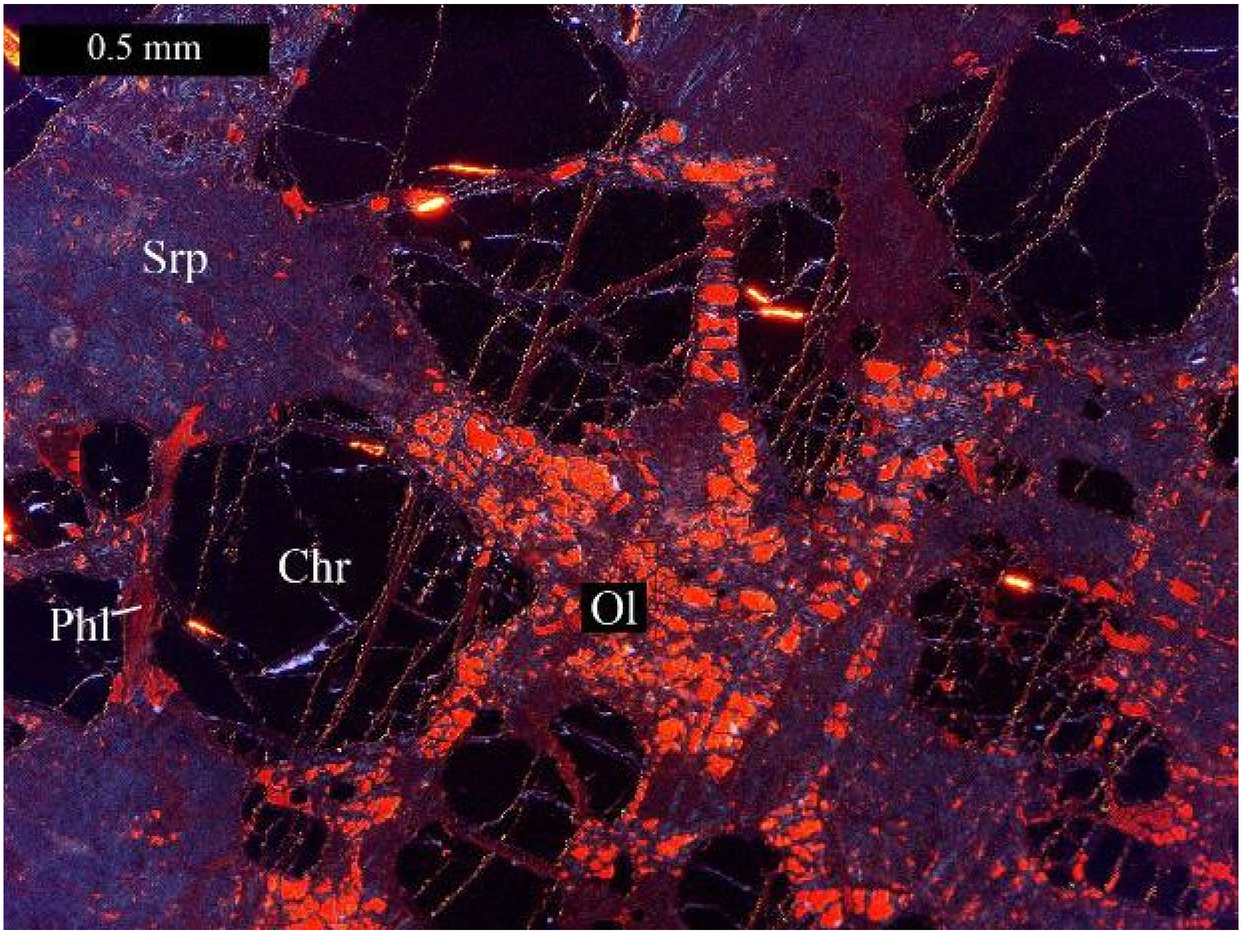



Figure 12. Optical cathodoluminescence photomicrograph of chromite-rich meta-ultramafic sample HP81-95 showing intercumulus relict igneous olivine and chromite in a matrix of serpentine with minor phlogopite.

### 4.1.3. Serpentinites

Six samples are classified as serpentinites (> 75% serpentine). Serpentinite samples preserve few relict silicate minerals. All serpentinites contain 1-3 % magnesio-hornblende, but only sample HP81-94 preserves olivine and orthopyroxene (fig. 13a). Chromite makes up 2% of samples 93-DM-7, 93-DM-18, 93-DM-23A, and 93DM-30 and is surrounded by magnetite rims. Serpentinites consist of flaky antigorite that commonly pseudomorphs magnesio-hornblende, olivine, and orthopyroxene (fig. 13). Serpentine pseudomorphic textures can be used to distinguish between serpentine that replaced olivine and serpentine that replaced another mineral

(Wicks and Whittaker, 1977). Bastite texture is observed in sample HP81-94 where serpentine pseudomorphs either orthopyroxene or magnesiohornblende. Hourglass texture is observed in sample WC82-28 where serpentine pseudomorphs olivine (fig 13b and 13c). Phlogopite is chloritized and sometimes completely replaced by chlorite (fig. 13b). Trace amounts of talc are found in the serpentine matrix in sample WC82-28 (fig. 13c). Serpentine occurs in multiple generations in some samples evidenced by its pseudomorphic and non-pseudomorphic textures occurring within the same sample. In sample WC82-28 there are serpentine minerals with hourglass texture and those with no pseudomorphic texture. The second generation is finer-grained, destroys the pseudomorphic texture, and is associated with talc (fig. 13c).

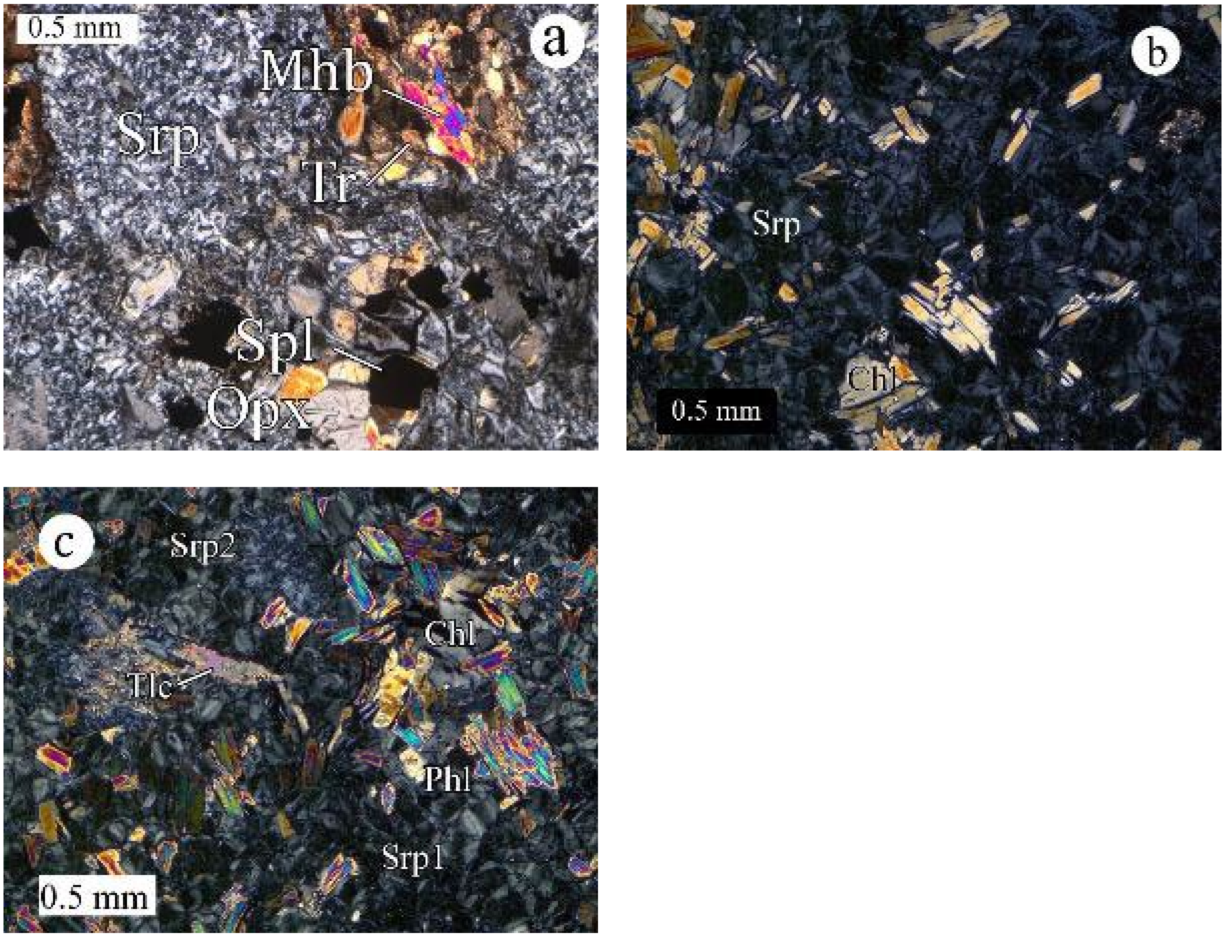



Figure 13. Photomicrographs of serpentinite samples showing the range of mineral assemblages and textures. (a) Sample HP81-94 showing relict magnesiohornblende and orthopyroxene replaced by tremolite and serpentinite. (b) XPL photomicrograph of sample WC82-28 consisting entirely of serpentine displaying hourglass texture and chloritized phlogopite. (c) XPL photomicrograph of sample WC82-28 with serpentinite pseudomorphs (Srp1) in an hourglass texture, late serpentinite (Srp2), phlogopite, talc, and chlorite.

Table 10. Lithologies and Modal Mineralogy of Serpentinite Sample.

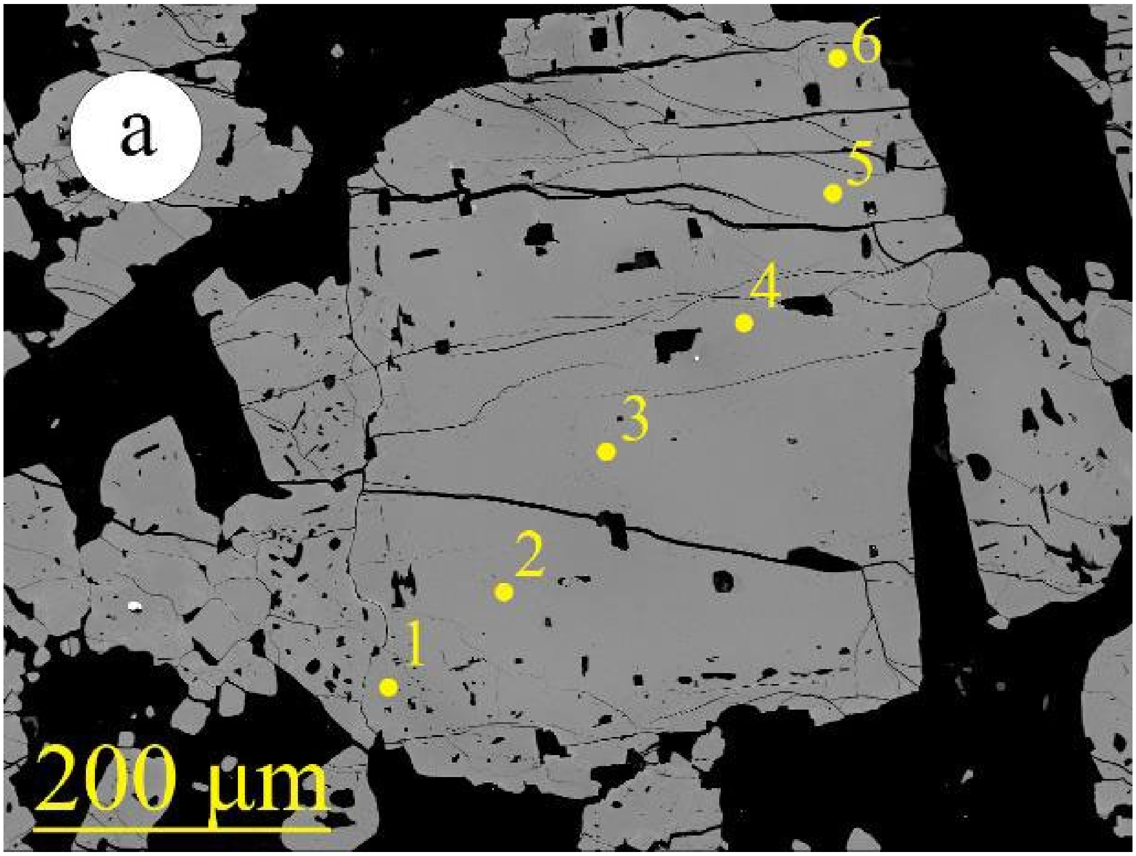
| Sample | Lithology | Ap | Cal | Chl | Chr | Cum | En | Fo | Mhb | Phl | Srp | Tlc | Tr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 93-DM-7 | Serpentinite | tr | 2 | 3 | 2 | | | | 3 | | 86 | 3 | |
| 93-DM-18 | Serpentinite | | | 2 | 2 | | | | 2 | | 94 | | |
| 93-DM-23A | Serpentinite | | | 1 | 2 | | | | 3 | | 94 | | |
| 93-DM-30 | Serpentinite | | | 1 | 2 | | | | 1 | | 96 | | |
| HP81-94 | Serpentinite with meta-ultramafic relicts | | 1 | | | 10 | 3 | 1 | 1 | | 81 | | 3 |
| WC82-28 | Serpentinite with chloritized phlogopite | | | 10 | | | | | 3 | 5 | 80 | 2 | |

## 4.2. Mineral chemistry

### 4.2.1. Meta-chromitites

#### 4.2.1.1. Chromite

Major (Cr, Al, Fe, and Mg; > 1.0 weight percent oxide), minor to trace (Mn, Ti, Ni, V, Zn, and Si; < 1.0 weight percent oxide) elements for chromite from ten samples were analyzed using the electron microprobe. Rim-to-rim traverses of chromite from each sample were obtained at ~ 100 µm intervals to check for major and minor element zoning. Most chromite from chromitite samples show minor core-to-rim chemical zoning. Representative rim-to-rim traverses are shown in figure 14. Cr and $Fe^{2+}$ contents slightly decrease towards the rims while Al and Mg, increase towards the rims, but zonation in most samples is subtle enough that it cannot be observed in BSE images except for sample 93DM-36 (fig. 14d). Chromite Cr/(Cr+Al) ranges from 0.69-0.83 and Mg/(Mg+$Fe^{2+}$) ranges from 0.11-0.56. Cr# (Cr/[Cr+Al+$Fe^{3+}$]), Al# (Al/[Cr+Al+$Fe^{3+}$]), and $Fe^{3+}$# ($Fe^{3+}$/[Cr+Al+$Fe^{3+}$]) of individual analytical points are plotted on a Cr-Al-$Fe^{3+}$ diagram (fig. 15). Chromite is low in $Fe^{3+}$ and high in Cr relative to Al. Representative chromite analyses from each sample are given in table 11 and complete analyses are found in appendix A.



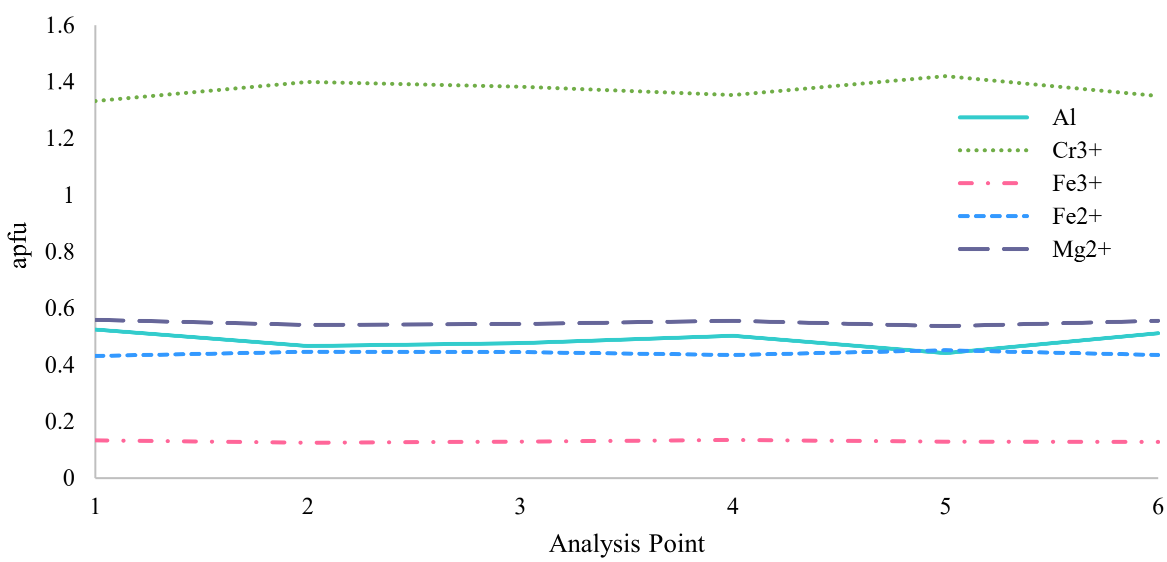
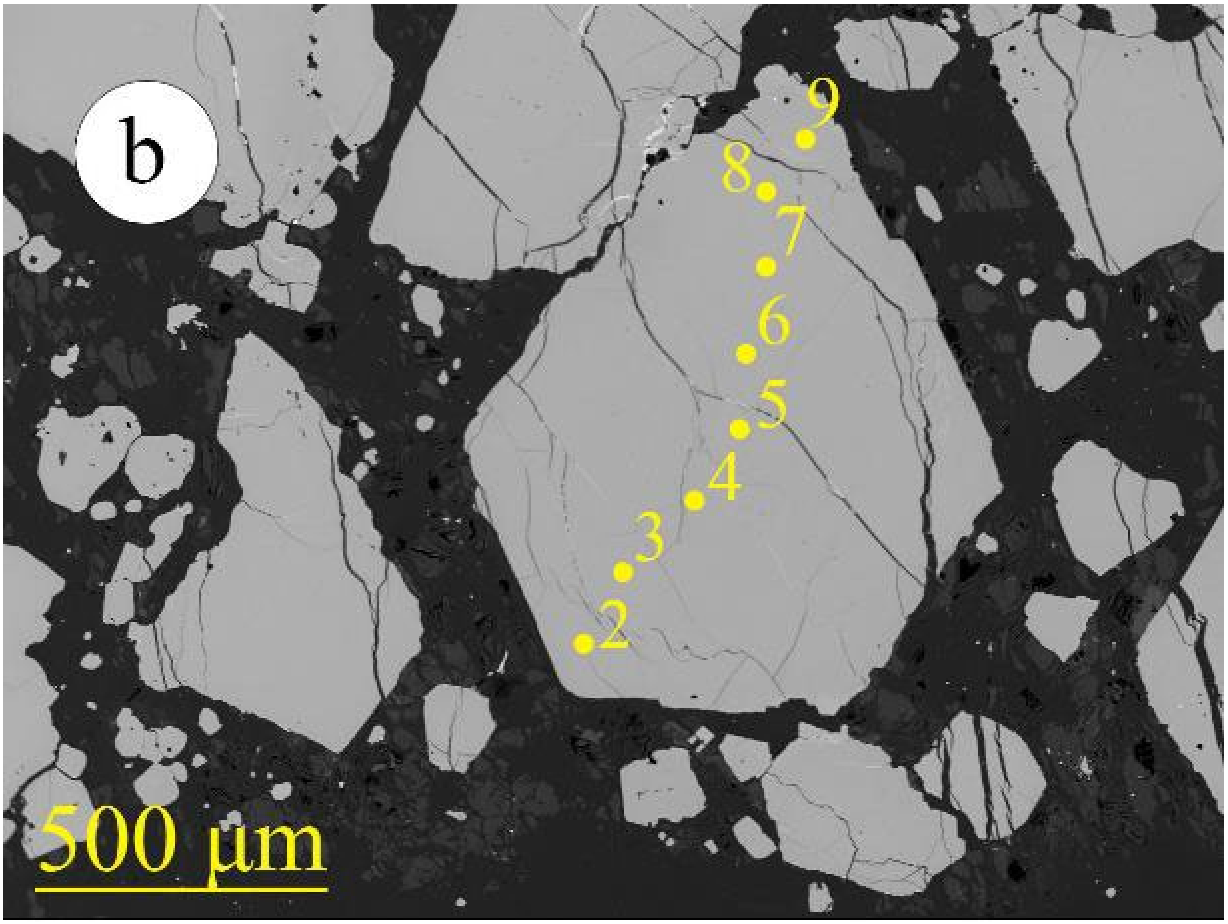
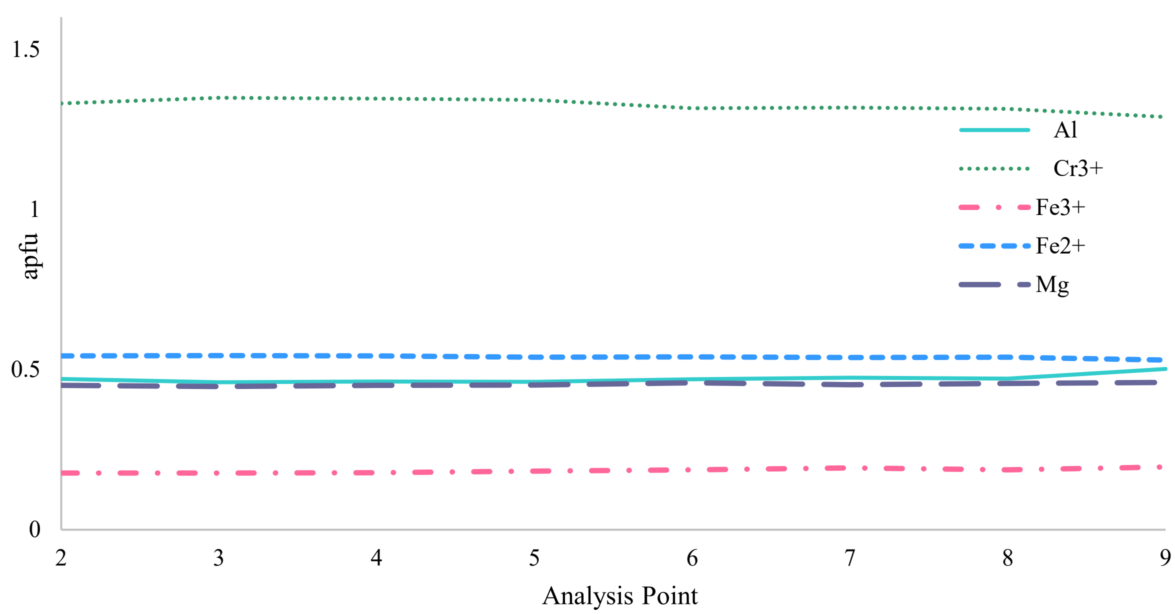
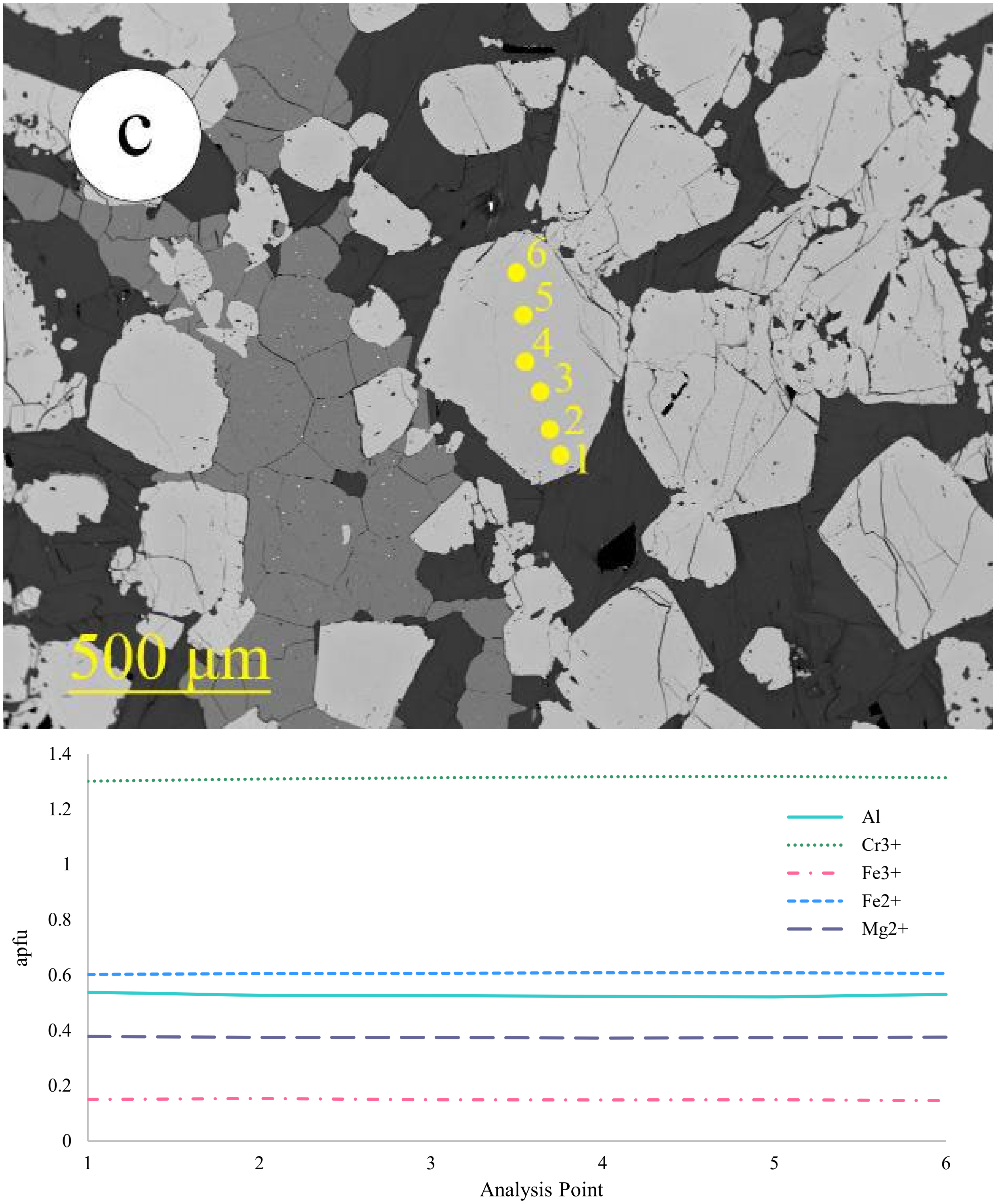



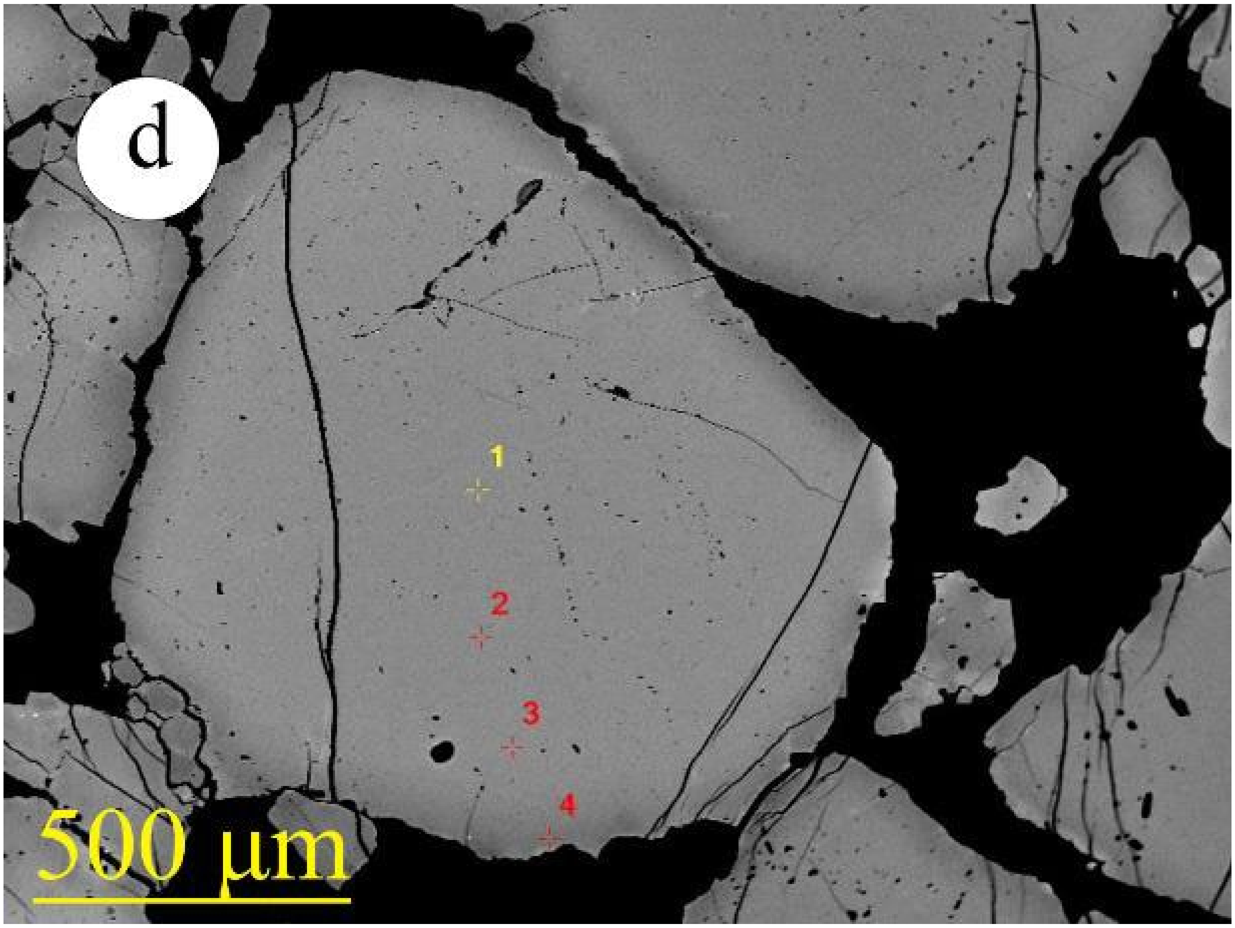

Figure 14. Chromite rim-to-rim transects superimposed on BSE images. $Fe^{2+}$ and $Fe^{3+}$ were calculated based on charge balance. Major elements are plotted on the y-axis and measured in atoms per formula unit (apfu). (a) Chromite rim-to-rim transect from sample HP20DM-02. (b) Chromite rim-to-rim transect from sample HP20DM-03. (c) Chromite rim-to-rim transects from sample QC20DM-08. (d) Chromite core-to-rim transect from sample 93DM-36.

(fig. cont'd)


b
9
8
7
6
5
4
3
2
500 µm


1.5
1
0.5
0
apfu
2
3
4
5
6
7
8
9
Analysis Point
Al
Cr3+
Fe3+
Fe2+
Mg


c
6
5
4
3
2
1
500 µm
1.4
1.2
1
0.8
0.6
0.4
0.2
0
apfu
Al
Cr3+
Fe3+
Fe2+
Mg2+
1
2
3
4
5
6
Analysis Point


d
1
2
3
4
500 µm

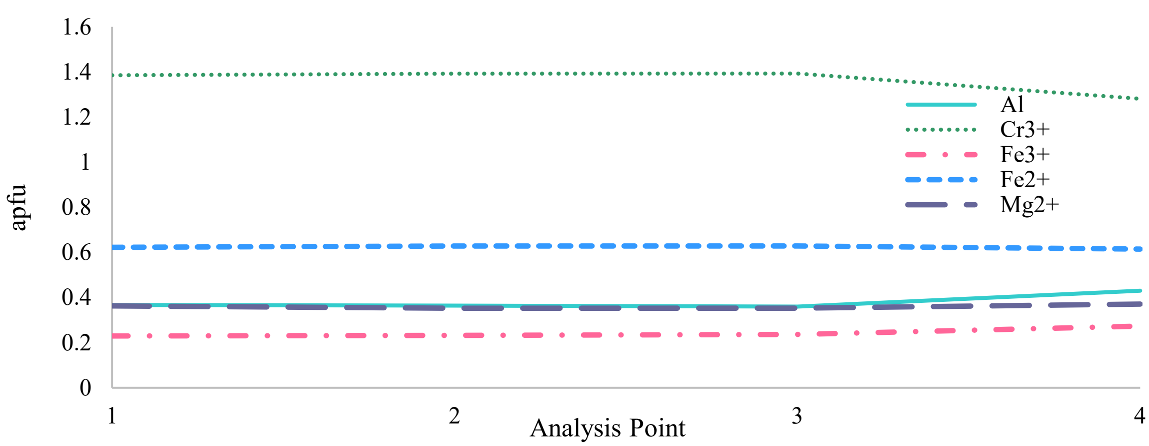

1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
apfu
1
2
3
4
Analysis Point
Al
Cr3+
Fe3+
Fe2+
Mg2+

Table 11. Representative Chromite Analyses from Meta-chromitite Samples.

| Sample # | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Cr_2O_3$ | $V_2O_3$ | $Fe_2O_3$ | FeO | MnO | MgO | NiO | ZnO | Total | Mg# | Cr# | $Fe^{3+}/Fe_{total}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| QC20DM-06 | 0 | 0.23 | 13.8 | 48.16 | 0.17 | 8.36 | 18.8 | 0.36 | 9.76 | 0.13 | 0.07 | 99.84 | 0.48 | 0.7 | 0.29 |
| QC20DM-08 | 0 | 0.1 | 13.81 | 49.78 | 0.18 | 6.03 | 21.79 | 0.61 | 7.68 | 0.09 | 0.07 | 100.15 | 0.39 | 0.71 | 0.2 |
| HP20DM-02 | 0 | 0.16 | 13.8 | 52.17 | 0.08 | 5.48 | 15.98 | 0.33 | 11.61 | 0.08 | 0.08 | 99.78 | 0.56 | 0.72 | 0.24 |
| HP20DM-03 | 0.11 | 0.21 | 11.97 | 50.43 | 0.12 | 7.06 | 19.43 | 0.32 | 9.06 | 0.11 | 0.14 | 98.94 | 0.45 | 0.74 | 0.25 |
| HP20DM-04 | 0 | 0.19 | 12.43 | 50.41 | 0.09 | 7.82 | 18.38 | 0.29 | 9.89 | 0.12 | 0.1 | 99.72 | 0.49 | 0.73 | 0.28 |
| HP20DM-05 | 0 | 0.21 | 13.64 | 52.91 | 0.11 | 5.38 | 16.83 | 0.4 | 11.24 | 0.08 | 0.15 | 100.94 | 0.54 | 0.72 | 0.22 |
| HP20DM-06 | 0 | 0.17 | 13.58 | 52.02 | 0.11 | 6.19 | 18.47 | 0.43 | 10.17 | 0.15 | 0.12 | 101.41 | 0.5 | 0.72 | 0.23 |
| HP20DM-07 | 0 | 0.17 | 12.28 | 52.3 | 0.11 | 6.52 | 20.08 | 0.65 | 8.88 | 0.08 | 0.03 | 101.1 | 0.44 | 0.74 | 0.23 |
| HP20DM-08 | 0 | 0.08 | 7.29 | 51.22 | 0.1 | 9.99 | 27.45 | 1.11 | 2.86 | 0.09 | 0.32 | 100.53 | 0.16 | 0.82 | 0.25 |
| 93DM36 | 0.07 | 0.19 | 9.3 | 52.2 | 0.09 | 9.1 | 22.18 | 0.5 | 7.26 | 0.13 | 0.15 | 101.18 | 0.37 | 0.79 | 0.27 |

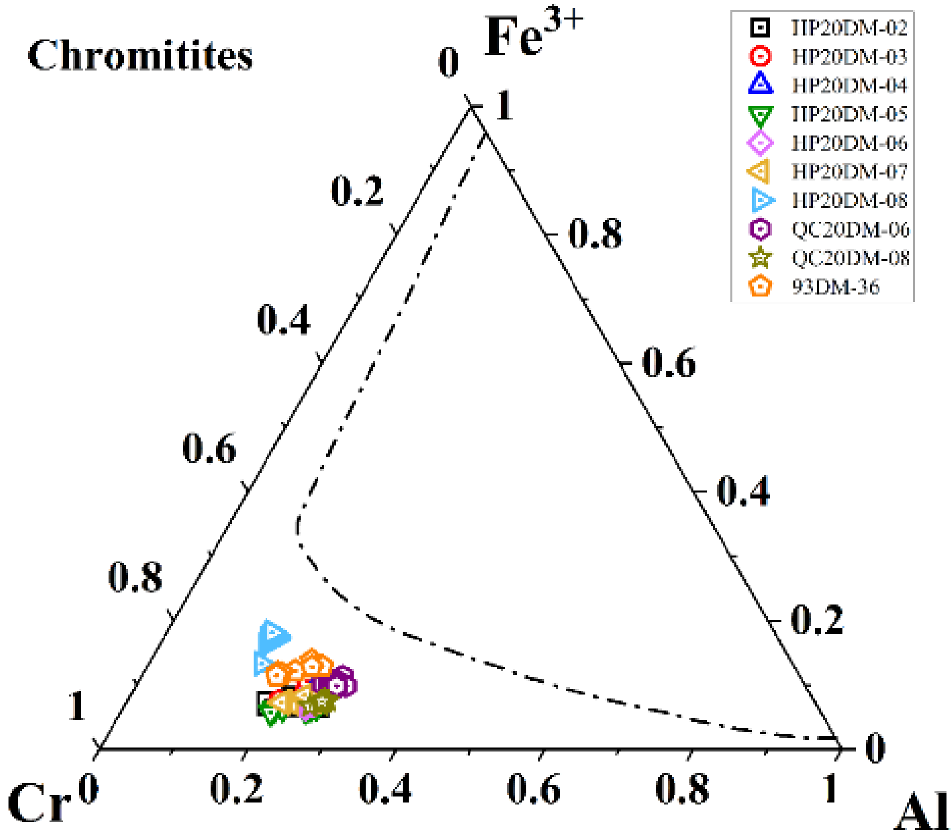



Figure 15. A ternary diagram showing chromite Cr#, Al#, and Fe3+# in meta-chromitites from this study. A dot-dashed line represents the miscibility gap of Loferski and Lipin (1983).

#### 4.2.1.2. Olivine

Olivine from meta-chromitites was analyzed in samples HP20DM-03, HP20DM-05, and HP20DM-07. Matrix olivine and olivine included in chromite were analyzed (fig. 16). Forsterite content of olivine in sample HP20DM-03 is $Fo_{94-96}$ with one outlier point measuring as $Fo_{92}$. Included olivine in HP20DM-03 is not chemically different than matrix olivine from the same sample. Forsterite content in HP20DM-05 is $Fo_{97}$. Forsterite content in HP20DM-07 is $Fo_{95-97}$. Ni content of olivine from sample HP20DM-03 is 0.005 – 0.012 apfu . Ni content of olivine from sample HP20DM-05 varies from 0.010 – 0.011 apfu. Ni content of olivine from sample

HP20DM-07 varies from 0.00 – 0.012, the highest Ni contents occur in olivine inclusions. Representative olivine analyses are given in table 12 with complete olivine analytical data in Appendix B.

Table 12. Representative Olivine Analyses from Meta-chromitite Samples.

| Sample # | HP20DM-07 | HP20DM-07 | HP20DM-07 | HP20DM-05 | HP20DM-05 | HP20DM-03 | HP20DM-03 | HP20DM-03 |
|---|---|---|---|---|---|---|---|---|
| Comment | Matrix | Matrix | Incl. | Incl. | Incl. | Matrix | Matrix | Incl. |
| $SiO_2$ | 42.11 | 41.3 | 41.48 | 41.59 | 41.43 | 42.06 | 42.16 | 41.75 |
| $Fe_2O_3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| FeO | 5.11 | 4.39 | 3.88 | 3.16 | 3.27 | 4.6 | 4.45 | 3.22 |
| MnO | 0.24 | 0.11 | 0.1 | 0.07 | 0.09 | 0.15 | 0.14 | 0.1 |
| MgO | 53.14 | 53.25 | 53.76 | 53.76 | 53.47 | 53.27 | 53.48 | 53.63 |
| NiO | 0.12 | 0.67 | 0.63 | 0.51 | 0.56 | 0 | 0.21 | 0.52 |
| CaO | 0.01 | 0 | 0 | 0 | 0 | 0.02 | 0.01 | 0 |
| Total | 100.72 | 99.71 | 99.85 | 99.09 | 98.82 | 100.1 | 100.45 | 99.22 |
| Fo% - Fo-Fa binary | 94.88 | 95.58 | 96.11 | 96.81 | 96.68 | 95.38 | 95.54 | 96.74 |
| Fa% - Fo-Fa binary | 5.12 | 4.42 | 3.89 | 3.19 | 3.32 | 4.62 | 4.46 | 3.26 |
| Ca% - Ca-Fo-Fa ternary | 0.01 | 0.01 | 0 | 0 | 0 | 0.02 | 0.02 | 0 |
| Teph% - Mn-Mg-Fe ternary | 0.24 | 0.11 | 0.11 | 0.07 | 0.09 | 0.15 | 0.14 | 0.1 |
| Ni-ol % - Ni-Mg-Fe ternary | 0.11 | 0.65 | 0.6 | 0.49 | 0.54 | 0 | 0.2 | 0.51 |

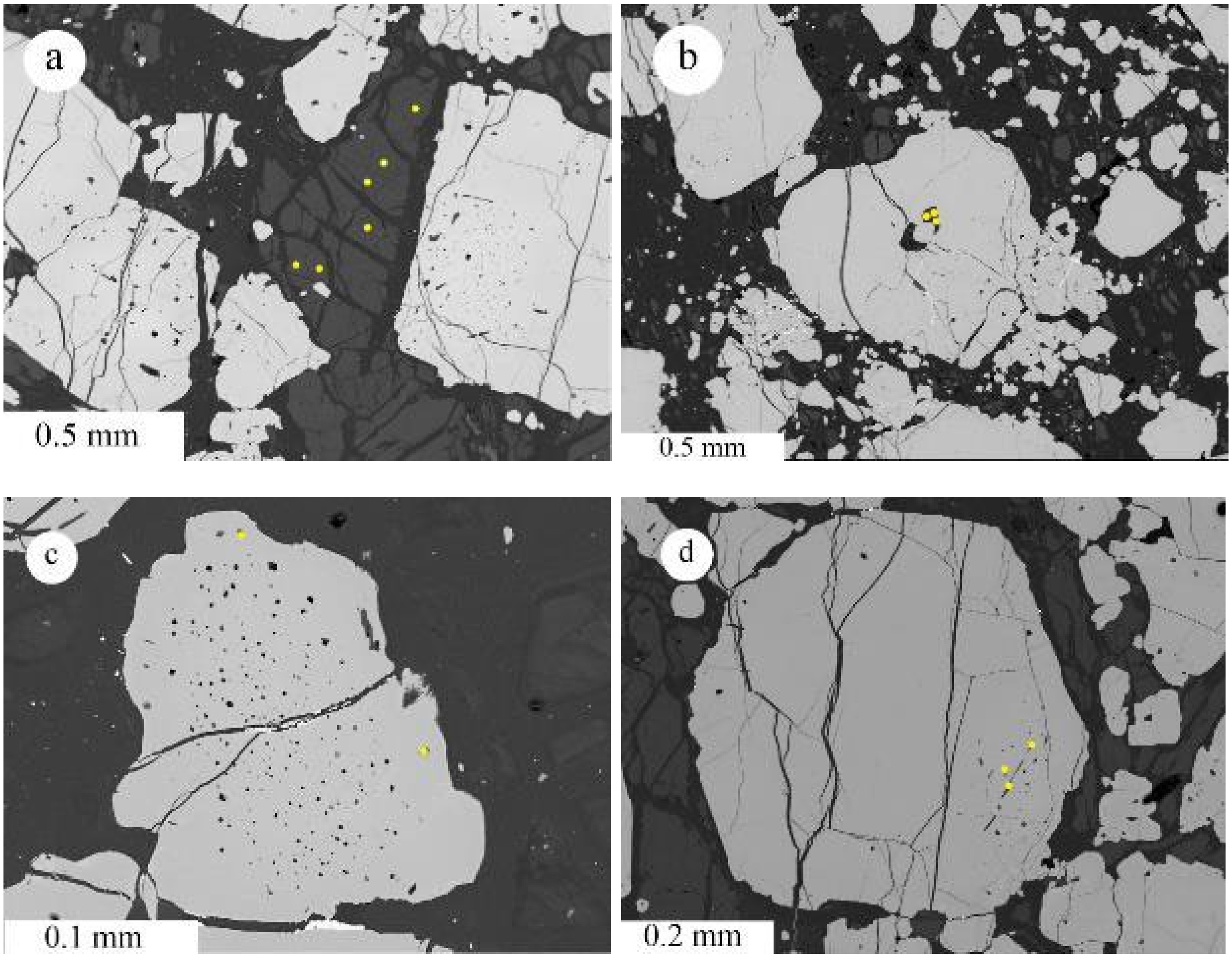



Figure 16. Olivine analysis points (yellow points) on BSE images from meta-chromitite samples. (a) HP20DM-07 matrix ol. (b) HP20DM-03 ol inclusions. (c) HP20DM-05 ol inclusions. (d) HP20DM-07 ol inclusions.

#### 4.2.1.3. Phlogopite

Phlogopite is chemically characterized in five meta-ultramafic samples: QC20DM-06, QC20DM-08, HP20DM-03, HP20DM-05, and HP20DM-07. Analyzed phlogopite grains occur in the matrix of meta-chromitites. The average structural formula of phlogopite from QC20DM-06 is $(K_{1.2}\square_{0.8})\,(Mg_{6.1}Fe^{2+}{}_{0.1}Cr^{3+}{}_{0.1}Ti_{0.1})\,(Si_{5.6}Al_{2.4})\,O_{24}\,(OH)_4$. The average structural formula of phlogopite from QC20DM-08 is $(K_{1.8}\square_{0.2})\,(Mg_{5.3}Fe^{2+}{}_{0.3}Cr^{3+}{}_{0.4}Ti_{0.1}Al_{0.1})\,(Si_{5.4}Al_{2.4})\,O_{24}$ $(OH_{3.9}F_{0.1})$. The average structural formula of phlogopite from HP20DM-03 is $(K_{1.5}\square_{0.5})$ $(Mg_{5.9}Fe^{2+}{}_{0.2}Cr^{3+}{}_{0.1}Ti_{0.1})\,(Si_{5.7}Al_{2.3})\,O_{24}\,(OH)_4$. The average structural formula of phlogopite

from HP20DM-05 is $(K_{1.5}\square_{0.5})$ $(Mg_{6.0}Fe^{2+}_{0.2}Cr^{3+}_{0.1}Ti_{0.1})$ $(Si_{5.6}Al_{2.3})$ $O_{24}$ $(OH)_4$. The average structural formula of phlogopite from HP20DM-07 is $(K_{1.6}\square_{0.4})$ $(Mg_{5.8}Fe^{2+}_{0.2}Cr^{3+}_{0.1}Ti_{0.1})$ $(Si_{5.7}Al_{2.3})$ $O_{24}$ $(OH)_4$. Representative phlogopite analyses are shown in table 13 with complete analytical data in Appendix C.

Table 13. Representative Phlogopite Analyses from Meta-Chromitite Samples.

| Sample # | QCDM20-06 | QC20DM-08 | HP20DM-03 | HP20DM-05 | HP20DM-07 |
|---|---|---|---|---|---|
| $SiO_2$ | 41.31 | 40.29 | 40.80 | 40.71 | 40.06 |
| $Al_2O_3$ | 14.59 | 15.18 | 13.98 | 14.44 | 13.96 |
| $TiO_2$ | 0.87 | 0.83 | 0.68 | 0.92 | 1.03 |
| $Cr_2O_3$ | 0.91 | 1.42 | 1.06 | 1.23 | 1.04 |
| $Fe_2O_3$ | 0.04 | 0.05 | 0.05 | 0.04 | 0.06 |
| FeO | 1.29 | 1.48 | 1.58 | 1.11 | 1.86 |
| MnO | 0.05 | 0.00 | 0.03 | 0.00 | 0.01 |
| MgO | 29.60 | 26.28 | 28.03 | 27.48 | 27.92 |
| CaO | 0.01 | 0.03 | 0.01 | 0.01 | 0.00 |
| BaO | 0.02 | 0.20 | 0.15 | 0.05 | 0.04 |
| $Na_2O$ | 0.09 | 0.06 | 0.04 | 0.13 | 0.08 |
| $K_2O$ | 6.40 | 10.48 | 8.89 | 9.68 | 8.92 |
| F | 0.03 | 0.20 | 0.01 | 0.17 | 0.00 |
| Cl | 0.10 | 0.03 | 0.07 | 0.06 | 0.03 |
| $H_2O$ | 4.33 | 4.19 | 4.27 | 4.21 | 4.26 |
| Total | 99.61 | 100.62 | 99.62 | 100.16 | 99.26 |
| $*Fe^{3+}/(Fe_{total})$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $Mg/(Mg+Fe^{2+})$ | 0.98 | 0.97 | 0.97 | 0.98 | 0.96 |

$H_2O$, $Fe_2O_3$, and FeO were calculated assuming ideal stoichiometry.

### 4.2.1.4. Apatite

Apatite is chemically characterized in four meta-chromitite samples: HP20DM-07, HP20DM-08, QC20DM-06, and QC20DM-08. These are all fluorapatites or hydroxylapatites with minor amounts of REEs Ce and Nd. Analyzed apatite occur in the matrix of meta-chromitite samples. The average structural formula of apatite in QC20DM-08 is $(Ca_{10.03}Na_{0.03}Ce_{0.01}Y_{0.01}Nd_{0.01}Fe^{2+}_{0.01})$ $([PO_4]_{5.95}[SO_4]_{0.01})$ $(F_{1.36}[OH]_{0.58}Cl_{0.07})$. The average structural formula of apatite in QC20DM-06 is $(Ca_{9.76}Ce_{0.16}Mg_{0.04}Na_{0.03}Fe^{2+}_{0.03}Nd_{0.01}Mn_{0.01})$

$([PO_4]_{5.93}[SO_4]_{0.02}[SiO_4]_{0.01})$ $([OH]_{0.99}F_{0.89}Cl_{0.12})$. The average structural formula of apatite in HP20DM-07 is $(Ca_{10.04}Mg_{0.02}Na_{0.02}Fe^{2+}_{0.02}\ Ce_{0.01})$ $([PO_4]_{5.94}\ [SO_4]_{0.01}[SiO_4]_{0.01})$ $([OH]_{0.93}F_{0.81}\ Cl_{0.26})$. The average structural formula of apatite in HP20DM-08 is $(Ca_{9.76}Ce_{0.16}Mg_{0.04}Na_{0.03}Fe^{2+}_{0.03}Nd_{0.01}Mn_{0.01})$ $([PO_4]_{5.93}[SiO_4]_{0.03}[SO_4]_{0.02})$ $([OH]_{0.99}F_{0.89}\ Cl_{0.12})$. Representative apatite analyses are shown in table 14 with complete analyses on Appendix D.

Table 14. Representative Apatite Analyses from Meta-Chromitite Samples.

| Sample | HP20DM-08 | HP20DM-07 | QC20DM-06 | QC20DM-08 |
|---|---|---|---|---|
| $SiO_2$ | 0.02 | 0.18 | 0.06 | 0.00 |
| FeO | 0.31 | 0.12 | 0.12 | 0.03 |
| MnO | 0.00 | 0.03 | 0.00 | 0.04 |
| MgO | 0.03 | 0.09 | 0.03 | 0.05 |
| CaO | 55.00 | 54.68 | 55.14 | 54.38 |
| $Na_2O$ | 0.01 | 0.01 | 0.02 | 0.11 |
| $P_2O_5$ | 40.58 | 40.88 | 40.92 | 41.01 |
| SrO | 0.02 | 0.06 | 0.08 | 0.03 |
| $Y_2O_3$ | 0.05 | 0.00 | 0.00 | 0.19 |
| $La_2O_3$ | 0.01 | 0.00 | 0.10 | 0.02 |
| $Ce_2O_3$ | 0.00 | 0.09 | 0.27 | 0.16 |
| $Nd_2O_3$ | 0.00 | 0.00 | 0.00 | 0.25 |
| $SO_3$ | 0.04 | 0.09 | 0.05 | 0.08 |
| F | 2.14 | 1.42 | 1.61 | 2.47 |
| Cl | 0.12 | 0.52 | 0.37 | 0.35 |
| Total | 97.41 | 97.45 | 98.01 | 98.03 |

### 4.2.2. Meta-ultramafic Rocks

#### 4.2.2.1. Chromite

Chromite from meta-ultramafic samples have either distinct exsolution features (QC81-28) or have no exsolution features (QC81-19 and HP81-95). The presence or absence of these features are related to the Cr-Al-$Fe^{3+}$ proportions of the bulk chromite in each of these samples.

Exsolution of chromite from sample QC81-28 is seen in BSE and reflected light images as intermixed dark (exsolved component) and light (host component) phases generally aligned

along crystallographic planes (fig. 12c and 12d). A representative EMPA traverse across an exsolved chromite shows the variation of major elements in the host and exsolved spinels (fig. 17a). The host spinel has relatively higher concentrations of $Fe^{3+}$ and $Fe^{2+}$ and the exsolved component has higher concentrations of Cr, Al, and Mg. Chromite Cr#, Al#, and $Fe^{3+}$# of individual analytical points are plotted on a Cr-Al-$Fe^{3+}$ diagram and show two general clusters (fig. 18). The host component cluster has a higher $Fe^{3+}$# and plots near the top of the ternary while the exsolved component cluster has higher Cr# and Al# and plots towards the base on the ternary. An average composition for the analyzed chromite was estimated based on the average chemistry of its analysis points and is shown as the black star on the Cr-Al-$Fe^{3+}$ diagram. The average host composition (purple star) and average exsolved composition (blue star) are also plotted. For reference the position of the upper-amphibolite facies miscibility gap for exsolved chromite are provided in the ternary diagram (Loferski and Lipin, 1983). The dark exsolved phase has an average Cr# of 0.51 and an average Mg# of 0.30 and the light component has an average Cr# of 0.82 and an average Mg # of 0.06. The average structural formula for the dark component is $(Cr_{0.8}\,Al_{0.8}\,Fe^{3+}_{0.3})\,(Fe^{2+}_{0.7}\,Mg_{0.3})\,O_4$ and the average structural formula for the light component is $(Fe^{3+}_{1.1}Cr_{0.5}Al_{0.1})\,(Fe^{2+}_{0.9}\,Mg_{0.1})\,O_4$ (Henry, personal communications).

Minor elements vary between the host and exsolved components of chromite in QC81-28 (fig. 17b). Ti and Ni are in higher concentrations in the host component relative to the exsolved component. Mn concentration does not vary based on which component it is found in. Ti in the dark component averages 0.010 apfu and Ti in the light component averages 0.021 apfu. Ni in the dark component averages 0.003 apfu and Ni in the light component averages 0.012 apfu. Si in the dark component averages at 0.000 apfu and Si in the light component averages 0.001 apfu. V, Zn, and Ca were not measured in this sample (Henry, personal

communications).

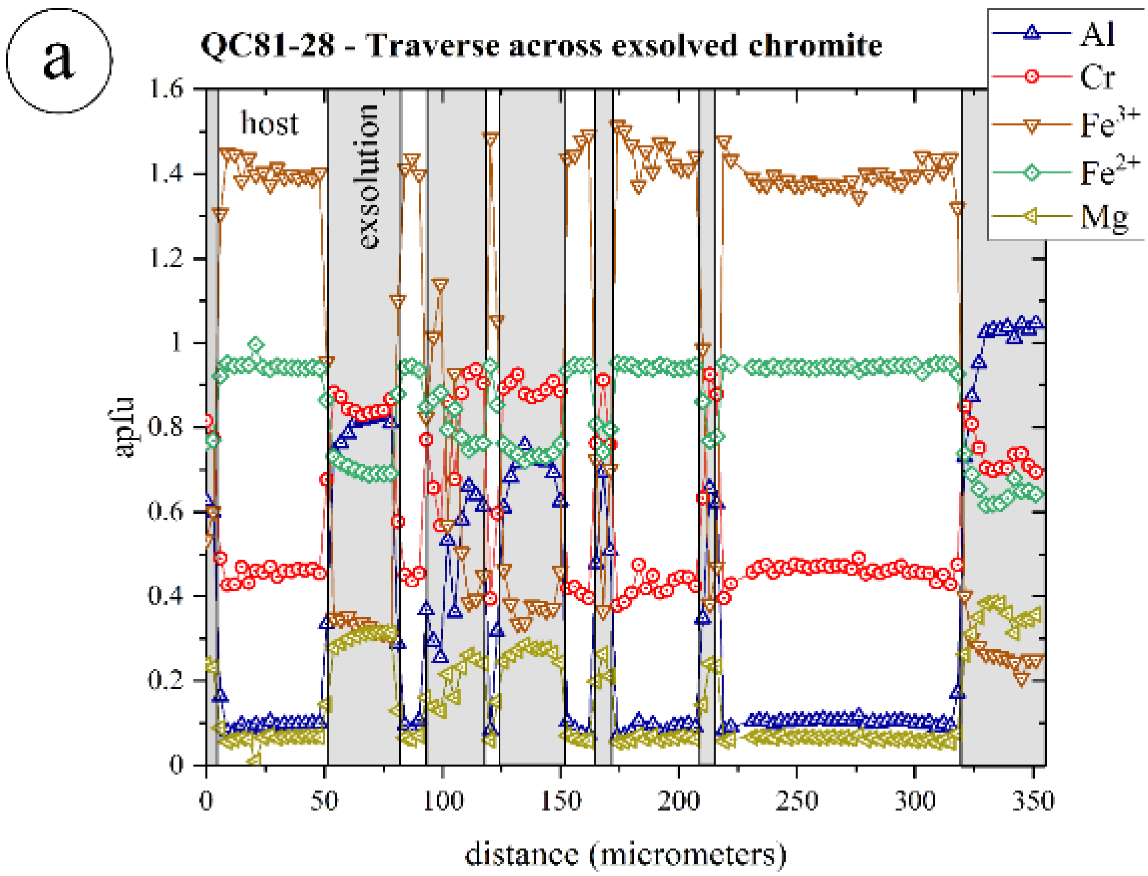
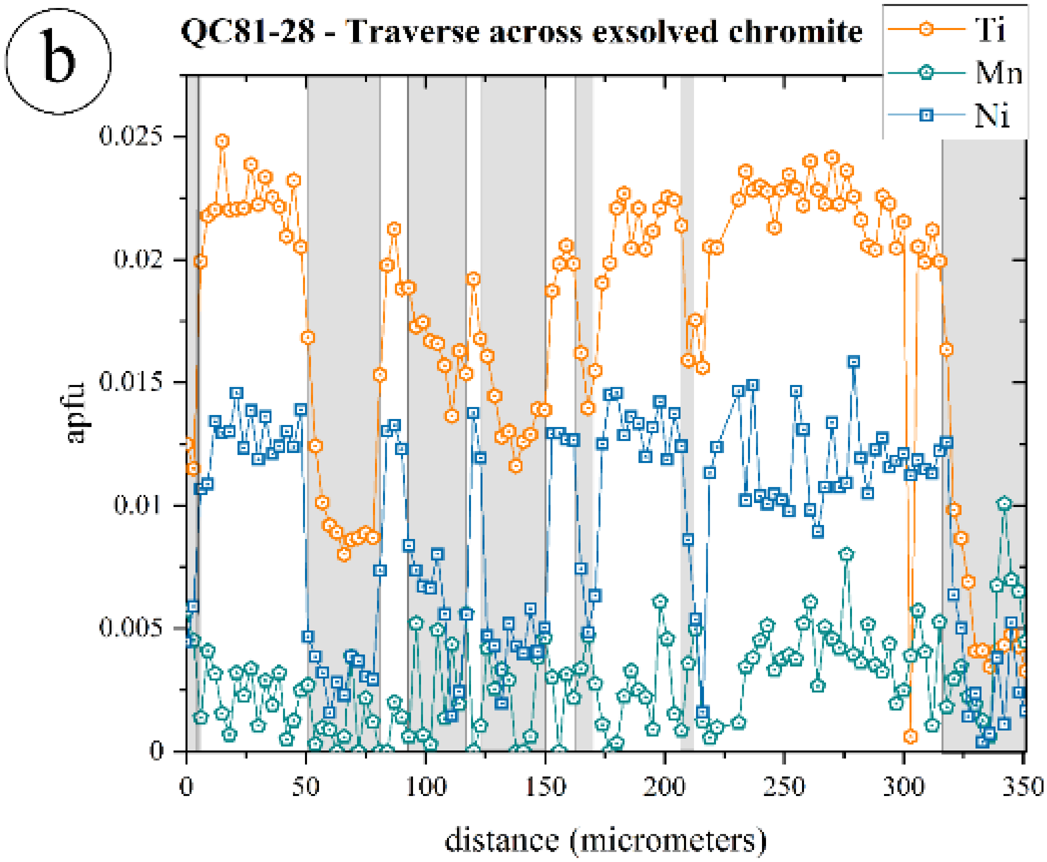



Figure 17. A representative traverse across a chromite from sample QC81-28. (a) Major elements in apfu. (b) Minor elements in apfu.

(fig. cont'd)


b
QC81-28 - Traverse across exsolved chromite
Ti
Mn
Ni
apfu
0.025
0.02
0.015
0.01
0.005
0
0
50
100
150
200
250
300
350
distance (micrometers)

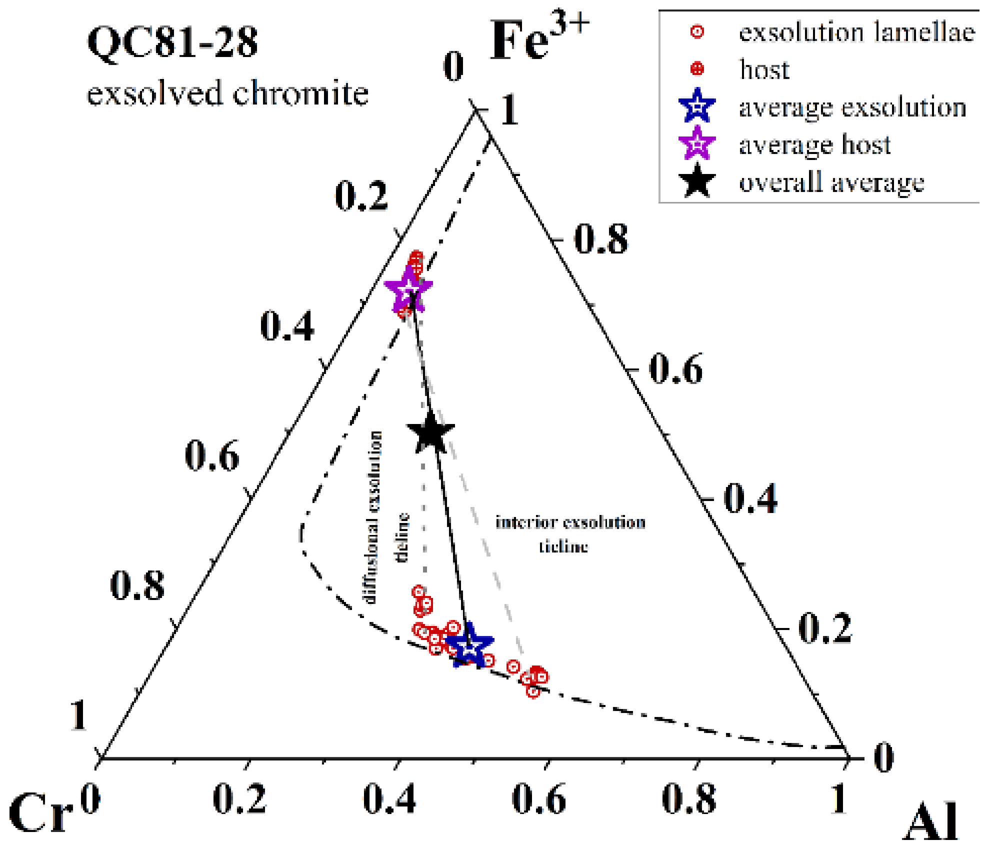



Figure 18. Sample QC81-28 chromite Cr#, Fe3+#, and Al# plotted on a ternary diagram. The miscibility gap at upper-amphibolite facies is shown as a dot-dashed line after Loferski and Lipin (1983). A line connects the average exsolved spinel and average host spinel across the miscibility gap. The long-dashed line connects the compositions of the interiors of the exsolved phases, and the short-dashed line connects the edges (last equilibrated) margins of the exsolved phases.

Chromite in chromite-rich meta-ultramafic samples (QC81-19 and HP81-95) without exsolution features are distinctly more Cr-rich and plot outside of the miscibility gap (Fig. 19). Sample QC81-19 does not show significant core to rim zoning with major elements ranging from 1.31-1.33 apfu Cr, 0.43-0.45 apfu Al, 0.22-0.24 $Fe^{3+}$, 0.42-0.44 apfu Mg, and 0.55-0.58 apfu $Fe^{2+}$. Core to rim variability in HP81-95 is relatively more significant with major elements ranging from 1.15-1.33 apfu Cr, 0.35-0.43 apfu Al, 0.23-0.42 $Fe^{3+}$, 0.34-0.42 apfu Mg, and 0.58-0.65 $Fe^{2+}$. Cr# of QC81-19 chromites ranges from 0.75 – 0.76 and Mg# ranges from 0.42 – 0.44.

Cr# of HP81-95 ranges from 0.73 – 0.79 and Mg# ranges from 0.34 – 0.42. The average structural formula for chromite in QC81-19 is $(Cr_{1.3}\,Al_{0.4}\,Fe^{3+}_{0.2})\,(Fe^{2+}_{0.6}\,Mg_{0.4})\,O_4$. The average structural formula for HP81-95 is $(Cr_{1.2}\,Al_{0.4}\,Fe^{3+}_{0.4})\,(Fe^{2+}_{0.6}\,Mg_{0.4})\,O_4$. Representative chromite analyses from chromite-rich meta-ultramafic samples are found in table 15 with complete analyses found in Appendix E.

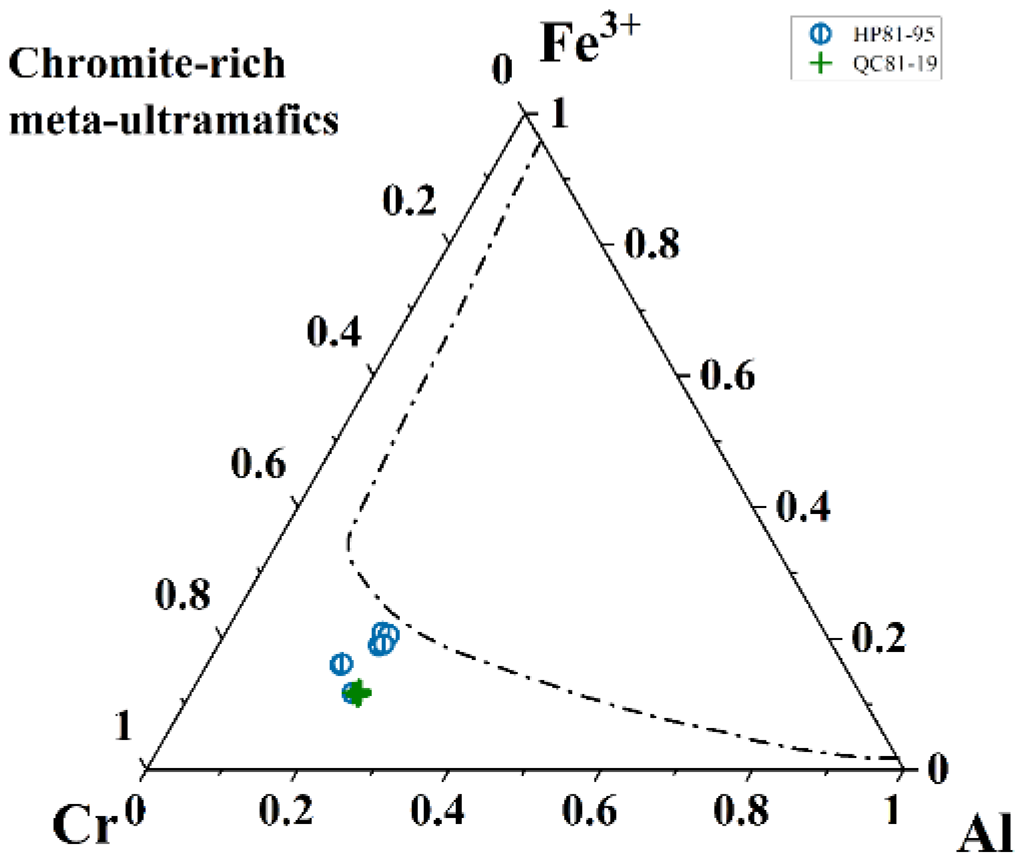



Figure 19. A ternary diagram showing chromite Cr#, Fe3+#, and Al# in chromite-rich meta-ultramafic rocks from this study. A dot-dashed line represents the miscibility gap of Lofersi and Lipin (1983).

Table 15. Representative Chromite Analyses from Meta-ultramafic Samples.

| Sample # | QC81-19 | HP81-95 |
|---|---|---|
| $SiO_2$ | 0.01 | 0.00 |
| $TiO_2$ | 0.18 | 0.14 |
| $Al_2O_3$ | 10.93 | 8.73 |
| $Cr_2O_3$ | 50.62 | 49.03 |
| $Fe_2O_3$ | 9.36 | 12.39 |
| FeO | 20.56 | 22.41 |
| MnO | 0.24 | 0.49 |
| MgO | 8.58 | 6.73 |
| NiO | 0.10 | 0.09 |
| ZnO | | 0.20 |
| Total | 100.58 | 100.20 |
| Mg# | 0.43 | 0.35 |
| Cr# | 0.76 | 0.79 |
| $Fe^{3+}/Fe_{total}$ | 0.29 | 0.33 |

Zn was not measured in QC81-19. Data from Minarik and Henry (2004)

### 4.2.3. Serpentinites

#### 4.2.3.1. Chromite

Chromite in serpentinite samples 93DM-07, 93DM-23A, and 93DM-30 do not exhibit exsolution features, but may have moderate compositional gradational zoning and rimmed by magnetite (fig. 20). From core to rim, zoned chromite from serpentinites have relatively less Al, Cr, and Mg and more $Fe^{3+}$ and $Fe^{2+}$. Representative core analysis points from chromite in serpentinite samples are plotted on a Cr-Al-$Fe^{3+}$ ternary shown in figure 21. Chromite in serpentinite samples fall outside the miscibility gap on the Cr-Al-$Fe^{3+}$ ternary. The average structural formula of chromite core analyses from sample 93DM-07 is $(Cr_{1.3}Al_{0.4}Fe^{3+}{}_{0.3})$ $(Fe^{2+}{}_{0.7}Mg_{0.3})$ $O_4$. The average structural formula of chromite rim analyses from sample 93DM-07 is $(Cr_{1.3}Fe^{3+}{}_{0.5}Al_{0.2})$ $(Fe^{2+}{}_{0.8}Mg_{0.2})$ $O_4$. The average structural formula of chromite core analyses from sample 93DM-23A is $(Cr_{1.2}Al_{0.5}Fe^{3+}{}_{0.2})$ $(Fe^{2+}{}_{0.7}Mg_{0.3})$ $O_4$. The average structural

formula of chromite rim analyses from sample 93DM-23A is $(Cr_{1.3}Fe^{3+}_{0.4}Al_{0.3})$ $(Fe^{2+}_{0.4}Mn_{0.3}Mg_{0.2})$ $O_4$. The average structural formula of chromite core analyses from sample 93DM-30 is $(Cr_{1.3}Fe^{3+}_{0.4}Al_{0.3})$ $(Fe^{2+}_{0.7}Mg_{0.3})$ $O_4$. The average structural formula of chromite rim analyses from sample 93DM-30 is $(Cr_{1.2}Fe^{3+}_{0.5}Al_{0.2})$ $(Fe^{2+}_{0.8}Mg_{0.1})$ $O_4$. Representative chromite analyses from serpentinite samples are shown in table 16 with complete data in Appendix F.

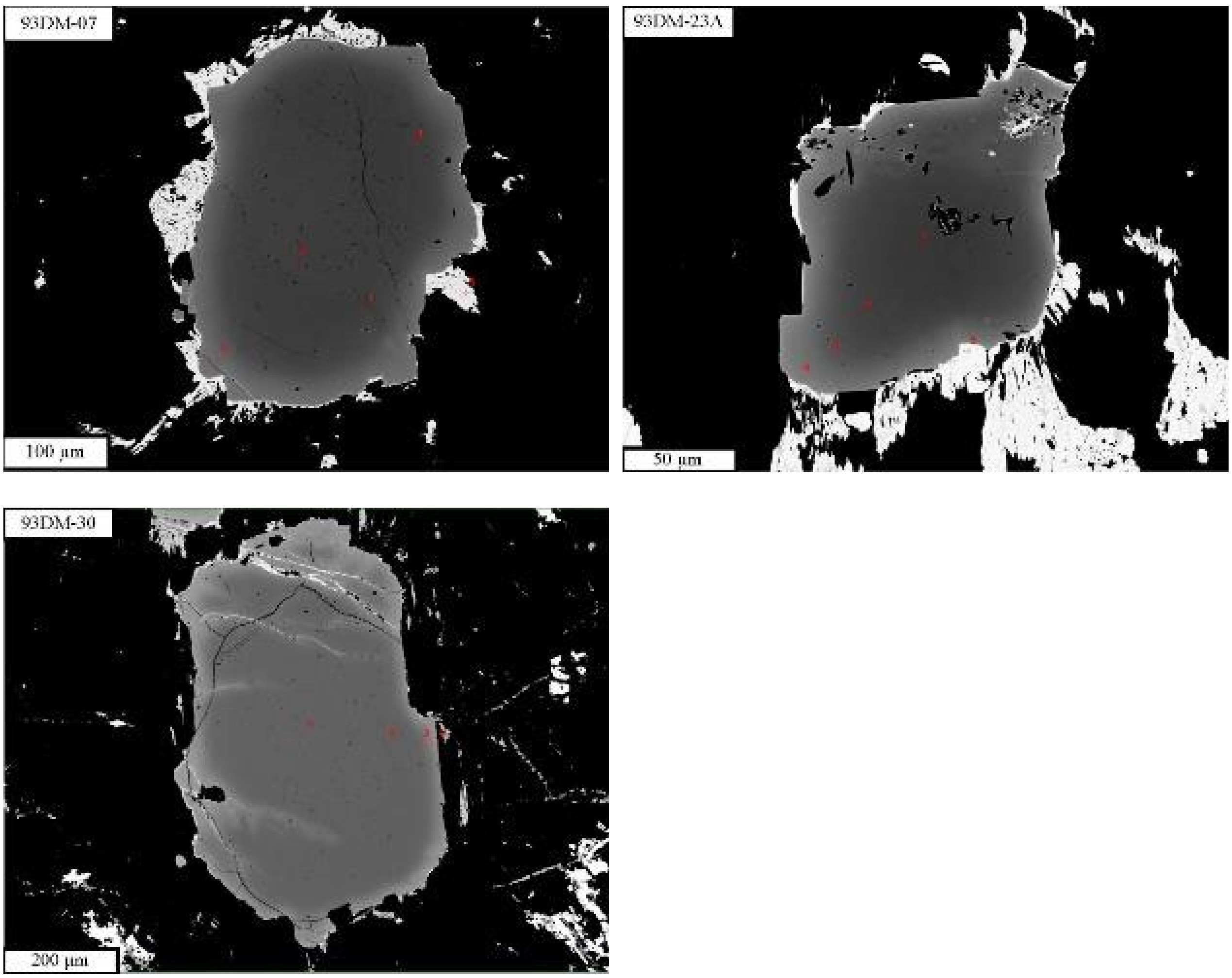



Figure 20. BSE images of chromite from serpentinite samples. Core to rim zonation is less subtle in serpentinite samples and chromite in serpentinite samples is typically rimmed by ferritchromite.

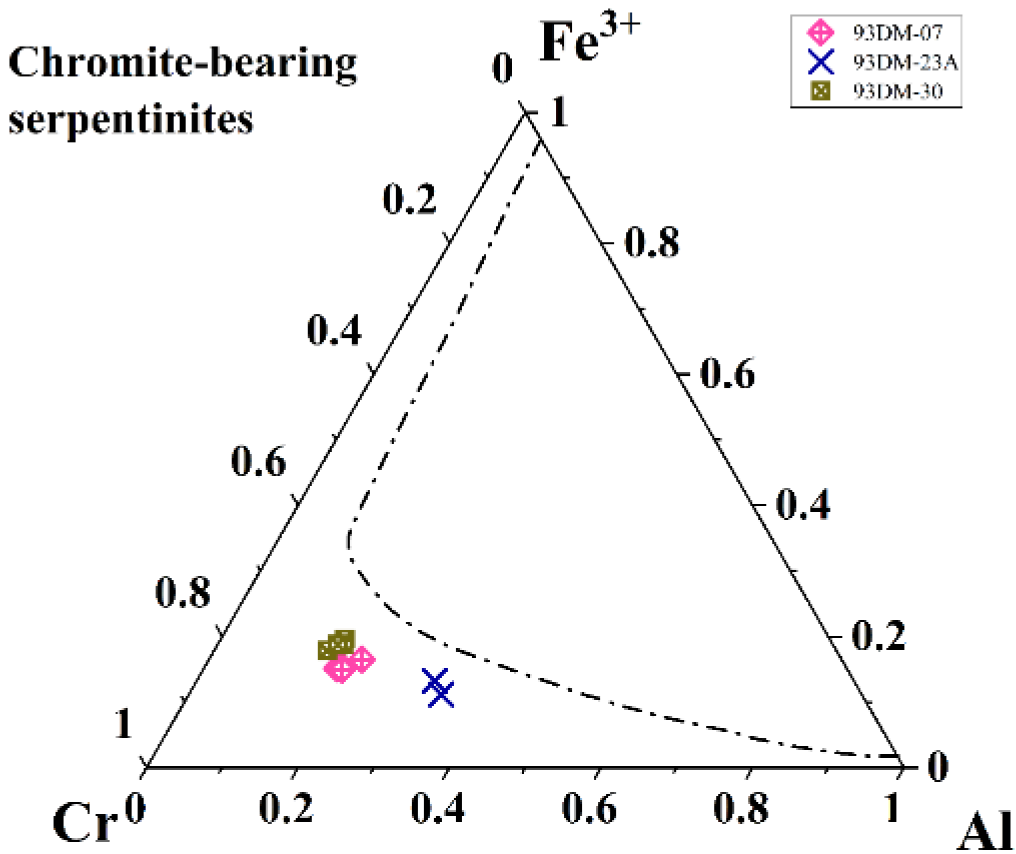



Figure 21. A ternary diagram showing core chromite Cr#, $Fe^{3+}$#, and Al# in serpentinites from this study. A dot-dashed line represents the miscibility gap of Loferski and Lipin (1983).

Table 16. Representative Chromite Analyses from Serpentinite Samples.

| Sample # | 93DM-07 | 93DM-07 | 93DM-23A | 93DM-23A | 93DM-30 | 93DM-30 |
|---|---|---|---|---|---|---|
| Comment | core | rim | core | rim | core | rim |
| $SiO_2$ | 0.00 | 0.00 | 0.00 | 0.16 | 0.00 | 0.01 |
| $TiO_2$ | 0.18 | 0.27 | 0.64 | 0.65 | 0.40 | 0.40 |
| $Al_2O_3$ | 8.62 | 5.27 | 5.62 | 6.30 | 7.27 | 6.09 |
| $Cr_2O_3$ | 49.19 | 46.07 | 52.81 | 44.15 | 48.79 | 44.90 |
| $V_2O_3$ | 0.12 | 0.14 | 0.21 | 0.19 | 0.16 | 0.16 |
| $Fe_2O_{3(calculated)}$ | 11.65 | 17.89 | 9.52 | 16.39 | 13.61 | 17.63 |
| $FeO_{(calculated)}$ | 24.34 | 25.82 | 27.47 | 24.91 | 24.68 | 28.02 |
| MnO | 0.55 | 1.27 | 0.60 | 2.62 | 0.54 | 1.04 |
| MgO | 5.42 | 3.68 | 3.25 | 2.89 | 5.29 | 2.64 |
| NiO | 0.05 | 0.14 | 0.13 | 0.10 | 0.10 | 0.14 |
| ZnO | 0.39 | 0.35 | 0.53 | 1.70 | 0.40 | 0.39 |
| Total | 100.51 | 100.90 | 100.78 | 100.04 | 101.24 | 101.42 |
| Mg # | 0.28 | 0.20 | 0.17 | 0.17 | 0.28 | 0.14 |
| Cr # | 0.79 | 0.85 | 0.86 | 0.82 | 0.82 | 0.83 |
| $Fe^{3+}/Fe_{total}$ | 0.30 | 0.38 | 0.24 | 0.37 | 0.33 | 0.36 |

$Fe_2O_3$, and FeO were calculated assuming ideal stoichiometry.

### 4.3. Whole-Rock Geochemistry

#### 4.3.1. Meta-ultramafic Rocks

Sixteen meta-ultramafic samples were analyzed for whole-rock geochemistry. Major oxides analyzed are $SiO_2$, $Al_2O_3$, FeO, $Fe_2O_3$, MgO, and CaO and minor oxides and elements analyzed are $TiO_2$, MnO, $Na_2O$, $K_2O$, $P_2O_5$, Ni, Cr, and Co. In general samples are low in $SiO_2$ (<51 wt%), high in MgO (>15 wt%), high in FeO (>10 wt%), low in $TiO_2$ (<1 wt%) and high in Cr (>1649 ppm). Samples show a wide range of $Al_2O_3$, CaO, MgO, and Cr (Table 17). Concentrations of major and minor elements in these samples correlate with the amount of MgO for most cases (fig. 22). $SiO_2$, $TiO_2$, $Al_2O_3$, and $Na_2O$ decrease with increasing MgO. Ni, Cr, and Co increase with increasing MgO. $FeO_{Total}$, MnO, $K_2O$, and $P_2O_5$ do not show any correlation to the amount of MgO. Complete meta-ultramafic whole-rock analyses are shown in table 18.

Table 17. Range of oxides, loss on ignition, and elements in samples analyzed for whole-rock geochemistry.

| Element | Range |
|---|---|
| $SiO_2$ | 40.53-50.37 (wt%) |
| $Al_2O_3$ | 1.25-10.62 (wt%) |
| FeO | 10.20-13.89 (wt%) |
| $Fe_2O_3$ | 3.06-4.36 (wt%) |
| MgO | 15.33-45.25 (wt%) |
| CaO | 0.10-9.22 (wt%) |
| $TiO_2$ | 0.07-0.62 (wt%) |
| MnO | 0.09-0.20 (wt%) |
| $Na_2O$ | 0.00-1.12 (wt%) |
| $K_2O$ | 0.05-3.03 (wt%) |
| $P_2O_5$ | 0.02-0.07 (wt%) |
| LOI | 0.00-10.66 (wt%) |
| Cr | 1649-13888 ppm |
| Ni | 160-2278 ppm |
| Co | 62-136 ppm |

Samples CB81-5, QC93-1, QC81-18, QC81-21, HP81-97, and WC82-12 fall within the picro-basalt field on a TAS diagram while all other samples plot within the basalt field (fig. 23). Samples that plot within the picro-basalt field on the TAS diagram fall within the peridot-gabbro field on a plutonic equivalent TAS diagram while all other samples plot within the gabbro field (fig. 24). Because these rocks (except for sample CB81-3) have MgO >18% and $TiO_2$ < 1% they can be classified further based on their $SiO_2$, MgO, and $TiO_2$ contents. When plotted on the classification for high-Mg mafic and ultramafic rocks based on their weight percent MgO and $SiO_2$ most samples plot within the komatiite field with a few plotting within the low-Si boninite field, and one plotting in the picrite field (fig. 25). When plotted on this diagram based on MgO and $TiO_2$ samples show similar results with most plotting in the komatiite field, few plotting in the boninite field, and one plotting in the picrite field (fig. 26).

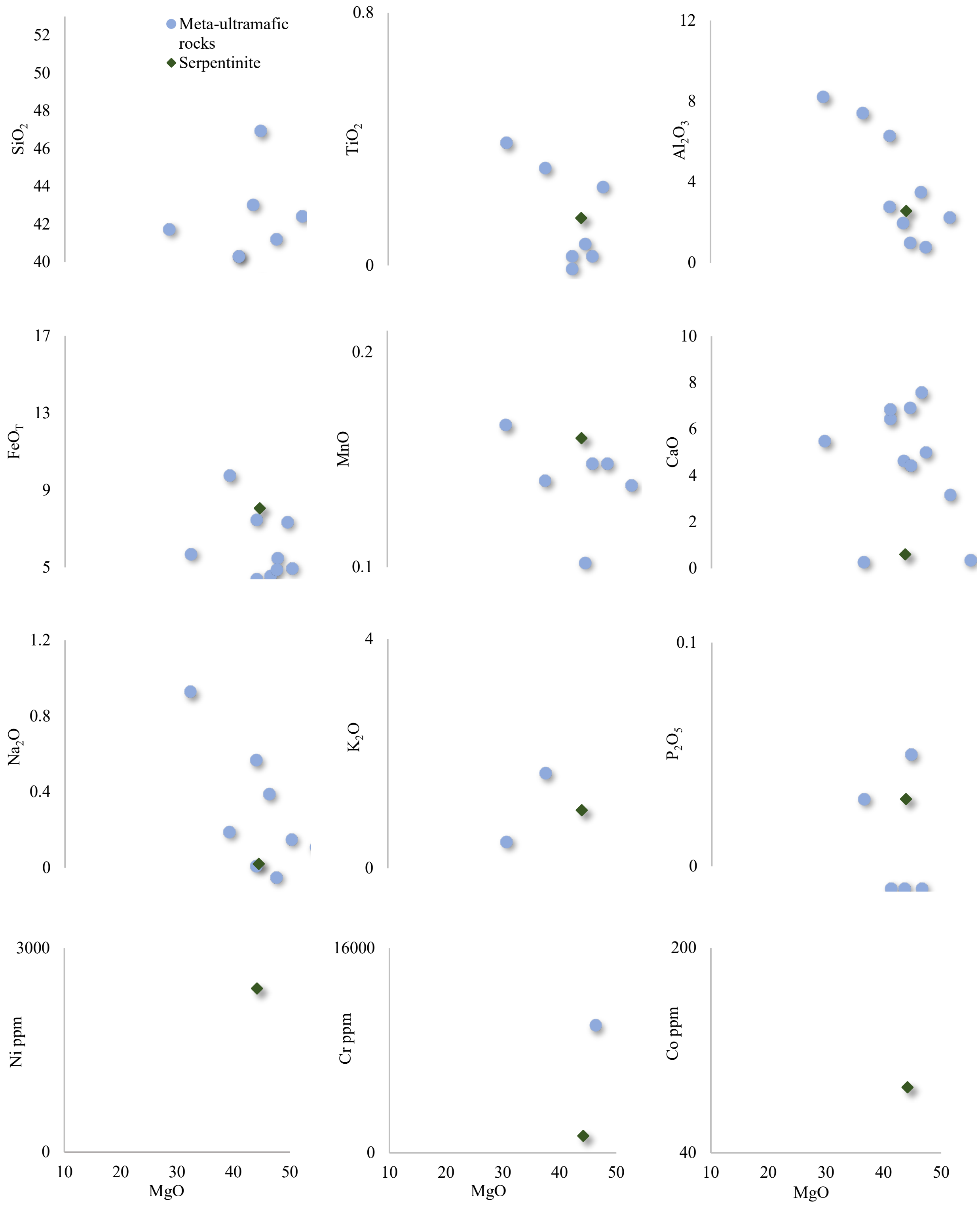



Figure 22. Harker diagrams of major and minor elements compared to MgO in weight percent oxide.

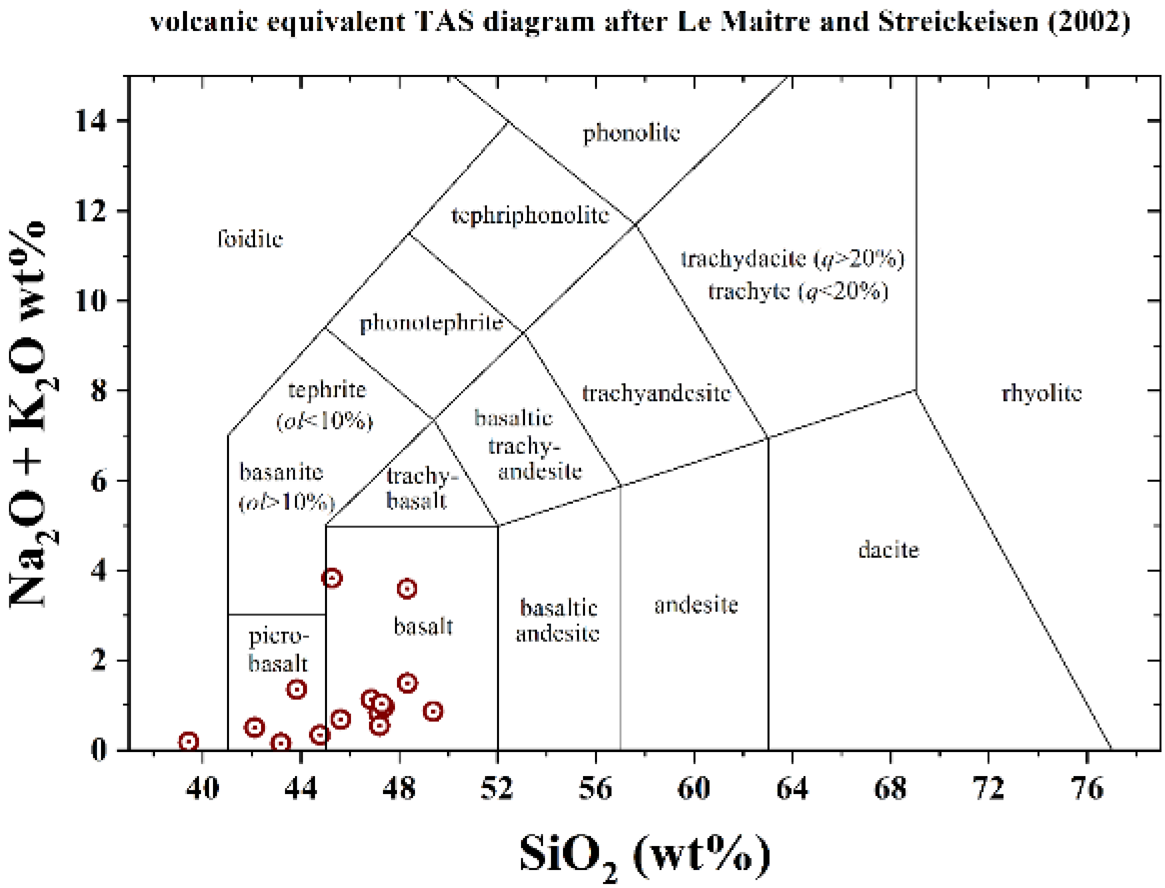



Figure 23. Volcanic equivalent TAS diagram with meta-ultramafic samples and serpentinite sample plotted. Samples with $SiO_2$ >45 wt% plot in the basalt fields. Fields are after Le Maitre et al. (2002).

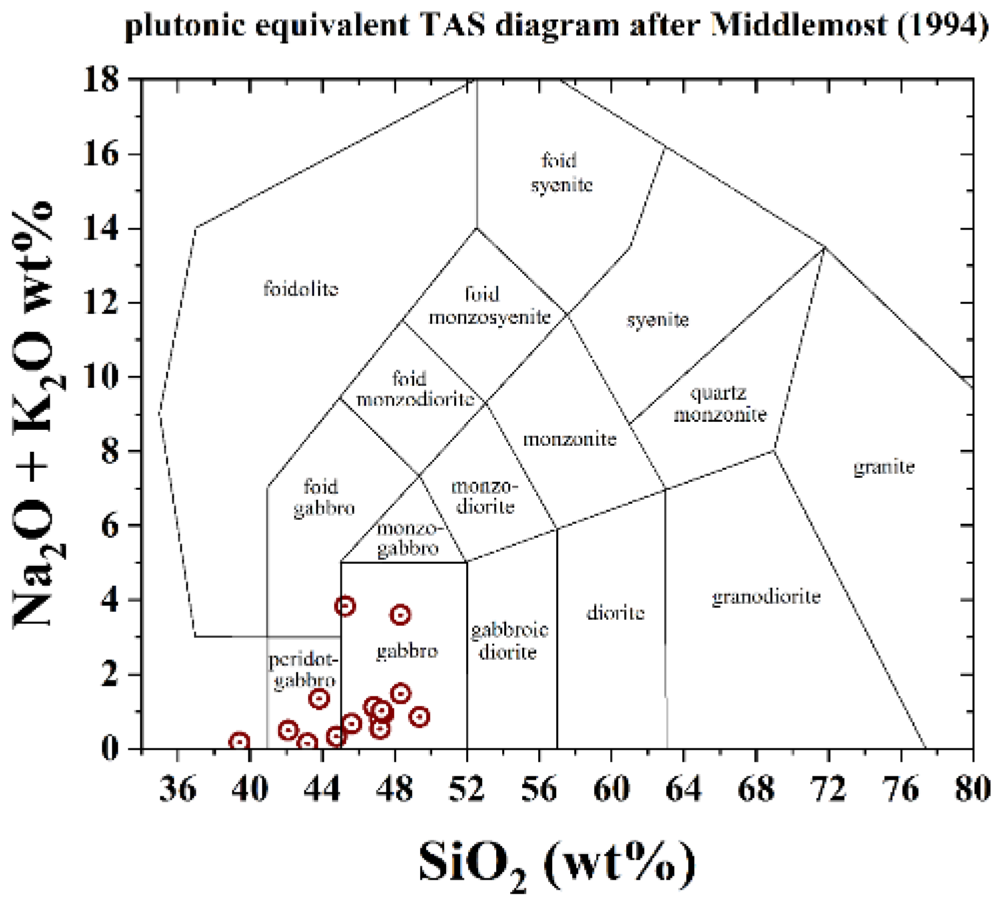



Figure 24. Plutonic equivalent TAS diagram with meta-ultramafic rocks and serpentinite plotted. Samples with $SiO_2$ > 45% plot in the gabbro field. Fields after Middlemost (1994).

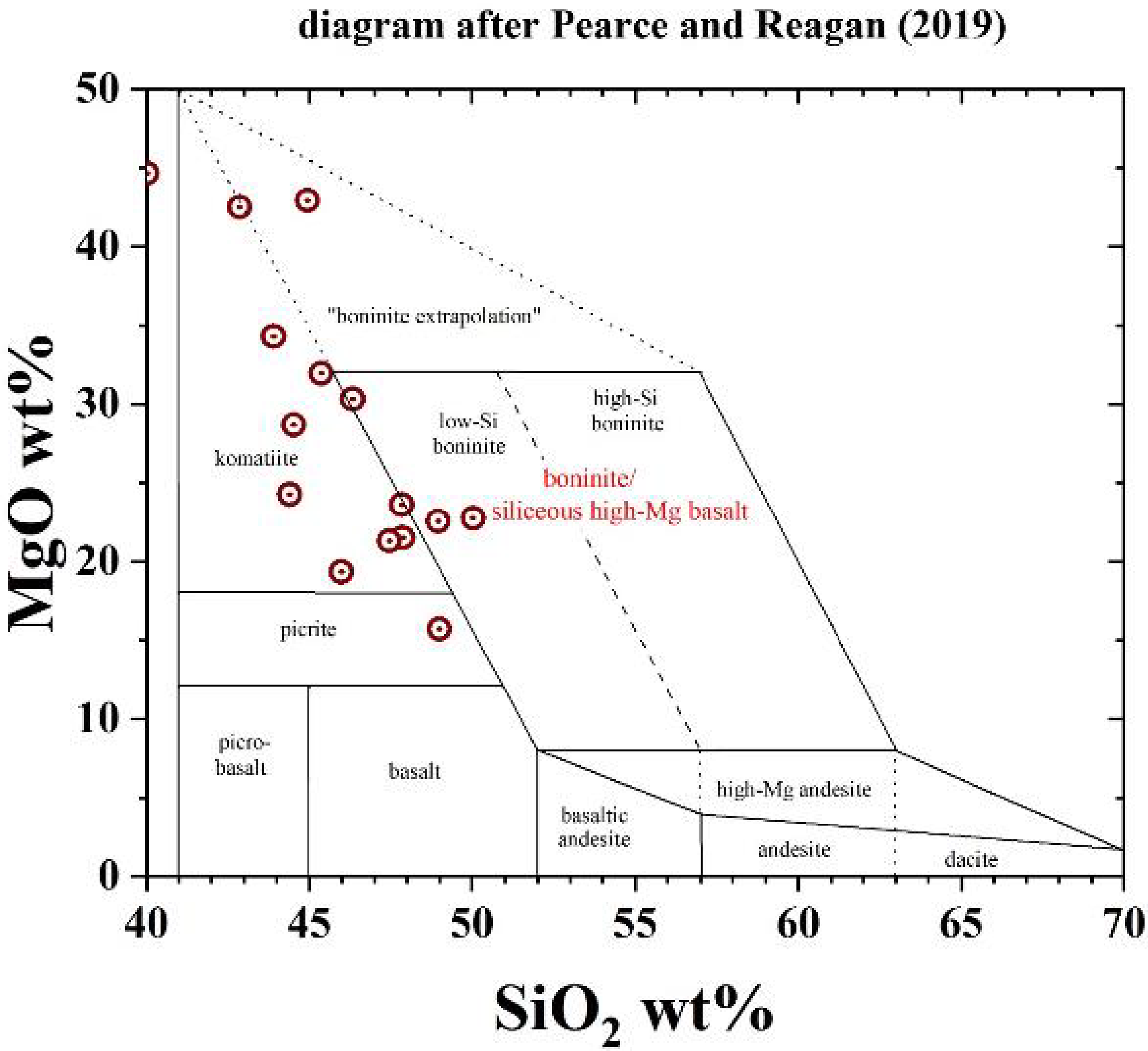



Figure 25. MgO wt% and $SiO_2$ wt% of meta-ultramafic-mafic rocks of the eastern Beartooths plotted on high-Mg mafic to ultramafic rock discrimination template from Pearce and Reagan (2019).

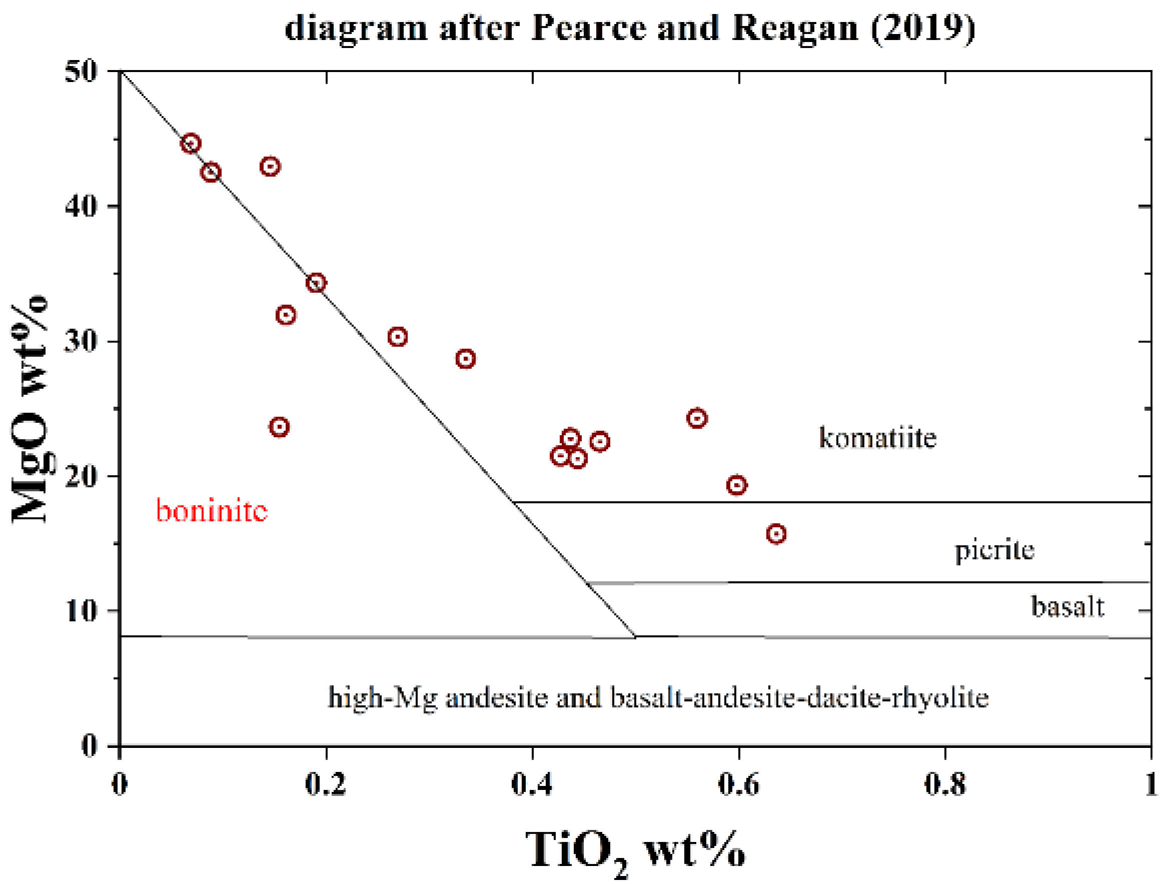



Figure 26. MgO wt% and $TiO_2$ wt% of meta-ultramafic-mafic rocks of the eastern Beartooths plotted on high-Mg mafic to ultramafic rock discrimination template from Pearce and Reagan (2019).

Trace elements are normalized to the primitive mantle to analyze how much they stray from primitive mantle values. Trace elements analyzed include La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Rb, Ba, Th, U, Nb, Ta, Pb, Sr, Zr, Hf, and Y. Samples are variably depleted and enriched in the high field strength elements (HFSE) and large ion lithophile elements (LILE) compared to the primitive mantle (fig. 26a). All samples are enriched in Rb, Th, U, and Pb relative to the primitive mantle. Samples have a negative Ba anomaly relative to the primitive mantle except for samples QC81-27 and QC81-29. Sample QC81-27 has a positive Ba anomaly relative to the primitive mantle. Samples are depleted in Sr relative to the primitive

mantle except for samples QC81-27, HP81-96, and WC82-12. Samples RB81-1, QC81-28, and QC93-1 are depleted in Ta relative to the primitive mantle. Samples RB81-1, QC81-28, QC93-1, and QC81-18 are depleted in Nb relative to the primitive mantle. Samples are overall enriched in the REEs relative to the primitive mantle except for samples HP81-96, QC93-1, QC81-18, QC81-28, and QC81-14. Sample HP81-96 is slightly depleted in Hf. Sample QC93-1 is depleted in all REE relative to the primitive mantle. Sample QC81-18 is depleted in all the REE except for La, Ce, and Nd. Sample QC81-28 is depleted in all REEs except for La and Ce. Sample QC81-14 has a negative Eu anomaly relative to the primitive mantle. Complete trace element whole-rock analyses are shown in Appendix G.

Samples are normalized to a chondrite to determine how much they stray from chondrite values. Samples are overall enriched in rare earth elements (REEs) relative to a chondrite except for samples QC93-1 and QC81-18 (fig. 26b). Sample QC93-1 is slightly enriched in La and slightly depleted in all other REEs relative to a chondrite with a noticeable depletion in Eu relative to the other elements. Sample QC81-18 is enriched in La-Eu, depleted in Gd-Yb, and slightly depleted in Lu relative to a chondrite.

Table 18. Whole-Rock Geochemistry of Meta-Ultramafic Samples.

| | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$* | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | LOI | Total | Ni | Cr | Co |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RB81-1 | 48.11 | 0.23 | 7.63 | 3.06 | 6.12 | 0.18 | 26.41 | 7.02 | 0.71 | 0.26 | 0.02 | 0.63 | 99.75 | 641 | 2306 | 66 |
| RB81-2 | 47.5 | 0.22 | 6.9 | 3.45 | 6.89 | 0.18 | 24.26 | 7.93 | 0.73 | 0.3 | 0.03 | 0.25 | 98.4 | 1091 | 2733 | 82 |
| CB81-3 | 47.76 | 0.62 | 10.62 | 3.56 | 7.12 | 0.19 | 15.33 | 8.17 | 1.12 | 2.43 | 0.04 | | 96.96 | 342 | 1754 | 62 |
| CB81-4 | 48.42 | 0.46 | 7.5 | 3.39 | 6.77 | 0.16 | 22.32 | 7.75 | 0.85 | 0.64 | 0.05 | | 96.31 | 655 | 2047 | 73 |
| CB81-5 | 44.64 | 0.58 | 10.22 | 4.17 | 8.33 | 0.18 | 18.77 | 5.57 | 0.75 | 3.03 | 0.07 | 0.61 | 100.12 | 814 | 2462 | 83 |
| CB81-6 | 50.37 | 0.44 | 7.01 | 3.53 | 7.05 | 0.18 | 22.93 | 7.65 | 0.63 | 0.25 | 0.08 | | 99.83 | 599 | 1649 | 73 |
| QC93-1 | 40.53 | 0.07 | 1.25 | 3.98 | 7.97 | 0.19 | 45.25 | 0.38 | 0.04 | 0.15 | 0.02 | | 99.3 | 2043 | 6539 | 136 |
| QC81-14 | 46.43 | 0.27 | 5.41 | 4.17 | 8.35 | 0.2 | 30.37 | 3.38 | 0.46 | 0.23 | 0.04 | 0.87 | 100.27 | 811 | 3574 | 112 |
| QC81-18 | 43.61 | 0.09 | 2.34 | 3.57 | 7.13 | 0.09 | 43.26 | 0.1 | 0 | 0.06 | 0.02 | 10.66 | 97.53 | 2278 | 6586 | 89 |
| QC81-21 | 43.8 | 0.33 | 5.75 | 4.09 | 8.17 | 0.18 | 28.22 | 5.61 | 0.64 | 0.71 | 0.03 | 3.19 | 97.63 | 811 | 3407 | 97 |
| QC81-27 | 47.04 | 0.42 | 7.9 | 3.83 | 7.65 | 0.14 | 21.14 | 8.65 | 0.66 | 0.16 | 0.04 | | 94.59 | 499 | 2276 | 78 |
| QC81-28 | 46.37 | 0.15 | 5.31 | 3.44 | 6.87 | 0.12 | 22.9 | 8.89 | 0.41 | 0.12 | 0.02 | 1.34 | 99.55 | 659 | 13888 | 92 |
| QC81-29 | 47.05 | 0.44 | 9.66 | 3.36 | 6.73 | 0.12 | 21.14 | 8.86 | 0.94 | 0.19 | 0.05 | | 98.54 | 160 | 2444 | 71 |
| HP81-97 | 43.82 | 0.19 | 4.22 | 4.36 | 8.72 | 0.2 | 34.26 | 2.76 | 0.1 | 0.05 | 0.03 | | 98.72 | 1274 | 4438 | 109 |
| HP81-96 | 45.03 | 0.16 | 3.81 | 3.51 | 7.01 | 0.12 | 31.69 | 6.82 | 0.2 | 0.13 | 0.02 | 6.92 | 98.5 | 939 | 2720 | 119 |
| WC82-12 | 43.66 | 0.55 | 8.26 | 3.8 | 7.61 | 0.14 | 23.86 | 9.22 | 0.42 | 0.17 | 0.05 | | 97.74 | 785 | 1769 | 74 |

*$Fe_2O_3$ and FeO are calculated assuming ideal stoichiometry.
Ni, Cr, and Co are reported in ppm.

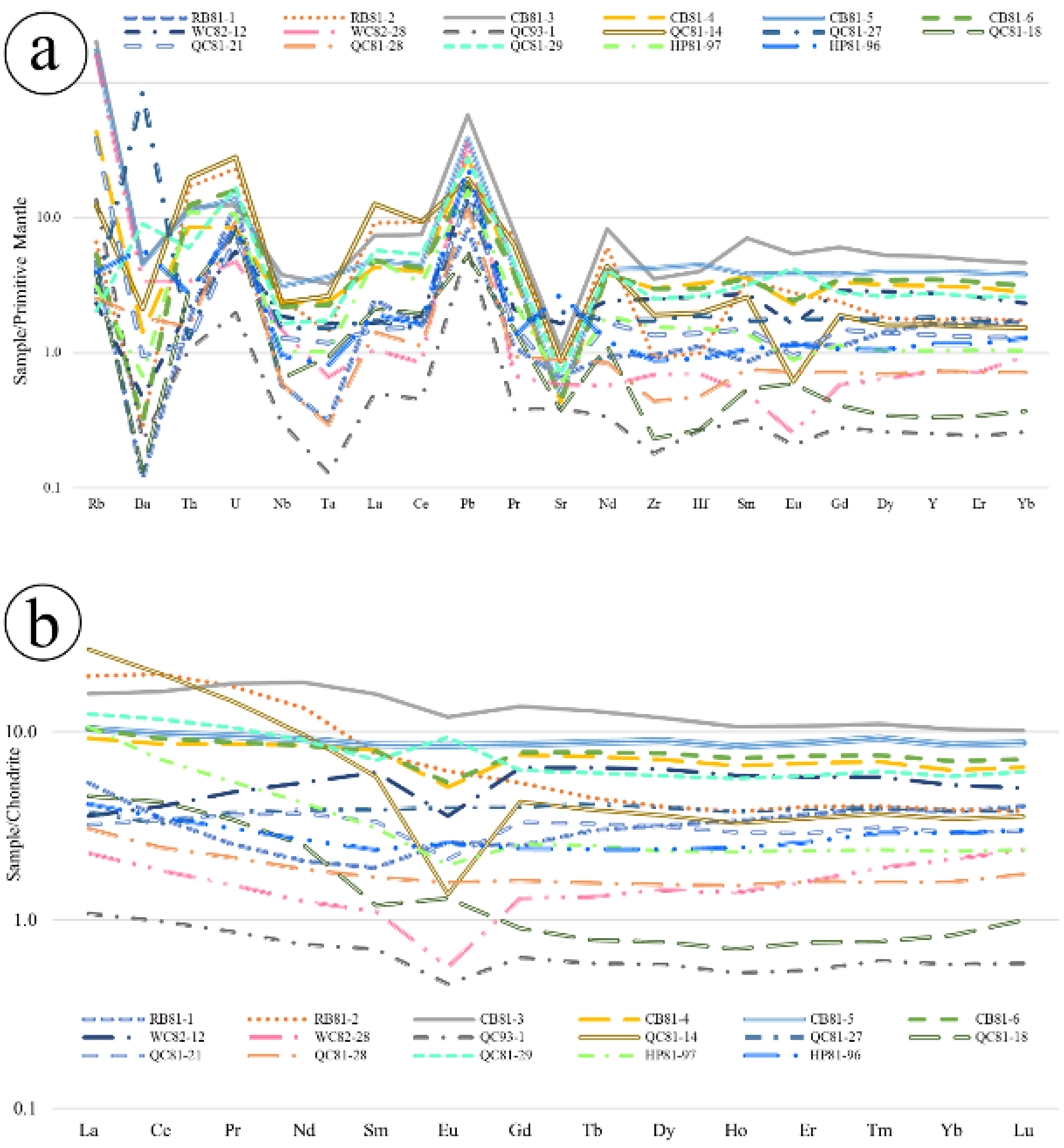



Figure 27. Trace elements displayed on spider diagrams normalized to (a) primitive mantle values from McDonough and Sun (1995) (b) chondrite values from Korotev et al. (2003).

### 4.3.2. Serpentinites

Whole-rock geochemistry serpentinite sample WC82-28 was analyzed. Weight percent $SiO_2$ is 46.21. Weight percent $Al_2O_3$ is 2.56. Weight percent FeO is 8.06. Weight percent $Fe_2O_3$ is 2.69. Weight percent MgO is 44.17. Weight percent CaO is 0.6. Weight percent $TiO_2$ is 0.15. Weight percent MnO is 0.16. Weight percent $Na_2O$ is 0.02. Weight percent $K_2O$ is 1.01. Weight percent $P_2O_5$ is 0.03. Loss on ignition is 0.00. Ni, Cr, and Co were analyzed and reported in parts per million. Ni is 2406 ppm. Cr is 1316 ppm, and Co is 91 ppm. Serpentinite whole-rock analysis is shown in table 19.

Sample WC82-28 is enriched in Rb, Ba, Th, U, Nb, and is depleted in Ta and all REEs with a negative Eu anomaly relative to the primitive mantle. Sample WC82-28 is enriched in REEs relative to a chondrite except for Eu in which it is depleted. Trace element analyses are normalized to the primitive mantle and to a chondrite and displayed on spider diagrams in figure 24.

Table 19. Serpentinite Sample WC82-28 Whole-Rock Analysis.

| | |
|---|---|
| $SiO_2$ | 46.21 |
| $TiO_2$ | 0.15 |
| $Al_2O_3$ | 2.56 |
| $Fe_2O_3$* | 2.42 |
| FeO | 4.84 |
| MnO | 0.16 |
| MgO | 44.17 |
| CaO | 0.6 |
| $Na_2O$ | 0.02 |
| $K_2O$ | 1.01 |
| $P_2O_5$ | 0.03 |
| LOI | |
| Total | 102.16 |
| Ni | 2406 |
| Cr | 1316 |
| Co | 91 |

*$Fe_2O_3$ and FeO are calculated assuming ideal stoichiometry.
Ni, Cr, and Co are reported in ppm.

**4.4. Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS)**

Chromite-rich meta-ultramafic samples HP81-95 and QC81-19 were chosen for LA-ICP-MS analysis. Major, minor, and trace elements were analyzed including platinum group elements (PGE). Two chromite core analyses were taken in each sample while the rest of the analyses targeted the chromite rims. Most PGE analyses were below the detection limit. Full LA-ICP-MS chromite analyses are shown in Appendix H.

Average chromite core compositions are normalized to chromite from a MORB chromitite-pod analyzed by Page and Barnes (2009) (fig. 28). Chromite from HP81-95 and

QC81-19 have similar minor element patterns, but HP81-95 is slightly depleted in Ga relative to MORB chromite and QC81-19 is slightly enriched. Chromite from HP81-95 is slightly depleted in Ti, and Ni and enriched in Zn, Co, Mn, and V relative to MORB chromite. Chromite from QC81-19 is slightly depleted in Ti and Ni and enriched in Zn, Co, Mn, and V relative to MORB chromite.

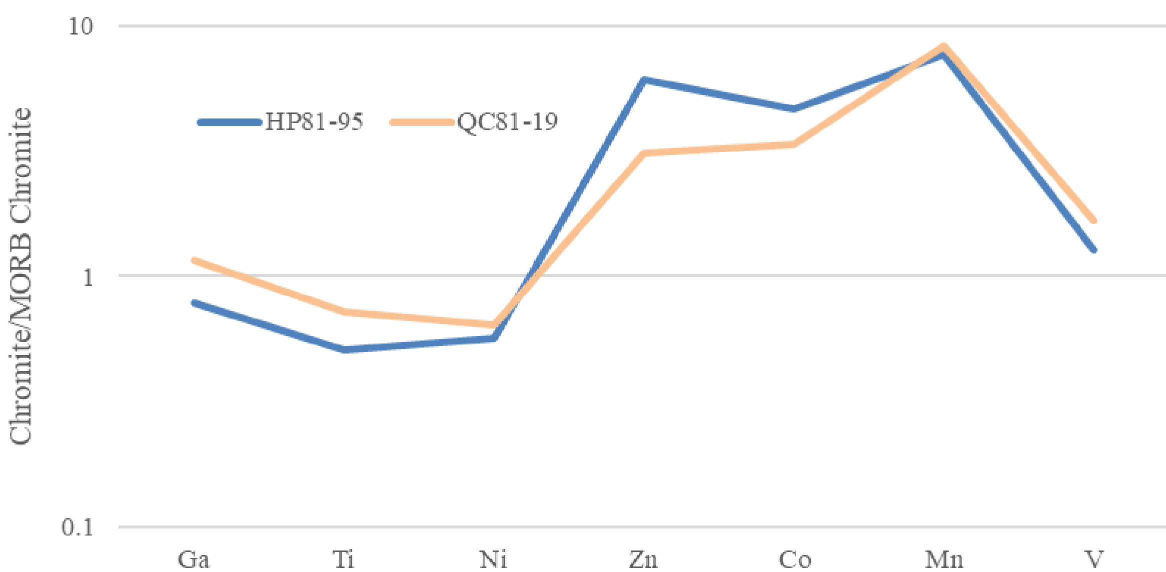



Figure 28. Minor elements in chromite from chromite-rich meta-ultramafic samples normalized to MORB chromite compositions from Page and Barnes (2009).

# Chapter 5. Discussion

The petrography, mineral chemistry, and whole-rock chemistry of the metamorphosed ultramafic rocks and meta-chromitites from the eastern Beartooth Mountains provide evidence for the tectonic setting in which they formed.

## 5.1. Petrography

Meta-chromitites show variable textures depending on which plateau locality. Chromitites on the Hellroaring Plateau show textures that differ from those in layered intrusions such as pull-apart structures (fig.6d) and general lack of euhedral chromite (Thayer, 1964). The bimodal size distribution of chromite in these chromitites is interpreted as being caused by deformation that breaks up larger chromite crystals similar to those textures found in chromite nodules. James (1961) argued that some of these clump-like structures are poorly formed nodular chromite. Smaller, more euhedral chromite crystals from the Quad Creek plateau are more akin to chromite developed in layered intrusions.

Mineral inclusions in the eastern Beartooth chromite can be compared to mineral inclusion from a range of meta-chromitite localities. The eastern Beartooth chromite can contain phlogopite, chlorite, olivine, calcite, dolomite, diopside and rutile. As a comparison, phlogopite and pargasite are the most common inclusions in ophiolitic chromite (González-Jiménez et al., 2014) and olivine, clinopyroxene, orthopyroxene, serpentine, chlorite, garnet, plagioclase, ilmenite, apatite, carbonates, and platinum-group minerals are also reported (e.g., Talkington et al., 1983; Melcher et al., 1997; Liu et al., 2017; Rollinson et al., 2018). Phlogopite and orthopyroxene are common inclusions in layered mafic complexes such as the Merensky Reef (Li et al., 2005) and the Stillwater Complex (Spandler et al., 2005) and amphiboles, olivine, clinopyroxene, carbonates, platinum-group minerals, apatite, and rutile are also reported

(Friedrich et al., 2019). While inclusions are not diagnostic of which setting chromitites form in, they do indicate something about the composition of the melt. Multi-phase inclusions, globular inclusions, and inclusions with a negative crystal-form bounded by chromite crystallographic planes suggest their entrapment as melt-droplets (Kamenetsky, 1996). The abundance of hydrous mineral inclusions and carbonate inclusions suggests that the melt that crystallized these chromitites was $H_2O$ and $CO_2$-rich.

### 5.2. Mineral Chemistry

Based on lack of chemical zonation in chromite from meta-chromitites, chromite suggests that it preserves its igneous composition. Chromite that has been affected by metamorphism typically shows enrichment of Cr, $Fe^{2+}$, and $Fe^{3+}$ at its rims (Colás et al., 2014) while chromite in these meta-chromitite samples show slight enrichment in Mg and Al at the rims and no change in $Fe^{3+}$ from core to rim (fig.14). Chromite mineral chemistry from meta-chromitites do not fit in any single field on discrimination diagrams. Based on Cr/(Cr+Al) and $Fe^{2+}/(Fe^{2+}+Mg)$ chromite fit in both the ophiolitic chromite field and the layered mafic intrusion field with some samples plotting outside of either field (fig. 29). Chromite is relatively $TiO_2$ poor compared to layered mafic intrusion chromite (fig. 30).

Chromite chemistry in meta-chromitites does not depend upon its textures or which plateau it was found. Chromite chemistry also does not depend on the matrix mineral assemblage except in sample HP20DM-08 (the outlying set of points on figure 29) which has high $Fe^{2+}$ and slightly higher Cr compared to the other chromite samples. HP20DM-08 has a matrix consisting of Cr-chlorite and anthophyllite with minor amounts of diopside. Equilibration with this matrix could be the cause of its high $Fe^{2+}$ content with chlorite and anthophyllite preferentially taking in Mg and Al.

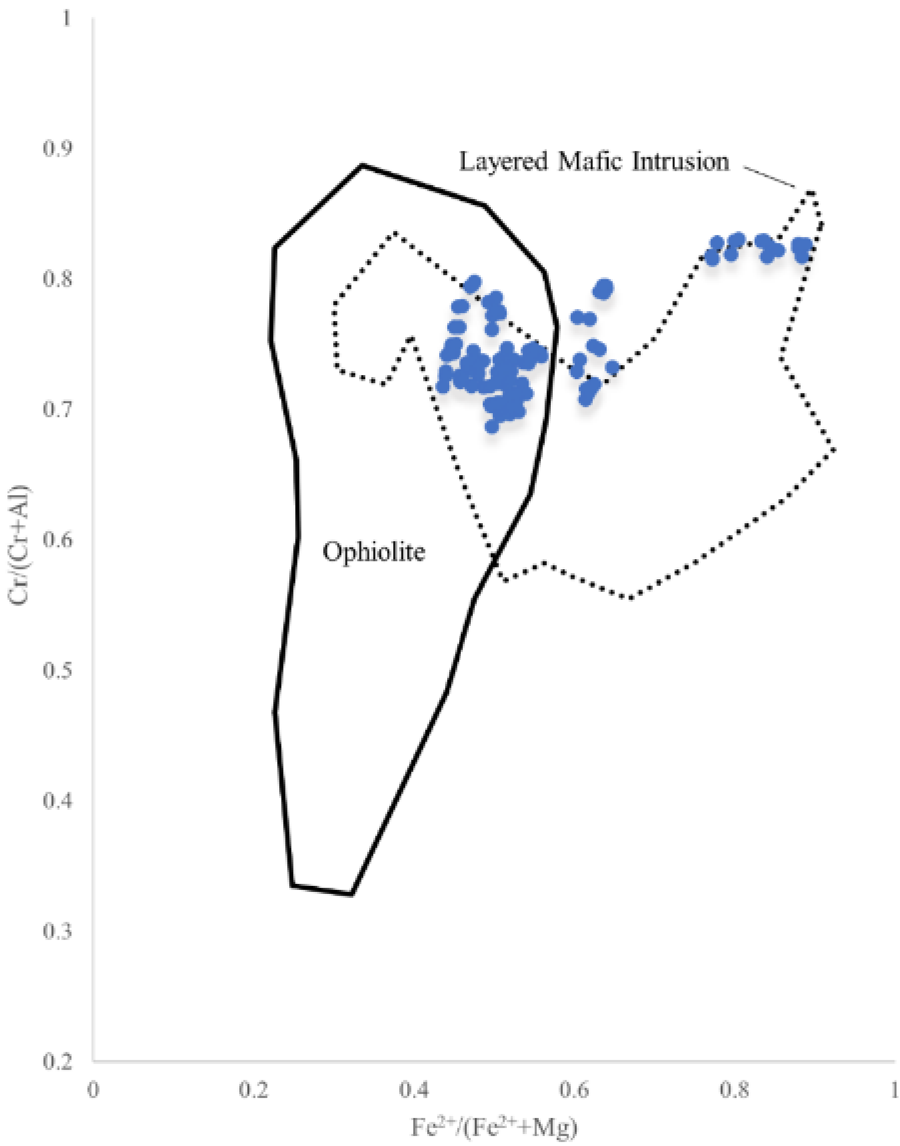



Figure 29. Chromite discrimination diagram with fields from Barnes and Roeder (2001) showing the range of Cr/(Cr+Al) and $Fe^{2+}/(Fe^{2+}+Mg)$ for chromite from chromitites from ophiolite and from layered mafic intrusions.

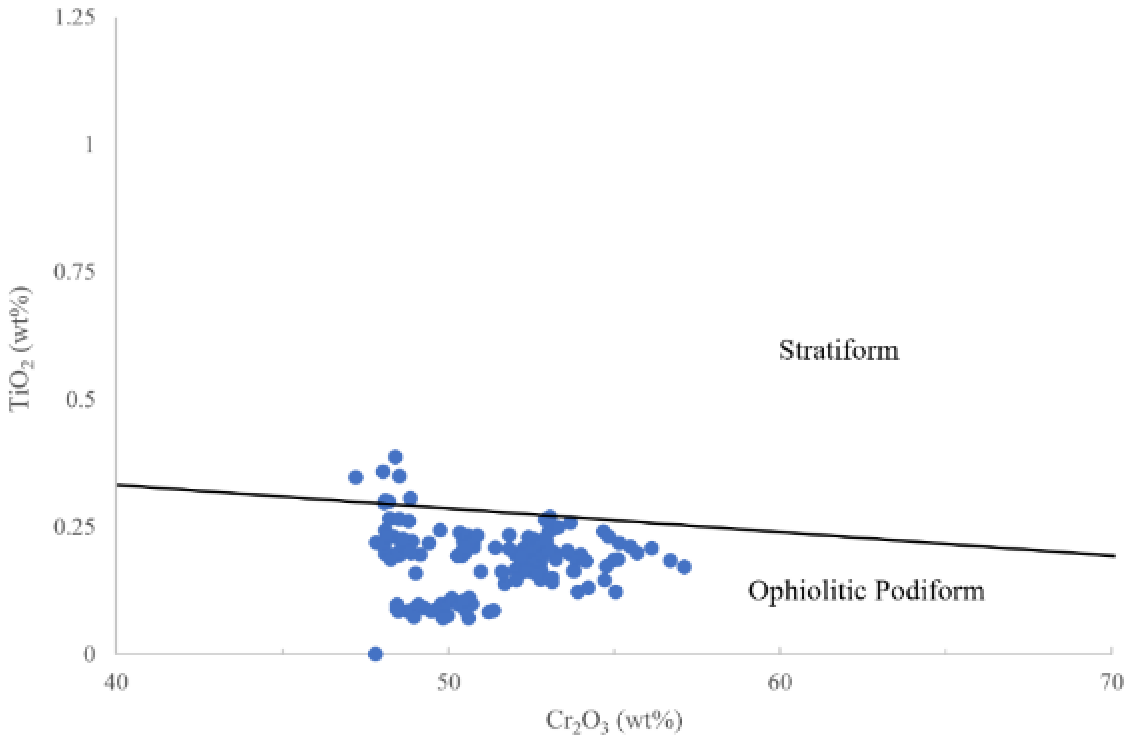



Figure 30. Chromite discrimination diagram based on the $TiO_2$ (wt%) and Cr2O3 (wt%) with fields from Arai et al. (2004).

Chromite from meta-chromitites and chromite-rich meta-ultramafic samples is chemically similar to those of previous studies from the meta-ultramafic rocks in the eastern Beartooths (Loferski and Lipin, 1983 and Loferski, 1986) (fig. 31). Chromite from meta-chromitites and chromite from samples HP81-95 and QC81-19 plot within the same range as disseminated and segregated chromite from Loferski and Lipin (1983) (fig. 31). Exsolved chromite from sample QC81-28 plotted on a Cr-Al-$Fe^{3+}$ ternary is chemically comparable to those of previous studies with the host and exsolved species plotting along the miscibility gap as in previous studies (fig. 31). The miscibility gap based on data from Loferski and Lipin (1983) is

interpreted as exsolution in the upper amphibolite facies and is only seen in chromite with a sufficiently high silicate-chromite ratio with chromite chemistry having relatively less Cr.

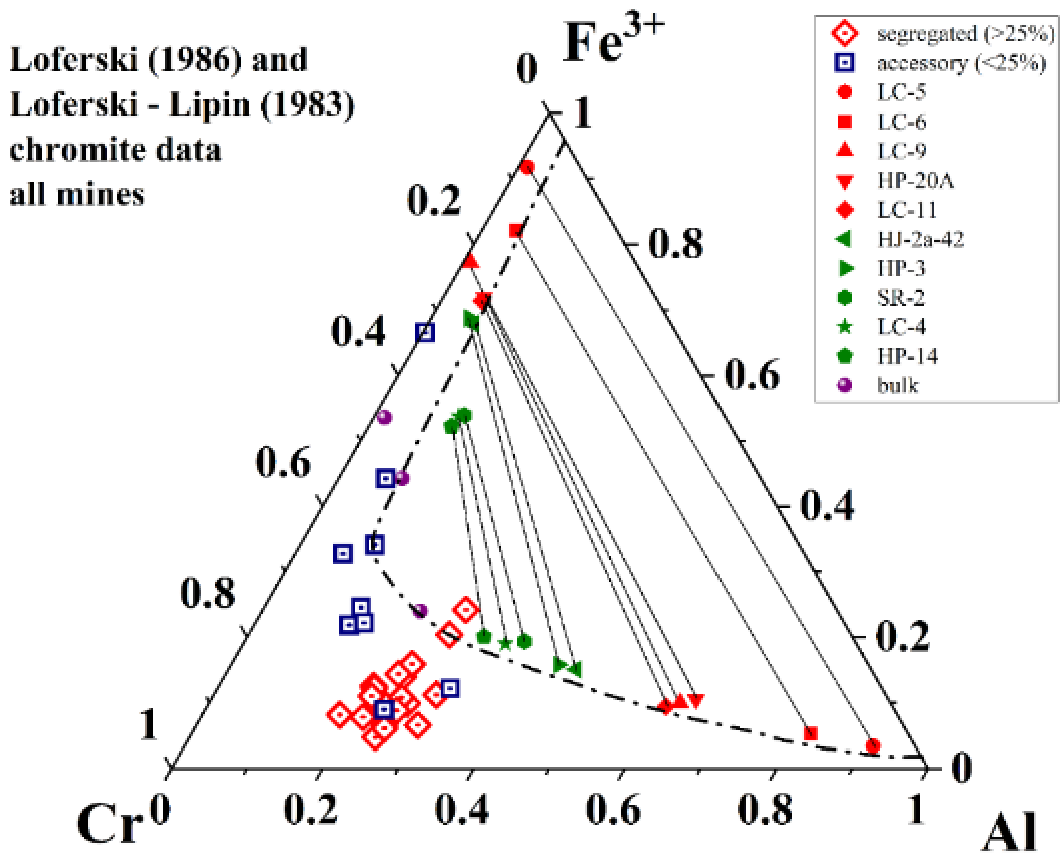



Figure 31. Chromite Cr#, Al#, and $Fe^{3+}$# from Loferski (1986) and Loferski and Lipin (1983) plotted on a ternary diagram. Segregated chromite refers to chromite from lithologies that contain >25% chromite and accessory chromite refers to lithologies that contain <25% chromite. Data points that are joined by a line crossing the miscibility gap are from chromite that are made up of two exsolved spinels.

$Al_2O_3$ and $TiO_2$ melt compositions in equilibrium with chromite from meta-chromitites and chromite-rich meta-ultramafic samples HP81-95 and QC81-19 were estimated using the methods of Peighambari et al. (2016). The equations used are as follows:

$$Al_2O_3\text{-}melt = 5.2181 \times Ln(Al_2O_3\text{-}chromite) - 1.0505$$

$$Ln(TiO_2\text{-}melt) = 1.0963 \times (TiO_2\text{-}chromite)^{0.7863}$$

$Al_2O_3$ and $TiO_2$ concentrations of melts in equilibrium with meta-chromitites are compared with those of melts generated in different tectonic settings in figure 32. All calculated melt compositions fall within the boninite field with one point falling in the area shared by boninite and experimental depleted mantle fields.

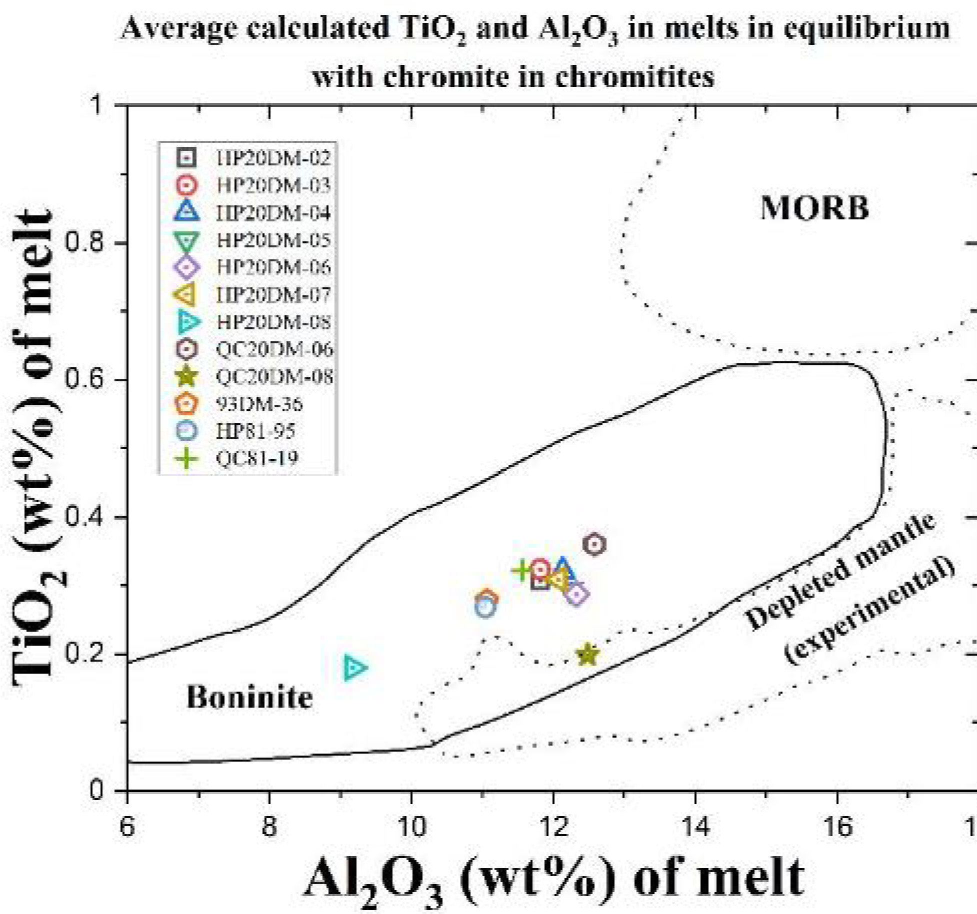



Figure 32. $TiO_2$ (wt%) and $Al_2O_3$ (wt%) of melts calculated to be in equilibrium with chromite from meta-chromitites. Modified after Peighambari et al. (2016).

### 5.3. Whole-Rock Geochemistry

The meta-ultramafic rocks of the eastern Beartooth Mountains analyzed for whole-rock data in previous studies are chemically similar to the ones of this study (Skinner, 1969; Loferski, 1986; Eckelmann and Poldervaart, 1957). Samples from previous studies also plot within the

basalt and picro-basalt fields on a TAS diagram and gabbro and peridot-gabbro fields on the plutonic TAS equivalent diagram (fig. 33 and 34). One sample analyzed by Loferski (1986), and all samples analyzed by Eckelmann and Poldervaart (1957) fall within the basaltic andesite field on a TAS diagram and gabbroic diorite field on the plutonic equivalent TAS diagram (fig. 33 and 34).

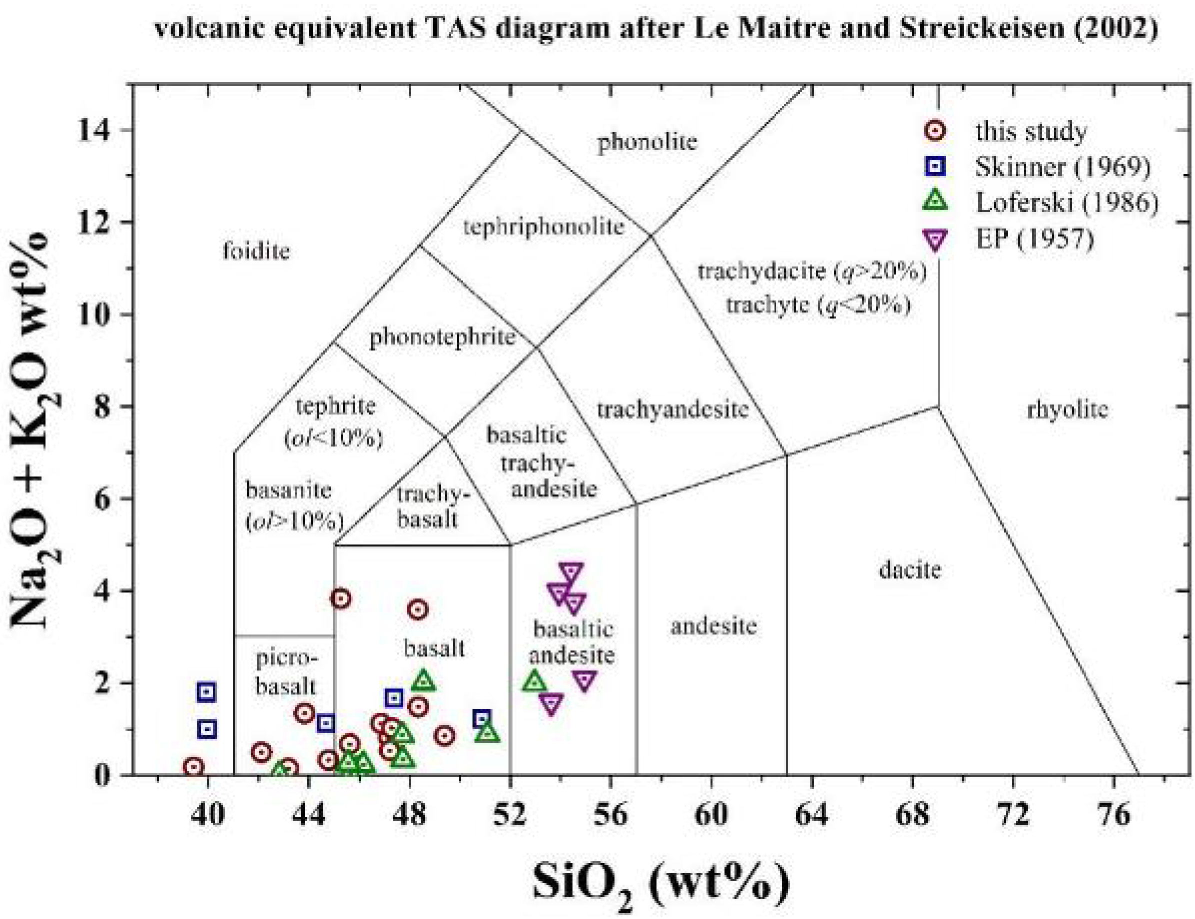



Figure 33. TAS diagram showing whole-rock analyses from previous studies of the eastern Beartooth Mountains and this study. Fields are after Le Maitre et al. (2002).

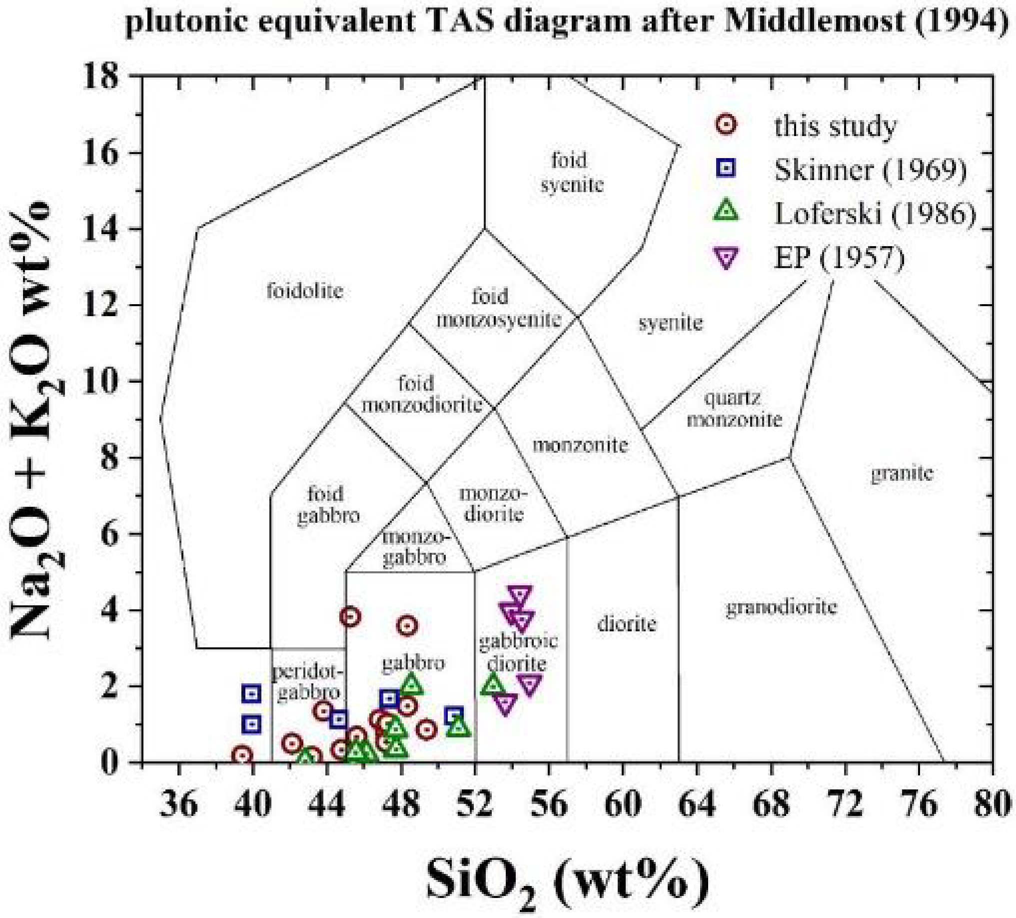



Figure 34. Plutonic equivalent TAS diagram showing whole-rock analyses from previous studies of the eastern Beartooth Mountains and this study. Fields are after Le Maitre et al. (2002).

The whole-rock chemical compositions of the meta-ultramafic rocks and serpentinites fall within the low-silica boninite, komatiite, or picrite field based on their MgO, $TiO_2$, and $SiO_2$ (wt%) (fig. 24 and 25). Based on Harker diagrams it is probable that MgO and $TiO_2$ were not mobile to any significant degree during metamorphism of these rocks, but $SiO_2$ may have been mobile based on its non-linear relation to MgO (fig. 21). Even considering the mobility of $SiO_2$ during metamorphism of these samples, they still plot within the same fields (fig. 24 and 25). The majority of rocks analyzed in previous studies of the meta-ultramafic rocks and serpentinites of the eastern Beartooths are also high in MgO (>18 wt%) and low in $TiO_2$ (<1 wt%), so they can

be classified further using the classification diagrams from Pearce and Reagan (2019) (fig. 35 and 36). Samples from previous studies fall within the boninite, picrite, and komatiite fields. Many more of the samples from previous studies fall within the boninite field than samples from this study. The apparent boninitic affinity of the chromitite pods suggests that they were likely in equilibrium with a boninitic melt (fig. 32).

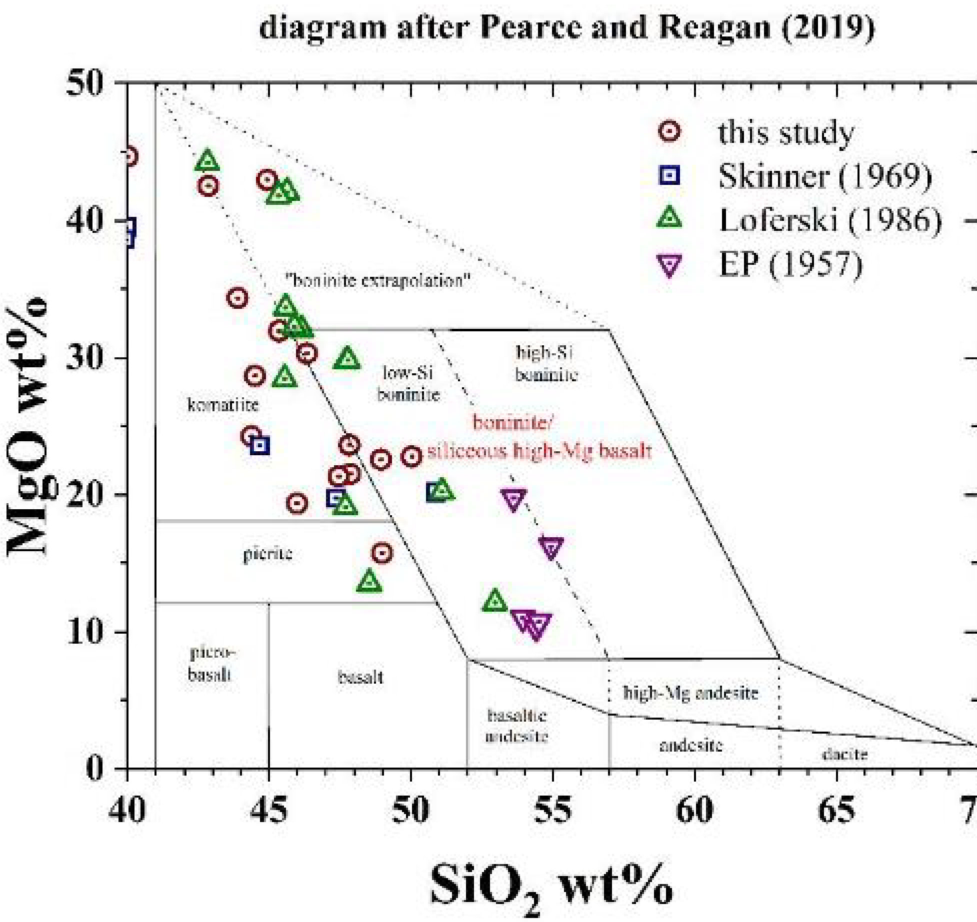



Figure 35. MgO wt% and $SiO_2$ wt% of meta-ultramafic rocks of the eastern Beartooths from this study and previous studies plotted on high-Mg mafic to ultramafic rock discrimination template from Pearce and Reagan (2019).

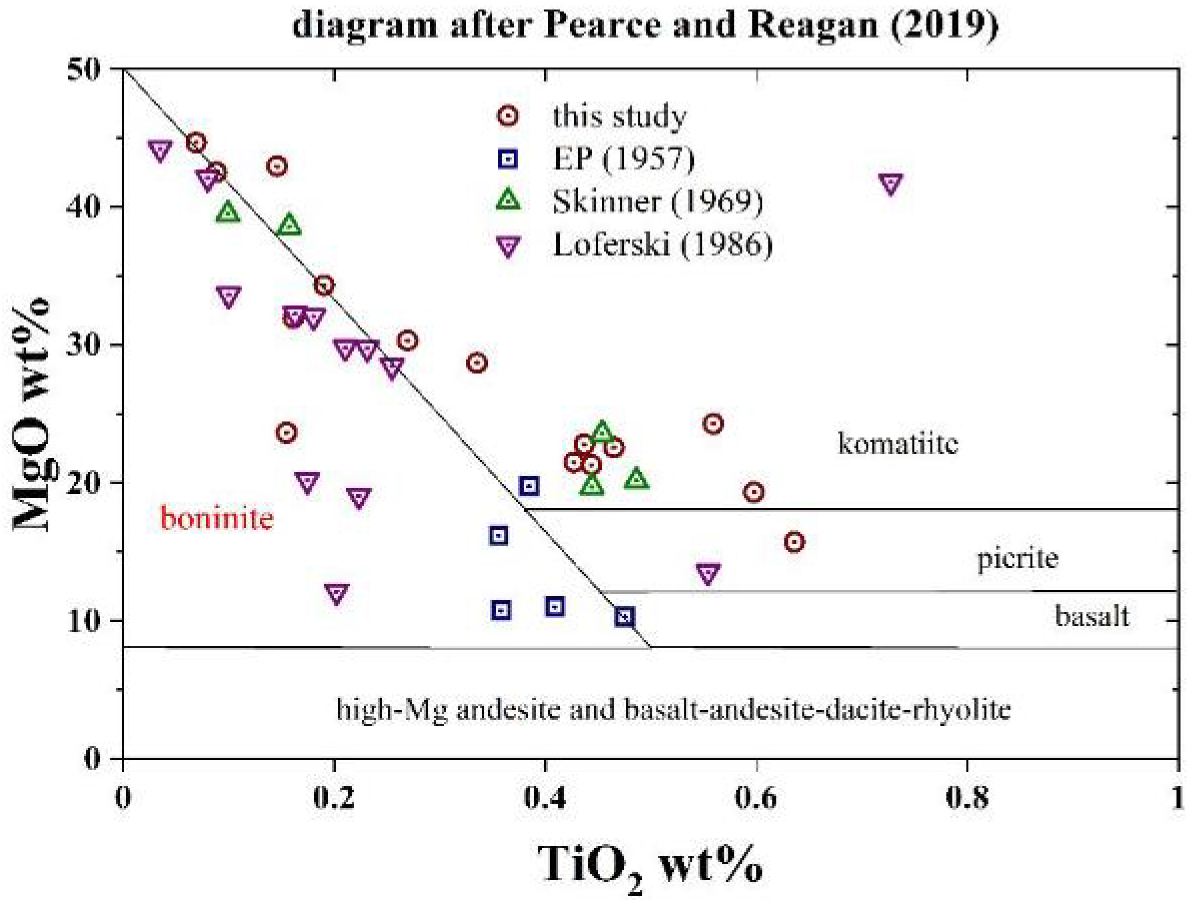
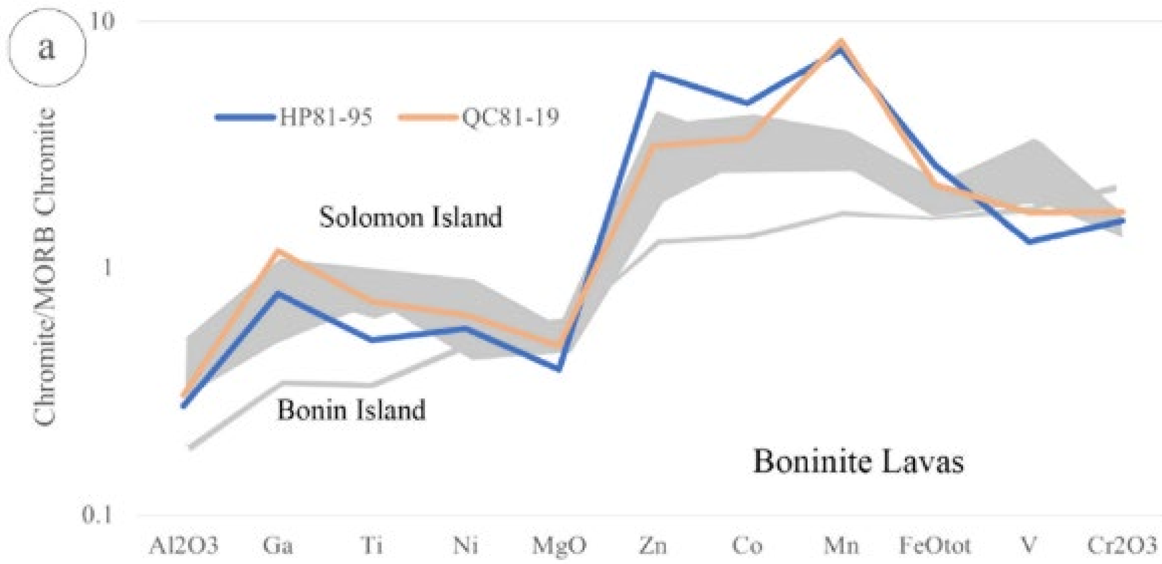



Figure 36. MgO wt% and $TiO_2$ wt% of meta-ultramafic rocks of the eastern Beartooths from this study and previous studies plotted on high-Mg mafic to ultramafic rock discrimination template from Pearce and Reagan (2019).

### 5.4. LA-ICP-MS

Trace and major elements in chromite from chromite-rich ultramafic samples HP81-95 and QC81-19 normalized to MORB chromite can be used to define development in different tectonic settings (fig. 37). Chromite from this study most closely resembles the patterns of boninitic lavas from Solomon Island, except it is relatively higher in Mn and lower in V (fig. 37a). Chromite from this study also resembles komatiitic chromite, except it is lower in Ti and higher in Mn (fig. 37b). Chromite does not closely resemble high-Al chromite from ophiolites because it is higher in Zn, Co, Mn, and $Fe_{tot}$ and lower in $Al_2O_3$ and MgO (fig. 37c).Chromite

from this study also does not closely resemble chromite from layered intrusions, in that it has relatively lower Ti and higher Zn, Co, and Mn (fig. 37d). Of the ophiolitic chromites, chromite from this study most closely resembles that of high-Cr chromite from the Thetford Mines ophiolite which is interpreted to have precipitated from the reaction of primitive boninitic melts with a depleted harzburgitic host rock (Page and Barnes, 2009) (fig. 37e). The field of chromite compositions from the Thetford Mines ophiolite has more variable compositions than that of the high-Cr chromite of the Tres Amigos ophiolite (fig. 37e and 37f). The narrow range of the Tres Amigos chromite compositions is because Thetford Mines compositions include massive, semi-massive and banded chromitite textures while the Tres Amigos ophiolite only includes compositions from massive chromitite. Chromite from massive chromite is less influenced by post-magmatic alteration because of its smaller ratio of silicate matrix to chromite (Colás et al., 2014). Chromite from samples HP81-95 and QC81-19 are considered semi-massive to massive (30-80% chromite). Chromite from these samples could be affected by alteration which would explain their high-Mn contents (Colás et al., 2014; Gonzáles-Jiménez et al., 2015).



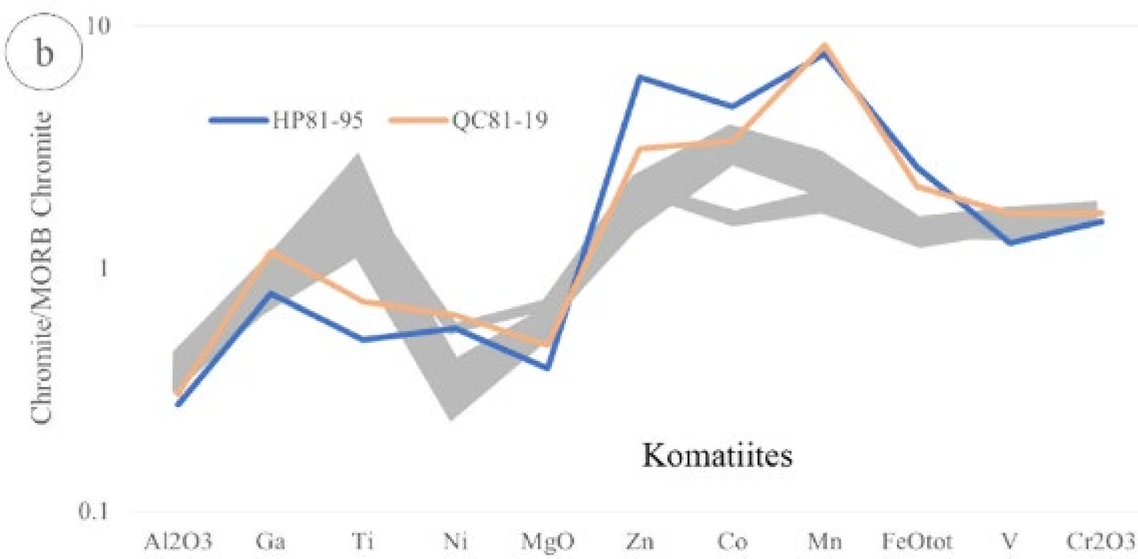
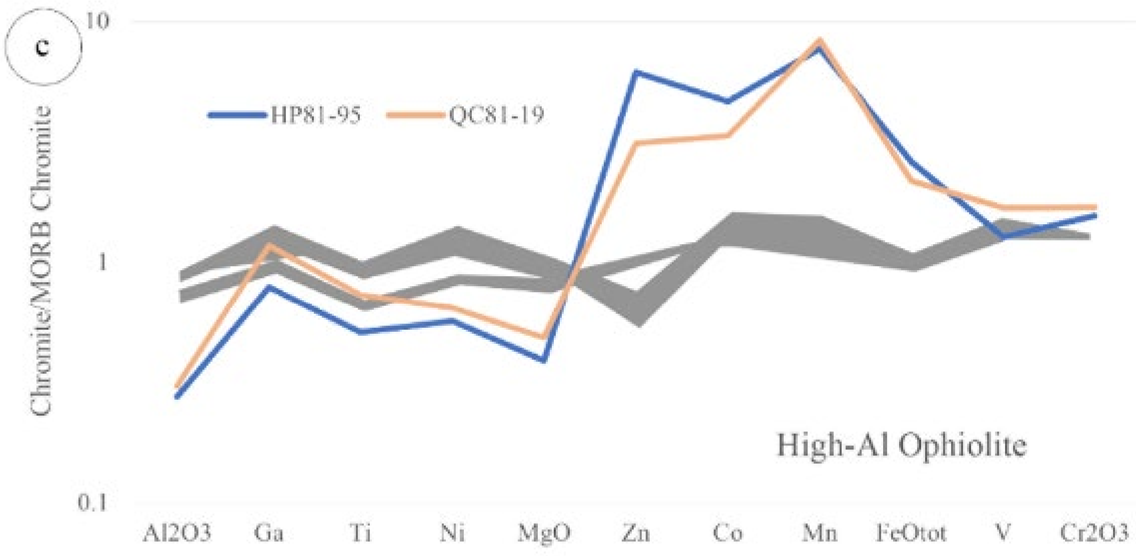
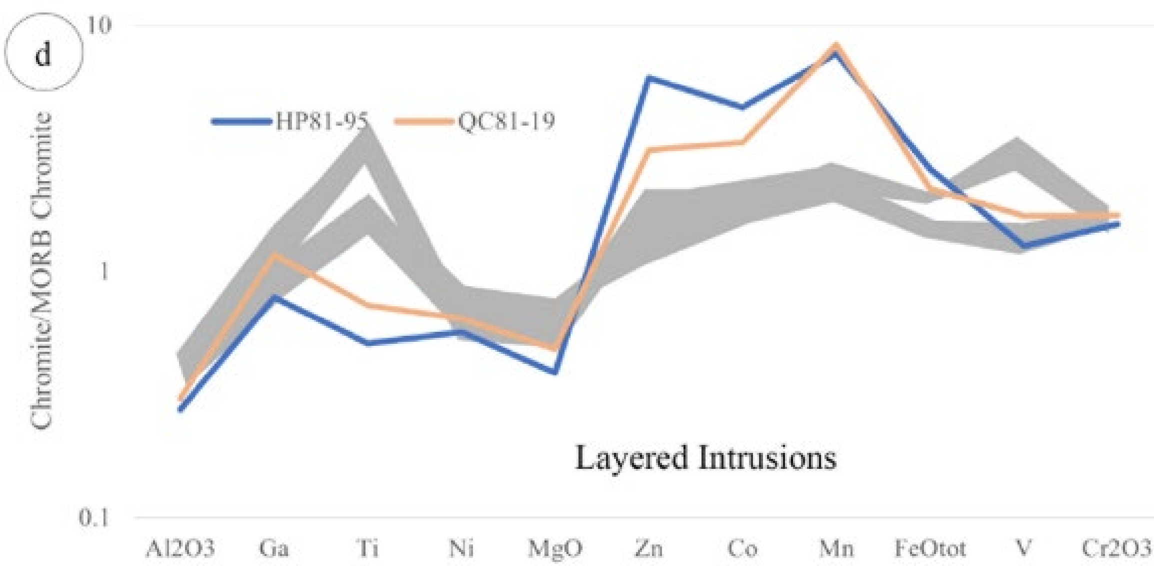




Figure 37. Chromite from chromite-rich meta-ultramafic samples HP81-95 and QC81-19 normalized to MORB chromite and compared to chromite derived from different tectonic settings. (a) Chromite from boninite lavas from Solomon Island and Bonin Island. (b) Ophiolitic high-Al chromite from Rupertina and Coto. (c) Chromite from komatiites of western Australia. (d) Chromite from the Bushveld Complex and Great Dike layered igneous intrusions. (e) Ophiolitic high-Cr chromite from the Toodos Ophiolite. (f) Ophiolitic high-Cr chromite from the Tres Amigos Ophiolite. All fields are after Gonzáles-Jiménez et al. (2015). $Al_2O_3$, MgO, $FeO_{tot}$, and $Cr_2O_3$ are from EMPA while all other elements were measured using LA-ICP-MS.

(fig. cont'd.)


c
10
1
0.1
Chromite/MORB Chromite
HP81-95
QC81-19
High-Al Ophiolite
Al2O3
Ga
Ti
Ni
MgO
Zn
Co
Mn
FeOtot
V
Cr2O3


d
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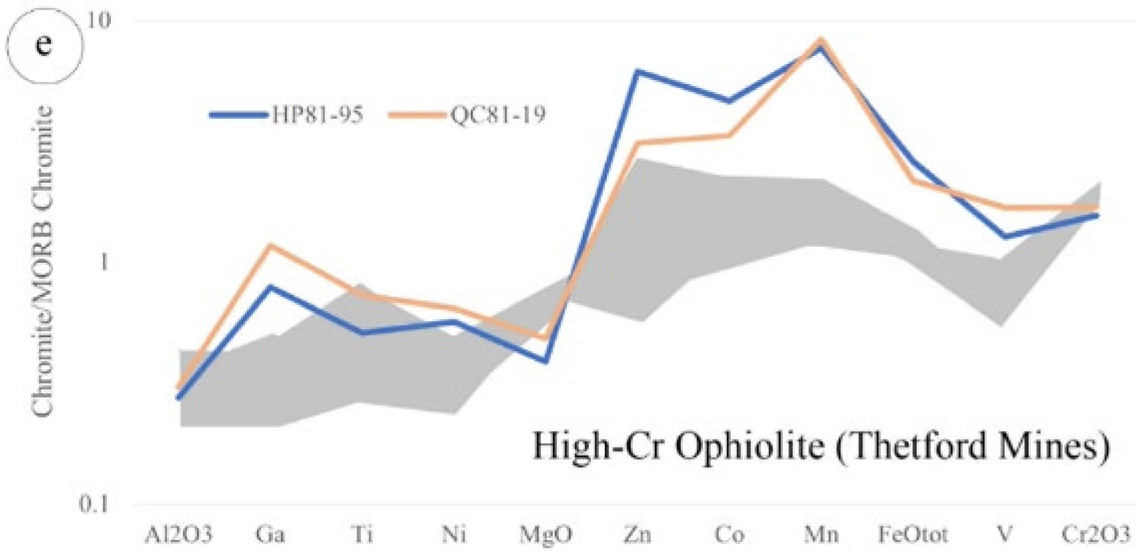
Chromite/MORB Chromite
HP81-95
QC81-19
Layered Intrusions
Al2O3
Ga
Ti
Ni
MgO
Zn
Co
Mn
FeOtot
V
Cr2O3

(fig. cont'd)


e
10
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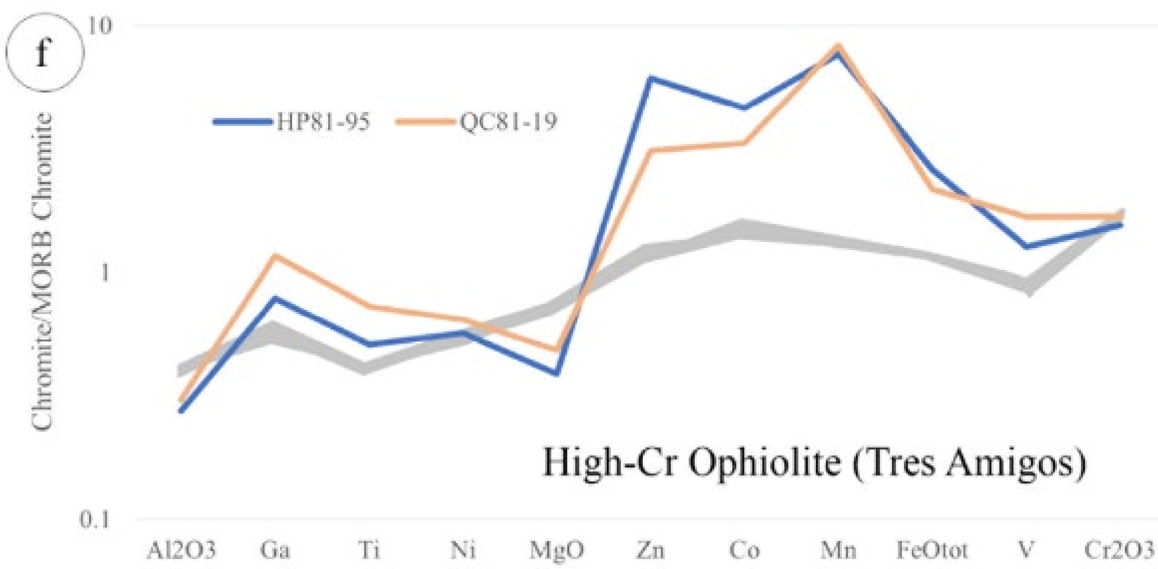
Chromite/MORB Chromite
HP81-95
QC81-19
High-Cr Ophiolite (Thetford Mines)
Al2O3
Ga
Ti
Ni
MgO
Zn
Co
Mn
FeOtot
V
Cr2O3


f
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Chromite/MORB Chromite
HP81-95
QC81-19
High-Cr Ophiolite (Tres Amigos)
Al2O3
Ga
Ti
Ni
MgO
Zn
Co
Mn
FeOtot
V
Cr2O3

# Chapter 6. Implications

The Archean meta-chromitites and associated meta-ultramafic rocks of the eastern Beartooth Mountains are derived from a subduction zone setting. Chromite in meta-chromitite samples show textures that differ from those found in layered mafic intrusions such as pull apart textures and lack of euhedral chromite. Mineral inclusions found in chromite from meta-chromitites indicate that their parent magma was rich in $H_2O$ and $CO_2$, consistent with a subduction zone source. Petrogenetic discrimination diagrams using major element chemistry of chromite provide inconclusive results, but $TiO_2$ from chromite in meta-chromitite is inconsistent with that of layered intrusions and plots within the podiform ophiolite field on discrimination diagrams. Trace element patterns of chromite from meta-chromitite samples show their similarities to boninite magmas and chromite is calculated to have crystalized in equilibrium with a boninitic magma. Meta-ultramafic samples associated with meta-chromitites plot within the boninite and komatiite fields with many more samples from previous studies plotting within the boninite field. HFSE depletions and enrichments in LILE for less modified rocks are interpreted as metasomatic modification in an arc setting.

Meta-chromitites from the eastern Beartooth Mountains are derived from the interaction of a boninite magma with their host meta-ultramafic rocks. This process is similar to the generation of high-Cr chromitite pods in modern supra-subduction-zone ophiolites (González-Jiménez et al., 2014). Although the meta-ultramafic rocks cannot be considered an ophiolite in terms of nomenclature, they closely resemble ultramafic cumulates from oceanic lithosphere formed in a supra-subduction zone that have been affected by boninitic melts. These rocks were likely formed in the forearc of an early subduction zone and then intercalated with the various

supracrustal rocks and TTG gneiss during plate convergence preceding the intrusion of the 2.8 Ga TTG rocks.

# Appendix A. Chromite EMPA Data from Meta-chromitites

| Sample # | HP20DM-03 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.00 | 0.11 | 0.00 | 0.00 | 0.00 | 0.23 | 0.00 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 |
| $TiO_2$ | 0.23 | 0.21 | 0.21 | 0.22 | 0.22 | 0.19 | 0.21 | 0.19 | 0.22 | 0.21 | 0.22 | 0.24 |
| $Al_2O_3$ | 10.44 | 11.97 | 11.62 | 11.65 | 11.72 | 12.05 | 12.20 | 12.11 | 12.91 | 11.62 | 11.59 | 11.48 |
| $Cr_2O_3$ | 54.83 | 50.43 | 50.76 | 50.56 | 50.76 | 50.26 | 50.51 | 50.27 | 49.41 | 50.60 | 50.45 | 50.34 |
| $V_2O_3$ | 0.11 | 0.12 | 0.13 | 0.09 | 0.10 | 0.10 | 0.13 | 0.10 | 0.11 | 0.11 | 0.11 | 0.11 |
| $Fe_2O_3$ (calculated) | 6.10 | 7.06 | 7.00 | 7.04 | 7.26 | 7.50 | 7.79 | 7.51 | 7.89 | 8.38 | 8.55 | 8.38 |
| FeO (calculated) | 16.59 | 19.43 | 19.34 | 19.27 | 19.25 | 19.48 | 19.47 | 19.48 | 19.20 | 19.46 | 19.43 | 19.53 |
| MnO | 0.33 | 0.32 | 0.32 | 0.29 | 0.35 | 0.35 | 0.32 | 0.34 | 0.34 | 0.33 | 0.31 | 0.34 |
| MgO | 10.90 | 9.06 | 8.93 | 8.97 | 9.05 | 9.29 | 9.20 | 9.28 | 9.35 | 9.14 | 9.17 | 9.01 |
| NiO | 0.09 | 0.11 | 0.12 | 0.07 | 0.08 | 0.10 | 0.12 | 0.11 | 0.15 | 0.14 | 0.14 | 0.14 |
| ZnO | 0.07 | 0.14 | 0.10 | 0.10 | 0.15 | 0.10 | 0.12 | 0.16 | 0.10 | 0.11 | 0.10 | 0.08 |
| Total | 99.68 | 98.94 | 98.52 | 98.26 | 98.93 | 99.66 | 100.06 | 99.77 | 99.68 | 100.10 | 100.06 | 99.65 |
| | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | |
| | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| Al | 0.41 | 0.47 | 0.46 | 0.46 | 0.46 | 0.47 | 0.47 | 0.47 | 0.50 | 0.45 | 0.45 | 0.45 |
| $Cr^{3+}$ | 1.43 | 1.33 | 1.35 | 1.35 | 1.34 | 1.32 | 1.32 | 1.31 | 1.29 | 1.32 | 1.32 | 1.32 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.15 | 0.18 | 0.18 | 0.18 | 0.18 | 0.19 | 0.19 | 0.19 | 0.20 | 0.21 | 0.21 | 0.21 |
| $Fe^{2+}$ | 0.46 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 | 0.53 | 0.54 | 0.54 | 0.54 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.54 | 0.45 | 0.45 | 0.45 | 0.45 | 0.46 | 0.45 | 0.46 | 0.46 | 0.45 | 0.45 | 0.45 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.98 | 1.99 | 1.98 | 1.99 | 1.99 | 1.99 | 1.99 |
| Total 2+ cations | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.54 | 0.45 | 0.45 | 0.45 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.45 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.46 | 0.55 | 0.55 | 0.55 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 | 0.55 |
| Cr/(Cr+Al) | 0.78 | 0.74 | 0.75 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.72 | 0.74 | 0.74 | 0.75 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.72 | 0.67 | 0.68 | 0.68 | 0.68 | 0.67 | 0.66 | 0.67 | 0.65 | 0.67 | 0.67 | 0.67 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.20 | 0.24 | 0.23 | 0.23 | 0.23 | 0.24 | 0.24 | 0.24 | 0.25 | 0.23 | 0.23 | 0.23 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.08 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.10 | 0.09 | 0.10 | 0.11 | 0.11 | 0.11 |
| $Fe^{3+}/Fe_{total}$ | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.26 | 0.26 | 0.26 | 0.27 | 0.28 | 0.28 | 0.28 |

| Sample # | HP20DM-02 | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 |
| $TiO_2$ | 0.16 | 0.13 | 0.16 | 0.16 | 0.15 | 0.16 | 0.21 | 0.20 | 0.21 | 0.20 | 0.22 | 0.22 | 0.22 | 0.21 | 0.20 | 0.23 | 0.26 | 0.26 | 0.24 |
| $Al_2O_3$ | 13.80 | 12.14 | 12.45 | 13.17 | 11.42 | 13.34 | 9.65 | 9.60 | 9.54 | 12.03 | 12.39 | 12.29 | 12.27 | 12.23 | 12.09 | 11.96 | 11.18 | 11.86 | 10.43 |
| $Cr_2O_3$ | 52.17 | 54.22 | 53.77 | 52.82 | 54.71 | 52.48 | 55.48 | 55.69 | 56.14 | 53.59 | 52.96 | 52.72 | 52.81 | 53.02 | 53.00 | 52.88 | 53.67 | 52.91 | 54.67 |
| $V_2O_3$ | 0.08 | 0.09 | 0.09 | 0.07 | 0.09 | 0.09 | 0.09 | 0.08 | 0.09 | 0.09 | 0.09 | 0.09 | 0.08 | 0.10 | 0.11 | 0.09 | 0.10 | 0.07 | 0.08 |
| $Fe_2O_3$ (calculated) | 5.48 | 5.10 | 5.26 | 5.54 | 5.21 | 5.24 | 5.64 | 5.63 | 5.29 | 6.16 | 6.26 | 6.07 | 6.41 | 6.24 | 6.37 | 6.72 | 6.38 | 6.76 | 6.35 |
| FeO (calculated) | 15.98 | 16.38 | 16.38 | 16.05 | 16.46 | 15.98 | 16.67 | 16.79 | 16.90 | 16.30 | 16.07 | 16.05 | 16.21 | 16.36 | 16.23 | 16.23 | 16.27 | 16.38 | 16.36 |
| MnO | 0.33 | 0.34 | 0.36 | 0.32 | 0.37 | 0.33 | 0.37 | 0.38 | 0.38 | 0.32 | 0.35 | 0.32 | 0.34 | 0.33 | 0.34 | 0.37 | 0.35 | 0.32 | 0.33 |
| MgO | 11.61 | 11.13 | 11.24 | 11.50 | 10.97 | 11.46 | 10.52 | 10.48 | 10.44 | 11.33 | 11.45 | 11.31 | 11.34 | 11.25 | 11.30 | 11.27 | 11.13 | 11.28 | 11.03 |
| NiO | 0.08 | 0.11 | 0.09 | 0.09 | 0.06 | 0.08 | 0.09 | 0.08 | 0.08 | 0.11 | 0.10 | 0.09 | 0.09 | 0.09 | 0.11 | 0.11 | 0.11 | 0.13 | 0.11 |
| ZnO | 0.08 | 0.10 | 0.08 | 0.09 | 0.12 | 0.07 | 0.12 | 0.08 | 0.10 | 0.08 | 0.09 | 0.15 | 0.09 | 0.09 | 0.05 | 0.11 | 0.08 | 0.09 | 0.07 |
| Total | 99.78 | 99.73 | 99.88 | 99.82 | 99.55 | 99.25 | 98.83 | 99.01 | 99.15 | 100.20 | 99.97 | 99.30 | 99.85 | 99.90 | 99.79 | 99.95 | 99.52 | 100.12 | 99.67 |
| | | | | | | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Al | 0.53 | 0.47 | 0.48 | 0.50 | 0.44 | 0.51 | 0.38 | 0.38 | 0.37 | 0.46 | 0.47 | 0.47 | 0.47 | 0.47 | 0.46 | 0.46 | 0.43 | 0.45 | 0.40 |
| $Cr^{3+}$ | 1.33 | 1.40 | 1.38 | 1.35 | 1.42 | 1.35 | 1.47 | 1.47 | 1.48 | 1.38 | 1.36 | 1.36 | 1.36 | 1.36 | 1.37 | 1.36 | 1.39 | 1.36 | 1.42 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.14 | 0.14 | 0.13 | 0.15 | 0.15 | 0.15 | 0.16 | 0.15 | 0.16 | 0.16 | 0.16 | 0.17 | 0.16 |
| $Fe^{2+}$ | 0.43 | 0.45 | 0.45 | 0.43 | 0.45 | 0.43 | 0.47 | 0.47 | 0.47 | 0.44 | 0.44 | 0.44 | 0.44 | 0.45 | 0.44 | 0.44 | 0.45 | 0.45 | 0.45 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.56 | 0.54 | 0.54 | 0.56 | 0.54 | 0.56 | 0.52 | 0.52 | 0.52 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.54 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 1.99 | 2.00 | 1.99 | 2.00 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 |
| Total 2+ cations | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.01 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| | | | | | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.56 | 0.55 | 0.55 | 0.56 | 0.54 | 0.56 | 0.53 | 0.53 | 0.52 | 0.55 | 0.56 | 0.56 | 0.56 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.44 | 0.45 | 0.45 | 0.44 | 0.46 | 0.44 | 0.47 | 0.47 | 0.48 | 0.45 | 0.44 | 0.44 | 0.44 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| Cr/(Cr+Al) | 0.72 | 0.75 | 0.74 | 0.73 | 0.76 | 0.73 | 0.79 | 0.80 | 0.80 | 0.75 | 0.74 | 0.74 | 0.74 | 0.74 | 0.75 | 0.75 | 0.76 | 0.75 | 0.78 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.67 | 0.70 | 0.70 | 0.68 | 0.71 | 0.68 | 0.74 | 0.74 | 0.74 | 0.69 | 0.68 | 0.69 | 0.68 | 0.69 | 0.69 | 0.69 | 0.70 | 0.69 | 0.72 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.26 | 0.23 | 0.24 | 0.25 | 0.22 | 0.26 | 0.19 | 0.19 | 0.19 | 0.23 | 0.24 | 0.24 | 0.24 | 0.24 | 0.23 | 0.23 | 0.22 | 0.23 | 0.20 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.07 | 0.06 | 0.06 | 0.07 | 0.06 | 0.06 | 0.07 | 0.07 | 0.07 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| $Fe^{3+}/Fe_{total}$ | 0.24 | 0.22 | 0.22 | 0.24 | 0.22 | 0.23 | 0.23 | 0.23 | 0.22 | 0.25 | 0.26 | 0.25 | 0.26 | 0.26 | 0.26 | 0.27 | 0.26 | 0.27 | 0.26 |

| Sample # | HP20DM-04 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 |
| $TiO_2$ | 0.19 | 0.21 | 0.23 | 0.20 | 0.20 | 0.22 | 0.23 | 0.21 |
| $Al_2O_3$ | 12.43 | 12.45 | 12.49 | 12.49 | 12.40 | 12.65 | 12.61 | 12.55 |
| $Cr_2O_3$ | 50.41 | 50.54 | 50.58 | 50.50 | 50.50 | 50.58 | 50.87 | 50.50 |
| $V_2O_3$ | 0.09 | 0.12 | 0.09 | 0.09 | 0.09 | 0.09 | 0.11 | 0.09 |
| $Fe_2O_3$ (calculated) | 7.82 | 7.65 | 7.79 | 7.85 | 7.62 | 7.62 | 7.43 | 7.57 |
| FeO (calculated) | 18.38 | 18.53 | 18.55 | 18.41 | 18.43 | 18.27 | 18.58 | 18.38 |
| MnO | 0.29 | 0.33 | 0.32 | 0.30 | 0.34 | 0.25 | 0.29 | 0.30 |
| MgO | 9.89 | 9.82 | 9.87 | 9.93 | 9.81 | 10.08 | 9.93 | 9.97 |
| NiO | 0.12 | 0.11 | 0.12 | 0.13 | 0.11 | 0.11 | 0.12 | 0.11 |
| ZnO | 0.10 | 0.07 | 0.11 | 0.08 | 0.09 | 0.10 | 0.07 | 0.02 |
| Total | 99.72 | 99.83 | 100.15 | 99.97 | 99.59 | 99.97 | 100.22 | 99.71 |
| | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | |
| | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| Al | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.49 | 0.49 | 0.49 |
| $Cr^{3+}$ | 1.31 | 1.31 | 1.31 | 1.31 | 1.32 | 1.31 | 1.32 | 1.31 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.18 | 0.19 |
| $Fe^{2+}$ | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.50 | 0.51 | 0.51 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.49 | 0.48 | 0.48 | 0.49 | 0.48 | 0.49 | 0.48 | 0.49 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 2.00 | 1.99 | 1.99 | 2.00 | 1.99 | 1.99 | 1.99 | 1.99 |
| Total 2+ cations | 1.00 | 1.01 | 1.01 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 |
| | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.50 | 0.49 | 0.49 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.50 | 0.51 | 0.51 |
| Cr/(Cr+Al) | 0.73 | 0.73 | 0.73 | 0.73 | 0.73 | 0.73 | 0.73 | 0.73 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.25 | 0.24 | 0.24 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.09 | 0.09 | 0.09 |
| $Fe^{3+}/Fe_{total}$ | 0.28 | 0.27 | 0.27 | 0.28 | 0.27 | 0.27 | 0.26 | 0.27 |

| Sample # | HP20DM-05 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.01 |
| $TiO_2$ | 0.20 | 0.20 | 0.14 | 0.12 | 0.12 | 0.18 | 0.17 | 0.14 | 0.21 | 0.24 | 0.22 | 0.25 | 0.21 | 0.22 |
| $Al_2O_3$ | 12.90 | 13.27 | 12.31 | 13.02 | 11.00 | 10.59 | 10.46 | 13.64 | 13.64 | 13.44 | 13.69 | 13.61 | 13.74 | 13.62 |
| $Cr_2O_3$ | 53.98 | 53.63 | 53.13 | 53.90 | 55.05 | 56.68 | 57.11 | 51.69 | 52.91 | 53.03 | 52.89 | 53.11 | 52.88 | 52.95 |
| $V_2O_3$ | 0.10 | 0.13 | 0.10 | 0.12 | 0.09 | 0.10 | 0.10 | 0.10 | 0.11 | 0.11 | 0.10 | 0.11 | 0.11 | 0.11 |
| $Fe_2O_3$ (calculated) | 5.00 | 5.24 | 5.67 | 5.26 | 5.09 | 5.00 | 4.64 | 6.12 | 5.38 | 5.57 | 5.79 | 5.70 | 5.68 | 5.66 |
| FeO (calculated) | 17.44 | 17.30 | 20.05 | 17.12 | 21.47 | 17.90 | 18.22 | 18.84 | 16.83 | 16.93 | 17.07 | 17.13 | 17.01 | 17.12 |
| MnO | 0.40 | 0.38 | 0.56 | 0.38 | 0.64 | 0.43 | 0.41 | 0.51 | 0.40 | 0.34 | 0.39 | 0.39 | 0.39 | 0.35 |
| MgO | 10.82 | 11.03 | 8.93 | 11.03 | 7.90 | 10.33 | 10.12 | 9.92 | 11.24 | 11.28 | 11.29 | 11.28 | 11.32 | 11.22 |
| NiO | 0.07 | 0.08 | 0.07 | 0.06 | 0.02 | 0.05 | 0.05 | 0.07 | 0.08 | 0.09 | 0.05 | 0.05 | 0.09 | 0.10 |
| ZnO | 0.07 | 0.06 | 0.05 | 0.10 | 0.12 | 0.10 | 0.09 | 0.03 | 0.15 | 0.07 | 0.06 | 0.07 | 0.09 | 0.09 |
| Total | 100.97 | 101.31 | 101.01 | 101.11 | 101.50 | 101.36 | 101.38 | 101.08 | 100.94 | 101.10 | 101.53 | 101.70 | 101.55 | 101.45 |
| | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Al | 0.49 | 0.50 | 0.48 | 0.49 | 0.43 | 0.41 | 0.40 | 0.52 | 0.52 | 0.51 | 0.51 | 0.51 | 0.52 | 0.51 |
| $Cr^{3+}$ | 1.38 | 1.36 | 1.38 | 1.37 | 1.44 | 1.46 | 1.47 | 1.32 | 1.34 | 1.34 | 1.33 | 1.34 | 1.33 | 1.34 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.12 | 0.13 | 0.14 | 0.13 | 0.13 | 0.12 | 0.11 | 0.15 | 0.13 | 0.13 | 0.14 | 0.14 | 0.14 | 0.14 |
| $Fe^{2+}$ | 0.47 | 0.46 | 0.55 | 0.46 | 0.59 | 0.49 | 0.50 | 0.51 | 0.45 | 0.45 | 0.46 | 0.46 | 0.45 | 0.46 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.52 | 0.53 | 0.44 | 0.53 | 0.39 | 0.50 | 0.49 | 0.48 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 | 0.53 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 |
| Total 2+ cations | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.53 | 0.53 | 0.44 | 0.53 | 0.40 | 0.51 | 0.50 | 0.48 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.47 | 0.47 | 0.56 | 0.47 | 0.60 | 0.49 | 0.50 | 0.52 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 |
| Cr/(Cr+Al) | 0.74 | 0.73 | 0.74 | 0.74 | 0.77 | 0.78 | 0.79 | 0.72 | 0.72 | 0.73 | 0.72 | 0.72 | 0.72 | 0.72 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.69 | 0.68 | 0.69 | 0.69 | 0.72 | 0.73 | 0.74 | 0.66 | 0.68 | 0.68 | 0.67 | 0.67 | 0.67 | 0.67 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.25 | 0.25 | 0.24 | 0.25 | 0.21 | 0.20 | 0.20 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.06 | 0.06 | 0.07 | 0.06 | 0.06 | 0.06 | 0.06 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| $Fe^{3+}/Fe_{total}$ | 0.21 | 0.21 | 0.20 | 0.22 | 0.18 | 0.20 | 0.19 | 0.23 | 0.22 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Quality control: oxide total test | | | | | | | | | | | Caution: high total | Caution: high total | Caution: high total | |

| Sample # | HP20DM-06 | | | | | | | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| $SiO_2$ | 0.00 | 0.00 | 0.27 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $TiO_2$ | 0.19 | 0.20 | 0.21 | 0.18 | 0.18 | 0.19 | 0.15 | 0.16 | 0.19 | 0.20 | 0.19 | 0.18 | 0.19 | 0.17 | 0.15 | 0.20 | 0.18 |
| $Al_2O_3$ | 12.82 | 12.56 | 12.99 | 13.01 | 13.09 | 12.58 | 12.80 | 12.24 | 12.88 | 13.07 | 12.97 | 13.15 | 13.08 | 13.58 | 13.18 | 13.49 | 13.41 |
| $Cr_2O_3$ | 53.84 | 53.18 | 52.27 | 52.77 | 52.58 | 52.78 | 53.12 | 53.79 | 52.65 | 52.55 | 52.68 | 52.59 | 53.23 | 52.02 | 52.78 | 52.14 | 52.19 |
| $V_2O_3$ | 0.10 | 0.11 | 0.10 | 0.09 | 0.10 | 0.10 | 0.10 | 0.10 | 0.09 | 0.10 | 0.09 | 0.09 | 0.09 | 0.11 | 0.10 | 0.12 | 0.12 |
| $Fe_2O_3$ (calculated) | 5.29 | 6.36 | 5.97 | 6.42 | 6.37 | 6.35 | 5.88 | 6.19 | 6.51 | 6.52 | 6.37 | 6.27 | 5.81 | 6.19 | 5.66 | 6.34 | 6.60 |
| FeO (calculated) | 18.54 | 18.68 | 18.96 | 18.65 | 18.78 | 19.09 | 19.51 | 18.82 | 18.79 | 18.74 | 18.69 | 18.64 | 18.77 | 18.47 | 18.98 | 18.54 | 18.56 |
| MnO | 0.44 | 0.48 | 0.45 | 0.46 | 0.46 | 0.48 | 0.54 | 0.49 | 0.46 | 0.44 | 0.48 | 0.44 | 0.48 | 0.43 | 0.48 | 0.42 | 0.48 |
| MgO | 10.11 | 10.02 | 10.11 | 10.08 | 10.03 | 9.68 | 9.44 | 9.90 | 9.96 | 10.11 | 10.06 | 10.10 | 10.06 | 10.17 | 9.77 | 10.23 | 10.22 |
| NiO | 0.16 | 0.16 | 0.14 | 0.15 | 0.13 | 0.15 | 0.13 | 0.15 | 0.16 | 0.15 | 0.13 | 0.13 | 0.13 | 0.15 | 0.13 | 0.15 | 0.17 |
| ZnO | 0.09 | 0.09 | 0.06 | 0.14 | 0.08 | 0.08 | 0.09 | 0.08 | 0.12 | 0.07 | 0.07 | 0.09 | 0.06 | 0.12 | 0.09 | 0.08 | 0.04 |
| Total | 101.58 | 101.83 | 101.51 | 101.96 | 101.80 | 101.49 | 101.77 | 101.92 | 101.81 | 101.95 | 101.72 | 101.69 | 101.90 | 101.41 | 101.32 | 101.70 | 101.97 |
| | | | | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Al | 0.49 | 0.48 | 0.49 | 0.49 | 0.50 | 0.48 | 0.49 | 0.47 | 0.49 | 0.50 | 0.49 | 0.50 | 0.50 | 0.52 | 0.50 | 0.51 | 0.51 |
| $Cr^{3+}$ | 1.37 | 1.36 | 1.33 | 1.34 | 1.34 | 1.35 | 1.36 | 1.37 | 1.34 | 1.33 | 1.34 | 1.34 | 1.35 | 1.32 | 1.35 | 1.32 | 1.32 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.13 | 0.15 | 0.14 | 0.16 | 0.15 | 0.16 | 0.14 | 0.15 | 0.16 | 0.16 | 0.15 | 0.15 | 0.14 | 0.15 | 0.14 | 0.15 | 0.16 |
| $Fe^{2+}$ | 0.50 | 0.50 | 0.51 | 0.50 | 0.51 | 0.52 | 0.53 | 0.51 | 0.51 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.51 | 0.50 | 0.50 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.49 | 0.48 | 0.49 | 0.48 | 0.48 | 0.47 | 0.46 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.49 | 0.47 | 0.49 | 0.49 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 2.00 | 2.00 | 1.98 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Total 2+ cations | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | | | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.47 | 0.46 | 0.48 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.50 | 0.48 | 0.50 | 0.50 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.53 | 0.54 | 0.52 | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.50 | 0.52 | 0.50 | 0.50 |
| Cr/(Cr+Al) | 0.74 | 0.74 | 0.73 | 0.73 | 0.73 | 0.74 | 0.74 | 0.75 | 0.73 | 0.73 | 0.73 | 0.73 | 0.73 | 0.72 | 0.73 | 0.72 | 0.72 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.69 | 0.68 | 0.68 | 0.67 | 0.67 | 0.68 | 0.68 | 0.69 | 0.67 | 0.67 | 0.67 | 0.67 | 0.68 | 0.67 | 0.68 | 0.67 | 0.67 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.25 | 0.24 | 0.25 | 0.25 | 0.25 | 0.24 | 0.25 | 0.23 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.26 | 0.25 | 0.26 | 0.25 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.06 | 0.08 | 0.07 | 0.08 | 0.08 | 0.08 | 0.07 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.07 | 0.08 | 0.07 | 0.08 | 0.08 |
| $Fe^{3+}/Fe_{total}$ | 0.20 | 0.23 | 0.22 | 0.24 | 0.23 | 0.23 | 0.21 | 0.23 | 0.24 | 0.24 | 0.23 | 0.23 | 0.22 | 0.23 | 0.21 | 0.24 | 0.24 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| Quality control: oxide total test | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | | | Caution: high total | Caution: high total |

| Sample # | HP20DM-07 | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 |
| $TiO_2$ | 0.23 | 0.21 | 0.19 | 0.18 | 0.16 | 0.17 | 0.16 | 0.17 | 0.20 | 0.19 | 0.17 | 0.22 | 0.24 | 0.25 | 0.27 | 0.23 | 0.21 |
| $Al_2O_3$ | 13.15 | 13.57 | 10.82 | 11.41 | 13.49 | 12.63 | 13.68 | 12.28 | 12.36 | 10.68 | 10.87 | 10.73 | 13.12 | 12.76 | 12.90 | 12.09 | 13.66 |
| $Cr_2O_3$ | 52.42 | 51.41 | 55.12 | 54.15 | 51.60 | 52.70 | 51.64 | 52.30 | 52.03 | 54.99 | 54.76 | 55.14 | 51.83 | 53.30 | 53.05 | 52.57 | 51.83 |
| $V_2O_3$ | 0.11 | 0.12 | 0.10 | 0.11 | 0.12 | 0.10 | 0.09 | 0.11 | 0.13 | 0.10 | 0.11 | 0.09 | 0.12 | 0.11 | 0.10 | 0.11 | 0.11 |
| $Nb_2O_5$ | | | | | | | | | | | | | | | | | |
| $Fe_2O_3$ (calculated) | 6.12 | 6.55 | 5.83 | 5.84 | 6.48 | 6.24 | 6.60 | 6.52 | 6.95 | 5.82 | 6.00 | 5.86 | 6.40 | 6.18 | 6.16 | 6.81 | 6.39 |
| FeO (calculated) | 17.67 | 17.32 | 18.35 | 17.95 | 18.83 | 17.76 | 17.92 | 20.08 | 18.74 | 18.21 | 17.99 | 18.08 | 17.54 | 17.78 | 17.69 | 17.29 | 18.20 |
| MnO | 0.41 | 0.41 | 0.45 | 0.42 | 0.57 | 0.41 | 0.44 | 0.65 | 0.51 | 0.45 | 0.44 | 0.47 | 0.41 | 0.44 | 0.41 | 0.41 | 0.52 |
| MgO | 10.69 | 10.87 | 9.98 | 10.18 | 9.90 | 10.50 | 10.58 | 8.88 | 9.80 | 9.96 | 10.16 | 10.12 | 10.66 | 10.71 | 10.76 | 10.77 | 10.41 |
| NiO | 0.10 | 0.11 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.08 | 0.07 | 0.07 | 0.05 | 0.06 | 0.08 | 0.06 | 0.08 | 0.08 | 0.09 |
| CoO | | | | | | | | | | | | | | | | | |
| ZnO | 0.03 | 0.03 | 0.04 | 0.06 | 0.06 | 0.03 | 0.08 | 0.03 | 0.05 | 0.04 | 0.00 | 0.06 | 0.08 | 0.11 | 0.12 | 0.08 | 0.08 |
| Total | 100.94 | 100.59 | 100.93 | 100.36 | 101.28 | 100.59 | 101.24 | 101.10 | 100.84 | 100.49 | 100.55 | 100.83 | 100.47 | 101.69 | 101.55 | 100.49 | 101.50 |
| | | | | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 |
| Al | 0.50 | 0.52 | 0.42 | 0.44 | 0.51 | 0.48 | 0.52 | 0.47 | 0.48 | 0.41 | 0.42 | 0.41 | 0.50 | 0.48 | 0.49 | 0.46 | 0.52 |
| $Cr^{3+}$ | 1.34 | 1.31 | 1.43 | 1.40 | 1.32 | 1.35 | 1.31 | 1.35 | 1.34 | 1.43 | 1.42 | 1.43 | 1.33 | 1.35 | 1.35 | 1.35 | 1.32 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Nb^{5+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.15 | 0.16 | 0.14 | 0.14 | 0.16 | 0.15 | 0.16 | 0.16 | 0.17 | 0.14 | 0.15 | 0.14 | 0.16 | 0.15 | 0.15 | 0.17 | 0.15 |
| $Fe^{2+}$ | 0.48 | 0.47 | 0.50 | 0.49 | 0.51 | 0.48 | 0.48 | 0.55 | 0.51 | 0.50 | 0.49 | 0.50 | 0.48 | 0.48 | 0.48 | 0.47 | 0.49 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.51 | 0.52 | 0.49 | 0.50 | 0.48 | 0.51 | 0.51 | 0.43 | 0.48 | 0.49 | 0.50 | 0.49 | 0.52 | 0.51 | 0.52 | 0.52 | 0.50 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Co^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 1.99 | 1.99 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 2.00 |
| Total 2+ cations | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.00 |
| | | | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.52 | 0.53 | 0.49 | 0.50 | 0.48 | 0.51 | 0.51 | 0.44 | 0.48 | 0.49 | 0.50 | 0.50 | 0.52 | 0.52 | 0.52 | 0.53 | 0.50 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.48 | 0.47 | 0.51 | 0.50 | 0.52 | 0.49 | 0.49 | 0.56 | 0.52 | 0.51 | 0.50 | 0.50 | 0.48 | 0.48 | 0.48 | 0.47 | 0.50 |
| $Cr/(Cr+Al)$ | 0.73 | 0.72 | 0.77 | 0.76 | 0.72 | 0.74 | 0.72 | 0.74 | 0.74 | 0.78 | 0.77 | 0.78 | 0.73 | 0.74 | 0.73 | 0.74 | 0.72 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.67 | 0.66 | 0.72 | 0.71 | 0.66 | 0.68 | 0.66 | 0.68 | 0.68 | 0.72 | 0.71 | 0.72 | 0.67 | 0.68 | 0.68 | 0.68 | 0.66 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.25 | 0.26 | 0.21 | 0.22 | 0.26 | 0.24 | 0.26 | 0.24 | 0.24 | 0.21 | 0.21 | 0.21 | 0.25 | 0.24 | 0.25 | 0.23 | 0.26 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.07 | 0.08 | 0.07 | 0.07 | 0.08 | 0.08 | 0.08 | 0.08 | 0.09 | 0.07 | 0.07 | 0.07 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| $Fe^{3+}/Fe_{total}$ | 0.24 | 0.25 | 0.22 | 0.23 | 0.24 | 0.24 | 0.25 | 0.23 | 0.25 | 0.22 | 0.23 | 0.23 | 0.25 | 0.24 | 0.24 | 0.26 | 0.24 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| Quality control: oxide total test | | | | | | | | | | | | | | Caution: high total | Caution: high total | | |

| Sample # | HP20DM-08 | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.00 | 0.00 | 0.10 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $TiO_2$ | 0.08 | 0.07 | 0.09 | 0.09 | 0.09 | 0.09 | 0.10 | 0.09 | 0.07 | 0.07 | 0.08 | 0.10 | 0.09 | 0.08 | 0.07 | 0.09 |
| $Al_2O_3$ | 7.29 | 7.07 | 7.43 | 7.37 | 7.50 | 7.36 | 7.15 | 6.83 | 6.84 | 6.87 | 6.92 | 7.28 | 7.01 | 6.91 | 6.89 | 6.84 |
| $Cr_2O_3$ | 51.22 | 50.60 | 49.60 | 48.99 | 49.28 | 49.49 | 49.09 | 48.47 | 49.87 | 49.83 | 49.98 | 48.45 | 48.78 | 49.85 | 48.96 | 48.45 |
| $V_2O_3$ | 0.10 | 0.10 | 0.12 | 0.08 | 0.11 | 0.10 | 0.11 | 0.10 | 0.10 | 0.09 | 0.09 | 0.09 | 0.10 | 0.10 | 0.09 | 0.08 |
| $Fe_2O_3$ (calculated) | 9.99 | 12.49 | 13.07 | 13.25 | 13.18 | 12.89 | 12.97 | 13.71 | 13.09 | 13.19 | 13.00 | 13.28 | 13.57 | 13.28 | 13.50 | 13.69 |
| FeO (calculated) | 27.45 | 26.09 | 26.12 | 27.37 | 25.93 | 26.34 | 27.52 | 28.36 | 26.76 | 27.45 | 26.69 | 28.33 | 28.28 | 27.46 | 28.24 | 28.21 |
| MnO | 1.11 | 0.83 | 0.77 | 1.60 | 0.84 | 1.11 | 1.75 | 1.78 | 0.83 | 1.30 | 0.80 | 1.79 | 1.75 | 1.26 | 1.76 | 1.72 |
| MgO | 2.86 | 4.17 | 4.36 | 2.92 | 4.29 | 3.80 | 2.63 | 2.00 | 3.64 | 3.01 | 3.74 | 2.09 | 2.17 | 3.08 | 2.17 | 2.11 |
| NiO | 0.09 | 0.08 | 0.11 | 0.09 | 0.10 | 0.09 | 0.08 | 0.09 | 0.12 | 0.09 | 0.10 | 0.10 | 0.10 | 0.10 | 0.08 | 0.10 |
| ZnO | 0.32 | 0.29 | 0.25 | 0.26 | 0.27 | 0.29 | 0.29 | 0.33 | 0.31 | 0.31 | 0.31 | 0.30 | 0.33 | 0.29 | 0.31 | 0.30 |
| Total | 100.53 | 101.78 | 102.01 | 102.02 | 101.58 | 101.54 | 101.69 | 101.75 | 101.61 | 102.22 | 101.69 | 101.80 | 102.16 | 102.40 | 102.08 | 101.59 |
| | | | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Al | 0.30 | 0.29 | 0.30 | 0.30 | 0.30 | 0.30 | 0.29 | 0.28 | 0.28 | 0.28 | 0.28 | 0.30 | 0.29 | 0.28 | 0.28 | 0.28 |
| $Cr^{3+}$ | 1.43 | 1.38 | 1.35 | 1.35 | 1.34 | 1.36 | 1.36 | 1.35 | 1.37 | 1.37 | 1.37 | 1.34 | 1.35 | 1.37 | 1.35 | 1.35 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.26 | 0.32 | 0.34 | 0.35 | 0.34 | 0.34 | 0.34 | 0.36 | 0.34 | 0.34 | 0.34 | 0.35 | 0.36 | 0.35 | 0.36 | 0.36 |
| $Fe^{2+}$ | 0.81 | 0.75 | 0.75 | 0.79 | 0.75 | 0.76 | 0.80 | 0.83 | 0.78 | 0.80 | 0.77 | 0.83 | 0.83 | 0.80 | 0.83 | 0.83 |
| $Mn^{2+}$ | 0.03 | 0.02 | 0.02 | 0.05 | 0.02 | 0.03 | 0.05 | 0.05 | 0.02 | 0.04 | 0.02 | 0.05 | 0.05 | 0.04 | 0.05 | 0.05 |
| $Mg^{2+}$ | 0.15 | 0.21 | 0.22 | 0.15 | 0.22 | 0.20 | 0.14 | 0.10 | 0.19 | 0.16 | 0.19 | 0.11 | 0.11 | 0.16 | 0.11 | 0.11 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 2.00 | 2.00 | 1.99 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Total 2+ cations | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.16 | 0.22 | 0.23 | 0.16 | 0.23 | 0.20 | 0.15 | 0.11 | 0.20 | 0.16 | 0.20 | 0.12 | 0.12 | 0.17 | 0.12 | 0.12 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.84 | 0.78 | 0.77 | 0.84 | 0.77 | 0.80 | 0.85 | 0.89 | 0.80 | 0.84 | 0.80 | 0.88 | 0.88 | 0.83 | 0.88 | 0.88 |
| Cr/(Cr+Al) | 0.82 | 0.83 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.83 | 0.83 | 0.83 | 0.83 | 0.82 | 0.82 | 0.83 | 0.83 | 0.83 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.72 | 0.69 | 0.68 | 0.67 | 0.68 | 0.68 | 0.68 | 0.68 | 0.69 | 0.69 | 0.69 | 0.67 | 0.68 | 0.68 | 0.68 | 0.68 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.15 | 0.14 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.14 | 0.14 | 0.14 | 0.14 | 0.15 | 0.14 | 0.14 | 0.14 | 0.14 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.13 | 0.16 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.17 | 0.17 | 0.17 | 0.18 | 0.18 | 0.17 | 0.18 | 0.18 |
| $Fe^{3+}/Fe_{total}$ | 0.25 | 0.30 | 0.31 | 0.30 | 0.31 | 0.31 | 0.30 | 0.30 | 0.31 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| Quality control: oxide total test | | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total | Caution: high total |

| Sample # | QC20DM-06 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.03 | 0.00 | 0.00 | 0.02 | 0.00 | 0.05 |
| $TiO_2$ | 0.23 | 0.20 | 0.20 | 0.22 | 0.30 | 0.26 | 0.27 | 0.23 | 0.22 | 0.20 | 0.27 | 0.24 | 0.24 | 0.22 |
| $Al_2O_3$ | 13.80 | 13.73 | 13.35 | 13.77 | 14.11 | 13.25 | 13.78 | 13.62 | 13.86 | 13.46 | 13.54 | 13.78 | 12.84 | 13.27 |
| $Cr_2O_3$ | 48.16 | 49.14 | 48.87 | 48.76 | 48.20 | 48.81 | 48.22 | 48.34 | 47.82 | 48.48 | 48.51 | 48.10 | 49.74 | 48.91 |
| $V_2O_3$ | 0.17 | 0.18 | 0.18 | 0.20 | 0.17 | 0.17 | 0.18 | 0.19 | 0.18 | 0.17 | 0.18 | 0.20 | 0.19 | 0.18 |
| $Fe_2O_3$ (calculated) | 8.36 | 7.78 | 8.03 | 8.09 | 8.40 | 8.69 | 8.42 | 8.20 | 8.37 | 8.31 | 8.39 | 8.34 | 8.14 | 7.91 |
| FeO (calculated) | 18.80 | 19.02 | 19.15 | 18.60 | 19.03 | 19.08 | 18.33 | 18.83 | 19.20 | 19.07 | 18.85 | 18.98 | 18.83 | 19.52 |
| MnO | 0.36 | 0.36 | 0.36 | 0.31 | 0.32 | 0.34 | 0.32 | 0.35 | 0.35 | 0.36 | 0.34 | 0.35 | 0.33 | 0.33 |
| MgO | 9.76 | 9.67 | 9.48 | 9.98 | 9.87 | 9.68 | 10.08 | 9.78 | 9.52 | 9.54 | 9.80 | 9.68 | 9.76 | 9.32 |
| NiO | 0.13 | 0.14 | 0.10 | 0.11 | 0.14 | 0.10 | 0.13 | 0.10 | 0.10 | 0.11 | 0.12 | 0.14 | 0.11 | 0.12 |
| ZnO | 0.07 | 0.10 | 0.06 | 0.08 | 0.06 | 0.12 | 0.12 | 0.05 | 0.09 | 0.04 | 0.04 | 0.08 | 0.09 | 0.05 |
| Total | 99.84 | 100.32 | 99.78 | 100.13 | 100.60 | 100.48 | 99.83 | 99.75 | 99.73 | 99.75 | 100.02 | 99.92 | 100.28 | 99.87 |
| | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| Al | 0.53 | 0.53 | 0.52 | 0.53 | 0.54 | 0.51 | 0.53 | 0.53 | 0.54 | 0.52 | 0.52 | 0.53 | 0.50 | 0.51 |
| $Cr^{3+}$ | 1.25 | 1.27 | 1.27 | 1.26 | 1.24 | 1.26 | 1.25 | 1.25 | 1.24 | 1.26 | 1.25 | 1.24 | 1.29 | 1.27 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.21 | 0.19 | 0.20 | 0.20 | 0.21 | 0.21 | 0.21 | 0.20 | 0.21 | 0.21 | 0.21 | 0.21 | 0.20 | 0.20 |
| $Fe^{2+}$ | 0.51 | 0.52 | 0.53 | 0.51 | 0.52 | 0.52 | 0.50 | 0.52 | 0.53 | 0.52 | 0.52 | 0.52 | 0.52 | 0.54 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.48 | 0.47 | 0.46 | 0.49 | 0.48 | 0.47 | 0.49 | 0.48 | 0.47 | 0.47 | 0.48 | 0.47 | 0.48 | 0.46 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 1.99 | 2.00 | 2.00 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 2.00 | 1.99 | 1.99 | 1.99 | 1.99 |
| Total 2+ cations | 1.01 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 |
| | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.48 | 0.48 | 0.47 | 0.49 | 0.48 | 0.47 | 0.49 | 0.48 | 0.47 | 0.47 | 0.48 | 0.48 | 0.48 | 0.46 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.52 | 0.52 | 0.53 | 0.51 | 0.52 | 0.53 | 0.51 | 0.52 | 0.53 | 0.53 | 0.52 | 0.52 | 0.52 | 0.54 |
| Cr/(Cr+Al) | 0.70 | 0.71 | 0.71 | 0.70 | 0.70 | 0.71 | 0.70 | 0.70 | 0.70 | 0.71 | 0.71 | 0.70 | 0.72 | 0.71 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.63 | 0.64 | 0.64 | 0.63 | 0.62 | 0.64 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 | 0.65 | 0.64 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.27 | 0.27 | 0.26 | 0.27 | 0.27 | 0.26 | 0.27 | 0.27 | 0.27 | 0.26 | 0.26 | 0.27 | 0.25 | 0.26 |
| | | | | | | | | | | | | | | |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.11 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| $Fe^{3+}/Fe_{otal}$ | 0.29 | 0.27 | 0.27 | 0.28 | 0.28 | 0.29 | 0.29 | 0.28 | 0.28 | 0.28 | 0.29 | 0.28 | 0.28 | 0.27 |

| Sample # | QC20DM-06 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.00 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 |
| $TiO_2$ | 0.00 | 0.31 | 0.30 | 0.39 | 0.36 | 0.22 | 0.21 | 0.35 | 0.20 | 0.23 | 0.22 | 0.24 | 0.30 | 0.35 | 0.20 |
| $Al_2O_3$ | 14.08 | 13.27 | 13.88 | 13.44 | 13.72 | 13.46 | 13.16 | 14.46 | 13.70 | 13.65 | 13.75 | 13.58 | 13.57 | 13.81 | 13.98 |
| $Cr_2O_3$ | 47.80 | 48.85 | 48.05 | 48.40 | 48.03 | 48.59 | 48.07 | 47.20 | 48.81 | 48.62 | 48.07 | 48.13 | 48.09 | 48.52 | 48.66 |
| $V_2O_3$ | 0.18 | 0.18 | 0.18 | 0.17 | 0.19 | 0.20 | 0.19 | 0.17 | 0.19 | 0.17 | 0.20 | 0.17 | 0.19 | 0.17 | 0.18 |
| $Fe_2O_3$ (calculated) | 9.21 | 8.08 | 8.48 | 8.13 | 8.33 | 7.53 | 7.92 | 7.89 | 7.48 | 8.02 | 7.46 | 7.83 | 7.69 | 8.36 | 7.98 |
| FeO (calculated) | 18.37 | 19.08 | 18.67 | 18.83 | 18.89 | 18.68 | 18.46 | 17.99 | 18.33 | 18.24 | 18.69 | 17.84 | 17.78 | 18.18 | 18.58 |
| MnO | 0.34 | 0.32 | 0.33 | 0.34 | 0.37 | 0.33 | 0.33 | 0.35 | 0.33 | 0.35 | 0.33 | 0.34 | 0.33 | 0.31 | 0.33 |
| MgO | 10.01 | 9.67 | 9.93 | 9.78 | 9.75 | 9.61 | 9.59 | 10.21 | 10.00 | 10.06 | 9.68 | 10.10 | 10.15 | 10.33 | 10.03 |
| NiO | 0.13 | 0.13 | 0.13 | 0.13 | 0.12 | 0.12 | 0.11 | 0.15 | 0.12 | 0.11 | 0.13 | 0.12 | 0.12 | 0.14 | |
| ZnO | 0.08 | 0.06 | 0.12 | 0.07 | 0.12 | 0.08 | 0.04 | 0.07 | 0.06 | 0.07 | 0.09 | 0.06 | 0.07 | 0.10 | 0.11 |
| Total | 100.19 | 99.98 | 100.08 | 99.67 | 99.88 | 98.83 | 98.07 | 98.84 | 99.27 | 99.51 | 98.69 | 98.41 | 98.28 | 100.28 | 100.06 |
| | | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 |
| Al | 0.54 | 0.51 | 0.53 | 0.52 | 0.53 | 0.53 | 0.52 | 0.56 | 0.53 | 0.53 | 0.54 | 0.53 | 0.53 | 0.53 | 0.54 |
| $Cr^{3+}$ | 1.23 | 1.27 | 1.24 | 1.26 | 1.24 | 1.27 | 1.27 | 1.22 | 1.27 | 1.26 | 1.26 | 1.26 | 1.26 | 1.25 | 1.25 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.23 | 0.20 | 0.21 | 0.20 | 0.21 | 0.19 | 0.20 | 0.19 | 0.18 | 0.20 | 0.19 | 0.20 | 0.19 | 0.20 | 0.20 |
| $Fe^{2+}$ | 0.50 | 0.52 | 0.51 | 0.52 | 0.52 | 0.52 | 0.52 | 0.49 | 0.50 | 0.50 | 0.52 | 0.49 | 0.49 | 0.49 | 0.51 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.49 | 0.47 | 0.48 | 0.48 | 0.48 | 0.47 | 0.48 | 0.50 | 0.49 | 0.49 | 0.48 | 0.50 | 0.50 | 0.50 | 0.49 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 2.00 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 2.00 |
| Total 2+ cations | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.00 |
| | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.49 | 0.47 | 0.49 | 0.48 | 0.48 | 0.48 | 0.48 | 0.50 | 0.49 | 0.50 | 0.48 | 0.50 | 0.50 | 0.50 | 0.49 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.51 | 0.53 | 0.51 | 0.52 | 0.52 | 0.52 | 0.52 | 0.50 | 0.51 | 0.50 | 0.52 | 0.50 | 0.50 | 0.50 | 0.51 |
| Cr/(Cr+Al) | 0.69 | 0.71 | 0.70 | 0.71 | 0.70 | 0.71 | 0.71 | 0.69 | 0.71 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.62 | 0.64 | 0.63 | 0.64 | 0.63 | 0.64 | 0.64 | 0.62 | 0.64 | 0.63 | 0.64 | 0.63 | 0.64 | 0.63 | 0.63 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.27 | 0.26 | 0.27 | 0.26 | 0.27 | 0.26 | 0.26 | 0.28 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.11 | 0.10 | 0.11 | 0.10 | 0.10 | 0.09 | 0.10 | 0.10 | 0.09 | 0.10 | 0.09 | 0.10 | 0.10 | 0.10 | 0.10 |
| $Fe^{3+}/Fet_{otal}$ | 0.31 | 0.28 | 0.29 | 0.28 | 0.28 | 0.27 | 0.28 | 0.28 | 0.27 | 0.28 | 0.26 | 0.28 | 0.28 | 0.29 | 0.28 |

| Sample # | QC20DM-08 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| $TiO_2$ | 0.10 | 0.10 | 0.11 | 0.10 | 0.11 | 0.10 | 0.09 | 0.10 | 0.09 | 0.11 | 0.11 |
| $Al_2O_3$ | 13.81 | 13.49 | 13.46 | 13.42 | 13.30 | 13.63 | 12.60 | 13.39 | 13.43 | 13.27 | 13.44 |
| $Cr_2O_3$ | 49.78 | 49.96 | 50.09 | 50.33 | 50.11 | 50.29 | 51.36 | 50.70 | 50.52 | 50.62 | 50.46 |
| $V_2O_3$ | 0.18 | 0.17 | 0.18 | 0.18 | 0.16 | 0.16 | 0.17 | 0.18 | 0.19 | 0.17 | 0.18 |
| $Fe_2O_3$ (calculated) | 6.03 | 6.17 | 6.00 | 5.96 | 5.96 | 5.89 | 5.27 | 5.46 | 5.79 | 5.75 | 5.98 |
| FeO (calculated) | 21.79 | 21.87 | 21.86 | 21.99 | 21.86 | 21.96 | 22.74 | 22.03 | 21.89 | 22.12 | 21.86 |
| MnO | 0.61 | 0.61 | 0.59 | 0.58 | 0.57 | 0.58 | 0.61 | 0.59 | 0.59 | 0.61 | 0.60 |
| MgO | 7.68 | 7.58 | 7.59 | 7.55 | 7.54 | 7.63 | 6.93 | 7.50 | 7.61 | 7.44 | 7.69 |
| NiO | 0.09 | 0.09 | 0.06 | 0.09 | 0.09 | 0.07 | 0.04 | 0.09 | 0.08 | 0.07 | 0.08 |
| ZnO | 0.07 | 0.08 | 0.11 | 0.09 | 0.06 | 0.05 | 0.04 | 0.05 | 0.07 | 0.10 | 0.05 |
| Total | 100.15 | 100.13 | 100.04 | 100.29 | 99.75 | 100.36 | 99.86 | 100.10 | 100.26 | 100.26 | 100.44 |
| | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | |
| | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Al | 0.54 | 0.53 | 0.53 | 0.52 | 0.52 | 0.53 | 0.50 | 0.52 | 0.52 | 0.52 | 0.52 |
| $Cr^{3+}$ | 1.30 | 1.31 | 1.31 | 1.32 | 1.32 | 1.31 | 1.36 | 1.33 | 1.32 | 1.33 | 1.32 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.13 | 0.14 | 0.14 | 0.14 | 0.15 |
| $Fe^{2+}$ | 0.60 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.64 | 0.61 | 0.61 | 0.61 | 0.60 |
| $Mn^{2+}$ | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| $Mg^{2+}$ | 0.38 | 0.37 | 0.38 | 0.37 | 0.37 | 0.38 | 0.35 | 0.37 | 0.38 | 0.37 | 0.38 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Total 2+ cations | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.39 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.35 | 0.38 | 0.38 | 0.37 | 0.39 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.61 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 | 0.65 | 0.62 | 0.62 | 0.63 | 0.61 |
| Cr/(Cr+Al) | 0.71 | 0.71 | 0.71 | 0.72 | 0.72 | 0.71 | 0.73 | 0.72 | 0.72 | 0.72 | 0.72 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.65 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.68 | 0.67 | 0.66 | 0.67 | 0.66 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.27 | 0.26 | 0.26 | 0.26 | 0.26 | 0.27 | 0.25 | 0.26 | 0.26 | 0.26 | 0.26 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.08 | 0.08 | 0.08 | 0.07 | 0.08 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| $Fe^{3+}/Fe_{total}$ | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.19 | 0.17 | 0.18 | 0.19 | 0.19 | 0.20 |

| Sample # | 93DM36 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.1 | 0.00 | 0.00 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $TiO_2$ | 0.19 | 0.17 | 0.16 | 0.19 | 0.16 | 0.20 | 0.20 | 0.15 | 0.16 | 0.16 |
| $Al_2O_3$ | 9.30 | 9.19 | 9.07 | 10.88 | 10.27 | 11.56 | 11.98 | 9.32 | 9.12 | 11.21 |
| $Cr_2O_3$ | 52.20 | 52.35 | 52.33 | 48.25 | 50.98 | 48.52 | 48.09 | 52.05 | 52.65 | 49.00 |
| $V_2O_3$ | 0.09 | 0.08 | 0.07 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.08 | 0.11 |
| $Fe_2O_3$ (calculated) | 9.10 | 9.17 | 9.34 | 10.82 | 9.64 | 10.38 | 10.26 | 9.29 | 9.00 | 10.16 |
| FeO (calculated) | 22.18 | 22.33 | 22.33 | 21.89 | 21.87 | 21.49 | 21.41 | 22.26 | 22.25 | 22.27 |
| MnO | 0.50 | 0.54 | 0.49 | 0.44 | 0.48 | 0.47 | 0.47 | 0.52 | 0.48 | 0.49 |
| MgO | 7.26 | 7.03 | 7.05 | 7.41 | 7.55 | 7.81 | 7.89 | 7.12 | 7.15 | 7.29 |
| NiO | 0.13 | 0.12 | 0.14 | 0.20 | 0.14 | 0.18 | 0.16 | 0.13 | 0.13 | 0.16 |
| ZnO | 0.15 | 0.17 | 0.15 | 0.08 | 0.07 | 0.10 | 0.11 | 0.06 | 0.08 | 0.08 |
| Total | 101.18 | 101.15 | 101.15 | 100.31 | 101.26 | 100.80 | 100.66 | 101.00 | 101.10 | 100.92 |
| | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | |
| | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Al | 0.37 | 0.36 | 0.36 | 0.43 | 0.40 | 0.45 | 0.47 | 0.37 | 0.36 | 0.44 |
| $Cr^{3+}$ | 1.39 | 1.39 | 1.39 | 1.28 | 1.34 | 1.28 | 1.26 | 1.38 | 1.40 | 1.29 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.23 | 0.23 | 0.24 | 0.27 | 0.24 | 0.26 | 0.26 | 0.24 | 0.23 | 0.26 |
| $Fe^{2+}$ | 0.62 | 0.63 | 0.63 | 0.61 | 0.61 | 0.60 | 0.59 | 0.63 | 0.63 | 0.62 |
| $Mn^{2+}$ | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.36 | 0.35 | 0.35 | 0.37 | 0.38 | 0.39 | 0.39 | 0.36 | 0.36 | 0.36 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 1.99 | 2.00 | 2.00 | 1.99 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Total 2+ cations | 1.01 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.37 | 0.36 | 0.36 | 0.38 | 0.38 | 0.39 | 0.40 | 0.36 | 0.36 | 0.37 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.63 | 0.64 | 0.64 | 0.62 | 0.62 | 0.61 | 0.60 | 0.64 | 0.64 | 0.63 |
| Cr/(Cr+Al) | 0.79 | 0.79 | 0.79 | 0.75 | 0.77 | 0.74 | 0.73 | 0.79 | 0.79 | 0.75 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.70 | 0.70 | 0.70 | 0.65 | 0.68 | 0.64 | 0.64 | 0.70 | 0.70 | 0.65 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.19 | 0.18 | 0.18 | 0.22 | 0.20 | 0.23 | 0.24 | 0.19 | 0.18 | 0.22 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.12 | 0.12 | 0.12 | 0.14 | 0.12 | 0.13 | 0.13 | 0.12 | 0.11 | 0.13 |
| $Fe^{3+}/Fe_{total}$ | 0.27 | 0.27 | 0.27 | 0.31 | 0.28 | 0.30 | 0.30 | 0.27 | 0.27 | 0.29 |

# Appendix B. Olivine EMPA Data from Meta-chromitites

| | | | | |
|---|---|---|---|---|
| Sample # | HP20DM-05 | | | |
| Comment | inclusion | inclusion | | |
| $SiO_2$ | 41.59 | 41.43 | | |
| FeO | 3.16 | 3.27 | | |
| MnO | 0.07 | 0.09 | | |
| MgO | 53.76 | 53.47 | | |
| NiO | 0.51 | 0.56 | | |
| CaO | 0.00 | 0.00 | | |
| Total | 99.09 | 98.82 | | |
| | | | | |
| Structural formula based on 4 oxygens | | | | |
| | | | | |
| T (iv) site: Si | 1.00 | 1.00 | | |
| | | | | |
| $Fe^{2+}$ | 0.06 | 0.07 | | |
| $Mn^{2+}$ | 0.00 | 0.00 | | |
| Mg | 1.93 | 1.92 | | |
| Ni | 0.01 | 0.01 | | |
| Ca | 0.00 | 0.00 | | |
| A-site total | 2.00 | 2.00 | | |
| | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.97 | 0.97 | | |
| Common olivine components (excluding Ca species) | | | | |
| Forsterite (mol%) | 96.26 | 96.07 | | |
| Fayalite (mol%) | 3.18 | 3.30 | | |
| Tephroite (mol%) | 0.07 | 0.09 | | |
| Ni-olivine (mol%) | 0.49 | 0.54 | | |
| | | | | |
| $Ca/(Fe^{2+}+Mg+Mn+Ni)$ | 0.00 | 0.00 | | |
| overriding Ca species | | | | |
| | | | | |
| Fo% - Fo-Fa binary | 96.81 | 96.68 | | |
| Fa% - Fo-Fa binary | 3.19 | 3.32 | | |
| Ca% - Ca-Fo-Fa ternary | 0.00 | 0.00 | | |
| Teph% - Mn-Mg-Fe ternary | 0.07 | 0.09 | | |
| Ni-ol % - Ni-Mg-Fe ternary | 0.49 | 0.54 | | |

| Sample # | HP20DM-03 | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Comment | matrix | matrix | matrix | matrix | matrix | matrix | inclusion | inclusion | inclusion | matrix | matrix | matrix | matrix | matrix | matrix | matrix |
| $SiO_2$ | 41.79 | 41.61 | 41.60 | 41.41 | 41.43 | 41.30 | 41.48 | 41.79 | 41.43 | 42.05 | 41.94 | 41.91 | 42.07 | 41.97 | 42.18 | 42.11 |
| FeO | 4.24 | 4.19 | 4.20 | 4.33 | 4.28 | 4.39 | 3.88 | 3.99 | 3.87 | 5.63 | 5.75 | 5.82 | 5.28 | 5.43 | 5.26 | 5.11 |
| MnO | 0.10 | 0.10 | 0.08 | 0.08 | 0.09 | 0.11 | 0.10 | 0.07 | 0.08 | 0.13 | 0.14 | 0.13 | 0.11 | 0.14 | 0.12 | 0.24 |
| MgO | 53.43 | 53.44 | 53.23 | 53.40 | 53.09 | 53.25 | 53.76 | 54.04 | 53.64 | 52.41 | 52.25 | 52.29 | 51.32 | 52.75 | 52.89 | 53.14 |
| NiO | 0.63 | 0.64 | 0.65 | 0.67 | 0.68 | 0.67 | 0.63 | 0.66 | 0.64 | 0.26 | 0.27 | 0.26 | 0.25 | 0.27 | 0.27 | 0.12 |
| CaO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 |
| Total | 100.18 | 99.98 | 99.75 | 99.88 | 99.57 | 99.71 | 99.85 | 100.54 | 99.67 | 100.47 | 100.35 | 100.42 | 99.05 | 100.55 | 100.72 | 100.72 |
| | | | | | | | | | | | | | | | | |
| | Structural formula based on 4 oxygens | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| T (iv) site: Si | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 | 0.99 | 0.99 | 0.99 | 1.01 | 1.01 | 1.00 | 1.02 | 1.00 | 1.00 | 1.00 |
| | | | | | | | | | | | | | | | | |
| $Fe^{2+}$ | 0.08 | 0.08 | 0.08 | 0.09 | 0.09 | 0.09 | 0.08 | 0.08 | 0.08 | 0.11 | 0.12 | 0.12 | 0.11 | 0.11 | 0.10 | 0.10 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 1.90 | 1.91 | 1.90 | 1.91 | 1.90 | 1.91 | 1.92 | 1.92 | 1.92 | 1.87 | 1.87 | 1.87 | 1.85 | 1.88 | 1.88 | 1.89 |
| Ni | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.00 |
| Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| A-site total | 2.00 | 2.01 | 2.00 | 2.01 | 2.01 | 2.01 | 2.01 | 2.01 | 2.01 | 1.99 | 1.99 | 1.99 | 1.96 | 1.99 | 1.99 | 2.00 |
| | | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.94 | 0.94 | 0.94 | 0.95 | 0.95 | 0.95 | 0.95 |
| | Common olivine components (excluding Ca species) | | | | | | | | | | | | | | | |
| Forsterite (mol%) | 95.07 | 95.10 | 95.09 | 94.97 | 94.96 | 94.86 | 95.43 | 95.36 | 95.44 | 93.96 | 93.80 | 93.76 | 94.19 | 94.16 | 94.35 | 94.55 |
| Fayalite (mol%) | 4.23 | 4.18 | 4.20 | 4.32 | 4.29 | 4.38 | 3.86 | 3.95 | 3.87 | 5.66 | 5.79 | 5.85 | 5.44 | 5.44 | 5.26 | 5.10 |
| Tephroite (mol%) | 0.10 | 0.11 | 0.08 | 0.08 | 0.09 | 0.11 | 0.10 | 0.07 | 0.08 | 0.13 | 0.14 | 0.14 | 0.12 | 0.14 | 0.12 | 0.24 |
| Ni-olivine (mol%) | 0.60 | 0.61 | 0.62 | 0.64 | 0.66 | 0.65 | 0.60 | 0.63 | 0.61 | 0.25 | 0.27 | 0.25 | 0.25 | 0.26 | 0.26 | 0.11 |
| | | | | | | | | | | | | | | | | |
| $Ca/(Fe^{2+}+Mg+Mn+Ni)$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| overriding Ca species | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| Fo% - Fo-Fa binary | 95.74 | 95.79 | 95.77 | 95.65 | 95.68 | 95.58 | 96.11 | 96.02 | 96.11 | 94.32 | 94.18 | 94.12 | 94.54 | 94.54 | 94.72 | 94.88 |
| Fa% - Fo-Fa binary | 4.26 | 4.21 | 4.23 | 4.35 | 4.32 | 4.42 | 3.89 | 3.98 | 3.89 | 5.68 | 5.82 | 5.88 | 5.46 | 5.46 | 5.28 | 5.12 |
| Ca% - Ca-Fo-Fa ternary | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 0.01 |
| Teph% - Mn-Mg-Fe ternary | 0.10 | 0.11 | 0.08 | 0.08 | 0.09 | 0.11 | 0.11 | 0.07 | 0.08 | 0.13 | 0.14 | 0.14 | 0.12 | 0.14 | 0.12 | 0.24 |
| Ni-ol % - Ni-Mg-Fe ternary | 0.60 | 0.61 | 0.62 | 0.64 | 0.66 | 0.65 | 0.60 | 0.63 | 0.61 | 0.25 | 0.27 | 0.25 | 0.25 | 0.26 | 0.26 | 0.11 |

| Sample # | HP20DM-03 | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Comment | matrix | matrix | matrix | matrix | matrix | matrix | matrix | matrix | matrix | matrix | matrix | matrix | matrix | matrix | matrix | matrix | matrix |
| SiO2 | 42.01 | 41.19 | 42.43 | 41.87 | 41.84 | 41.97 | 41.87 | 41.92 | 41.79 | 41.61 | 41.60 | 41.41 | 41.43 | 41.30 | 41.48 | 41.79 | 41.43 |
| FeO | 5.07 | 7.77 | 4.82 | 5.01 | 4.92 | 4.94 | 4.93 | 4.94 | 4.24 | 4.19 | 4.20 | 4.33 | 4.28 | 4.39 | 3.88 | 3.99 | 3.87 |
| MnO | 0.29 | 0.23 | 0.24 | 0.25 | 0.24 | 0.24 | 0.25 | 0.24 | 0.10 | 0.10 | 0.08 | 0.08 | 0.09 | 0.11 | 0.10 | 0.07 | 0.08 |
| MgO | 52.94 | 49.62 | 53.13 | 53.09 | 53.14 | 53.07 | 53.20 | 53.21 | 53.43 | 53.44 | 53.23 | 53.40 | 53.09 | 53.25 | 53.76 | 54.04 | 53.64 |
| NiO | 0.13 | 0.16 | 0.13 | 0.13 | 0.13 | 0.14 | 0.13 | 0.13 | 0.63 | 0.64 | 0.65 | 0.67 | 0.68 | 0.67 | 0.63 | 0.66 | 0.64 |
| CaO | 0.02 | 0.12 | 0.07 | 0.00 | 0.01 | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 100.45 | 99.07 | 100.82 | 100.35 | 100.29 | 100.36 | 100.41 | 100.45 | 100.18 | 99.98 | 99.75 | 99.88 | 99.57 | 99.71 | 99.85 | 100.54 | 99.67 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| T (iv) site: Si | 1.00 | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 | 0.99 | 0.99 | 0.99 |
| | | | | | | | | | | | | | | | | | |
| Fe2+ | 0.10 | 0.16 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.08 | 0.08 | 0.08 | 0.09 | 0.09 | 0.09 | 0.08 | 0.08 | 0.08 |
| Mn2+ | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 1.88 | 1.81 | 1.88 | 1.89 | 1.89 | 1.89 | 1.89 | 1.89 | 1.90 | 1.91 | 1.90 | 1.91 | 1.90 | 1.91 | 1.92 | 1.92 | 1.92 |
| Ni | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| A-site total | 1.99 | 1.98 | 1.99 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.01 | 2.00 | 2.01 | 2.01 | 2.01 | 2.01 | 2.01 | 2.01 |
| | | | | | | | | | | | | | | | | | |
| Mg/(Mg+Fe2+) | 0.95 | 0.92 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 |
| | | | | | | | | | | | | | | | | | |
| Forsterite (mol%) | 94.51 | 91.56 | 94.80 | 94.61 | 94.72 | 94.68 | 94.69 | 94.70 | 95.07 | 95.10 | 95.09 | 94.97 | 94.96 | 94.86 | 95.43 | 95.36 | 95.44 |
| Fayalite (mol%) | 5.08 | 8.04 | 4.83 | 5.01 | 4.92 | 4.94 | 4.93 | 4.93 | 4.23 | 4.18 | 4.20 | 4.32 | 4.29 | 4.38 | 3.86 | 3.95 | 3.87 |
| Tephroite (mol%) | 0.29 | 0.24 | 0.24 | 0.26 | 0.24 | 0.24 | 0.26 | 0.24 | 0.10 | 0.11 | 0.08 | 0.08 | 0.09 | 0.11 | 0.10 | 0.07 | 0.08 |
| Ni-olivine (mol%) | 0.13 | 0.15 | 0.13 | 0.12 | 0.12 | 0.13 | 0.13 | 0.13 | 0.60 | 0.61 | 0.62 | 0.64 | 0.66 | 0.65 | 0.60 | 0.63 | 0.61 |
| | | | | | | | | | | | | | | | | | |
| Ca/(Fe2++Mg+Mn+Ni) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| overriding Ca species | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| Fo% - Fo-Fa binary | 94.90 | 91.93 | 95.16 | 94.97 | 95.06 | 95.04 | 95.05 | 95.05 | 95.74 | 95.79 | 95.77 | 95.65 | 95.68 | 95.58 | 96.11 | 96.02 | 96.11 |
| Fa% - Fo-Fa binary | 5.10 | 8.07 | 4.84 | 5.03 | 4.94 | 4.96 | 4.95 | 4.95 | 4.26 | 4.21 | 4.23 | 4.35 | 4.32 | 4.42 | 3.89 | 3.98 | 3.89 |
| Ca% - Ca-Fo-Fa ternary | 0.02 | 0.15 | 0.09 | 0.00 | 0.02 | 0.01 | 0.02 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| Teph% - Mn-Mg-Fe ternary | 0.29 | 0.24 | 0.24 | 0.26 | 0.24 | 0.24 | 0.26 | 0.24 | 0.10 | 0.11 | 0.08 | 0.08 | 0.09 | 0.11 | 0.11 | 0.07 | 0.08 |
| Ni-ol % - Ni-Mg-Fe ternary | 0.13 | 0.15 | 0.13 | 0.12 | 0.12 | 0.13 | 0.13 | 0.13 | 0.60 | 0.61 | 0.62 | 0.64 | 0.66 | 0.65 | 0.60 | 0.63 | 0.61 |

| Sample # | HP20DM-07 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Comment | matrix | matrix | matrix/inc | matrix | matrix | matrix | matrix | matrix | matrix | matrix | inclusion | inclusion | inclusion | inclusion |
| $SiO_2$ | 42.03 | 41.79 | 42.03 | 41.89 | 42.19 | 42.06 | 41.87 | 42.25 | 42.22 | 42.16 | 41.75 | 41.82 | 41.42 | 41.49 |
| FeO | 4.02 | 3.84 | 3.78 | 3.92 | 4.32 | 4.60 | 4.72 | 4.66 | 4.37 | 4.45 | 3.22 | 3.18 | 3.14 | 3.30 |
| MnO | 0.11 | 0.12 | 0.12 | 0.11 | 0.13 | 0.15 | 0.13 | 0.13 | 0.13 | 0.14 | 0.10 | 0.11 | 0.10 | 0.09 |
| MgO | 54.03 | 53.53 | 53.26 | 53.67 | 53.99 | 53.27 | 53.09 | 53.50 | 53.67 | 53.48 | 53.63 | 54.30 | 54.11 | 54.20 |
| NiO | 0.27 | 0.26 | 0.22 | 0.23 | 0.22 | 0.00 | 0.00 | 0.22 | 0.22 | 0.21 | 0.52 | 0.51 | 0.61 | 0.55 |
| CaO | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 100.47 | 99.53 | 99.42 | 99.82 | 100.84 | 100.10 | 99.81 | 100.76 | 100.60 | 100.45 | 99.22 | 99.91 | 99.38 | 99.62 |
| | | | | | | | | | | | | | | |
| | Structural formula based on 4 oxygens | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| T (iv) site: Si | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.99 |
| | | | | | | | | | | | | | | |
| $Fe^{2+}$ | 0.08 | 0.08 | 0.08 | 0.08 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.06 | 0.06 | 0.06 | 0.07 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 1.91 | 1.91 | 1.90 | 1.91 | 1.91 | 1.90 | 1.90 | 1.89 | 1.90 | 1.90 | 1.92 | 1.93 | 1.94 | 1.93 |
| Ni | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| A-site total | 2.00 | 2.00 | 1.99 | 2.00 | 2.00 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 2.00 | 2.01 | 2.01 | 2.01 |
| | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.95 | 0.95 | 0.95 | 0.96 | 0.96 | 0.97 | 0.97 | 0.97 | 0.97 |
| | Common olivine components (excluding Ca species) | | | | | | | | | | | | | |
| Forsterite (mol%) | 95.64 | 95.78 | 95.84 | 95.75 | 95.38 | 95.24 | 95.13 | 95.02 | 95.32 | 95.21 | 96.16 | 96.24 | 96.19 | 96.10 |
| Fayalite (mol%) | 3.99 | 3.85 | 3.82 | 3.93 | 4.28 | 4.61 | 4.74 | 4.64 | 4.35 | 4.45 | 3.24 | 3.16 | 3.13 | 3.28 |
| Tephroite (mol%) | 0.11 | 0.12 | 0.12 | 0.11 | 0.13 | 0.15 | 0.13 | 0.13 | 0.13 | 0.14 | 0.10 | 0.11 | 0.10 | 0.09 |
| Ni-olivine (mol%) | 0.26 | 0.25 | 0.21 | 0.22 | 0.21 | 0.00 | 0.00 | 0.21 | 0.21 | 0.20 | 0.51 | 0.49 | 0.58 | 0.52 |
| | | | | | | | | | | | | | | |
| $Ca/(Fe^{2+}+Mg+Mn+Ni)$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| overriding Ca species | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Fo% - Fo-Fa binary | 95.99 | 96.13 | 96.17 | 96.06 | 95.71 | 95.38 | 95.25 | 95.34 | 95.63 | 95.54 | 96.74 | 96.82 | 96.85 | 96.70 |
| Fa% - Fo-Fa binary | 4.01 | 3.87 | 3.83 | 3.94 | 4.29 | 4.62 | 4.75 | 4.66 | 4.37 | 4.46 | 3.26 | 3.18 | 3.15 | 3.30 |
| Ca% - Ca-Fo-Fa ternary | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Teph% - Mn-Mg-Fe ternary | 0.11 | 0.12 | 0.12 | 0.11 | 0.13 | 0.15 | 0.13 | 0.13 | 0.13 | 0.14 | 0.10 | 0.11 | 0.10 | 0.09 |
| Ni-ol % - Ni-Mg-Fe ternary | 0.26 | 0.25 | 0.21 | 0.22 | 0.21 | 0.00 | 0.00 | 0.21 | 0.21 | 0.20 | 0.51 | 0.49 | 0.58 | 0.52 |

# Appendix C. Phlogopite EMPA Data from Meta-chromitites

| Sample # | HP20DM-03 | | | | | | |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 40.80 | 40.62 | 41.58 | 40.34 | 40.55 | 40.86 | 40.43 |
| $Al_2O_3$ | 13.98 | 14.00 | 12.44 | 14.04 | 14.17 | 14.01 | 14.11 |
| $TiO_2$ | 0.68 | 0.57 | 0.48 | 0.57 | 0.51 | 0.68 | 0.59 |
| $Cr_2O_3$ | 1.06 | 1.01 | 0.99 | 1.02 | 1.07 | 0.98 | 1.04 |
| $Fe_2O_3$ (assumed) | 0.05 | 0.06 | 0.07 | 0.06 | 0.05 | 0.05 | 0.06 |
| FeO (assumed) | 1.58 | 1.78 | 1.89 | 1.62 | 1.59 | 1.54 | 1.67 |
| MnO | 0.03 | 0.03 | 0.02 | 0.03 | 0.00 | 0.01 | 0.04 |
| MgO | 28.03 | 28.00 | 29.03 | 28.43 | 27.76 | 27.71 | 27.84 |
| CaO | 0.01 | 0.00 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 |
| BaO | 0.15 | 0.15 | 0.10 | 0.13 | 0.11 | 0.12 | 0.12 |
| $Na_2O$ | 0.04 | 0.02 | 0.07 | 0.10 | 0.08 | 0.08 | 0.09 |
| $K_2O$ | 8.89 | 9.07 | 7.80 | 8.53 | 9.02 | 8.33 | 9.06 |
| F | 0.01 | 0.00 | 0.10 | 0.06 | 0.02 | 0.05 | 0.10 |
| Cl | 0.07 | 0.06 | 0.04 | 0.06 | 0.06 | 0.07 | 0.07 |
| $H_2O$ (calculated) | 4.27 | 4.27 | 4.22 | 4.24 | 4.25 | 4.23 | 4.21 |
| Subtotal | 99.63 | 99.61 | 98.84 | 99.22 | 99.25 | 98.74 | 99.43 |
| O=F,Cl | 0.02 | 0.01 | 0.05 | 0.04 | 0.02 | 0.04 | 0.06 |
| Total | 99.62 | 99.60 | 98.78 | 99.19 | 99.23 | 98.70 | 99.37 |
| | | | | | | | |
| | Structural formula based on 24 anions | | | | | | |
| | | | | | | | |
| T (iv) site: Si | 5.70 | 5.68 | 5.82 | 5.65 | 5.69 | 5.73 | 5.67 |
| Al | 2.30 | 2.31 | 2.05 | 2.32 | 2.31 | 2.27 | 2.33 |
| $Fe^{3+}$ | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| T site total | 8.00 | 8.00 | 7.88 | 7.98 | 8.00 | 8.00 | 8.00 |
| Al (total) | 2.30 | 2.31 | 2.05 | 2.32 | 2.34 | 2.32 | 2.33 |
| R (vi) site: Al | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.05 | 0.00 |
| Ti | 0.07 | 0.06 | 0.05 | 0.06 | 0.05 | 0.07 | 0.06 |
| $Cr^{3+}$ | 0.12 | 0.11 | 0.11 | 0.11 | 0.12 | 0.11 | 0.12 |
| $Fe^{3+}$ (assumed) | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 |
| $Fe^{2+}$ (assumed) | 0.18 | 0.21 | 0.22 | 0.19 | 0.19 | 0.18 | 0.20 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 5.83 | 5.84 | 6.06 | 5.94 | 5.80 | 5.80 | 5.82 |
| R site vacancy | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y-site total | 6.21 | 6.22 | 6.44 | 6.31 | 6.20 | 6.21 | 6.21 |
| A (XII) site: Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ba | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Na | 0.01 | 0.00 | 0.02 | 0.03 | 0.02 | 0.02 | 0.02 |
| K | 1.58 | 1.62 | 1.39 | 1.52 | 1.61 | 1.49 | 1.62 |
| A-site vacancy | 0.40 | 0.37 | 0.58 | 0.44 | 0.35 | 0.48 | 0.35 |
| A-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| X (anion) site: OH | 3.98 | 3.99 | 3.95 | 3.96 | 3.98 | 3.96 | 3.94 |
| O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 0.00 | 0.00 | 0.04 | 0.03 | 0.01 | 0.02 | 0.05 |
| Cl | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 |
| anion-site total | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| | | | | | | | |
| $Fe^{3+}/(Fe_{tot})$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $Mg/(Mg+Fe_{tot})$ | 0.97 | 0.96 | 0.96 | 0.97 | 0.97 | 0.97 | 0.97 |
| Mg/(Mg+Fe2+) | 0.97 | 0.97 | 0.96 | 0.97 | 0.97 | 0.97 | 0.97 |
| $viAl/(viAl+viR^{2+})$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Fe/(Fe + Mg + Alvi + Ti) | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 |
| Mg/(Fe + Mg + Alvi + Ti) | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.95 | 0.96 |
| Ti/(Fe + Mg + Alvi + Ti) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Alvi/(Fe + Mg + Alvi + Ti) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| K/(A-site total) | 0.79 | 0.81 | 0.70 | 0.76 | 0.81 | 0.75 | 0.81 |
| Vacancy/(A-site | 0.20 | 0.18 | 0.29 | 0.22 | 0.18 | 0.24 | 0.17 |
| Ba/(A-site total) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na/(A-site total) | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| | | | | | | | |
| Quality control: | | | | | | | |
| R site test | R site high | R site high | R site high | R site high | R site high | R site high | R site high |

| Sample # | HP20DM-03 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 41.03 | 40.88 | 40.89 | 39.86 | 40.11 | 40.63 | 38.94 | 40.39 |
| $Al_2O_3$ | 14.49 | 13.91 | 14.37 | 14.09 | 14.22 | 13.99 | 14.20 | 14.29 |
| $TiO_2$ | 0.55 | 0.73 | 0.72 | 0.69 | 0.65 | 0.61 | 0.59 | 0.63 |
| $Cr_2O_3$ | 1.08 | 1.08 | 1.14 | 1.23 | 1.03 | 1.01 | 1.04 | 0.97 |
| $Fe_2O_3$ (assumed) | 0.05 | 0.05 | 0.05 | 0.07 | 0.06 | 0.05 | 0.07 | 0.06 |
| FeO (assumed) | 1.46 | 1.58 | 1.45 | 1.94 | 1.76 | 1.60 | 2.03 | 1.66 |
| MnO | 0.02 | 0.00 | 0.01 | 0.02 | 0.01 | 0.00 | 0.03 | 0.04 |
| MgO | 27.76 | 27.84 | 27.83 | 28.31 | 28.56 | 28.19 | 29.19 | 27.62 |
| CaO | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 |
| BaO | 0.14 | 0.16 | 0.12 | 0.13 | 0.11 | 0.13 | 0.02 | 0.02 |
| $Na_2O$ | 0.08 | 0.12 | 0.23 | 0.07 | 0.07 | 0.09 | 0.04 | 0.06 |
| $K_2O$ | 8.95 | 8.94 | 8.61 | 8.20 | 8.39 | 8.55 | 7.59 | 8.85 |
| F | 0.00 | 0.02 | 0.02 | 0.03 | 0.00 | 0.07 | 0.00 | 0.00 |
| Cl | 0.06 | 0.07 | 0.08 | 0.07 | 0.08 | 0.09 | 0.09 | 0.08 |
| $H_2O$ (calculated) | 4.30 | 4.27 | 4.28 | 4.23 | 4.26 | 4.23 | 4.21 | 4.25 |
| Subtotal | 99.98 | 99.66 | 99.81 | 98.92 | 99.30 | 99.22 | 98.06 | 98.90 |
| O=F,Cl | 0.01 | 0.02 | 0.03 | 0.03 | 0.02 | 0.05 | 0.02 | 0.02 |
| Total | 99.97 | 99.63 | 99.79 | 98.90 | 99.29 | 99.18 | 98.04 | 98.88 |
| | | | | | | | | |
| | Structural formula based on 24 anions | | | | | | | |
| | | | | | | | | |
| T (iv) site: Si | 5.70 | 5.71 | 5.69 | 5.61 | 5.62 | 5.69 | 5.52 | 5.68 |
| Al | 2.30 | 2.29 | 2.31 | 2.34 | 2.35 | 2.31 | 2.37 | 2.32 |
| $Fe^{3+}$ | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 |
| T site total | 8.00 | 8.00 | 8.00 | 7.95 | 7.97 | 8.00 | 7.89 | 8.00 |
| Al (total) | 2.37 | 2.29 | 2.36 | 2.34 | 2.35 | 2.31 | 2.37 | 2.37 |
| R (vi) site: Al | 0.08 | 0.00 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 |
| Ti | 0.06 | 0.08 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 | 0.07 |
| $Cr^{3+}$ | 0.12 | 0.12 | 0.13 | 0.14 | 0.11 | 0.11 | 0.12 | 0.11 |
| $Fe^{3+}$ (assumed) | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| $Fe^{2+}$ (assumed) | 0.17 | 0.18 | 0.17 | 0.23 | 0.21 | 0.19 | 0.24 | 0.19 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 5.75 | 5.80 | 5.77 | 5.94 | 5.96 | 5.88 | 6.16 | 5.79 |
| R site vacancy | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y-site total | 6.18 | 6.18 | 6.19 | 6.38 | 6.35 | 6.25 | 6.59 | 6.21 |
| A (XII) site: Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ba | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |
| Na | 0.02 | 0.03 | 0.06 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 |
| K | 1.59 | 1.59 | 1.53 | 1.47 | 1.50 | 1.53 | 1.37 | 1.59 |
| A-site vacancy | 0.38 | 0.36 | 0.40 | 0.50 | 0.48 | 0.44 | 0.62 | 0.40 |
| A-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| X (anion) site: OH | 3.99 | 3.98 | 3.97 | 3.97 | 3.98 | 3.95 | 3.98 | 3.98 |
| O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.03 | 0.00 | 0.00 |
| Cl | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| anion-site total | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| | | | | | | | | |
| $Fe^{3+}/(Fe_{tot})$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $Mg/(Mg+Fe_{tot})$ | 0.97 | 0.97 | 0.97 | 0.96 | 0.97 | 0.97 | 0.96 | 0.97 |
| Mg/(Mg+Fe2+) | 0.97 | 0.97 | 0.97 | 0.96 | 0.97 | 0.97 | 0.96 | 0.97 |
| $viAl/(viAl+viR^{2+})$ | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Fe/(Fe + Mg + Alvi + Ti) | 0.03 | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 | 0.04 | 0.03 |
| Mg/(Fe + Mg + Alvi + Ti) | 0.95 | 0.96 | 0.95 | 0.95 | 0.96 | 0.96 | 0.95 | 0.95 |
| Ti/(Fe + Mg + Alvi + Ti) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Alvi/(Fe + Mg + Alvi + Ti) | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| K/(A-site total) | 0.79 | 0.80 | 0.76 | 0.74 | 0.75 | 0.76 | 0.69 | 0.79 |
| Vacancy/(A-site total) | 0.19 | 0.18 | 0.20 | 0.25 | 0.24 | 0.22 | 0.31 | 0.20 |
| Ba/(A-site total) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na/(A-site total) | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| | | | | | | | | |
| Quality control: | | | | | | | | |
| R site test | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high |

| Sample # | HP20DM-05 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 40.71 | 39.86 | 40.85 | 41.33 | 40.70 | 40.42 | 40.31 | 40.70 | 40.22 | 39.12 | 39.43 | 38.97 | 39.06 | 39.86 |
| $Al_2O_3$ | 14.44 | 13.88 | 13.76 | 13.14 | 13.85 | 14.27 | 14.11 | 14.24 | 14.34 | 13.92 | 13.78 | 13.86 | 13.82 | 12.85 |
| $TiO_2$ | 0.92 | 0.81 | 0.85 | 0.75 | 0.85 | 0.95 | 0.95 | 0.91 | 0.86 | 0.83 | 0.87 | 1.02 | 0.82 | 0.86 |
| $Cr_2O_3$ | 1.23 | 1.12 | 1.14 | 1.07 | 1.13 | 1.27 | 1.15 | 1.16 | 1.13 | 1.17 | 1.24 | 1.27 | 1.19 | 1.10 |
| $Fe_2O_3$ | 0.04 | 0.05 | 0.04 | 0.05 | 0.04 | 0.05 | 0.04 | 0.04 | 0.04 | 0.06 | 0.06 | 0.07 | 0.08 | 0.06 |
| FeO (assumed) | 1.11 | 1.41 | 1.23 | 1.40 | 1.28 | 1.38 | 1.28 | 1.16 | 1.29 | 1.65 | 1.73 | 1.90 | 2.35 | 1.76 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 0.02 | 0.00 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 |
| MgO | 27.48 | 29.03 | 28.20 | 28.92 | 28.44 | 28.36 | 27.99 | 27.65 | 27.64 | 29.62 | 29.94 | 31.47 | 30.35 | 29.80 |
| CaO | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.03 | 0.00 | 0.00 |
| BaO | 0.05 | 0.04 | 0.03 | 0.03 | 0.03 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 | 0.00 | 0.03 | 0.04 | 0.03 |
| $Na_2O$ | 0.13 | 0.05 | 0.00 | 0.05 | 0.06 | 0.12 | 0.10 | 0.13 | 0.10 | 0.06 | 0.03 | 0.03 | 0.02 | 0.01 |
| $K_2O$ | 9.68 | 8.53 | 9.56 | 8.86 | 9.02 | 8.96 | 8.94 | 9.30 | 9.28 | 7.87 | 7.74 | 7.89 | 8.01 | 7.90 |
| F | 0.17 | 0.00 | 0.09 | 0.01 | 0.05 | 0.04 | 0.00 | 0.17 | 0.07 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 |
| Cl | 0.06 | 0.06 | 0.07 | 0.06 | 0.06 | 0.07 | 0.07 | 0.07 | 0.07 | 0.08 | 0.07 | 0.05 | 0.07 | 0.08 |
| $H_2O$ | 4.21 | 4.26 | 4.25 | 4.30 | 4.26 | 4.28 | 4.26 | 4.20 | 4.22 | 4.24 | 4.26 | 4.33 | 4.28 | 4.23 |
| Subtotal | 100.25 | 99.11 | 100.06 | 99.97 | 99.79 | 100.25 | 99.26 | 99.80 | 99.29 | 98.66 | 99.20 | 100.93 | 100.11 | 98.55 |
| O=F,Cl | 0.09 | 0.01 | 0.05 | 0.02 | 0.04 | 0.03 | 0.02 | 0.09 | 0.04 | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 |
| Total | 100.16 | 99.10 | 100.01 | 99.95 | 99.75 | 100.21 | 99.25 | 99.71 | 99.25 | 98.64 | 99.18 | 100.92 | 100.10 | 98.53 |
| | | | | | | | | | | | | | | |
| | Structural formula based on 24 anions | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| T (iv) site: Si | 5.67 | 5.59 | 5.69 | 5.74 | 5.67 | 5.62 | 5.65 | 5.68 | 5.64 | 5.51 | 5.52 | 5.39 | 5.45 | 5.62 |
| Al | 2.33 | 2.30 | 2.26 | 2.15 | 2.27 | 2.34 | 2.33 | 2.32 | 2.36 | 2.31 | 2.27 | 2.26 | 2.27 | 2.13 |
| $Fe^{3+}$ | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| T site total | 8.00 | 7.89 | 7.96 | 7.90 | 7.95 | 7.96 | 7.98 | 8.00 | 8.00 | 7.83 | 7.80 | 7.65 | 7.73 | 7.76 |
| Al (total) | 2.37 | 2.30 | 2.26 | 2.15 | 2.27 | 2.34 | 2.33 | 2.34 | 2.37 | 2.31 | 2.27 | 2.26 | 2.27 | 2.13 |
| R (vi) site: Al | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.10 | 0.09 | 0.09 | 0.08 | 0.09 | 0.10 | 0.10 | 0.10 | 0.09 | 0.09 | 0.09 | 0.11 | 0.09 | 0.09 |
| $Cr^{3+}$ | 0.14 | 0.12 | 0.13 | 0.12 | 0.12 | 0.14 | 0.13 | 0.13 | 0.13 | 0.13 | 0.14 | 0.14 | 0.13 | 0.12 |
| $Fe^{3+}$ (assumed) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{2+}$ (assumed) | 0.13 | 0.17 | 0.14 | 0.16 | 0.15 | 0.16 | 0.15 | 0.14 | 0.15 | 0.19 | 0.20 | 0.22 | 0.27 | 0.21 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 5.70 | 6.07 | 5.86 | 5.99 | 5.91 | 5.87 | 5.85 | 5.75 | 5.78 | 6.22 | 6.25 | 6.48 | 6.31 | 6.26 |
| R site vacancy | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y-site total | 6.10 | 6.45 | 6.21 | 6.35 | 6.27 | 6.28 | 6.22 | 6.14 | 6.17 | 6.63 | 6.68 | 6.95 | 6.81 | 6.68 |
| A (XII) site: Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ba | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 0.04 | 0.01 | 0.00 | 0.01 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 |
| K | 1.72 | 1.53 | 1.70 | 1.57 | 1.60 | 1.59 | 1.60 | 1.65 | 1.66 | 1.41 | 1.38 | 1.39 | 1.43 | 1.42 |
| A-site vacancy | 0.24 | 0.46 | 0.30 | 0.41 | 0.38 | 0.38 | 0.37 | 0.31 | 0.31 | 0.57 | 0.61 | 0.60 | 0.57 | 0.57 |
| A-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| X (anion) site: | 3.91 | 3.99 | 3.95 | 3.98 | 3.96 | 3.96 | 3.98 | 3.91 | 3.95 | 3.98 | 3.97 | 3.99 | 3.98 | 3.98 |
| O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 0.08 | 0.00 | 0.04 | 0.00 | 0.02 | 0.02 | 0.00 | 0.07 | 0.03 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| Cl | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 |
| anion-site total | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| | | | | | | | | | | | | | | |
| $Fe^{3+}/(Fe_{tot})$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $Mg/(Mg+Fe_{tot})$ | 0.98 | 0.97 | 0.98 | 0.97 | 0.97 | 0.97 | 0.97 | 0.98 | 0.97 | 0.97 | 0.97 | 0.97 | 0.96 | 0.97 |
| $Mg/(Mg+Fe^{2+})$ | 0.98 | 0.97 | 0.98 | 0.97 | 0.98 | 0.97 | 0.97 | 0.98 | 0.97 | 0.97 | 0.97 | 0.97 | 0.96 | 0.97 |
| $viAl/(viAl+viR^{2+})$ | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fe/(Fe + Mg + Alvi + Ti) | 0.02 | 0.03 | 0.02 | 0.03 | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.03 |
| Mg/(Fe + Mg + Alvi + Ti) | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.95 | 0.95 | 0.95 |
| Ti/(Fe + Mg + Alvi + Ti) | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 |
| Alvi/(Fe + Mg + Alvi + Ti) | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| K/(A-site total) | 0.86 | 0.76 | 0.85 | 0.79 | 0.80 | 0.79 | 0.80 | 0.83 | 0.83 | 0.71 | 0.69 | 0.70 | 0.71 | 0.71 |
| Vacancy/(A-site total) | 0.12 | 0.23 | 0.15 | 0.21 | 0.19 | 0.19 | 0.19 | 0.15 | 0.16 | 0.28 | 0.30 | 0.30 | 0.28 | 0.29 |
| Ba/(A-site total) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na/(A-site total) | 0.02 | 0.01 | 0.00 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | | | | | |
| Quality control: | | | | | | | | | | | | | | |
| R site test | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high |

| Sample # | HP20DM-07 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 38.74 | 40.06 | 40.23 | 39.15 | 40.89 | 40.54 | 40.12 | 41.00 | 40.25 | 40.34 | 40.73 |
| $Al_2O_3$ | 13.69 | 13.96 | 14.20 | 13.23 | 13.45 | 13.56 | 13.74 | 14.33 | 14.19 | 14.34 | 14.46 |
| $TiO_2$ | 0.78 | 1.03 | 0.86 | 0.85 | 0.81 | 0.94 | 0.86 | 0.95 | 0.78 | 0.80 | 0.83 |
| $Cr_2O_3$ | 1.32 | 1.04 | 1.02 | 1.20 | 1.16 | 1.18 | 1.23 | 1.07 | 1.10 | 1.15 | 1.20 |
| $Fe_2O_3$ (assumed) | 0.06 | 0.06 | 0.06 | 0.08 | 0.06 | 0.06 | 0.06 | 0.04 | 0.05 | 0.05 | 0.05 |
| FeO (assumed) | 1.85 | 1.86 | 1.72 | 2.20 | 1.63 | 1.67 | 1.75 | 1.22 | 1.53 | 1.31 | 1.31 |
| MnO | 0.01 | 0.01 | 0.00 | 0.03 | 0.00 | 0.03 | 0.00 | 0.00 | 0.02 | 0.02 | 0.01 |
| MgO | 29.60 | 27.92 | 27.99 | 29.85 | 28.27 | 28.68 | 28.65 | 27.58 | 27.80 | 27.80 | 27.77 |
| CaO | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 |
| BaO | 0.02 | 0.04 | 0.03 | 0.17 | 0.17 | 0.16 | 0.16 | 0.17 | 0.15 | 0.14 | 0.14 |
| $Na_2O$ | 0.01 | 0.08 | 0.03 | 0.04 | 0.03 | 0.05 | 0.03 | 0.07 | 0.07 | 0.05 | 0.04 |
| $K_2O$ | 7.62 | 8.92 | 8.98 | 7.67 | 9.00 | 8.53 | 8.43 | 9.67 | 9.04 | 9.19 | 9.92 |
| F | 0.00 | 0.00 | 0.02 | 0.03 | 0.00 | 0.00 | 0.07 | 0.17 | 0.00 | 0.07 | 0.16 |
| Cl | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 |
| $H_2O$ (calculated) | 4.22 | 4.26 | 4.26 | 4.22 | 4.29 | 4.29 | 4.24 | 4.23 | 4.26 | 4.24 | 4.24 |
| Subtotal | 97.96 | 99.27 | 99.44 | 98.74 | 99.79 | 99.72 | 99.37 | 100.54 | 99.30 | 99.53 | 100.89 |
| O=F,Cl | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.04 | 0.08 | 0.01 | 0.04 | 0.08 |
| Total | 97.95 | 99.26 | 99.42 | 98.72 | 99.78 | 99.72 | 99.33 | 100.46 | 99.29 | 99.49 | 100.82 |
| | | | | | | | | | | | |
| | Structural formula based on 24 anions | | | | | | | | | | |
| | | | | | | | | | | | |
| T (iv) site: Si | 5.50 | 5.63 | 5.63 | 5.53 | 5.71 | 5.66 | 5.62 | 5.69 | 5.65 | 5.65 | 5.65 |
| Al | 2.29 | 2.31 | 2.34 | 2.20 | 2.21 | 2.23 | 2.27 | 2.31 | 2.35 | 2.35 | 2.35 |
| $Fe^{3+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 |
| T site total | 7.79 | 7.94 | 7.98 | 7.74 | 7.93 | 7.89 | 7.90 | 8.00 | 8.00 | 8.00 | 8.00 |
| Al (total) | 2.29 | 2.31 | 2.34 | 2.20 | 2.21 | 2.23 | 2.27 | 2.34 | 2.35 | 2.37 | 2.36 |
| R (vi) site: Al | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 0.01 | 0.01 |
| Ti | 0.08 | 0.11 | 0.09 | 0.09 | 0.08 | 0.10 | 0.09 | 0.10 | 0.08 | 0.08 | 0.09 |
| $Cr^{3+}$ | 0.15 | 0.12 | 0.11 | 0.13 | 0.13 | 0.13 | 0.14 | 0.12 | 0.12 | 0.13 | 0.13 |
| $Fe^{3+}$ (assumed) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{2+}$ (assumed) | 0.22 | 0.22 | 0.20 | 0.26 | 0.19 | 0.19 | 0.21 | 0.14 | 0.18 | 0.15 | 0.15 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 6.26 | 5.85 | 5.85 | 6.28 | 5.88 | 5.97 | 5.99 | 5.71 | 5.82 | 5.80 | 5.74 |
| R site vacancy | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y-site total | 6.71 | 6.29 | 6.25 | 6.77 | 6.29 | 6.39 | 6.42 | 6.10 | 6.20 | 6.19 | 6.13 |
| A (XII) site: Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ba | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Na | 0.00 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 |
| K | 1.38 | 1.60 | 1.60 | 1.38 | 1.60 | 1.52 | 1.51 | 1.71 | 1.62 | 1.64 | 1.76 |
| A-site vacancy | 0.62 | 0.38 | 0.39 | 0.60 | 0.38 | 0.46 | 0.48 | 0.26 | 0.35 | 0.34 | 0.22 |
| A-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| X (anion) site: OH | 3.99 | 3.99 | 3.98 | 3.98 | 3.99 | 3.99 | 3.96 | 3.92 | 3.99 | 3.96 | 3.92 |
| O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.03 | 0.07 | 0.00 | 0.03 | 0.07 |
| Cl | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| anion-site total | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| | | | | | | | | | | | |
| $Fe^{3+}/(Fe_{tot})$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $Mg/(Mg+Fe_{tot})$ | 0.97 | 0.96 | 0.97 | 0.96 | 0.97 | 0.97 | 0.97 | 0.98 | 0.97 | 0.97 | 0.97 |
| $Mg/(Mg+Fe^{2+})$ | 0.97 | 0.96 | 0.97 | 0.96 | 0.97 | 0.97 | 0.97 | 0.98 | 0.97 | 0.97 | 0.97 |
| $viAl/(viAl+viR^{2+})$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| XFe = Fe/(Fe + Mg + Alvi + Ti) | 0.03 | 0.04 | 0.03 | 0.04 | 0.03 | 0.03 | 0.03 | 0.02 | 0.03 | 0.03 | 0.03 |
| XMg = Mg/(Fe + Mg + Alvi + Ti) | 0.95 | 0.95 | 0.95 | 0.95 | 0.96 | 0.95 | 0.95 | 0.95 | 0.96 | 0.96 | 0.96 |
| XTi = Ti/(Fe + Mg + Alvi + Ti) | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 |
| XAlvi = Alvi/(Fe + Mg + Alvi + Ti) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| K/(A-site total) | 0.69 | 0.80 | 0.80 | 0.69 | 0.80 | 0.76 | 0.75 | 0.86 | 0.81 | 0.82 | 0.88 |
| Vacancy/(A-site total) | 0.31 | 0.19 | 0.19 | 0.30 | 0.19 | 0.23 | 0.24 | 0.13 | 0.18 | 0.17 | 0.11 |
| Ba/(A-site total) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na/(A-site total) | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| | | | | | | | | | | | |
| Quality control: oxide total test | Caution: low total | | | | | | | | | | |
| R site test | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high |

| Sample # | HP20DM-07 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 40.41 | 41.02 | 40.82 | 40.87 | 40.86 | 40.75 | 39.64 | 40.28 | 40.79 | 40.24 |
| $Al_2O_3$ | 13.86 | 13.94 | 14.62 | 14.24 | 14.45 | 14.50 | 14.05 | 14.14 | 14.44 | 14.40 |
| $TiO_2$ | 0.84 | 0.88 | 0.76 | 0.85 | 0.88 | 0.80 | 0.97 | 0.86 | 0.99 | 0.95 |
| $Cr_2O_3$ | 1.04 | 1.13 | 1.12 | 1.06 | 1.11 | 1.09 | 1.15 | 1.23 | 1.09 | 1.15 |
| $Fe_2O_3$ (assumed) | 0.05 | 0.05 | 0.04 | 0.05 | 0.04 | 0.04 | 0.05 | 0.06 | 0.05 | 0.05 |
| FeO (assumed) | 1.52 | 1.40 | 1.27 | 1.31 | 1.26 | 1.29 | 1.45 | 1.69 | 1.42 | 1.32 |
| MnO | 0.07 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| MgO | 28.10 | 27.61 | 27.08 | 27.39 | 27.47 | 27.34 | 27.25 | 28.37 | 27.41 | 26.97 |
| CaO | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.02 | 0.01 | 0.01 |
| BaO | 0.17 | 0.15 | 0.05 | 0.04 | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 | 0.04 |
| $Na_2O$ | 0.06 | 0.09 | 0.04 | 0.07 | 0.06 | 0.07 | 0.08 | 0.14 | 0.15 | 0.16 |
| $K_2O$ | 8.91 | 8.89 | 9.68 | 9.53 | 9.74 | 10.01 | 9.04 | 8.28 | 8.97 | 9.63 |
| F | 0.00 | 0.19 | 0.00 | 0.12 | 0.00 | 0.21 | 0.00 | 0.02 | 0.00 | 0.00 |
| Cl | 0.04 | 0.04 | 0.05 | 0.04 | 0.05 | 0.04 | 0.05 | 0.05 | 0.05 | 0.04 |
| $H_2O$ (calculated) | 4.27 | 4.19 | 4.29 | 4.23 | 4.30 | 4.20 | 4.20 | 4.27 | 4.29 | 4.25 |
| Subtotal | 99.34 | 99.60 | 99.84 | 99.80 | 100.26 | 100.38 | 97.98 | 99.43 | 99.70 | 99.21 |
| O=F,Cl | 0.01 | 0.09 | 0.01 | 0.06 | 0.01 | 0.10 | 0.01 | 0.02 | 0.01 | 0.01 |
| Total | 99.33 | 99.51 | 99.83 | 99.74 | 100.25 | 100.28 | 97.96 | 99.41 | 99.69 | 99.20 |
| | | | | | | | | | | |
| | Structural formula based on 24 anions | | | | | | | | | |
| | | | | | | | | | | |
| T (iv) site: Si | 5.67 | 5.73 | 5.70 | 5.71 | 5.68 | 5.68 | 5.64 | 5.63 | 5.68 | 5.66 |
| Al | 2.29 | 2.27 | 2.30 | 2.29 | 2.32 | 2.32 | 2.35 | 2.33 | 2.32 | 2.34 |
| $Fe^{3+}$ | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 |
| T site total | 7.96 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 7.96 | 8.00 | 8.00 |
| Al (total) | 2.29 | 2.29 | 2.40 | 2.34 | 2.37 | 2.38 | 2.35 | 2.33 | 2.37 | 2.39 |
| R (vi) site: Al | 0.00 | 0.02 | 0.10 | 0.05 | 0.05 | 0.05 | 0.00 | 0.00 | 0.06 | 0.05 |
| Ti | 0.09 | 0.09 | 0.08 | 0.09 | 0.09 | 0.08 | 0.10 | 0.09 | 0.10 | 0.10 |
| $Cr^{3+}$ | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.13 | 0.14 | 0.12 | 0.13 |
| $Fe^{3+}$ (assumed) | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| $Fe^{2+}$ (assumed) | 0.18 | 0.16 | 0.15 | 0.15 | 0.15 | 0.15 | 0.17 | 0.20 | 0.17 | 0.16 |
| $Mn^{2+}$ | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 5.87 | 5.75 | 5.63 | 5.70 | 5.69 | 5.68 | 5.78 | 5.91 | 5.69 | 5.65 |
| R site vacancy | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y-site total | 6.26 | 6.16 | 6.09 | 6.11 | 6.11 | 6.09 | 6.18 | 6.33 | 6.14 | 6.09 |
| A (XII) site: Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ba | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.04 | 0.04 | 0.04 |
| K | 1.59 | 1.58 | 1.72 | 1.70 | 1.73 | 1.78 | 1.64 | 1.48 | 1.59 | 1.73 |
| A-site vacancy | 0.38 | 0.38 | 0.27 | 0.28 | 0.25 | 0.20 | 0.33 | 0.48 | 0.36 | 0.23 |
| A-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| X (anion) site: OH | 3.99 | 3.90 | 3.99 | 3.94 | 3.99 | 3.90 | 3.99 | 3.98 | 3.99 | 3.99 |
| O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 0.00 | 0.09 | 0.00 | 0.05 | 0.00 | 0.09 | 0.00 | 0.01 | 0.00 | 0.00 |
| Cl | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| anion-site total | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| | | | | | | | | | | |
| $Fe^{3+}/(Fe_{tot})$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $Mg/(Mg+Fe_{tot})$ | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| $Mg/(Mg+Fe^{2+})$ | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| $viAl/(viAl+viR^{2+})$ | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 |
| XFe = Fe/(Fe + Mg + Alvi + Ti) | 0.03 | 0.03 | 0.02 | 0.03 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| XMg = Mg/(Fe + Mg + Alvi + Ti) | 0.96 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 |
| XTi = Ti/(Fe + Mg + Alvi + Ti) | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 |
| XAlvi = Alvi/(Fe + Mg + Alvi + Ti) | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 |
| K/(A-site total) | 0.80 | 0.79 | 0.86 | 0.85 | 0.86 | 0.89 | 0.82 | 0.74 | 0.80 | 0.86 |
| Vacancy/(A-site total) | 0.19 | 0.19 | 0.13 | 0.14 | 0.13 | 0.10 | 0.17 | 0.24 | 0.18 | 0.11 |
| Ba/(A-site total) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na/(A-site total) | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 |
| | | | | | | | | | | |
| Quality control: oxide total test | | | | | | | Caution: low total | | | |
| R site test | R site high | R site high | | R site high | R site high | | R site high | R site high | R site high | |

| Sample # | QC20DM-06 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 41.31 | 40.87 | 40.67 | 40.97 | 40.66 | 39.89 | 39.41 | 39.84 | 40.48 | 40.81 | 40.75 | 41.24 |
| $Al_2O_3$ | 14.59 | 14.95 | 14.81 | 14.57 | 14.55 | 15.10 | 15.27 | 15.23 | 15.28 | 15.19 | 15.25 | 14.58 |
| $TiO_2$ | 0.87 | 0.51 | 0.53 | 0.67 | 0.76 | 0.64 | 0.69 | 0.78 | 1.01 | 1.06 | 0.89 | 0.87 |
| $Cr_2O_3$ | 0.91 | 1.04 | 1.02 | 0.88 | 0.86 | 0.93 | 0.84 | 0.86 | 0.78 | 0.78 | 0.87 | 0.88 |
| $Fe_2O_3$ (assumed) | 0.04 | 0.04 | 0.04 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.04 | 0.05 |
| FeO (assumed) | 1.29 | 1.17 | 1.25 | 0.89 | 1.08 | 1.08 | 1.04 | 1.11 | 1.24 | 1.32 | 1.28 | 1.34 |
| MnO | 0.05 | 0.04 | 0.01 | 0.00 | 0.02 | 0.00 | 0.02 | 0.01 | 0.03 | 0.04 | 0.00 | 0.02 |
| MgO | 29.60 | 31.33 | 28.99 | 29.93 | 27.51 | 32.09 | 30.45 | 29.93 | 29.06 | 28.39 | 28.87 | 29.24 |
| CaO | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.02 | 0.01 | 0.02 | 0.01 | 0.00 | 0.01 |
| BaO | 0.02 | 0.02 | 0.03 | 0.05 | 0.04 | 0.05 | 0.01 | 0.00 | 0.00 | 0.06 | 0.03 | 0.06 |
| $Na_2O$ | 0.09 | 0.03 | 0.00 | 0.03 | 0.06 | 0.00 | 0.01 | 0.02 | 0.05 | 0.05 | 0.06 | 0.07 |
| $K_2O$ | 6.40 | 4.88 | 7.82 | 7.00 | 9.18 | 5.84 | 6.22 | 6.96 | 8.97 | 9.64 | 6.69 | 6.56 |
| F | 0.03 | 0.02 | 0.03 | 0.01 | 0.03 | 0.02 | 0.02 | 0.02 | 0.03 | 0.04 | 0.03 | 0.03 |
| Cl | 0.10 | 0.08 | 0.08 | 0.09 | 0.10 | 0.07 | 0.08 | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 |
| $H_2O$ (calculated) | 4.33 | 4.36 | 4.30 | 4.32 | 4.24 | 4.36 | 4.28 | 4.32 | 4.36 | 4.36 | 4.33 | 4.34 |
| Subtotal | 99.65 | 99.34 | 99.58 | 99.43 | 99.12 | 100.11 | 98.39 | 99.13 | 101.36 | 101.81 | 99.11 | 99.31 |
| O=F,Cl | 0.03 | 0.02 | 0.03 | 0.02 | 0.04 | 0.02 | 0.03 | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 |
| Total | 99.61 | 99.32 | 99.55 | 99.41 | 99.09 | 100.09 | 98.37 | 99.12 | 101.34 | 101.79 | 99.10 | 99.29 |
| | | | | | | | | | | | | |
| | Structural formula based on 24 anions | | | | | | | | | | | |
| | | | | | | | | | | | | |
| T (iv) site: Si | 5.67 | 5.58 | 5.63 | 5.65 | 5.69 | 5.45 | 5.48 | 5.52 | 5.54 | 5.59 | 5.63 | 5.68 |
| Al | 2.33 | 2.41 | 2.37 | 2.35 | 2.31 | 2.43 | 2.50 | 2.48 | 2.46 | 2.41 | 2.37 | 2.32 |
| $Fe^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| T site total | 8.00 | 7.99 | 8.00 | 8.00 | 8.00 | 7.88 | 7.99 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Al (total) | 2.36 | 2.41 | 2.42 | 2.37 | 2.40 | 2.43 | 2.50 | 2.49 | 2.47 | 2.45 | 2.48 | 2.37 |
| R (vi) site: Al | 0.03 | 0.00 | 0.05 | 0.01 | 0.09 | 0.00 | 0.00 | 0.00 | 0.01 | 0.04 | 0.11 | 0.05 |
| Ti | 0.09 | 0.05 | 0.05 | 0.07 | 0.08 | 0.07 | 0.07 | 0.08 | 0.10 | 0.11 | 0.09 | 0.09 |
| $Cr^{3+}$ | 0.10 | 0.11 | 0.11 | 0.10 | 0.10 | 0.10 | 0.09 | 0.09 | 0.08 | 0.08 | 0.10 | 0.10 |
| $Fe^{3+}$ (assumed) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{2+}$ (assumed) | 0.15 | 0.13 | 0.14 | 0.10 | 0.13 | 0.12 | 0.12 | 0.13 | 0.14 | 0.15 | 0.15 | 0.15 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Mg | 6.06 | 6.38 | 5.99 | 6.15 | 5.74 | 6.53 | 6.31 | 6.18 | 5.93 | 5.79 | 5.94 | 6.01 |
| R site vacancy | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y-site total | 6.43 | 6.68 | 6.35 | 6.43 | 6.15 | 6.82 | 6.60 | 6.49 | 6.28 | 6.18 | 6.39 | 6.40 |
| A (XII) site: Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ba | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 0.02 | 0.01 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 |
| K | 1.12 | 0.85 | 1.38 | 1.23 | 1.64 | 1.02 | 1.10 | 1.23 | 1.57 | 1.68 | 1.18 | 1.15 |
| A-site vacancy | 0.85 | 1.14 | 0.62 | 0.76 | 0.34 | 0.98 | 0.89 | 0.76 | 0.42 | 0.30 | 0.80 | 0.82 |
| A-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| X (anion) site: OH | 3.96 | 3.97 | 3.97 | 3.97 | 3.96 | 3.97 | 3.97 | 3.99 | 3.98 | 3.98 | 3.99 | 3.98 |
| O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 |
| Cl | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| anion-site total | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| | | | | | | | | | | | | |
| $Fe^{3+}/(Fe_{tot})$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $Mg/(Mg+Fe_{tot})$ | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.97 | 0.97 | 0.97 |
| $Mg/(Mg+Fe^{2+})$ | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.97 | 0.98 | 0.97 |
| $viAl/(viAl+viR^{2+})$ | 0.00 | 0.00 | 0.01 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.01 |
| Fe/(Fe + Mg + Alvi + Ti) | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Mg/(Fe + Mg + Alvi + Ti) | 0.96 | 0.97 | 0.96 | 0.97 | 0.95 | 0.97 | 0.97 | 0.97 | 0.96 | 0.95 | 0.94 | 0.95 |
| Ti/(Fe + Mg + Alvi + Ti) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 |
| Alvi/(Fe + Mg + Alvi + Ti) | 0.00 | 0.00 | 0.01 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.01 |
| K/(A-site total) | 0.56 | 0.43 | 0.69 | 0.62 | 0.82 | 0.51 | 0.55 | 0.61 | 0.78 | 0.84 | 0.59 | 0.58 |
| Vacancy/(A-site total) | 0.43 | 0.57 | 0.31 | 0.38 | 0.17 | 0.49 | 0.45 | 0.38 | 0.21 | 0.15 | 0.40 | 0.41 |
| Ba/(A-site total) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na/(A-site total) | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| | | | | | | | | | | | | |
| Quality control: | | | | | | | | | | | | |
| R site test | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high |

| Sample # | QC20DM-06 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 39.75 | 40.10 | 40.51 | 40.01 | 39.68 | 39.53 | 41.51 | 41.35 | 41.61 | 41.05 |
| $Al_2O_3$ | 15.15 | 14.66 | 15.23 | 15.30 | 15.47 | 15.21 | 14.97 | 15.25 | 15.16 | 15.59 |
| $TiO_2$ | 0.59 | 0.48 | 0.75 | 0.63 | 0.91 | 0.85 | 0.84 | 0.62 | 0.89 | 1.02 |
| $Cr_2O_3$ | 0.83 | 0.96 | 0.81 | 0.77 | 0.76 | 0.80 | 0.77 | 0.80 | 0.88 | 0.79 |
| $Fe_2O_3$ (assumed) | 0.03 | 0.04 | 0.04 | 0.03 | 0.04 | 0.03 | 0.04 | 0.03 | 0.04 | 0.05 |
| FeO (assumed) | 1.00 | 1.10 | 1.23 | 0.95 | 1.24 | 0.96 | 1.09 | 0.93 | 1.26 | 1.31 |
| MnO | 0.00 | 0.02 | 0.01 | 0.00 | 0.05 | 0.03 | 0.03 | 0.02 | 0.01 | 0.03 |
| MgO | 31.15 | 32.04 | 28.79 | 30.25 | 29.01 | 30.34 | 28.41 | 29.68 | 29.89 | 28.97 |
| CaO | 0.01 | 0.00 | 0.02 | 0.00 | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 0.01 |
| BaO | 0.04 | 0.00 | 0.04 | 0.05 | 0.08 | 0.02 | 0.02 | 0.02 | 0.03 | 0.06 |
| $Na_2O$ | 0.00 | 0.03 | 0.08 | 0.03 | 0.00 | 0.04 | 0.06 | 0.05 | 0.05 | 0.03 |
| $K_2O$ | 6.62 | 5.29 | 7.19 | 6.31 | 7.42 | 6.67 | 8.68 | 6.77 | 7.00 | 8.43 |
| F | 0.01 | 0.01 | 0.04 | 0.02 | 0.03 | 0.02 | 0.03 | 0.02 | 0.03 | 0.03 |
| Cl | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.09 | 0.10 | 0.07 | 0.09 | 0.12 |
| $H_2O$ (calculated) | 4.34 | 4.36 | 4.31 | 4.32 | 4.29 | 4.29 | 4.34 | 4.36 | 4.40 | 4.37 |
| Subtotal | 99.54 | 99.09 | 99.05 | 98.68 | 98.99 | 98.87 | 100.89 | 99.96 | 101.32 | 101.83 |
| O=F,Cl | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.03 | 0.03 | 0.02 | 0.03 | 0.04 |
| Total | 99.53 | 99.08 | 99.03 | 98.67 | 98.97 | 98.84 | 100.85 | 99.94 | 101.29 | 101.79 |
| | | | | | | | | | | |
| | Structural formula based on 24 anions | | | | | | | | | |
| | | | | | | | | | | |
| T (iv) site: Si | 5.48 | 5.51 | 5.61 | 5.54 | 5.52 | 5.49 | 5.69 | 5.65 | 5.63 | 5.58 |
| Al | 2.46 | 2.37 | 2.39 | 2.46 | 2.48 | 2.49 | 2.31 | 2.35 | 2.37 | 2.42 |
| $Fe^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| T site total | 7.94 | 7.89 | 8.00 | 8.00 | 8.00 | 7.98 | 8.00 | 8.00 | 8.00 | 8.00 |
| Al (total) | 2.46 | 2.37 | 2.49 | 2.50 | 2.54 | 2.49 | 2.42 | 2.46 | 2.42 | 2.50 |
| R (vi) site: Al | 0.00 | 0.00 | 0.10 | 0.03 | 0.06 | 0.00 | 0.10 | 0.11 | 0.05 | 0.07 |
| Ti | 0.06 | 0.05 | 0.08 | 0.07 | 0.09 | 0.09 | 0.09 | 0.06 | 0.09 | 0.10 |
| $Cr^{3+}$ | 0.09 | 0.10 | 0.09 | 0.08 | 0.08 | 0.09 | 0.08 | 0.09 | 0.09 | 0.09 |
| $Fe^{3+}$ (assumed) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{2+}$ (assumed) | 0.11 | 0.13 | 0.14 | 0.11 | 0.14 | 0.11 | 0.12 | 0.11 | 0.14 | 0.15 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 6.40 | 6.56 | 5.95 | 6.24 | 6.02 | 6.28 | 5.80 | 6.05 | 6.03 | 5.87 |
| R site vacancy | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y-site total | 6.66 | 6.84 | 6.37 | 6.54 | 6.41 | 6.57 | 6.21 | 6.42 | 6.41 | 6.29 |
| A (XII) site: Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ba | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 0.00 | 0.01 | 0.02 | 0.01 | 0.00 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 |
| K | 1.16 | 0.93 | 1.27 | 1.11 | 1.32 | 1.18 | 1.52 | 1.18 | 1.21 | 1.46 |
| A-site vacancy | 0.83 | 1.06 | 0.70 | 0.87 | 0.68 | 0.81 | 0.46 | 0.81 | 0.78 | 0.53 |
| A-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| X (anion) site: OH | 3.99 | 3.99 | 3.98 | 3.99 | 3.98 | 3.97 | 3.97 | 3.98 | 3.97 | 3.96 |
| O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 0.01 | 0.00 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Cl | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 |
| anion-site total | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| | | | | | | | | | | |
| $Fe^{3+}/(Fe_{tot})$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $Mg/(Mg+Fe_{tot})$ | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.97 |
| $Mg/(Mg+Fe^{2+})$ | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 |
| $viAl/(viAl+viR^{2+})$ | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | 0.00 | 0.02 | 0.02 | 0.01 | 0.01 |
| Fe/(Fe + Mg + Alvi + Ti) | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Mg/(Fe + Mg + Alvi + Ti) | 0.97 | 0.97 | 0.95 | 0.97 | 0.95 | 0.97 | 0.95 | 0.96 | 0.96 | 0.95 |
| Ti/(Fe + Mg + Alvi + Ti) | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 |
| Alvi/(Fe + Mg + Alvi + Ti) | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | 0.00 | 0.02 | 0.02 | 0.01 | 0.01 |
| K/(A-site total) | 0.58 | 0.46 | 0.64 | 0.56 | 0.66 | 0.59 | 0.76 | 0.59 | 0.60 | 0.73 |
| Vacancy/(A-site total) | 0.42 | 0.53 | 0.35 | 0.44 | 0.34 | 0.40 | 0.23 | 0.40 | 0.39 | 0.26 |
| Ba/(A-site total) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na/(A-site total) | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 |
| | | | | | | | | | | |
| Quality control: | | | | | | | | | | |
| R site test | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high | R site high |

| Sample # | QC20DM-08 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 40.29 | 40.35 | 40.22 | 40.36 | 39.90 | 40.18 | 40.61 | 40.20 | 40.32 | 40.05 | 39.29 | 39.35 | 39.59 |
| $Al_2O_3$ | 15.18 | 15.19 | 15.24 | 15.07 | 15.04 | 15.14 | 15.16 | 15.06 | 15.09 | 15.19 | 15.27 | 15.28 | 15.23 |
| $TiO_2$ | 0.83 | 0.85 | 0.81 | 0.80 | 0.92 | 0.91 | 0.71 | 0.81 | 0.86 | 0.91 | 0.84 | 0.80 | 0.73 |
| $Cr_2O_3$ | 1.42 | 1.46 | 1.43 | 1.52 | 1.55 | 1.48 | 1.49 | 1.44 | 1.38 | 1.39 | 1.77 | 1.57 | 1.50 |
| $Fe_2O_3$ (assumed) | 0.05 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 |
| FeO (assumed) | 1.48 | 1.54 | 1.31 | 1.65 | 1.51 | 1.41 | 1.48 | 1.49 | 1.69 | 1.57 | 1.50 | 1.46 | 1.45 |
| MnO | 0.00 | 0.03 | 0.03 | 0.00 | 0.04 | 0.00 | 0.00 | 0.01 | 0.03 | 0.00 | 0.01 | 0.00 | 0.00 |
| MgO | 26.28 | 26.21 | 26.09 | 26.18 | 26.12 | 26.39 | 26.19 | 26.14 | 26.23 | 26.15 | 26.25 | 26.52 | 26.54 |
| CaO | 0.03 | 0.01 | 0.02 | 0.00 | 0.01 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.03 | 0.02 | 0.02 |
| BaO | 0.20 | 0.18 | 0.21 | 0.19 | 0.18 | 0.19 | 0.04 | 0.04 | 0.03 | 0.05 | 0.00 | 0.05 | 0.05 |
| $Na_2O$ | 0.06 | 0.07 | 0.06 | 0.06 | 0.08 | 0.08 | 0.05 | 0.09 | 0.05 | 0.07 | 0.03 | 0.08 | 0.06 |
| $K_2O$ | 10.48 | 10.46 | 10.61 | 10.57 | 10.28 | 10.62 | 10.54 | 10.61 | 10.47 | 10.41 | 10.33 | 9.93 | 9.95 |
| F | 0.20 | 0.20 | 0.24 | 0.26 | 0.27 | 0.23 | 0.17 | 0.28 | 0.22 | 0.28 | 0.25 | 0.20 | 0.39 |
| Cl | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 |
| $H_2O$ (calculated) | 4.19 | 4.20 | 4.16 | 4.17 | 4.14 | 4.18 | 4.22 | 4.14 | 4.18 | 4.14 | 4.13 | 4.15 | 4.07 |
| Subtotal | 100.71 | 100.82 | 100.51 | 100.92 | 100.13 | 100.91 | 100.76 | 100.38 | 100.66 | 100.30 | 99.78 | 99.48 | 99.65 |
| O=F,Cl | 0.09 | 0.09 | 0.11 | 0.12 | 0.12 | 0.10 | 0.08 | 0.12 | 0.10 | 0.12 | 0.11 | 0.09 | 0.17 |
| Total | 100.62 | 100.72 | 100.40 | 100.80 | 100.01 | 100.81 | 100.68 | 100.26 | 100.56 | 100.18 | 99.67 | 99.39 | 99.48 |
| | | | | | | | | | | | | | |
| | Structural formula based on 24 anions | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| T (iv) site: Si | 5.62 | 5.62 | 5.63 | 5.63 | 5.60 | 5.60 | 5.65 | 5.63 | 5.63 | 5.61 | 5.54 | 5.55 | 5.57 |
| Al | 2.38 | 2.38 | 2.37 | 2.37 | 2.40 | 2.40 | 2.35 | 2.37 | 2.37 | 2.39 | 2.46 | 2.45 | 2.43 |
| $Fe^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| T site total | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Al (total) | 2.50 | 2.50 | 2.51 | 2.48 | 2.49 | 2.49 | 2.49 | 2.49 | 2.48 | 2.51 | 2.54 | 2.54 | 2.53 |
| R (vi) site: Al | 0.12 | 0.12 | 0.14 | 0.11 | 0.09 | 0.09 | 0.14 | 0.12 | 0.11 | 0.12 | 0.08 | 0.09 | 0.10 |
| Ti | 0.09 | 0.09 | 0.09 | 0.08 | 0.10 | 0.10 | 0.07 | 0.09 | 0.09 | 0.10 | 0.09 | 0.08 | 0.08 |
| $Cr^{3+}$ | 0.16 | 0.16 | 0.16 | 0.17 | 0.17 | 0.16 | 0.16 | 0.16 | 0.15 | 0.15 | 0.20 | 0.17 | 0.17 |
| $Fe^{3+}$ (assumed) | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Fe^{2+}$ (assumed) | 0.17 | 0.18 | 0.15 | 0.19 | 0.18 | 0.16 | 0.17 | 0.17 | 0.20 | 0.18 | 0.18 | 0.17 | 0.17 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 5.47 | 5.45 | 5.44 | 5.44 | 5.47 | 5.49 | 5.44 | 5.46 | 5.46 | 5.46 | 5.52 | 5.57 | 5.57 |
| R site vacancy | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y-site total | 6.01 | 6.01 | 6.00 | 6.00 | 6.02 | 6.01 | 6.00 | 6.00 | 6.02 | 6.02 | 6.06 | 6.10 | 6.09 |
| A (XII) site: Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ba | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 |
| K | 1.87 | 1.86 | 1.89 | 1.88 | 1.84 | 1.89 | 1.87 | 1.90 | 1.87 | 1.86 | 1.86 | 1.79 | 1.79 |
| A-site vacancy | 0.11 | 0.11 | 0.08 | 0.09 | 0.12 | 0.08 | 0.11 | 0.08 | 0.12 | 0.12 | 0.13 | 0.18 | 0.19 |
| A-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| X (anion) site: OH | 3.90 | 3.90 | 3.88 | 3.88 | 3.87 | 3.89 | 3.92 | 3.87 | 3.89 | 3.87 | 3.88 | 3.90 | 3.82 |
| O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 0.09 | 0.09 | 0.11 | 0.11 | 0.12 | 0.10 | 0.08 | 0.12 | 0.10 | 0.12 | 0.11 | 0.09 | 0.17 |
| Cl | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| anion-site total | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| | | | | | | | | | | | | | |
| $Fe^{3+}/(Fe_{tot})$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $Mg/(Mg+Fe_{tot})$ | 0.97 | 0.97 | 0.97 | 0.96 | 0.97 | 0.97 | 0.97 | 0.97 | 0.96 | 0.97 | 0.97 | 0.97 | 0.97 |
| $Mg/(Mg+Fe^{2+})$ | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| $viAl/(viAl+viR^{2+})$ | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 |
| Fe/(Fe + Mg + Alvi + Ti) | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| Mg/(Fe + Mg + Alvi + Ti) | 0.94 | 0.93 | 0.94 | 0.93 | 0.94 | 0.94 | 0.93 | 0.94 | 0.93 | 0.93 | 0.94 | 0.94 | 0.94 |
| Ti/(Fe + Mg + Alvi + Ti) | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 |
| Alvi/(Fe + Mg + Alvi + Ti) | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 |
| K/(A-site total) | 0.93 | 0.93 | 0.95 | 0.94 | 0.92 | 0.94 | 0.94 | 0.95 | 0.93 | 0.93 | 0.93 | 0.89 | 0.89 |
| Vacancy/(A-site total) | 0.05 | 0.06 | 0.04 | 0.05 | 0.06 | 0.04 | 0.05 | 0.04 | 0.06 | 0.06 | 0.07 | 0.09 | 0.10 |
| Ba/(A-site total) | 0.01 | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na/(A-site total) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 |

| Sample # | QC20DM-08 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 39.84 | 39.89 | 40.12 | 39.70 | 40.28 | 40.18 | 40.06 | 38.94 | 40.14 | 39.81 |
| $Al_2O_3$ | 15.16 | 15.26 | 15.18 | 15.14 | 15.37 | 15.38 | 15.04 | 15.30 | 15.10 | 15.02 |
| $TiO_2$ | 0.90 | 0.85 | 0.70 | 0.77 | 0.83 | 0.90 | 0.90 | 0.77 | 0.91 | 0.86 |
| $Cr_2O_3$ | 1.52 | 1.40 | 1.60 | 1.37 | 1.34 | 1.36 | 1.42 | 1.26 | 1.38 | 1.41 |
| $Fe_2O_3$ (assumed) | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.06 |
| FeO (assumed) | 1.56 | 1.46 | 1.43 | 1.47 | 1.33 | 1.49 | 1.60 | 1.45 | 1.44 | 1.64 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 |
| MgO | 26.00 | 26.27 | 26.77 | 26.45 | 26.55 | 26.52 | 26.18 | 26.15 | 26.73 | 26.07 |
| CaO | 0.02 | 0.03 | 0.37 | 0.04 | 0.03 | 0.03 | 0.02 | 0.01 | 0.03 | 0.00 |
| BaO | 0.04 | 0.04 | 0.01 | 0.18 | 0.18 | 0.18 | 0.20 | 0.18 | 0.18 | 0.19 |
| $Na_2O$ | 0.03 | 0.05 | 0.05 | 0.03 | 0.07 | 0.05 | 0.04 | 0.04 | 0.08 | 0.11 |
| $K_2O$ | 10.34 | 10.20 | 10.38 | 9.91 | 10.43 | 10.25 | 10.56 | 10.18 | 10.31 | 10.29 |
| F | 0.44 | 0.55 | 0.39 | 0.14 | 0.25 | 0.35 | 0.51 | 0.46 | 0.31 | 0.48 |
| Cl | 0.04 | 0.04 | 0.02 | 0.03 | 0.03 | 0.04 | 0.03 | 0.05 | 0.03 | 0.04 |
| $H_2O$ (calculated) | 4.04 | 4.00 | 4.12 | 4.18 | 4.19 | 4.13 | 4.03 | 3.98 | 4.15 | 4.02 |
| Subtotal | 99.98 | 100.07 | 101.19 | 99.45 | 100.92 | 100.92 | 100.65 | 98.83 | 100.84 | 100.01 |
| O=F,Cl | 0.20 | 0.24 | 0.17 | 0.07 | 0.11 | 0.15 | 0.22 | 0.21 | 0.14 | 0.21 |
| Total | 99.79 | 99.83 | 101.02 | 99.39 | 100.81 | 100.77 | 100.42 | 98.62 | 100.71 | 99.80 |
| | | | | | | | | | | |
| | Structural formula based on 24 anions | | | | | | | | | |
| | | | | | | | | | | |
| T (iv) site: Si | 5.60 | 5.60 | 5.58 | 5.59 | 5.60 | 5.59 | 5.61 | 5.55 | 5.59 | 5.61 |
| Al | 2.40 | 2.40 | 2.42 | 2.41 | 2.40 | 2.41 | 2.39 | 2.45 | 2.41 | 2.39 |
| $Fe^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| T site total | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Al (total) | 2.51 | 2.53 | 2.49 | 2.51 | 2.52 | 2.52 | 2.48 | 2.57 | 2.48 | 2.49 |
| R (vi) site: Al | 0.12 | 0.12 | 0.06 | 0.11 | 0.12 | 0.12 | 0.09 | 0.11 | 0.07 | 0.10 |
| Ti | 0.09 | 0.09 | 0.07 | 0.08 | 0.09 | 0.09 | 0.09 | 0.08 | 0.10 | 0.09 |
| $Cr^{3+}$ | 0.17 | 0.16 | 0.18 | 0.15 | 0.15 | 0.15 | 0.16 | 0.14 | 0.15 | 0.16 |
| $Fe^{3+}$ (assumed) | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Fe^{2+}$ (assumed) | 0.18 | 0.17 | 0.17 | 0.17 | 0.15 | 0.17 | 0.19 | 0.17 | 0.17 | 0.19 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 5.45 | 5.50 | 5.55 | 5.56 | 5.51 | 5.50 | 5.47 | 5.55 | 5.55 | 5.47 |
| R site vacancy | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y-site total | 6.02 | 6.04 | 6.03 | 6.08 | 6.03 | 6.04 | 6.01 | 6.07 | 6.05 | 6.02 |
| A (XII) site: Ca | 0.00 | 0.00 | 0.05 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ba | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Na | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.03 |
| K | 1.86 | 1.83 | 1.84 | 1.78 | 1.85 | 1.82 | 1.89 | 1.85 | 1.83 | 1.85 |
| A-site vacancy | 0.13 | 0.15 | 0.09 | 0.19 | 0.12 | 0.15 | 0.09 | 0.13 | 0.13 | 0.11 |
| A-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| X (anion) site: OH | 3.79 | 3.75 | 3.83 | 3.93 | 3.88 | 3.84 | 3.77 | 3.78 | 3.86 | 3.78 |
| O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 0.20 | 0.24 | 0.17 | 0.06 | 0.11 | 0.15 | 0.23 | 0.21 | 0.14 | 0.21 |
| Cl | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| anion-site total | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| | | | | | | | | | | |
| $Fe^{3+}/(Fe_{tot})$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $Mg/(Mg+Fe_{tot})$ | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.96 |
| $Mg/(Mg+Fe^{2+})$ | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| $viAl/(viAl+viR^{2+})$ | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 |
| Fe/(Fe + Mg + Alvi + Ti) | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| Mg/(Fe + Mg + Alvi + Ti) | 0.93 | 0.93 | 0.95 | 0.94 | 0.94 | 0.93 | 0.94 | 0.94 | 0.94 | 0.93 |
| Ti/(Fe + Mg + Alvi + Ti) | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 |
| Alvi/(Fe + Mg + Alvi + Ti) | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 |
| K/(A-site total) | 0.93 | 0.91 | 0.92 | 0.89 | 0.93 | 0.91 | 0.94 | 0.93 | 0.92 | 0.92 |
| Vacancy/(A-site total) | 0.07 | 0.08 | 0.05 | 0.10 | 0.06 | 0.08 | 0.04 | 0.06 | 0.07 | 0.06 |
| Ba/(A-site total) | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| Na/(A-site total) | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 |

# Appendix D. Apatite EMPA Data from Meta-chromitites

| Sample # | HP20DM-07 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_2O_5$ | 40.88 | 42.01 | 41.29 | 41.33 | 40.73 | 40.40 | 40.71 | 40.21 | 40.66 | 40.92 | 41.40 | 40.33 |
| $SiO_2$ | 0.18 | 0.00 | 0.00 | 0.00 | 0.11 | 0.05 | 0.04 | 0.25 | 0.02 | 0.11 | 0.00 | 0.01 |
| $SO_3$ | 0.09 | 0.05 | 0.00 | 0.10 | 0.05 | 0.08 | 0.08 | 0.11 | 0.05 | 0.06 | 0.04 | 0.04 |
| $La_2O_3$ | 0.00 | 0.05 | 0.00 | 0.02 | 0.01 | 0.05 | 0.10 | 0.00 | 0.00 | 0.04 | 0.07 | 0.08 |
| $Ce_2O_3$ | 0.09 | 0.21 | 0.08 | 0.17 | 0.14 | 0.25 | 0.18 | 0.16 | 0.11 | 0.17 | 0.05 | 0.12 |
| $Nd_2O_3$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 |
| $Y_2O_3$ | 0.00 | 0.00 | 0.04 | 0.05 | 0.02 | 0.00 | 0.00 | 0.07 | 0.03 | 0.01 | 0.00 | 0.01 |
| FeO | 0.12 | 0.25 | 0.10 | 0.13 | 0.06 | 0.17 | 0.16 | 0.18 | 0.14 | 0.12 | 0.00 | 0.14 |
| MnO | 0.03 | 0.01 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.01 | 0.02 |
| MgO | 0.09 | 0.04 | 0.03 | 0.05 | 0.05 | 0.05 | 0.06 | 0.18 | 0.09 | 0.07 | 0.05 | 0.09 |
| CaO | 54.68 | 54.56 | 55.04 | 54.69 | 54.71 | 54.14 | 54.52 | 54.13 | 54.49 | 54.44 | 55.22 | 54.75 |
| SrO | 0.06 | 0.02 | 0.04 | 0.07 | 0.06 | 0.04 | 0.00 | 0.00 | 0.01 | 0.04 | 0.04 | 0.02 |
| $Na_2O$ | 0.01 | 0.04 | 0.05 | 0.04 | 0.09 | 0.07 | 0.05 | 0.08 | 0.08 | 0.00 | 0.02 | 0.03 |
| F | 1.42 | 1.62 | 1.45 | 1.79 | 1.59 | 1.02 | 1.43 | 1.55 | 1.70 | 1.58 | 1.30 | 1.51 |
| Cl | 0.52 | 0.51 | 0.56 | 0.47 | 0.99 | 2.17 | 1.17 | 1.04 | 1.04 | 1.11 | 0.67 | 0.59 |
| $H_2O$ | 0.95 | 0.88 | 0.93 | 0.79 | 0.74 | 0.70 | 0.77 | 0.74 | 0.67 | 0.71 | 0.98 | 0.87 |
| Subtotal | 99.12 | 100.24 | 99.60 | 99.68 | 99.37 | 99.19 | 99.26 | 98.72 | 99.08 | 99.38 | 99.86 | 98.59 |
| O=F,Cl | 0.72 | 0.80 | 0.74 | 0.86 | 0.89 | 0.92 | 0.87 | 0.89 | 0.95 | 0.92 | 0.70 | 0.77 |
| Total | 98.40 | 99.44 | 98.86 | 98.83 | 98.48 | 98.27 | 98.39 | 97.84 | 98.13 | 98.46 | 99.17 | 97.82 |
| | | | | | | | | | | | | |
| | Structural formula on the basis of 24 anions | | | | | | | | | | | |
| | | | | | | | | | | | | |
| P | 5.93 | 6.01 | 5.96 | 5.96 | 5.92 | 5.93 | 5.93 | 5.89 | 5.93 | 5.95 | 5.96 | 5.91 |
| Si | 0.03 | 0.00 | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | 0.04 | 0.00 | 0.02 | 0.00 | 0.00 |
| S | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |
| P-group total | 5.97 | 6.02 | 5.96 | 5.98 | 5.95 | 5.95 | 5.95 | 5.95 | 5.95 | 5.97 | 5.96 | 5.91 |
| La | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Ce | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 |
| Y | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{2+}$ | 0.02 | 0.04 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.00 | 0.02 |
| Mn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.05 | 0.02 | 0.02 | 0.01 | 0.02 |
| Ca | 10.03 | 9.88 | 10.06 | 9.99 | 10.07 | 10.05 | 10.05 | 10.03 | 10.06 | 10.01 | 10.06 | 10.15 |
| Sr | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 0.00 | 0.01 | 0.02 | 0.01 | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 | 0.00 | 0.01 | 0.01 |
| Ca-site total | 10.09 | 9.96 | 10.10 | 10.05 | 10.14 | 10.14 | 10.13 | 10.15 | 10.14 | 10.07 | 10.09 | 10.22 |
| F | 0.77 | 0.87 | 0.78 | 0.96 | 0.87 | 0.56 | 0.78 | 0.85 | 0.93 | 0.86 | 0.70 | 0.82 |
| Cl | 0.15 | 0.15 | 0.16 | 0.14 | 0.29 | 0.64 | 0.34 | 0.30 | 0.30 | 0.32 | 0.19 | 0.17 |
| OH | 1.08 | 0.99 | 1.06 | 0.90 | 0.85 | 0.80 | 0.88 | 0.85 | 0.77 | 0.82 | 1.11 | 1.00 |
| X-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| | | | | | | | | | | | | |
| F/(F+Cl+OH) | 0.38 | 0.43 | 0.39 | 0.48 | 0.43 | 0.28 | 0.39 | 0.42 | 0.46 | 0.43 | 0.35 | 0.41 |
| Cl/(F+Cl+OH) | 0.08 | 0.07 | 0.08 | 0.07 | 0.14 | 0.32 | 0.17 | 0.15 | 0.15 | 0.16 | 0.10 | 0.09 |
| OH/(F+Cl+OH) | 0.54 | 0.49 | 0.53 | 0.45 | 0.42 | 0.40 | 0.44 | 0.42 | 0.38 | 0.41 | 0.56 | 0.50 |
| | | | | | | | | | | | | |
| Quality control: oxide total test | | | | | | | | Caution: low total | | | | Caution: low total |

| Sample # | HP20DM-08 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Analysis pt. # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 1 | 2 | 1 |
| $P_2O_5$ | 40.58 | 41.06 | 41.08 | 40.79 | 41.09 | 40.98 | 41.34 | 40.56 | 41.39 | 41.21 | 41.46 | 40.77 |
| $SiO_2$ | 0.02 | 0.08 | 0.00 | 0.09 | 0.31 | 0.03 | 0.02 | 0.22 | 0.50 | 0.75 | 0.12 | 0.16 |
| $SO_3$ | 0.04 | 0.05 | 0.05 | 0.07 | 0.13 | 0.01 | 0.00 | 0.02 | 0.04 | 0.14 | 0.33 | 0.03 |
| $La_2O_3$ | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 | 0.05 | 0.03 | 0.05 | 0.01 | 0.00 | 0.00 | 0.05 |
| $Ce_2O_3$ | 0.00 | 0.17 | 0.07 | 0.22 | 0.12 | 0.11 | 0.11 | 0.18 | 0.24 | 0.19 | 0.15 | 0.22 |
| $Y_2O_3$ | 0.05 | 0.08 | 0.06 | 0.07 | 0.08 | 0.05 | 0.13 | 0.07 | 0.13 | 0.09 | 0.03 | 0.02 |
| FeO | 0.31 | 0.17 | 0.20 | 0.22 | 0.26 | 0.14 | 0.28 | 0.24 | 0.08 | 0.27 | 0.22 | 0.27 |
| MnO | 0.00 | 0.00 | 0.00 | 0.05 | 0.03 | 0.00 | 0.02 | 0.03 | 0.02 | 0.02 | 0.04 | 0.00 |
| MgO | 0.03 | 0.00 | 0.01 | 0.04 | 0.05 | 0.01 | 0.03 | 0.13 | 0.29 | 0.46 | 0.01 | 0.12 |
| CaO | 55.00 | 54.96 | 54.78 | 55.41 | 54.19 | 55.36 | 54.94 | 54.36 | 54.25 | 54.48 | 54.81 | 54.80 |
| SrO | 0.02 | 0.05 | 0.07 | 0.11 | 0.06 | 0.09 | 0.00 | 0.02 | 0.05 | 0.08 | 0.01 | 0.05 |
| $Na_2O$ | 0.01 | 0.08 | 0.04 | 0.00 | 0.00 | 0.05 | 0.03 | 0.04 | 0.07 | 0.00 | 0.10 | 0.01 |
| F | 2.14 | 1.86 | 2.09 | 2.05 | 2.01 | 1.92 | 1.84 | 2.08 | 2.25 | 2.23 | 2.21 | 2.02 |
| Cl | 0.12 | 0.12 | 0.13 | 0.12 | 0.13 | 0.13 | 0.12 | 0.11 | 0.13 | 0.19 | 0.19 | 0.12 |
| $H_2O$ | 0.70 | 0.85 | 0.73 | 0.75 | 0.77 | 0.81 | 0.86 | 0.73 | 0.67 | 0.68 | 0.68 | 0.76 |
| Subtotal | 99.04 | 99.52 | 99.30 | 100.02 | 99.22 | 99.76 | 99.75 | 98.83 | 100.11 | 100.78 | 100.41 | 99.41 |
| O=F,Cl | 0.93 | 0.81 | 0.91 | 0.89 | 0.87 | 0.84 | 0.80 | 0.90 | 0.97 | 0.98 | 0.97 | 0.88 |
| Total | 98.11 | 98.71 | 98.39 | 99.13 | 98.35 | 98.92 | 98.95 | 97.93 | 99.13 | 99.80 | 99.44 | 98.53 |
| | | | | | | | | | | | | |
| | Structural formula on the basis of 24 anions | | | | | | | | | | | |
| | | | | | | | | | | | | |
| P | 5.91 | 5.93 | 5.95 | 5.89 | 5.94 | 5.92 | 5.96 | 5.91 | 5.93 | 5.87 | 5.93 | 5.91 |
| Si | 0.00 | 0.01 | 0.00 | 0.02 | 0.05 | 0.00 | 0.00 | 0.04 | 0.08 | 0.13 | 0.02 | 0.03 |
| S | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.04 | 0.00 |
| P-group total | 5.92 | 5.95 | 5.96 | 5.91 | 6.01 | 5.93 | 5.96 | 5.95 | 6.02 | 6.02 | 5.99 | 5.94 |
| La | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ce | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Nd | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |
| $Fe^{2+}$ | 0.04 | 0.02 | 0.03 | 0.03 | 0.04 | 0.02 | 0.04 | 0.03 | 0.01 | 0.04 | 0.03 | 0.04 |
| Mn | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Mg | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.03 | 0.07 | 0.12 | 0.00 | 0.03 |
| Ca | 10.14 | 10.05 | 10.04 | 10.13 | 9.91 | 10.12 | 10.02 | 10.03 | 9.84 | 9.82 | 9.93 | 10.05 |
| Sr | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 |
| Na | 0.00 | 0.03 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.00 | 0.03 | 0.00 |
| Ca-site total | 10.20 | 10.13 | 10.10 | 10.21 | 9.99 | 10.19 | 10.10 | 10.13 | 9.99 | 10.01 | 10.01 | 10.15 |
| F | 1.17 | 1.00 | 1.13 | 1.11 | 1.08 | 1.04 | 0.99 | 1.13 | 1.20 | 1.18 | 1.18 | 1.09 |
| Cl | 0.04 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.03 | 0.03 | 0.04 | 0.06 | 0.05 | 0.04 |
| OH | 0.80 | 0.96 | 0.83 | 0.86 | 0.88 | 0.92 | 0.98 | 0.84 | 0.76 | 0.76 | 0.77 | 0.87 |
| X-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| | | | | | | | | | | | | |
| F/(F+Cl+OH) | 0.58 | 0.50 | 0.57 | 0.55 | 0.54 | 0.52 | 0.50 | 0.57 | 0.60 | 0.59 | 0.59 | 0.55 |
| Cl/(F+Cl+OH) | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.02 |
| OH/(F+Cl+OH) | 0.40 | 0.48 | 0.42 | 0.43 | 0.44 | 0.46 | 0.49 | 0.42 | 0.38 | 0.38 | 0.38 | 0.44 |
| | | | | | | | | | | | | |
| Quality control: oxide total test | | | | | | | | Caution: low total | | | | |

| Sample # | QC20DM-06 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_2O_5$ | 40.92 | 40.94 | 41.54 | 40.98 | 40.43 | 40.51 | 40.47 | 40.56 | 41.80 | 40.63 | 40.59 | 41.18 | 41.16 | 41.85 | 40.97 |
| $SiO_2$ | 0.06 | 0.00 | 0.00 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.17 | 0.10 | 0.00 | 0.04 | 0.00 | 0.03 |
| $SO_3$ | 0.05 | 0.14 | 0.12 | 0.20 | 0.12 | 0.14 | 0.08 | 0.08 | 0.10 | 0.07 | 0.07 | 0.09 | 0.19 | 0.29 | 0.12 |
| $La_2O_3$ | 0.10 | 0.00 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| $Ce_2O_3$ | 0.27 | 0.10 | 0.06 | 0.23 | 4.49 | 5.55 | 6.46 | 9.34 | 2.22 | 0.81 | 3.37 | 0.94 | 0.81 | 0.60 | 2.52 |
| $Nd_2O_3$ | 0.00 | 0.00 | 0.03 | 0.04 | 0.61 | 0.40 | 0.22 | 0.12 | 0.00 | 0.66 | 0.18 | 0.79 | 0.14 | 0.07 | 0.23 |
| $Y_2O_3$ | 0.00 | 0.00 | 0.05 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.00 | 0.01 |
| FeO | 0.12 | 0.07 | 0.10 | 0.02 | 0.00 | 0.00 | 0.00 | 0.28 | 0.21 | 0.75 | 0.79 | 0.00 | 0.00 | 0.19 | 0.18 |
| MnO | 0.00 | 0.00 | 0.00 | 0.04 | 0.08 | 0.25 | 0.00 | 0.10 | 0.00 | 0.30 | 0.00 | 0.00 | 0.17 | 0.00 | 0.07 |
| MgO | 0.03 | 0.01 | 0.03 | 0.03 | 0.69 | 0.06 | 0.30 | 0.24 | 0.03 | 0.00 | 0.79 | 0.00 | 0.00 | 0.03 | 0.16 |
| CaO | 55.14 | 54.81 | 55.43 | 55.05 | 50.96 | 50.25 | 50.63 | 47.87 | 53.32 | 54.30 | 53.14 | 54.60 | 54.98 | 54.93 | 53.24 |
| SrO | 0.08 | 0.03 | 0.04 | 0.00 | 0.06 | 0.16 | 0.01 | 0.00 | 0.00 | 0.04 | 0.00 | 0.05 | 0.00 | 0.01 | 0.03 |
| $Na_2O$ | 0.02 | 0.06 | 0.06 | 0.04 | 0.05 | 0.15 | 0.00 | 0.11 | 0.07 | 0.13 | 0.06 | 0.08 | 0.14 | 0.11 | 0.08 |
| F | 1.61 | 2.10 | 2.05 | 1.89 | 1.44 | 1.62 | 1.40 | 1.51 | 1.97 | 1.25 | 1.28 | 1.28 | 1.83 | 1.88 | 1.65 |
| Cl | 0.37 | 0.42 | 0.41 | 0.43 | 0.31 | 0.40 | 0.40 | 0.50 | 0.46 | 0.43 | 0.34 | 0.40 | 0.49 | 0.49 | 0.42 |
| H2O | 0.90 | 0.65 | 0.70 | 0.75 | 0.97 | 0.85 | 0.96 | 0.88 | 0.72 | 1.06 | 1.07 | 1.06 | 0.78 | 0.77 | 0.86 |
| Subtotal | 99.66 | 99.31 | 100.69 | 99.77 | 100.21 | 100.34 | 100.93 | 101.58 | 100.88 | 100.59 | 101.77 | 100.45 | 100.75 | 101.21 | 100.58 |
| O=F,Cl | 0.76 | 0.98 | 0.96 | 0.89 | 0.67 | 0.77 | 0.68 | 0.75 | 0.93 | 0.62 | 0.62 | 0.63 | 0.88 | 0.90 | 0.79 |
| Total | 98.90 | 98.33 | 99.73 | 98.88 | 99.54 | 99.56 | 100.25 | 100.83 | 99.95 | 99.97 | 101.16 | 99.82 | 99.87 | 100.31 | 99.79 |
| | | | | | | | | | | | | | | | |
| | Structural formula on the basis of 24 anions | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| P | 5.92 | 5.94 | 5.94 | 5.92 | 5.93 | 5.97 | 5.94 | 5.99 | 6.00 | 5.87 | 5.84 | 5.93 | 5.91 | 5.95 | 5.93 |
| Si | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.02 | 0.00 | 0.01 | 0.00 | 0.01 |
| S | 0.01 | 0.02 | 0.01 | 0.03 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.04 | 0.02 |
| P-group t | 5.93 | 5.96 | 5.96 | 5.95 | 5.94 | 5.98 | 5.95 | 6.00 | 6.02 | 5.91 | 5.87 | 5.94 | 5.94 | 5.99 | 5.95 |
| La | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ce | 0.02 | 0.01 | 0.00 | 0.01 | 0.28 | 0.35 | 0.41 | 0.60 | 0.14 | 0.05 | 0.21 | 0.06 | 0.05 | 0.04 | 0.16 |
| Nd | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.03 | 0.01 | 0.01 | 0.00 | 0.04 | 0.01 | 0.05 | 0.01 | 0.00 | 0.01 |
| Y | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{2+}$ | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.03 | 0.11 | 0.11 | 0.00 | 0.00 | 0.03 | 0.03 |
| Mn | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.04 | 0.00 | 0.01 | 0.00 | 0.04 | 0.00 | 0.00 | 0.02 | 0.00 | 0.01 |
| Mg | 0.01 | 0.00 | 0.01 | 0.01 | 0.18 | 0.02 | 0.08 | 0.06 | 0.01 | 0.00 | 0.20 | 0.00 | 0.00 | 0.01 | 0.04 |
| Ca | 10.09 | 10.06 | 10.04 | 10.06 | 9.45 | 9.37 | 9.41 | 8.95 | 9.70 | 9.93 | 9.68 | 9.96 | 9.99 | 9.89 | 9.76 |
| Sr | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| Na | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 | 0.05 | 0.00 | 0.04 | 0.02 | 0.04 | 0.02 | 0.03 | 0.05 | 0.04 | 0.03 |
| Ca-site to | 10.16 | 10.11 | 10.10 | 10.11 | 9.99 | 9.87 | 9.91 | 9.71 | 9.89 | 10.22 | 10.23 | 10.09 | 10.13 | 10.00 | 10.04 |
| F | 0.87 | 1.14 | 1.10 | 1.02 | 0.79 | 0.89 | 0.77 | 0.83 | 1.06 | 0.68 | 0.69 | 0.69 | 0.98 | 1.00 | 0.89 |
| Cl | 0.11 | 0.12 | 0.12 | 0.12 | 0.09 | 0.12 | 0.12 | 0.15 | 0.13 | 0.12 | 0.10 | 0.11 | 0.14 | 0.14 | 0.12 |
| OH | 1.02 | 0.74 | 0.79 | 0.86 | 1.12 | 0.99 | 1.11 | 1.02 | 0.81 | 1.20 | 1.21 | 1.20 | 0.88 | 0.86 | 0.99 |
| X-site tota | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| | | | | | | | | | | | | | | | |
| F/(F+Cl+C | 0.43 | 0.57 | 0.55 | 0.51 | 0.39 | 0.45 | 0.38 | 0.42 | 0.53 | 0.34 | 0.34 | 0.34 | 0.49 | 0.50 | 0.45 |
| Cl/(F+Cl+ | 0.05 | 0.06 | 0.06 | 0.06 | 0.04 | 0.06 | 0.06 | 0.07 | 0.07 | 0.06 | 0.05 | 0.06 | 0.07 | 0.07 | 0.06 |
| OH/(F+Cl- | 0.51 | 0.37 | 0.39 | 0.43 | 0.56 | 0.50 | 0.56 | 0.51 | 0.41 | 0.60 | 0.61 | 0.60 | 0.44 | 0.43 | 0.49 |
| | | | | | | | | | | | | | | | |
| Quality control: | | | | | | | | | | | | | | | |
| P test | | | | | | | | | | | P low | | | | |
| Ca site test | | | | | | | | Ca site low | | | | | | | |

| Sample # | QC20DM-08 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_2O_5$ | 41.01 | 41.56 | 41.22 | 41.03 | 41.28 | 41.46 | 41.26 | 40.98 | 41.59 | 41.06 | 40.82 | 40.81 |
| $SiO_2$ | 0.00 | 0.03 | 0.04 | 0.06 | 0.04 | 0.00 | 0.01 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 |
| $SO_3$ | 0.08 | 0.03 | 0.03 | 0.07 | 0.05 | 0.08 | 0.06 | 0.05 | 0.04 | 0.04 | 0.10 | 0.01 |
| $La_2O_3$ | 0.02 | 0.00 | 0.10 | 0.12 | 0.05 | 0.00 | 0.06 | 0.10 | 0.12 | 0.07 | 0.06 | 0.02 |
| $Ce_2O_3$ | 0.16 | 0.17 | 0.18 | 0.22 | 0.18 | 0.17 | 0.21 | 0.17 | 0.15 | 0.20 | 0.10 | 0.05 |
| $Nd_2O_3$ | 0.25 | 0.07 | 0.19 | 0.25 | 0.00 | 0.07 | 0.07 | 0.12 | 0.14 | 0.07 | 0.09 | 0.11 |
| $Y_2O_3$ | 0.19 | 0.13 | 0.12 | 0.15 | 0.19 | 0.18 | 0.13 | 0.17 | 0.18 | 0.18 | 0.25 | 0.08 |
| FeO | 0.03 | 0.04 | 0.05 | 0.08 | 0.05 | 0.04 | 0.00 | 0.05 | 0.04 | 0.06 | 0.01 | 0.01 |
| MnO | 0.04 | 0.01 | 0.00 | 0.04 | 0.03 | 0.01 | 0.00 | 0.02 | 0.00 | 0.00 | 0.05 | 0.04 |
| MgO | 0.05 | 0.00 | 0.00 | 0.07 | 0.02 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.06 | 0.01 |
| CaO | 54.38 | 54.47 | 55.11 | 54.41 | 54.89 | 55.02 | 54.92 | 54.95 | 54.65 | 55.00 | 54.62 | 55.13 |
| SrO | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.02 | 0.00 | 0.01 | 0.00 |
| $Na_2O$ | 0.11 | 0.06 | 0.04 | 0.12 | 0.08 | 0.08 | 0.09 | 0.09 | 0.07 | 0.12 | 0.13 | 0.02 |
| F | 2.47 | 2.93 | 2.55 | 2.36 | 2.55 | 2.39 | 2.48 | 2.46 | 2.58 | 2.76 | 2.76 | 2.94 |
| Cl | 0.35 | 0.25 | 0.19 | 0.27 | 0.19 | 0.19 | 0.23 | 0.18 | 0.20 | 0.21 | 0.32 | 0.22 |
| $H_2O$ | 0.49 | 0.31 | 0.50 | 0.56 | 0.50 | 0.59 | 0.53 | 0.54 | 0.49 | 0.40 | 0.36 | 0.30 |
| Subtotal | 99.64 | 100.05 | 100.31 | 99.83 | 100.07 | 100.26 | 100.04 | 99.92 | 100.27 | 100.18 | 99.73 | 99.74 |
| O=F,Cl | 1.12 | 1.29 | 1.12 | 1.06 | 1.12 | 1.05 | 1.10 | 1.08 | 1.13 | 1.21 | 1.23 | 1.29 |
| Total | 98.52 | 98.76 | 99.19 | 98.78 | 98.96 | 99.22 | 98.95 | 98.84 | 99.14 | 98.97 | 98.49 | 98.45 |
| | | | | | | | | | | | | |
| | Structural formula on the basis of 24 anions | | | | | | | | | | | |
| | | | | | | | | | | | | |
| P | 5.95 | 5.99 | 5.94 | 5.94 | 5.95 | 5.96 | 5.95 | 5.93 | 5.98 | 5.93 | 5.93 | 5.93 |
| Si | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| S | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 |
| P-group total | 5.96 | 6.00 | 5.95 | 5.96 | 5.96 | 5.97 | 5.96 | 5.94 | 5.99 | 5.94 | 5.94 | 5.93 |
| La | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| Ce | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 |
| Nd | 0.01 | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 |
| Y | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 |
| $Fe^{2+}$ | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |
| Mn | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| Mg | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Ca | 9.99 | 9.94 | 10.05 | 9.97 | 10.02 | 10.01 | 10.03 | 10.06 | 9.95 | 10.06 | 10.04 | 10.14 |
| Sr | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 0.04 | 0.02 | 0.01 | 0.04 | 0.03 | 0.02 | 0.03 | 0.03 | 0.02 | 0.04 | 0.04 | 0.01 |
| Ca-site total | 10.09 | 9.99 | 10.11 | 10.10 | 10.09 | 10.07 | 10.09 | 10.15 | 10.02 | 10.15 | 10.14 | 10.17 |
| F | 1.34 | 1.58 | 1.38 | 1.28 | 1.38 | 1.28 | 1.34 | 1.33 | 1.39 | 1.49 | 1.49 | 1.59 |
| Cl | 0.10 | 0.07 | 0.05 | 0.08 | 0.06 | 0.05 | 0.07 | 0.05 | 0.06 | 0.06 | 0.09 | 0.06 |
| OH | 0.56 | 0.35 | 0.57 | 0.64 | 0.57 | 0.66 | 0.60 | 0.62 | 0.56 | 0.45 | 0.41 | 0.34 |
| X-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| | | | | | | | | | | | | |
| F/(F+Cl+OH) | 0.67 | 0.79 | 0.69 | 0.64 | 0.69 | 0.64 | 0.67 | 0.66 | 0.69 | 0.74 | 0.75 | 0.80 |
| Cl/(F+Cl+OH) | 0.05 | 0.04 | 0.03 | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.05 | 0.03 |
| OH/(F+Cl+OH) | 0.28 | 0.18 | 0.29 | 0.32 | 0.28 | 0.33 | 0.30 | 0.31 | 0.28 | 0.23 | 0.21 | 0.17 |

| Sample # | QC20DM-08 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_2O_5$ | 41.34 | 41.04 | 41.20 | 41.46 | 41.01 | 41.32 | 41.02 | 41.04 | 41.21 | 41.11 | 41.09 | 41.21 |
| $SiO_2$ | 0.04 | 0.06 | 0.03 | 0.02 | 0.00 | 0.07 | 0.05 | 0.02 | 0.02 | 0.04 | 0.05 | 0.03 |
| $SO_3$ | 0.09 | 0.06 | 0.11 | 0.07 | 0.05 | 0.00 | 0.11 | 0.05 | 0.05 | 0.05 | 0.01 | 0.02 |
| $La_2O_3$ | 0.03 | 0.05 | 0.03 | 0.00 | 0.07 | 0.00 | 0.05 | 0.00 | 0.00 | 0.00 | 0.09 | 0.09 |
| $Ce_2O_3$ | 0.17 | 0.15 | 0.17 | 0.12 | 0.08 | 0.08 | 0.17 | 0.12 | 0.15 | 0.15 | 0.15 | 0.12 |
| $Nd_2O_3$ | 0.04 | 0.12 | 0.00 | 0.00 | 0.08 | 0.24 | 0.02 | 0.06 | 0.17 | 0.02 | 0.24 | 0.09 |
| $Y_2O_3$ | 0.14 | 0.11 | 0.16 | 0.20 | 0.13 | 0.18 | 0.19 | 0.20 | 0.16 | 0.20 | 0.15 | 0.17 |
| FeO | 0.06 | 0.00 | 0.13 | 0.04 | 0.03 | 0.03 | 0.07 | 0.06 | 0.00 | 0.03 | 0.00 | 0.00 |
| MnO | 0.00 | 0.03 | 0.02 | 0.00 | 0.00 | 0.01 | 0.00 | 0.03 | 0.01 | 0.01 | 0.00 | 0.01 |
| MgO | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.02 | 0.05 | 0.05 | 0.00 | 0.00 | 0.01 | 0.02 |
| CaO | 54.96 | 54.84 | 55.01 | 55.20 | 55.05 | 54.92 | 54.57 | 55.15 | 55.09 | 54.77 | 55.22 | 55.04 |
| SrO | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.04 |
| $Na_2O$ | 0.06 | 0.08 | 0.08 | 0.11 | 0.09 | 0.03 | 0.11 | 0.05 | 0.06 | 0.11 | 0.08 | 0.08 |
| F | 2.61 | 2.29 | 2.70 | 2.54 | 2.27 | 2.53 | 2.15 | 2.51 | 2.24 | 2.35 | 2.65 | 2.37 |
| Cl | 0.20 | 0.19 | 0.17 | 0.16 | 0.22 | 0.21 | 0.29 | 0.35 | 0.22 | 0.20 | 0.26 | 0.20 |
| $H_2O$ | 0.47 | 0.62 | 0.44 | 0.52 | 0.62 | 0.51 | 0.66 | 0.48 | 0.64 | 0.59 | 0.44 | 0.58 |
| Subtotal | 100.24 | 99.67 | 100.25 | 100.45 | 99.73 | 100.14 | 99.49 | 100.18 | 100.02 | 99.63 | 100.43 | 100.05 |
| O=F,Cl | 1.15 | 1.01 | 1.17 | 1.11 | 1.00 | 1.11 | 0.97 | 1.13 | 0.99 | 1.04 | 1.17 | 1.04 |
| Total | 99.09 | 98.66 | 99.07 | 99.34 | 98.72 | 99.02 | 98.52 | 99.04 | 99.03 | 98.60 | 99.26 | 99.01 |
| | | | | | | | | | | | | |
| | Structural formula on the basis of 24 anions | | | | | | | | | | | |
| | | | | | | | | | | | | |
| P | 5.95 | 5.94 | 5.94 | 5.95 | 5.93 | 5.96 | 5.94 | 5.93 | 5.94 | 5.95 | 5.93 | 5.94 |
| Si | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 |
| S | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |
| P-group total | 5.97 | 5.96 | 5.96 | 5.96 | 5.94 | 5.97 | 5.96 | 5.94 | 5.95 | 5.96 | 5.94 | 5.95 |
| La | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| Ce | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Nd | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 |
| Y | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.01 | 0.02 |
| $Fe^{2+}$ | 0.01 | 0.00 | 0.02 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ca | 10.01 | 10.04 | 10.03 | 10.03 | 10.08 | 10.02 | 10.00 | 10.08 | 10.06 | 10.03 | 10.08 | 10.05 |
| Sr | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 0.02 | 0.03 | 0.03 | 0.04 | 0.03 | 0.01 | 0.04 | 0.02 | 0.02 | 0.04 | 0.03 | 0.03 |
| Ca-site total | 10.07 | 10.11 | 10.11 | 10.09 | 10.14 | 10.08 | 10.09 | 10.15 | 10.11 | 10.10 | 10.15 | 10.12 |
| F | 1.40 | 1.24 | 1.45 | 1.36 | 1.22 | 1.36 | 1.16 | 1.35 | 1.21 | 1.27 | 1.43 | 1.28 |
| Cl | 0.06 | 0.06 | 0.05 | 0.05 | 0.06 | 0.06 | 0.08 | 0.10 | 0.06 | 0.06 | 0.07 | 0.06 |
| OH | 0.54 | 0.70 | 0.50 | 0.59 | 0.71 | 0.58 | 0.75 | 0.55 | 0.73 | 0.67 | 0.50 | 0.66 |
| X-site total | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| | | | | | | | | | | | | |
| F/(F+Cl+OH) | 0.70 | 0.62 | 0.73 | 0.68 | 0.61 | 0.68 | 0.58 | 0.68 | 0.60 | 0.64 | 0.71 | 0.64 |
| Cl/(F+Cl+OH) | 0.03 | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 | 0.04 | 0.05 | 0.03 | 0.03 | 0.04 | 0.03 |
| OH/(F+Cl+OH) | 0.27 | 0.35 | 0.25 | 0.29 | 0.36 | 0.29 | 0.38 | 0.27 | 0.37 | 0.34 | 0.25 | 0.33 |

# Appendix E. Chromite EMPA Data from Chromite-rich Meta-ultramafic Samples

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Data source | Henry | | | | | | |
| Sample # | HP81-95 | | | | | | |
| $SiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 |
| $TiO_2$ | 0.14 | 0.11 | 0.17 | 0.15 | 0.17 | 0.21 | 0.20 |
| $Al_2O_3$ | 8.73 | 8.81 | 10.62 | 10.33 | 10.86 | 10.86 | 10.87 |
| $Cr_2O_3$ | 49.03 | 48.76 | 44.57 | 43.34 | 42.97 | 43.95 | 50.73 |
| $Fe_2O_3$ (calculated) | 12.39 | 12.48 | 14.82 | 16.28 | 16.04 | 14.94 | 9.29 |
| FeO (calculated) | 22.41 | 22.40 | 22.50 | 22.77 | 22.59 | 22.49 | 20.73 |
| MnO | 0.49 | 0.49 | 0.46 | 0.43 | 0.49 | 0.46 | 0.38 |
| MgO | 6.73 | 6.75 | 6.92 | 6.68 | 6.85 | 6.92 | 8.44 |
| NiO | 0.09 | 0.05 | 0.08 | 0.09 | 0.07 | 0.09 | 0.10 |
| ZnO | 0.20 | 0.12 | 0.18 | 0.17 | 0.14 | 0.16 | 0.16 |
| Total | 100.20 | 99.95 | 100.31 | 100.25 | 100.18 | 100.07 | 100.77 |
| | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | |
| | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Al | 0.35 | 0.35 | 0.42 | 0.41 | 0.43 | 0.43 | 0.43 |
| $Cr^{3+}$ | 1.32 | 1.32 | 1.19 | 1.16 | 1.15 | 1.18 | 1.33 |
| $Fe^{3+}$ | 0.32 | 0.32 | 0.38 | 0.42 | 0.41 | 0.38 | 0.23 |
| $Fe^{2+}$ | 0.64 | 0.64 | 0.64 | 0.65 | 0.64 | 0.64 | 0.58 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.34 | 0.34 | 0.35 | 0.34 | 0.35 | 0.35 | 0.42 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 1.99 | 1.99 |
| Total 2+ cations | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 |
| | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.35 | 0.35 | 0.35 | 0.34 | 0.35 | 0.35 | 0.42 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.65 | 0.65 | 0.65 | 0.66 | 0.65 | 0.65 | 0.58 |
| Cr/(Cr+Al) | 0.79 | 0.79 | 0.74 | 0.74 | 0.73 | 0.73 | 0.76 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.66 | 0.66 | 0.60 | 0.58 | 0.58 | 0.59 | 0.67 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.18 | 0.18 | 0.21 | 0.21 | 0.22 | 0.22 | 0.21 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.16 | 0.16 | 0.19 | 0.21 | 0.21 | 0.19 | 0.12 |
| $Fe^{3+}/Fe_{total}$ | 0.33 | 0.33 | 0.37 | 0.39 | 0.39 | 0.37 | 0.29 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data source | Henry | | | | | | | | | | | | | | |
| Sample # | QC81-19 | | | | | | | | | | | | | | |
| $SiO_2$ | 0.01 | 0.00 | 0.01 | 0.04 | 0.02 | 0.11 | 0.03 | 0.03 | 0.01 | 0.24 | 0.00 | 0.08 | 0.00 | 0.01 | 0.03 |
| $TiO_2$ | 0.18 | 0.20 | 0.23 | 0.23 | 0.22 | 0.26 | 0.20 | 0.21 | 0.24 | 0.22 | 0.22 | 0.19 | 0.19 | 0.22 | 0.20 |
| $Al_2O_3$ | 10.93 | 11.09 | 11.23 | 11.18 | 11.24 | 11.31 | 11.29 | 11.46 | 11.39 | 11.26 | 11.45 | 11.24 | 11.24 | 11.20 | 10.87 |
| $Cr_2O_3$ | 50.62 | 50.57 | 50.52 | 50.07 | 50.48 | 50.53 | 50.22 | 50.19 | 49.98 | 50.14 | 50.17 | 50.24 | 50.46 | 50.37 | 50.73 |
| $Fe_2O_3$ (calculat | 9.36 | 9.28 | 9.34 | 9.52 | 9.45 | 9.39 | 9.72 | 9.13 | 9.61 | 8.85 | 9.38 | 9.05 | 9.35 | 9.09 | 9.29 |
| FeO (calculated | 20.56 | 20.31 | 20.33 | 20.02 | 20.03 | 20.65 | 20.16 | 20.20 | 20.40 | 21.08 | 20.37 | 20.34 | 20.34 | 20.47 | 20.73 |
| MnO | 0.24 | 0.23 | 0.26 | 0.35 | 0.34 | 0.36 | 0.30 | 0.24 | 0.35 | 0.21 | 0.29 | 0.23 | 0.30 | 0.33 | 0.38 |
| MgO | 8.58 | 8.77 | 8.82 | 8.92 | 9.01 | 8.82 | 8.96 | 8.88 | 8.74 | 8.54 | 8.78 | 8.77 | 8.76 | 8.60 | 8.44 |
| NiO | 0.10 | 0.08 | 0.12 | 0.07 | 0.04 | 0.08 | 0.07 | 0.09 | 0.10 | 0.08 | 0.09 | 0.07 | 0.06 | 0.08 | 0.10 |
| Total | 100.58 | 100.53 | 100.87 | 100.40 | 100.83 | 101.51 | 100.95 | 100.43 | 100.82 | 100.62 | 100.75 | 100.21 | 100.70 | 100.37 | 100.77 |
| | | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 |
| Al | 0.43 | 0.43 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.45 | 0.44 | 0.44 | 0.45 | 0.44 | 0.44 | 0.44 | 0.43 |
| $Cr^{3+}$ | 1.33 | 1.33 | 1.32 | 1.31 | 1.32 | 1.31 | 1.31 | 1.31 | 1.31 | 1.31 | 1.31 | 1.32 | 1.32 | 1.32 | 1.33 |
| $Fe^{3+}$ | 0.23 | 0.23 | 0.23 | 0.24 | 0.23 | 0.23 | 0.24 | 0.23 | 0.24 | 0.22 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| $Fe^{2+}$ | 0.57 | 0.56 | 0.56 | 0.55 | 0.55 | 0.57 | 0.56 | 0.56 | 0.56 | 0.58 | 0.56 | 0.56 | 0.56 | 0.57 | 0.58 |
| $Mn^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Mg^{2+}$ | 0.42 | 0.43 | 0.43 | 0.44 | 0.44 | 0.43 | 0.44 | 0.44 | 0.43 | 0.42 | 0.43 | 0.43 | 0.43 | 0.43 | 0.42 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 1.99 | 2.00 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.98 | 1.99 | 1.99 | 2.00 | 1.99 | 1.99 |
| Total 2+ cations | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.00 | 1.01 | 1.01 |
| | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.43 | 0.43 | 0.44 | 0.44 | 0.44 | 0.43 | 0.44 | 0.44 | 0.43 | 0.42 | 0.43 | 0.43 | 0.43 | 0.43 | 0.42 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.57 | 0.57 | 0.56 | 0.56 | 0.56 | 0.57 | 0.56 | 0.56 | 0.57 | 0.58 | 0.57 | 0.57 | 0.57 | 0.57 | 0.58 |
| Cr/(Cr+Al) | 0.76 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.76 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.67 | 0.67 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.67 | 0.66 | 0.66 | 0.66 | 0.67 | 0.67 |
| Al/(Cr+Al+Fe3+ | 0.21 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.21 |
| $Fe^{3+}/(Cr+Al+Fe^{3}$ | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.11 | 0.12 | 0.11 | 0.12 | 0.11 | 0.12 | 0.11 | 0.12 |
| $Fe^{3+}/Fe_{total}$ | 0.29 | 0.29 | 0.29 | 0.30 | 0.30 | 0.29 | 0.30 | 0.29 | 0.30 | 0.27 | 0.29 | 0.29 | 0.29 | 0.29 | 0.29 |
| | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| Quality control: oxide total test | | | | | | Caution: high total | | | | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data source | Henry | | | | | | | | | | | |
| Sample # | QC81-28 | | | | | | | | | | | |
| Analysis pt. # | 1 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| distance (um) | 0 | 3 | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 | 33 |
| $SiO_2$ | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.04 | 0.02 | 0.03 |
| $TiO_2$ | 0.50 | 0.45 | 0.72 | 0.77 | 0.78 | 0.88 | 0.79 | 0.77 | 0.78 | 0.85 | 0.79 | 0.84 |
| $Al_2O_3$ | 16.00 | 15.07 | 3.74 | 1.80 | 1.82 | 2.18 | 1.97 | 2.15 | 2.09 | 2.38 | 2.09 | 2.24 |
| $Cr_2O_3$ | 31.07 | 29.06 | 16.83 | 14.42 | 14.49 | 15.93 | 14.66 | 15.30 | 15.44 | 16.01 | 15.14 | 15.73 |
| $Fe_2O_3$ (assumed | 21.37 | 23.65 | 47.09 | 51.40 | 51.39 | 49.29 | 51.31 | 48.69 | 49.79 | 49.08 | 50.28 | 49.84 |
| FeO (assumed) | 27.50 | 27.25 | 29.85 | 30.35 | 30.20 | 30.33 | 30.40 | 31.18 | 30.01 | 30.10 | 30.21 | 30.34 |
| MnO | 0.20 | 0.16 | 0.04 | 0.13 | 0.10 | 0.05 | 0.02 | 0.10 | 0.07 | 0.11 | 0.03 | 0.09 |
| MgO | 4.83 | 4.61 | 1.60 | 1.01 | 1.09 | 1.16 | 1.11 | 0.17 | 1.18 | 1.29 | 1.17 | 1.21 |
| NiO | 0.17 | 0.22 | 0.36 | 0.36 | 0.45 | 0.43 | 0.43 | 0.48 | 0.41 | 0.46 | 0.40 | 0.46 |
| Total | 101.64 | 100.48 | 100.25 | 100.26 | 100.32 | 100.26 | 100.70 | 98.83 | 99.77 | 100.32 | 100.13 | 100.79 |
| | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | |
| | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Al | 0.63 | 0.60 | 0.16 | 0.08 | 0.08 | 0.10 | 0.09 | 0.10 | 0.09 | 0.10 | 0.09 | 0.10 |
| $Cr^{3+}$ | 0.82 | 0.78 | 0.49 | 0.43 | 0.43 | 0.47 | 0.43 | 0.46 | 0.46 | 0.47 | 0.45 | 0.46 |
| $Fe^{3+}$ (assumed) | 0.53 | 0.60 | 1.31 | 1.45 | 1.45 | 1.38 | 1.44 | 1.40 | 1.41 | 1.37 | 1.41 | 1.39 |
| $Fe^{2+}$ | 0.76 | 0.77 | 0.92 | 0.95 | 0.94 | 0.95 | 0.95 | 0.99 | 0.94 | 0.94 | 0.94 | 0.94 |
| $Mn^{2+}$ | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Mg^{2+}$ | 0.24 | 0.23 | 0.09 | 0.06 | 0.06 | 0.06 | 0.06 | 0.01 | 0.07 | 0.07 | 0.07 | 0.07 |
| $Ni^{2+}$ | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Total 2+ | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 1.02 |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.24 | 0.23 | 0.09 | 0.06 | 0.06 | 0.06 | 0.06 | 0.01 | 0.07 | 0.07 | 0.06 | 0.07 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.76 | 0.77 | 0.91 | 0.94 | 0.94 | 0.94 | 0.94 | 0.99 | 0.93 | 0.93 | 0.94 | 0.93 |
| Cr/(Cr+Al) | 0.57 | 0.56 | 0.75 | 0.84 | 0.84 | 0.83 | 0.83 | 0.83 | 0.83 | 0.82 | 0.83 | 0.82 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.41 | 0.39 | 0.25 | 0.22 | 0.22 | 0.24 | 0.22 | 0.24 | 0.23 | 0.24 | 0.23 | 0.24 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.32 | 0.30 | 0.08 | 0.04 | 0.04 | 0.05 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $Fe^{3+}/(Cr+Al+Fe^{3+}$ | 0.27 | 0.30 | 0.67 | 0.74 | 0.74 | 0.71 | 0.74 | 0.71 | 0.72 | 0.70 | 0.72 | 0.24 |
| $Fe^{3+}/Fe_{total}$ | 0.41 | 0.44 | 0.59 | 0.60 | 0.60 | 0.59 | 0.60 | 0.58 | 0.60 | 0.59 | 0.60 | 0.60 |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| Quality control: oxide total test | Caution: high total | | | | | | | | | | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data source | Henry | | | | | | | | | | | | | |
| Sample # | QC81-28 | | | | | | | | | | | | | |
| Analysis pt. # | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| distance (um) | 90 | 93 | 96 | 99 | 102 | 105 | 108 | 111 | 114 | 117 | 120 | 123 | 126 | 129 |
| $SiO_2$ | 0.02 | 0.00 | 0.00 | 0.03 | 0.03 | 0.02 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 |
| $TiO_2$ | 0.68 | 0.70 | 0.64 | 0.65 | 0.65 | 0.63 | 0.62 | 0.54 | 0.65 | 0.61 | 0.69 | 0.63 | 0.63 | 0.58 |
| $Al_2O_3$ | 2.44 | 8.73 | 6.98 | 6.02 | 13.21 | 8.68 | 14.57 | 16.71 | 16.16 | 15.43 | 1.88 | 7.61 | 15.31 | 17.34 |
| $Cr_2O_3$ | 15.57 | 27.33 | 23.27 | 20.01 | 31.79 | 24.32 | 32.92 | 34.90 | 35.28 | 33.89 | 13.36 | 21.30 | 33.35 | 34.36 |
| $Fe_2O_3$ (assumed | 50.24 | 30.70 | 37.69 | 42.18 | 22.08 | 34.94 | 19.82 | 15.21 | 15.50 | 17.74 | 52.90 | 39.50 | 18.24 | 15.21 |
| FeO (assumed) | 30.21 | 28.44 | 28.95 | 29.34 | 27.72 | 28.59 | 27.42 | 26.58 | 27.13 | 27.03 | 30.31 | 28.80 | 26.90 | 26.74 |
| MnO | 0.05 | 0.02 | 0.17 | 0.02 | 0.01 | 0.17 | 0.05 | 0.15 | 0.07 | 0.20 | 0.00 | 0.04 | 0.15 | 0.09 |
| MgO | 1.28 | 3.03 | 2.61 | 2.42 | 4.23 | 3.07 | 4.61 | 5.22 | 5.00 | 4.80 | 1.08 | 2.87 | 4.87 | 5.26 |
| NiO | 0.41 | 0.29 | 0.26 | 0.23 | 0.24 | 0.28 | 0.21 | 0.05 | 0.09 | 0.21 | 0.46 | 0.42 | 0.17 | 0.16 |
| | 100.89 | 99.25 | 100.57 | 100.89 | 99.96 | 100.68 | 100.22 | 99.36 | 99.88 | 99.90 | 100.67 | 101.16 | 99.62 | 99.74 |
| Total | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 |
| Al | 0.11 | 0.37 | 0.29 | 0.25 | 0.53 | 0.36 | 0.58 | 0.66 | 0.64 | 0.61 | 0.08 | 0.32 | 0.61 | 0.68 |
| $Cr^{3+}$ | 0.46 | 0.77 | 0.66 | 0.57 | 0.86 | 0.68 | 0.88 | 0.93 | 0.94 | 0.90 | 0.39 | 0.60 | 0.89 | 0.91 |
| $Fe^{3+}$ (assumed) | 1.40 | 0.82 | 1.01 | 1.14 | 0.57 | 0.93 | 0.51 | 0.38 | 0.39 | 0.45 | 1.49 | 1.05 | 0.46 | 0.38 |
| $Fe^{2+}$ | 0.93 | 0.85 | 0.87 | 0.88 | 0.79 | 0.84 | 0.78 | 0.75 | 0.76 | 0.76 | 0.95 | 0.85 | 0.76 | 0.75 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Mg^{2+}$ | 0.07 | 0.16 | 0.14 | 0.13 | 0.22 | 0.16 | 0.23 | 0.26 | 0.25 | 0.24 | 0.06 | 0.15 | 0.25 | 0.26 |
| $Ni^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |
| Total 2+ | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.01 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.01 |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.07 | 0.16 | 0.14 | 0.13 | 0.21 | 0.16 | 0.23 | 0.26 | 0.25 | 0.24 | 0.06 | 0.15 | 0.24 | 0.26 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.93 | 0.84 | 0.86 | 0.87 | 0.79 | 0.84 | 0.77 | 0.74 | 0.75 | 0.76 | 0.94 | 0.85 | 0.76 | 0.74 |
| $Cr/(Cr+Al)$ | 0.81 | 0.68 | 0.69 | 0.69 | 0.62 | 0.65 | 0.60 | 0.58 | 0.59 | 0.60 | 0.83 | 0.65 | 0.59 | 0.57 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.23 | 0.39 | 0.33 | 0.29 | 0.44 | 0.34 | 0.45 | 0.47 | 0.48 | 0.46 | 0.20 | 0.30 | 0.45 | 0.46 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.05 | 0.19 | 0.15 | 0.13 | 0.27 | 0.18 | 0.30 | 0.34 | 0.32 | 0.31 | 0.04 | 0.16 | 0.31 | 0.35 |
| $Fe^{3+}/(Cr+Al+Fe^{3+}$ | 0.23 | 0.39 | 0.33 | 0.29 | 0.44 | 0.34 | 0.45 | 0.47 | 0.48 | 0.46 | 0.20 | 0.30 | 0.45 | 0.46 |
| $Fe^{3+}/Fe_{total}$ | 0.60 | 0.49 | 0.54 | 0.56 | 0.42 | 0.52 | 0.39 | 0.34 | 0.34 | 0.37 | 0.61 | 0.55 | 0.38 | 0.34 |

| Data source | Henry | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample # | QC81-28 | | | | | | | | | | | | | | | |
| Analysis pt. # | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |
| distance (um) | 132 | 135 | 138 | 141 | 144 | 147 | 150 | 153 | 156 | 159 | 162 | 165 | 168 | 171 | 174 | 177 |
| $SiO_2$ | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.05 | 0.10 | 0.00 | 0.00 | 0.04 | 0.02 | 0.00 | 0.03 | 0.01 |
| $TiO_2$ | 0.52 | 0.53 | 0.47 | 0.51 | 0.52 | 0.56 | 0.55 | 0.68 | 0.71 | 0.74 | 0.71 | 0.62 | 0.56 | 0.60 | 0.68 | 0.71 |
| $Al_2O_3$ | 18.47 | 19.69 | 18.76 | 18.58 | 18.50 | 17.61 | 15.72 | 2.38 | 1.95 | 1.71 | 1.65 | 11.76 | 17.80 | 12.63 | 1.56 | 1.63 |
| $Cr_2O_3$ | 35.64 | 34.03 | 33.47 | 33.59 | 34.04 | 34.42 | 33.18 | 14.39 | 14.34 | 13.81 | 13.45 | 27.90 | 34.84 | 28.09 | 12.87 | 13.15 |
| $Fe_2O_3$ (assume | 13.56 | 13.69 | 15.24 | 15.14 | 14.72 | 14.81 | 18.09 | 51.80 | 51.48 | 52.97 | 53.31 | 27.82 | 14.65 | 27.24 | 54.22 | 53.82 |
| FeO (assumed | 26.81 | 26.37 | 26.56 | 26.58 | 26.46 | 26.52 | 26.96 | 30.31 | 30.39 | 30.47 | 30.44 | 27.95 | 26.82 | 27.81 | 30.66 | 30.56 |
| MnO | 0.12 | 0.11 | 0.00 | 0.00 | 0.02 | 0.13 | 0.16 | 0.10 | 0.00 | 0.10 | 0.07 | 0.12 | 0.17 | 0.10 | 0.04 | 0.00 |
| MgO | 5.55 | 5.86 | 5.63 | 5.59 | 5.61 | 5.35 | 4.85 | 1.29 | 1.14 | 1.07 | 1.05 | 3.86 | 5.33 | 4.15 | 0.99 | 1.03 |
| NiO | 0.07 | 0.20 | 0.16 | 0.15 | 0.22 | 0.15 | 0.19 | 0.44 | 0.43 | 0.43 | 0.42 | 0.27 | 0.18 | 0.23 | 0.42 | 0.49 |
| Total | 100.75 | 100.49 | 100.29 | 100.15 | 100.08 | 99.56 | 99.71 | 101.42 | 100.53 | 101.29 | 101.09 | 100.33 | 100.37 | 100.84 | 101.47 | 101.39 |
| | | | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 |
| Al | 0.71 | 0.76 | 0.73 | 0.72 | 0.72 | 0.69 | 0.63 | 0.10 | 0.09 | 0.07 | 0.07 | 0.48 | 0.69 | 0.51 | 0.07 | 0.07 |
| $Cr^{3+}$ | 0.92 | 0.88 | 0.87 | 0.88 | 0.89 | 0.91 | 0.89 | 0.42 | 0.42 | 0.41 | 0.40 | 0.76 | 0.91 | 0.76 | 0.38 | 0.39 |
| $Fe^{3+}$ (assumed | 0.34 | 0.34 | 0.38 | 0.38 | 0.37 | 0.37 | 0.46 | 1.44 | 1.44 | 1.48 | 1.49 | 0.72 | 0.36 | 0.70 | 1.51 | 1.50 |
| $Fe^{2+}$ | 0.74 | 0.72 | 0.73 | 0.73 | 0.73 | 0.74 | 0.76 | 0.93 | 0.95 | 0.95 | 0.95 | 0.81 | 0.74 | 0.80 | 0.95 | 0.95 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Mg^{2+}$ | 0.27 | 0.29 | 0.28 | 0.28 | 0.28 | 0.27 | 0.24 | 0.07 | 0.06 | 0.06 | 0.06 | 0.20 | 0.26 | 0.21 | 0.05 | 0.06 |
| $Ni^{2+}$ | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 |
| Total 2+ | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.01 | 1.02 | 1.02 | 1.02 |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.27 | 0.28 | 0.27 | 0.27 | 0.27 | 0.26 | 0.24 | 0.07 | 0.06 | 0.06 | 0.06 | 0.20 | 0.26 | 0.21 | 0.05 | 0.06 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.73 | 0.72 | 0.73 | 0.73 | 0.73 | 0.74 | 0.76 | 0.93 | 0.94 | 0.94 | 0.94 | 0.80 | 0.74 | 0.79 | 0.95 | 0.94 |
| Cr/(Cr+Al) | 0.56 | 0.54 | 0.54 | 0.55 | 0.55 | 0.57 | 0.59 | 0.80 | 0.83 | 0.84 | 0.85 | 0.61 | 0.57 | 0.60 | 0.85 | 0.84 |
| $Cr/(Cr+Al+Fe^{3+}$ | 0.47 | 0.45 | 0.44 | 0.44 | 0.45 | 0.46 | 0.45 | 0.21 | 0.22 | 0.21 | 0.20 | 0.39 | 0.46 | 0.39 | 0.19 | 0.20 |
| $Al/(Cr+Al+Fe^{3+}$ | 0.36 | 0.38 | 0.37 | 0.37 | 0.36 | 0.35 | 0.32 | 0.05 | 0.04 | 0.04 | 0.04 | 0.24 | 0.35 | 0.26 | 0.03 | 0.04 |
| $Fe^{3+}/(Cr+Al+Fe$ | 0.47 | 0.45 | 0.44 | 0.44 | 0.45 | 0.46 | 0.45 | 0.21 | 0.22 | 0.21 | 0.20 | 0.39 | 0.46 | 0.39 | 0.19 | 0.20 |
| $Fe^{3+}/Fe_{total}$ | 0.31 | 0.32 | 0.34 | 0.34 | 0.33 | 0.33 | 0.38 | 0.61 | 0.60 | 0.61 | 0.61 | 0.47 | 0.33 | 0.47 | 0.61 | 0.61 |

| Sample # | QC81-28 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Analysis pt. # | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 |
| distance (um) | 180 | 183 | 186 | 189 | 192 | 195 | 198 | 201 | 204 | 207 | 210 | 213 | 216 | 219 | 222 |
| $SiO_2$ | 0.00 | 0.03 | 0.03 | 0.04 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.01 | 0.02 | 0.04 | 0.00 | 0.02 | 0.04 |
| $TiO_2$ | 0.79 | 0.82 | 0.74 | 0.80 | 0.73 | 0.76 | 0.79 | 0.81 | 0.80 | 0.77 | 0.60 | 0.70 | 0.61 | 0.74 | 0.73 |
| $Al_2O_3$ | 1.80 | 2.41 | 1.94 | 2.23 | 1.74 | 1.85 | 2.15 | 2.15 | 2.25 | 2.05 | 8.31 | 16.69 | 15.55 | 1.92 | 2.07 |
| $Cr_2O_3$ | 13.82 | 16.29 | 14.37 | 15.41 | 13.87 | 14.08 | 15.02 | 15.31 | 15.19 | 14.49 | 22.59 | 35.07 | 32.84 | 13.51 | 14.62 |
| $Fe_2O_3$ (assumed | 52.30 | 49.39 | 52.37 | 50.58 | 52.60 | 52.36 | 51.06 | 50.75 | 50.64 | 51.70 | 36.95 | 15.19 | 18.53 | 53.14 | 51.12 |
| FeO (assumed) | 30.35 | 30.36 | 30.54 | 30.36 | 30.41 | 30.40 | 30.24 | 30.31 | 30.34 | 30.52 | 29.02 | 27.52 | 27.52 | 30.76 | 30.38 |
| MnO | 0.01 | 0.07 | 0.11 | 0.08 | 0.07 | 0.03 | 0.19 | 0.15 | 0.05 | 0.03 | 0.12 | 0.18 | 0.04 | 0.02 | 0.03 |
| MgO | 1.07 | 1.30 | 1.14 | 1.27 | 1.06 | 1.14 | 1.19 | 1.26 | 1.21 | 1.12 | 2.72 | 4.83 | 4.66 | 1.05 | 1.11 |
| NiO | 0.49 | 0.43 | 0.46 | 0.45 | 0.40 | 0.44 | 0.48 | 0.40 | 0.46 | 0.42 | 0.30 | 0.20 | 0.06 | 0.38 | 0.41 |
| Total | 100.62 | 101.10 | 101.69 | 101.22 | 100.89 | 101.06 | 101.11 | 101.15 | 100.94 | 101.09 | 100.62 | 100.41 | 99.82 | 101.53 | 100.52 |
| | | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Al | 0.08 | 0.10 | 0.08 | 0.10 | 0.08 | 0.08 | 0.09 | 0.09 | 0.10 | 0.09 | 0.35 | 0.66 | 0.62 | 0.08 | 0.09 |
| $Cr^{3+}$ | 0.41 | 0.48 | 0.42 | 0.45 | 0.41 | 0.41 | 0.44 | 0.45 | 0.44 | 0.42 | 0.63 | 0.93 | 0.88 | 0.40 | 0.43 |
| $Fe^{3+}$ (assumed) | 1.47 | 1.37 | 1.45 | 1.41 | 1.47 | 1.46 | 1.42 | 1.41 | 1.41 | 1.44 | 0.99 | 0.38 | 0.47 | 1.48 | 1.43 |
| $Fe^{2+}$ | 0.95 | 0.94 | 0.94 | 0.94 | 0.95 | 0.94 | 0.94 | 0.94 | 0.94 | 0.95 | 0.86 | 0.77 | 0.78 | 0.95 | 0.95 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Mg^{2+}$ | 0.06 | 0.07 | 0.06 | 0.07 | 0.06 | 0.06 | 0.07 | 0.07 | 0.07 | 0.06 | 0.14 | 0.24 | 0.23 | 0.06 | 0.06 |
| $Ni^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 |
| Total 2+ | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 |
| | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.06 | 0.07 | 0.06 | 0.07 | 0.06 | 0.06 | 0.07 | 0.07 | 0.07 | 0.06 | 0.14 | 0.24 | 0.23 | 0.06 | 0.06 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.94 | 0.93 | 0.94 | 0.93 | 0.94 | 0.94 | 0.93 | 0.93 | 0.93 | 0.94 | 0.86 | 0.76 | 0.77 | 0.94 | 0.94 |
| Cr/(Cr+Al) | 0.84 | 0.82 | 0.83 | 0.82 | 0.84 | 0.84 | 0.82 | 0.83 | 0.82 | 0.83 | 0.65 | 0.59 | 0.59 | 0.83 | 0.83 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.21 | 0.24 | 0.21 | 0.23 | 0.21 | 0.21 | 0.22 | 0.23 | 0.23 | 0.22 | 0.32 | 0.47 | 0.45 | 0.20 | 0.22 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.04 | 0.05 | 0.04 | 0.05 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.18 | 0.33 | 0.31 | 0.04 | 0.05 |
| $Fe^{3+}/(Cr+Al+Fe^{3+}$ | 0.21 | 0.24 | 0.21 | 0.23 | 0.21 | 0.21 | 0.22 | 0.23 | 0.23 | 0.22 | 0.32 | 0.47 | 0.45 | 0.20 | 0.22 |
| $Fe^{3+}/Fe_{total}$ | 0.61 | 0.59 | 0.61 | 0.60 | 0.61 | 0.61 | 0.60 | 0.60 | 0.60 | 0.60 | 0.53 | 0.33 | 0.38 | 0.61 | 0.60 |
| | | | | | | | | | | | | | | | |
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| Quality control: oxide total test | | | Caution: high total | | | | | | | | | | | Caution: high total | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data source | Henry | | | | | | | | | | | | | | |
| Sample # | QC81-28 | | | | | | | | | | | | | | |
| Analysis pt. # | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 |
| distance (um) | 225 | 228 | 231 | 234 | 237 | 240 | 243 | 246 | 249 | 252 | 255 | 258 | 261 | 264 | 267 |
| $SiO_2$ | 5.94 | 2.51 | 0.03 | 0.01 | 0.02 | 0.03 | 0.02 | 0.04 | 0.01 | 0.03 | 0.01 | 0.00 | 0.01 | 0.02 | 0.03 |
| $TiO_2$ | 0.71 | 0.79 | 0.80 | 0.85 | 0.82 | 0.83 | 0.82 | 0.76 | 0.82 | 0.84 | 0.82 | 0.80 | 0.86 | 0.82 | 0.80 |
| $Al_2O_3$ | 3.72 | 2.56 | 2.36 | 2.46 | 2.41 | 2.24 | 2.42 | 2.34 | 2.43 | 2.42 | 2.39 | 2.47 | 2.52 | 2.42 | 2.42 |
| $Cr_2O_3$ | 14.59 | 15.02 | 15.58 | 16.12 | 16.27 | 15.63 | 16.03 | 15.83 | 16.20 | 16.13 | 16.00 | 16.21 | 16.26 | 16.11 | 16.13 |
| $Fe_2O_3$ (assumed) | 35.81 | 44.48 | 49.70 | 49.62 | 49.44 | 50.17 | 49.31 | 49.38 | 48.98 | 49.22 | 49.68 | 49.71 | 49.20 | 49.55 | 49.20 |
| FeO (assumed) | 36.29 | 32.57 | 30.25 | 30.56 | 30.38 | 30.52 | 30.25 | 30.28 | 30.30 | 30.42 | 30.36 | 30.51 | 30.53 | 30.59 | 30.36 |
| MnO | 0.13 | 0.17 | 0.04 | 0.11 | 0.12 | 0.14 | 0.16 | 0.11 | 0.12 | 0.13 | 0.12 | 0.17 | 0.19 | 0.09 | 0.16 |
| MgO | 2.37 | 1.79 | 1.20 | 1.25 | 1.22 | 1.17 | 1.26 | 1.17 | 1.21 | 1.24 | 1.21 | 1.18 | 1.20 | 1.22 | 1.19 |
| NiO | 0.49 | 0.43 | 0.49 | 0.35 | 0.50 | 0.35 | 0.34 | 0.35 | 0.34 | 0.33 | 0.49 | 0.44 | 0.33 | 0.30 | 0.36 |
| Total | 100.05 | 100.32 | 100.45 | 101.32 | 101.19 | 101.08 | 100.62 | 100.25 | 100.40 | 100.75 | 101.08 | 101.50 | 101.11 | 101.12 | 100.64 |
| | | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| Si | 0.21 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Al | 0.16 | 0.11 | 0.10 | 0.11 | 0.10 | 0.10 | 0.11 | 0.10 | 0.11 | 0.11 | 0.10 | 0.11 | 0.11 | 0.11 | 0.11 |
| $Cr^{3+}$ | 0.41 | 0.44 | 0.46 | 0.47 | 0.47 | 0.46 | 0.47 | 0.47 | 0.48 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 |
| $Fe^{3+}$ (assumed) | 0.97 | 1.23 | 1.39 | 1.38 | 1.37 | 1.40 | 1.38 | 1.39 | 1.37 | 1.37 | 1.38 | 1.38 | 1.37 | 1.38 | 1.37 |
| $Fe^{2+}$ | 1.09 | 1.00 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 |
| $Mn^{2+}$ | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 |
| $Mg^{2+}$ | 0.13 | 0.10 | 0.07 | 0.07 | 0.07 | 0.06 | 0.07 | 0.06 | 0.07 | 0.07 | 0.07 | 0.06 | 0.07 | 0.07 | 0.07 |
| $Ni^{2+}$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Total 2+ | 1.23 | 1.11 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 |
| | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.10 | 0.09 | 0.07 | 0.07 | 0.07 | 0.06 | 0.07 | 0.06 | 0.07 | 0.07 | 0.07 | 0.06 | 0.07 | 0.07 | 0.07 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.90 | 0.91 | 0.93 | 0.93 | 0.93 | 0.94 | 0.93 | 0.94 | 0.93 | 0.93 | 0.93 | 0.94 | 0.93 | 0.93 | 0.93 |
| Cr/(Cr+Al) | 0.72 | 0.80 | 0.82 | 0.81 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.81 | 0.81 | 0.82 | 0.82 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.27 | 0.25 | 0.23 | 0.24 | 0.24 | 0.23 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.10 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.27 | 0.25 | 0.23 | 0.24 | 0.24 | 0.23 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 |
| $Fe^{3+}/Fe_{total}$ | 0.47 | 0.55 | 0.60 | 0.59 | 0.59 | 0.60 | 0.59 | 0.59 | 0.59 | 0.59 | 0.60 | 0.59 | 0.59 | 0.59 | 0.59 |
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| Quality control: oxide total test | | | | | | | | | | | | | | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data source | Henry | | | | | | | | | | | | | | | |
| Sample # | QC81-28 | | | | | | | | | | | | | | | |
| Analysis pt. # | 94 | 95 | 96 | 97 | 98 | 99 | 100 | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 | 109 |
| distance (um) | 270 | 273 | 276 | 279 | 282 | 285 | 288 | 291 | 294 | 297 | 300 | 303 | 306 | 309 | 312 | 315 |
| $SiO_2$ | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.02 | 0.01 | 0.02 | 0.02 | 0.01 | 0.00 | 0.03 | 0.03 | 0.01 | 0.00 | 0.03 |
| $TiO_2$ | 0.87 | 0.80 | 0.85 | 0.81 | 0.78 | 0.74 | 0.74 | 0.81 | 0.80 | 0.74 | 0.77 | 0.02 | 0.74 | 0.71 | 0.76 | 0.72 |
| $Al_2O_3$ | 2.48 | 2.41 | 2.68 | 2.25 | 2.40 | 2.30 | 2.41 | 2.42 | 2.45 | 2.37 | 2.30 | 2.24 | 2.37 | 2.07 | 2.30 | 2.13 |
| $Cr_2O_3$ | 16.22 | 15.92 | 16.80 | 15.43 | 15.93 | 15.58 | 15.89 | 15.92 | 16.21 | 15.63 | 15.71 | 15.47 | 15.67 | 14.77 | 15.43 | 14.73 |
| $Fe_2O_3$ (assumed) | 49.43 | 49.71 | 48.32 | 50.06 | 50.29 | 50.43 | 50.38 | 49.45 | 49.55 | 50.16 | 50.05 | 51.30 | 50.62 | 51.51 | 50.40 | 51.85 |
| FeO (assumed) | 30.52 | 30.54 | 30.16 | 30.27 | 30.65 | 30.60 | 30.61 | 30.50 | 30.65 | 30.51 | 30.62 | 29.71 | 30.73 | 30.65 | 30.66 | 30.83 |
| MnO | 0.15 | 0.13 | 0.26 | 0.13 | 0.12 | 0.17 | 0.11 | 0.10 | 0.14 | 0.06 | 0.08 | 0.12 | 0.18 | 0.13 | 0.03 | 0.17 |
| MgO | 1.20 | 1.14 | 1.30 | 1.09 | 1.17 | 1.10 | 1.17 | 1.10 | 1.12 | 1.13 | 1.05 | 1.06 | 1.10 | 0.99 | 1.06 | 0.98 |
| NiO | 0.45 | 0.36 | 0.37 | 0.53 | 0.40 | 0.35 | 0.42 | 0.43 | 0.39 | 0.40 | 0.41 | 0.37 | 0.40 | 0.39 | 0.38 | 0.41 |
| Total | 101.33 | 101.02 | 100.74 | 100.56 | 101.74 | 101.28 | 101.72 | 100.74 | 101.33 | 101.00 | 100.98 | 100.33 | 101.84 | 101.23 | 101.02 | 101.85 |
| | | | | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.00 | 0.02 | 0.02 | 0.02 | 0.02 |
| Al | 0.11 | 0.11 | 0.12 | 0.10 | 0.10 | 0.10 | 0.10 | 0.11 | 0.11 | 0.10 | 0.10 | 0.10 | 0.10 | 0.09 | 0.10 | 0.09 |
| $Cr^{3+}$ | 0.47 | 0.47 | 0.49 | 0.45 | 0.46 | 0.46 | 0.46 | 0.47 | 0.47 | 0.46 | 0.46 | 0.46 | 0.46 | 0.43 | 0.45 | 0.43 |
| $Fe^{3+}$ (assumed) | 1.37 | 1.38 | 1.34 | 1.40 | 1.39 | 1.40 | 1.39 | 1.38 | 1.37 | 1.40 | 1.40 | 1.44 | 1.40 | 1.44 | 1.41 | 1.44 |
| $Fe^{2+}$ | 0.94 | 0.94 | 0.93 | 0.94 | 0.94 | 0.95 | 0.94 | 0.95 | 0.95 | 0.94 | 0.95 | 0.93 | 0.94 | 0.95 | 0.95 | 0.95 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 |
| $Mg^{2+}$ | 0.07 | 0.06 | 0.07 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.05 |
| $Ni^{2+}$ | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Total 2+ | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.00 | 1.02 | 1.02 | 1.02 | 1.02 |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.07 | 0.06 | 0.07 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.05 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.93 | 0.94 | 0.93 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.95 | 0.94 | 0.95 |
| Cr/(Cr+Al) | 0.81 | 0.82 | 0.81 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.83 | 0.82 | 0.82 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.24 | 0.24 | 0.25 | 0.23 | 0.24 | 0.23 | 0.24 | 0.24 | 0.24 | 0.23 | 0.24 | 0.23 | 0.23 | 0.22 | 0.23 | 0.22 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.06 | 0.05 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $Fe^{3+}/(Cr+Al+Fe^{3+}$ | 0.24 | 0.24 | 0.25 | 0.23 | 0.24 | 0.23 | 0.24 | 0.24 | 0.24 | 0.23 | 0.24 | 0.23 | 0.23 | 0.22 | 0.23 | 0.22 |
| $Fe^{3+}/Fe_{total}$ | 0.59 | 0.59 | 0.59 | 0.60 | 0.60 | 0.60 | 0.60 | 0.59 | 0.59 | 0.60 | 0.60 | 0.61 | 0.60 | 0.60 | 0.60 | 0.60 |
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| Quality control: oxide total test | | | | | Caution: high total | | Caution: high total | | | | | | Caution: high total | | | Caution: high total |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data source | Henry | | | | | | | | | | | |
| Sample # | QC81-28 | | | | | | | | | | | |
| Analysis pt. # | 110 | 111 | 112 | 113 | 114 | 115 | 116 | 117 | 118 | 119 | 120 | 121 |
| distance (um) | 318 | 321 | 324 | 327 | 330 | 333 | 336 | 339 | 342 | 345 | 348 | 351 |
| $SiO_2$ | 0.00 | 0.01 | 0.04 | 0.05 | 0.00 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 |
| $TiO_2$ | 0.60 | 0.39 | 0.36 | 0.29 | 0.18 | 0.18 | 0.15 | 0.18 | 0.18 | 0.20 | 0.18 | 0.14 |
| $Al_2O_3$ | 4.01 | 18.62 | 23.02 | 25.57 | 27.99 | 28.16 | 28.15 | 28.27 | 27.28 | 27.59 | 28.00 | 28.30 |
| $Cr_2O_3$ | 16.56 | 32.31 | 31.78 | 30.13 | 28.71 | 28.42 | 28.76 | 28.59 | 29.64 | 29.08 | 28.73 | 28.04 |
| $Fe_2O_3$ (assumed) | 48.25 | 15.98 | 12.37 | 11.82 | 11.29 | 11.20 | 11.07 | 10.74 | 10.34 | 8.58 | 10.67 | 10.61 |
| FeO (assumed) | 30.47 | 26.53 | 25.62 | 24.80 | 23.74 | 23.83 | 23.92 | 24.37 | 25.89 | 24.16 | 24.92 | 24.50 |
| MnO | 0.06 | 0.11 | 0.13 | 0.08 | 0.07 | 0.05 | 0.02 | 0.26 | 0.38 | 0.26 | 0.25 | 0.17 |
| MgO | 1.41 | 5.30 | 6.52 | 7.45 | 8.29 | 8.31 | 8.27 | 7.76 | 6.69 | 7.19 | 7.41 | 7.64 |
| NiO | 0.43 | 0.24 | 0.19 | 0.06 | 0.09 | 0.02 | 0.03 | 0.15 | 0.04 | 0.20 | 0.10 | 0.07 |
| Total | 101.78 | 99.48 | 100.03 | 100.26 | 100.36 | 100.19 | 100.38 | 100.33 | 100.47 | 97.28 | 100.28 | 99.52 |
| | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | |
| | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Al | 0.17 | 0.73 | 0.87 | 0.95 | 1.02 | 1.03 | 1.03 | 1.04 | 1.01 | 1.04 | 1.03 | 1.05 |
| $Cr^{3+}$ | 0.48 | 0.85 | 0.81 | 0.75 | 0.70 | 0.70 | 0.71 | 0.70 | 0.74 | 0.74 | 0.71 | 0.69 |
| $Fe^{3+}$ (assumed) | 1.32 | 0.40 | 0.30 | 0.28 | 0.26 | 0.26 | 0.26 | 0.25 | 0.24 | 0.21 | 0.25 | 0.25 |
| $Fe^{2+}$ | 0.93 | 0.74 | 0.69 | 0.65 | 0.62 | 0.62 | 0.62 | 0.63 | 0.68 | 0.65 | 0.65 | 0.64 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 |
| $Mg^{2+}$ | 0.08 | 0.26 | 0.31 | 0.35 | 0.38 | 0.38 | 0.38 | 0.36 | 0.31 | 0.34 | 0.35 | 0.36 |
| $Ni^{2+}$ | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Total 2+ | 1.02 | 1.01 | 1.01 | 1.01 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 |
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| | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.08 | 0.26 | 0.31 | 0.35 | 0.38 | 0.38 | 0.38 | 0.36 | 0.32 | 0.35 | 0.35 | 0.36 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.92 | 0.74 | 0.69 | 0.65 | 0.62 | 0.62 | 0.62 | 0.64 | 0.68 | 0.65 | 0.65 | 0.64 |
| $Cr/(Cr+Al)$ | 0.74 | 0.54 | 0.48 | 0.44 | 0.41 | 0.40 | 0.41 | 0.40 | 0.42 | 0.41 | 0.41 | 0.40 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.24 | 0.43 | 0.41 | 0.38 | 0.35 | 0.35 | 0.35 | 0.35 | 0.37 | 0.37 | 0.36 | 0.35 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.09 | 0.37 | 0.44 | 0.48 | 0.51 | 0.52 | 0.52 | 0.52 | 0.51 | 0.52 | 0.52 | 0.53 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.24 | 0.43 | 0.41 | 0.38 | 0.35 | 0.35 | 0.35 | 0.35 | 0.37 | 0.37 | 0.36 | 0.35 |
| $Fe^{3+}/Fe_{total}$ | 0.59 | 0.35 | 0.30 | 0.30 | 0.30 | 0.30 | 0.29 | 0.28 | 0.26 | 0.24 | 0.28 | 0.28 |
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| | | | | | | | | | | | | |
| Quality control: oxide total test | Caution: high total | | | | | | | | | Caution: low total | | |

| Data source | Henry | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample # | QC81-28 | | | | | | | | | | | | |
| Analysis pt. # | average | dark lamell | light BSE n | light BSE n | light BSE n | light BSE n | light BSE n | light BSE ı | light BSE ı | light BSE n | light BSE n | light BSE n | light BSE m |
| distance (um) | ave of 119 | average | average | average | average | average | average | average | average | average | average | average | average |
| $SiO_2$ | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.10 | 0.14 | 0.14 | 0.14 | 0.14 |
| $TiO_2$ | 0.64 | 0.42 | 0.76 | 0.38 | 0.38 | 0.37 | 0.00 | 0.37 | 0.67 | 0.65 | 0.64 | 0.62 | 0.61 |
| $Al_2O_3$ | 8.90 | 20.89 | 2.22 | 10.87 | 11.09 | 11.52 | 22.70 | 11.87 | 7.21 | 7.80 | 8.60 | 9.29 | 9.72 |
| $Cr_2O_3$ | 21.75 | 32.42 | 15.27 | 24.79 | 25.01 | 25.45 | 30.77 | 25.79 | 19.98 | 20.31 | 21.00 | 21.53 | 21.67 |
| $Fe_2O_3$ (assumed | 37.08 | 13.93 | 50.49 | 33.61 | 33.28 | 32.62 | 11.90 | 32.11 | 40.50 | 39.49 | 37.95 | 36.66 | 36.11 |
| FeO (assumed) | 28.78 | 25.95 | 30.38 | 17.32 | 17.29 | 17.23 | 21.68 | 17.18 | 29.32 | 29.21 | 29.04 | 28.87 | 28.77 |
| MnO | 0.10 | 0.10 | 0.09 | 0.06 | 0.60 | 0.06 | | 0.06 | 0.09 | 0.10 | 0.10 | 0.10 | 0.10 |
| MgO | 2.94 | 6.12 | 1.14 | 1.77 | 1.80 | 1.96 | 8.98 | 1.91 | 2.51 | 2.67 | 2.87 | 3.04 | 3.15 |
| NiO | 0.31 | 0.13 | 0.42 | 0.09 | 0.09 | 0.10 | 0.00 | 0.10 | 0.33 | 0.32 | 0.32 | 0.30 | 0.30 |
| Total | 100.50 | 99.97 | 100.79 | 88.90 | 89.55 | 89.32 | 96.03 | 89.40 | 100.72 | 100.69 | 100.65 | 100.57 | 100.57 |
| | | | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| Ti | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Al | 0.37 | 0.80 | 0.10 | 0.44 | 0.44 | 0.46 | 0.85 | 0.47 | 0.30 | 0.33 | 0.36 | 0.39 | 0.40 |
| $Cr^{3+}$ | 0.61 | 0.84 | 0.45 | 0.67 | 0.67 | 0.68 | 0.77 | 0.69 | 0.56 | 0.57 | 0.59 | 0.60 | 0.60 |
| $Fe^{3+}$ (assumed) | 0.99 | 0.34 | 1.41 | 0.86 | 0.85 | 0.83 | 0.28 | 0.82 | 1.09 | 1.06 | 1.01 | 0.97 | 0.95 |
| $Fe^{2+}$ | 0.85 | 0.71 | 0.94 | 0.50 | 0.49 | 0.49 | 0.58 | 0.49 | 0.88 | 0.87 | 0.86 | 0.85 | 0.84 |
| $Mn^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Mg^{2+}$ | 0.15 | 0.30 | 0.06 | 0.09 | 0.09 | 0.10 | 0.42 | 0.10 | 0.13 | 0.14 | 0.15 | 0.16 | 0.16 |
| $Ni^{2+}$ | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Total 2+ | 1.02 | 1.01 | 1.02 | 0.59 | 0.60 | 0.59 | 1.00 | 0.59 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.15 | 0.30 | 0.06 | 0.15 | 0.16 | 0.17 | 0.42 | 0.17 | 0.13 | 0.14 | 0.15 | 0.16 | 0.16 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.85 | 0.70 | 0.94 | 0.85 | 0.84 | 0.83 | 0.58 | 0.83 | 0.87 | 0.86 | 0.85 | 0.84 | 0.84 |
| Cr/(Cr+Al) | 0.62 | 0.51 | 0.82 | 0.60 | 0.60 | 0.60 | 0.48 | 0.59 | 0.65 | 0.64 | 0.62 | 0.61 | 0.60 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.31 | 0.42 | 0.23 | 0.34 | 0.34 | 0.35 | 0.41 | 0.35 | 0.29 | 0.29 | 0.30 | 0.31 | 0.31 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.19 | 0.41 | 0.05 | 0.22 | 0.23 | 0.23 | 0.45 | 0.24 | 0.16 | 0.17 | 0.18 | 0.20 | 0.21 |
| $Fe^{3+}/(Cr+Al+Fe^{3+}$ | 0.31 | 0.42 | 0.23 | 0.34 | 0.34 | 0.35 | 0.41 | 0.35 | 0.29 | 0.29 | 0.30 | 0.31 | 0.31 |
| $Fe^{3+}/Fe_{total}$ | 0.54 | 0.33 | 0.60 | 0.64 | 0.63 | 0.63 | 0.33 | 0.63 | 0.55 | 0.55 | 0.54 | 0.53 | 0.53 |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| Quality control: oxide total test | | | | Caution: low total | Caution: low total | Caution: low total | Caution: low total | Caution: low total | | | | | |

# Appendix F. Chromite EMPA Data from Serpentinites

| Sample # | 93DM-07 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Comment | rim | core-rim | core | rim | core-rim | core | core-rim | core | core | rim | core-rim |
| $SiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| $TiO_2$ | 0.27 | 0.15 | 0.18 | 0.28 | 0.22 | 0.16 | 0.27 | 0.16 | 0.19 | 0.24 | 0.20 |
| $Al_2O_3$ | 5.27 | 7.53 | 8.62 | 5.26 | 7.76 | 9.97 | 6.81 | 8.95 | 9.02 | 5.34 | 8.99 |
| $Cr_2O_3$ | 46.07 | 48.76 | 49.19 | 45.81 | 46.70 | 46.64 | 46.02 | 48.87 | 48.91 | 47.11 | 48.49 |
| $V_2O_3$ | 0.14 | 0.12 | 0.12 | 0.15 | 0.12 | 0.14 | 0.14 | 0.14 | 0.14 | 0.18 | 0.15 |
| $Fe_2O_3$ (calculated) | 17.89 | 13.58 | 11.65 | 18.15 | 15.05 | 12.76 | 16.96 | 11.81 | 11.51 | 17.47 | 11.88 |
| FeO (calculated) | 25.82 | 24.61 | 24.34 | 25.99 | 24.54 | 23.62 | 25.00 | 24.62 | 24.37 | 25.87 | 24.54 |
| MnO | 1.27 | 0.59 | 0.55 | 1.24 | 0.70 | 0.53 | 0.72 | 0.59 | 0.61 | 1.11 | 0.56 |
| MgO | 3.68 | 5.16 | 5.42 | 3.63 | 5.13 | 5.94 | 4.84 | 5.31 | 5.44 | 3.94 | 5.35 |
| NiO | 0.14 | 0.08 | 0.05 | 0.12 | 0.10 | 0.08 | 0.11 | 0.07 | 0.07 | 0.15 | 0.08 |
| ZnO | 0.35 | 0.36 | 0.39 | 0.30 | 0.31 | 0.41 | 0.32 | 0.37 | 0.34 | 0.28 | 0.36 |
| Total | 100.90 | 100.94 | 100.51 | 100.93 | 100.62 | 100.25 | 101.18 | 100.90 | 100.60 | 101.69 | 100.60 |
| | | | | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | | | | |
| | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 |
| Al | 0.22 | 0.31 | 0.35 | 0.22 | 0.32 | 0.40 | 0.28 | 0.36 | 0.36 | 0.22 | 0.36 |
| $Cr^{3+}$ | 1.29 | 1.33 | 1.34 | 1.28 | 1.28 | 1.26 | 1.26 | 1.32 | 1.33 | 1.30 | 1.32 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Fe^{3+}$ | 0.48 | 0.35 | 0.30 | 0.48 | 0.39 | 0.33 | 0.44 | 0.30 | 0.30 | 0.46 | 0.31 |
| $Fe^{2+}$ | 0.76 | 0.71 | 0.70 | 0.77 | 0.71 | 0.67 | 0.72 | 0.70 | 0.70 | 0.76 | 0.70 |
| $Mn^{2+}$ | 0.04 | 0.02 | 0.02 | 0.04 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 |
| $Mg^{2+}$ | 0.19 | 0.27 | 0.28 | 0.19 | 0.26 | 0.30 | 0.25 | 0.27 | 0.28 | 0.21 | 0.27 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 1.99 | 2.00 | 2.00 | 1.99 | 1.99 | 2.00 | 1.99 | 2.00 | 2.00 | 1.99 | 1.99 |
| Total 2+ cations | 1.01 | 1.00 | 1.00 | 1.01 | 1.01 | 1.00 | 1.01 | 1.00 | 1.00 | 1.01 | 1.01 |
| | | | | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.20 | 0.27 | 0.28 | 0.20 | 0.27 | 0.31 | 0.26 | 0.28 | 0.28 | 0.21 | 0.28 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.80 | 0.73 | 0.72 | 0.80 | 0.73 | 0.69 | 0.74 | 0.72 | 0.72 | 0.79 | 0.72 |
| Cr/(Cr+Al) | 0.85 | 0.81 | 0.79 | 0.85 | 0.80 | 0.76 | 0.82 | 0.79 | 0.78 | 0.86 | 0.78 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.65 | 0.67 | 0.67 | 0.65 | 0.64 | 0.63 | 0.64 | 0.67 | 0.67 | 0.66 | 0.66 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.11 | 0.15 | 0.18 | 0.11 | 0.16 | 0.20 | 0.14 | 0.18 | 0.18 | 0.11 | 0.18 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.24 | 0.18 | 0.15 | 0.24 | 0.20 | 0.16 | 0.22 | 0.15 | 0.15 | 0.23 | 0.15 |
| $Fe^{3+}/Fe_{total}$ | 0.38 | 0.33 | 0.30 | 0.39 | 0.36 | 0.33 | 0.38 | 0.30 | 0.30 | 0.38 | 0.30 |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| Quality control: oxide total test | | | | | | | | | | Caution: high total | |

| Sample # | 93DM-23A | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Comment | core | core | core-rim | rim | core | core | core-rim | rim |
| $SiO_2$ | 0.11 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.16 |
| $TiO_2$ | 0.28 | 0.64 | 0.34 | 0.02 | 0.44 | 0.53 | 1.02 | 0.65 |
| $Al_2O_3$ | 18.60 | 5.62 | 5.40 | 0.00 | 16.83 | 15.63 | 12.74 | 6.30 |
| $Cr_2O_3$ | 40.02 | 52.81 | 54.01 | 0.76 | 41.76 | 41.02 | 39.96 | 44.15 |
| $V_2O_3$ | 0.15 | 0.21 | 0.18 | 0.00 | 0.18 | 0.19 | 0.21 | 0.19 |
| $Fe_2O_3$ (calculated) | 7.89 | 9.52 | 8.86 | 68.86 | 8.83 | 10.30 | 14.19 | 16.39 |
| FeO (calculated) | 24.05 | 27.47 | 25.94 | 30.78 | 24.47 | 25.14 | 26.60 | 24.91 |
| MnO | 0.48 | 0.60 | 1.94 | 0.07 | 0.43 | 0.44 | 0.49 | 2.62 |
| MgO | 6.22 | 3.25 | 3.03 | 0.13 | 6.05 | 5.51 | 4.71 | 2.89 |
| NiO | 0.07 | 0.13 | 0.08 | 0.36 | 0.08 | 0.07 | 0.13 | 0.10 |
| ZnO | 0.81 | 0.53 | 0.72 | 0.02 | 0.77 | 0.70 | 0.65 | 1.70 |
| Total | 98.67 | 100.78 | 100.49 | 101.04 | 99.82 | 99.52 | 100.68 | 100.04 |
| | | | | | | | | |
| | Structural formula based on 32 oxygens | | | | | | | |
| | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Ti | 0.01 | 0.02 | 0.01 | 0.00 | 0.01 | 0.01 | 0.03 | 0.02 |
| Al | 0.73 | 0.23 | 0.23 | 0.00 | 0.66 | 0.62 | 0.51 | 0.26 |
| $Cr^{3+}$ | 1.05 | 1.47 | 1.51 | 0.02 | 1.10 | 1.09 | 1.07 | 1.24 |
| $V^{3+}$ | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 |
| $Fe^{3+}$ | 0.20 | 0.25 | 0.24 | 1.97 | 0.22 | 0.26 | 0.36 | 0.44 |
| $Fe^{2+}$ | 0.67 | 0.81 | 0.77 | 0.98 | 0.68 | 0.71 | 0.75 | 0.74 |
| $Mn^{2+}$ | 0.01 | 0.02 | 0.06 | 0.00 | 0.01 | 0.01 | 0.01 | 0.08 |
| $Mg^{2+}$ | 0.31 | 0.17 | 0.16 | 0.01 | 0.30 | 0.28 | 0.24 | 0.15 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zn | 0.02 | 0.01 | 0.02 | 0.00 | 0.02 | 0.02 | 0.02 | 0.04 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 1.99 | 1.98 | 1.99 | 2.00 | 1.99 | 1.99 | 1.97 | 1.97 |
| Total 2+ cations | 1.01 | 1.02 | 1.01 | 1.00 | 1.01 | 1.01 | 1.03 | 1.02 |
| | | | | | | | | |
| $Mg/(Mg+Fe^{2+})$ | 0.32 | 0.17 | 0.17 | 0.01 | 0.31 | 0.28 | 0.24 | 0.17 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.68 | 0.83 | 0.83 | 0.99 | 0.69 | 0.72 | 0.76 | 0.83 |
| Cr/(Cr+Al) | 0.59 | 0.86 | 0.87 | 0.99 | 0.62 | 0.64 | 0.68 | 0.82 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.53 | 0.75 | 0.77 | 0.01 | 0.55 | 0.55 | 0.55 | 0.64 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.37 | 0.12 | 0.11 | 0.00 | 0.33 | 0.31 | 0.26 | 0.14 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.10 | 0.13 | 0.12 | 0.99 | 0.11 | 0.13 | 0.19 | 0.23 |
| $Fe^{3+}/Fe_{total}$ | 0.23 | 0.24 | 0.24 | 0.67 | 0.25 | 0.27 | 0.32 | 0.37 |

| Sample # | 93DM-30 | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Comment | core | core-rim | core-rim | rim | core | core-rim | core-rim | rim | core | core-rim | core-rim | rim | core | core-rim | core-rim | rim |
| $SiO_2$ | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $TiO_2$ | 0.40 | 0.41 | 0.37 | 0.40 | 0.30 | 0.29 | 0.33 | 0.42 | 0.35 | 0.34 | 0.27 | 0.37 | 0.39 | 0.35 | 0.33 | 0.39 |
| $Al_2O_3$ | 7.27 | 7.53 | 6.91 | 6.09 | 8.01 | 7.84 | 6.37 | 4.65 | 8.13 | 8.05 | 7.84 | 5.05 | 7.73 | 7.84 | 7.04 | 5.42 |
| $Cr_2O_3$ | 48.79 | 48.17 | 47.20 | 44.90 | 46.72 | 46.65 | 45.71 | 43.05 | 47.16 | 47.28 | 46.88 | 45.36 | 47.47 | 47.48 | 46.18 | 42.90 |
| $V_2O_3$ | 0.16 | 0.15 | 0.18 | 0.16 | 0.16 | 0.15 | 0.14 | 0.17 | 0.17 | 0.17 | 0.17 | 0.16 | 0.18 | 0.18 | 0.16 | 0.19 |
| $Fe_2O_3$ (calculated) | 13.61 | 14.24 | 15.86 | 17.63 | 15.02 | 15.38 | 17.66 | 20.91 | 14.41 | 14.38 | 15.31 | 19.01 | 14.30 | 14.73 | 15.87 | 19.63 |
| FeO (calculated) | 24.68 | 24.82 | 25.12 | 28.02 | 24.96 | 24.85 | 26.08 | 29.39 | 24.66 | 24.84 | 24.69 | 27.11 | 24.30 | 24.36 | 27.08 | 29.54 |
| MnO | 0.54 | 0.58 | 0.64 | 1.04 | 0.65 | 0.60 | 0.62 | 1.40 | 0.62 | 0.61 | 0.63 | 0.89 | 0.58 | 0.61 | 0.88 | 1.53 |
| MgO | 5.29 | 5.29 | 4.96 | 2.64 | 5.07 | 5.16 | 4.23 | 1.47 | 5.29 | 5.22 | 5.25 | 3.29 | 5.52 | 5.35 | 3.48 | 1.21 |
| NiO | 0.10 | 0.11 | 0.13 | 0.14 | 0.09 | 0.08 | 0.10 | 0.17 | 0.11 | 0.06 | 0.09 | 0.12 | 0.09 | 0.45 | 0.13 | 0.09 |
| ZnO | 0.40 | 0.40 | 0.39 | 0.39 | 0.40 | 0.40 | 0.39 | 0.33 | 0.46 | 0.41 | 0.41 | 0.35 | 0.33 | 0.41 | 0.36 | 0.45 |
| Total | 101.24 | 101.69 | 101.75 | 101.42 | 101.38 | 101.41 | 101.63 | 101.98 | 101.36 | 101.35 | 101.54 | 101.70 | 100.88 | 101.77 | 101.50 | 101.35 |
| | Structural formula based on 32 oxygens | | | | | | | | | | | | | | | |
| Si | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Al | 0.29 | 0.30 | 0.28 | 0.25 | 0.32 | 0.32 | 0.26 | 0.20 | 0.33 | 0.33 | 0.32 | 0.21 | 0.31 | 0.32 | 0.29 | 0.23 |
| $Cr^{3+}$ | 1.33 | 1.30 | 1.28 | 1.25 | 1.27 | 1.27 | 1.26 | 1.21 | 1.28 | 1.28 | 1.27 | 1.26 | 1.29 | 1.28 | 1.27 | 1.22 |
| $V^{3+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| $Fe^{3+}$ | 0.35 | 0.37 | 0.41 | 0.47 | 0.39 | 0.40 | 0.46 | 0.56 | 0.37 | 0.37 | 0.39 | 0.50 | 0.37 | 0.38 | 0.42 | 0.53 |
| $Fe^{2+}$ | 0.71 | 0.71 | 0.72 | 0.83 | 0.72 | 0.71 | 0.76 | 0.88 | 0.71 | 0.71 | 0.71 | 0.80 | 0.70 | 0.70 | 0.79 | 0.89 |
| $Mn^{2+}$ | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.02 | 0.04 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | 0.05 |
| $Mg^{2+}$ | 0.27 | 0.27 | 0.25 | 0.14 | 0.26 | 0.26 | 0.22 | 0.08 | 0.27 | 0.27 | 0.27 | 0.17 | 0.28 | 0.27 | 0.18 | 0.06 |
| $Ni^{2+}$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Zn | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Total cations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Total 3+ cations | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 | 1.99 |
| Total 2+ cations | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| $Mg/(Mg+Fe^{2+})$ | 0.28 | 0.28 | 0.26 | 0.14 | 0.27 | 0.27 | 0.22 | 0.08 | 0.28 | 0.27 | 0.27 | 0.18 | 0.29 | 0.28 | 0.19 | 0.07 |
| $Fe^{2+}/(Mg+Fe^{2+})$ | 0.72 | 0.72 | 0.74 | 0.86 | 0.73 | 0.73 | 0.78 | 0.92 | 0.72 | 0.73 | 0.73 | 0.82 | 0.71 | 0.72 | 0.81 | 0.93 |
| $Cr/(Cr+Al)$ | 0.82 | 0.81 | 0.82 | 0.83 | 0.80 | 0.80 | 0.83 | 0.86 | 0.80 | 0.80 | 0.80 | 0.86 | 0.80 | 0.80 | 0.81 | 0.84 |
| $Cr/(Cr+Al+Fe^{3+})$ | 0.67 | 0.66 | 0.65 | 0.63 | 0.64 | 0.64 | 0.63 | 0.62 | 0.65 | 0.65 | 0.64 | 0.64 | 0.65 | 0.65 | 0.64 | 0.62 |
| $Al/(Cr+Al+Fe^{3+})$ | 0.15 | 0.15 | 0.14 | 0.13 | 0.16 | 0.16 | 0.13 | 0.10 | 0.17 | 0.16 | 0.16 | 0.11 | 0.16 | 0.16 | 0.15 | 0.12 |
| $Fe^{3+}/(Cr+Al+Fe^{3+})$ | 0.18 | 0.19 | 0.21 | 0.24 | 0.20 | 0.20 | 0.23 | 0.28 | 0.19 | 0.19 | 0.20 | 0.25 | 0.19 | 0.19 | 0.21 | 0.27 |
| $Fe^{3+}/Fe_{total}$ | 0.33 | 0.34 | 0.36 | 0.36 | 0.35 | 0.36 | 0.38 | 0.39 | 0.34 | 0.34 | 0.36 | 0.39 | 0.35 | 0.35 | 0.35 | 0.37 |
| Quality control: oxide total test | | Caution: high total | Caution: high total | | | | Caution: high total | Caution: high total | | | Caution: high total | Caution: high total | | Caution: high total | | |

# Appendix G. Trace Elements from Whole-rock Analyses

| | AGV1 drft1 | RB81-1 | RB81-2 | CB81-3 | CB81-4 | CB81-5 | CB81-6 | WC82-12 | WC82-28 | QC93-1 | QC81-14 | QC81-27 | QC81-18 | QC81-21 | QC81-28 | QC81-29 | HP81-97 | HP81-96 | AGV1 drift |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sc45(MR) | 12.22 | 29.18 | 21.42 | 27.15 | 22.81 | 32.92 | 23.74 | 30.53 | 14.74 | 6.87 | 16.47 | 28.10 | 10.18 | 22.43 | 18.32 | 40.11 | 13.69 | 18.02 | 12.06 |
| Ti49(MR) | 6088.42 | 1621.57 | 1606.11 | 3759.07 | 2640.06 | 3623.53 | 2600.71 | 3323.15 | 1223.83 | 866.52 | 1731.72 | 2624.37 | 928.70 | 2043.09 | 1344.02 | 2648.12 | 1329.45 | 1323.39 | 5950.31 |
| V51(MR) | 117.56 | 146.70 | 130.62 | 235.38 | 141.26 | 212.22 | 148.57 | 196.87 | 48.26 | 42.87 | 89.25 | 157.41 | 90.67 | 122.29 | 142.11 | 197.61 | 75.55 | 79.66 | 115.94 |
| Cr52(MR) | 10.93 | 2411.82 | 2988.84 | 1921.73 | 2089.70 | 2933.23 | 1662.89 | 1908.26 | 1336.48 | 6543.60 | 3576.22 | 2523.49 | 6491.27 | 3589.84 | 17784.71 | 2567.67 | 4400.37 | 2857.45 | 12.32 |
| Co59(MR) | 15.29 | 63.32 | 85.93 | 55.52 | 62.51 | 88.99 | 61.67 | 79.50 | 97.78 | 138.42 | 105.45 | 80.46 | 81.04 | 103.73 | 99.53 | 64.37 | 112.45 | 121.07 | 15.23 |
| Ni60(MR) | 15.52 | 620.31 | 1132.99 | 376.65 | 645.31 | 954.92 | 614.30 | 842.50 | 2131.20 | 1902.21 | 785.60 | 518.48 | 2142.54 | 830.99 | 726.31 | 173.76 | 1225.64 | 911.99 | 15.62 |
| Cu63(MR) | 55.67 | 13.20 | 62.78 | 6.22 | 5.85 | 355.12 | 7.73 | 14.86 | 7.21 | 6.14 | 6.90 | 93.70 | 5.59 | 34.86 | 18.33 | 29.60 | 5.90 | 52.34 | 55.17 |
| Zn66(MR) | 86.90 | 127.33 | 75.71 | 74.45 | 39.08 | 123.83 | 36.18 | 80.32 | 99.35 | 74.43 | 94.22 | 54.99 | 61.91 | 78.17 | 95.92 | 49.69 | 69.98 | 30.67 | 84.09 |
| Ga69(MR) | 20.88 | 6.61 | 7.96 | 11.11 | 6.87 | 15.42 | 5.78 | 9.91 | 2.22 | 0.54 | 5.12 | 6.91 | 1.51 | 5.08 | 6.78 | 7.15 | 3.90 | 1.44 | 20.32 |
| Rb85(MR) | 68.16 | 2.96 | 4.18 | 128.01 | 27.67 | 109.55 | 3.39 | 1.48 | 101.61 | 8.58 | 7.80 | 1.79 | 2.44 | 24.56 | 1.60 | 1.29 | 1.97 | 2.53 | 67.80 |
| Sr88(MR) | 677.90 | 14.00 | 15.06 | 22.45 | 9.14 | 10.30 | 9.27 | 34.73 | 12.21 | 8.11 | 18.45 | 42.24 | 7.91 | 12.94 | 18.53 | 14.60 | 12.62 | 57.27 | 666.78 |
| Y89(MR) | 19.62 | 7.41 | 8.04 | 23.48 | 14.24 | 18.20 | 15.95 | 12.60 | 3.31 | 1.15 | 7.35 | 8.31 | 1.51 | 6.17 | 3.31 | 12.63 | 4.74 | 5.30 | 19.51 |
| Zr90(MR) | 229.53 | 10.74 | 10.31 | 39.54 | 33.48 | 47.60 | 33.56 | 27.91 | 7.75 | 2.01 | 21.42 | 19.58 | 2.60 | 15.04 | 4.88 | 28.16 | 17.27 | 9.88 | 228.82 |
| Nb93(MR) | 14.81 | 0.41 | 1.77 | 2.69 | 1.66 | 2.24 | 1.58 | 1.33 | 1.05 | 0.22 | 1.68 | 1.08 | 0.46 | 0.92 | 0.42 | 1.18 | 0.73 | 0.68 | 14.85 |
| Cs133(MR) | 1.20 | 0.06 | 0.19 | 3.28 | 2.74 | 7.75 | 0.15 | 0.06 | 4.08 | 0.93 | 0.25 | 0.18 | 0.34 | 2.25 | 0.24 | 0.12 | 0.89 | 0.34 | 1.22 |
| Ba137(MR) | 1269.98 | 0.82 | 1.92 | 32.06 | 9.89 | 31.75 | 2.14 | 3.27 | 23.65 | 1.55 | 14.76 | 595.69 | 0.93 | 6.59 | 12.81 | 63.23 | 4.71 | 40.67 | 1264.75 |
| La139(MR) | 38.59 | 1.70 | 6.29 | 5.07 | 2.95 | 3.31 | 3.30 | 1.14 | 0.72 | 0.34 | 8.69 | 1.19 | 1.45 | 1.02 | 0.97 | 3.94 | 3.38 | 1.32 | 38.32 |
| Ce140(MR) | 68.92 | 2.85 | 16.49 | 13.30 | 7.07 | 8.01 | 7.53 | 3.30 | 1.50 | 0.80 | 16.52 | 2.65 | 3.48 | 2.78 | 1.99 | 9.51 | 5.85 | 2.88 | 68.06 |
| Pr141(MR) | 8.46 | 0.30 | 2.10 | 2.17 | 1.05 | 1.16 | 1.06 | 0.58 | 0.18 | 0.10 | 1.74 | 0.45 | 0.41 | 0.44 | 0.26 | 1.28 | 0.66 | 0.37 | 8.30 |
| Nd143(MR) | 32.24 | 1.26 | 8.19 | 11.16 | 5.20 | 5.60 | 5.19 | 3.30 | 0.77 | 0.45 | 5.93 | 2.36 | 1.53 | 2.26 | 1.14 | 5.52 | 2.56 | 1.64 | 32.00 |
| Sm149(MR) | 5.91 | 0.38 | 1.53 | 3.15 | 1.60 | 1.70 | 1.58 | 1.22 | 0.22 | 0.14 | 1.15 | 0.77 | 0.24 | 0.67 | 0.34 | 1.42 | 0.61 | 0.47 | 5.66 |
| Eu153(MR) | 1.65 | 0.20 | 0.47 | 0.91 | 0.38 | 0.64 | 0.41 | 0.27 | 0.04 | 0.03 | 0.10 | 0.30 | 0.10 | 0.16 | 0.12 | 0.71 | 0.15 | 0.19 | 1.65 |
| Gd157(MR) | 4.84 | 0.66 | 1.43 | 3.62 | 2.00 | 2.28 | 2.08 | 1.72 | 0.35 | 0.17 | 1.13 | 1.06 | 0.24 | 0.88 | 0.43 | 1.66 | 0.67 | 0.64 | 4.84 |
| Tb159(MR) | 0.67 | 0.15 | 0.22 | 0.63 | 0.36 | 0.43 | 0.38 | 0.32 | 0.07 | 0.03 | 0.19 | 0.20 | 0.04 | 0.16 | 0.08 | 0.30 | 0.12 | 0.12 | 0.66 |
| Dy163(MR) | 3.58 | 1.05 | 1.32 | 3.87 | 2.35 | 2.95 | 2.53 | 2.09 | 0.47 | 0.19 | 1.18 | 1.31 | 0.25 | 1.03 | 0.51 | 1.92 | 0.76 | 0.78 | 3.52 |
| Ho165(MR) | 0.68 | 0.25 | 0.28 | 0.80 | 0.50 | 0.63 | 0.55 | 0.44 | 0.11 | 0.04 | 0.25 | 0.28 | 0.05 | 0.22 | 0.11 | 0.43 | 0.17 | 0.18 | 0.66 |
| Er166(MR) | 1.82 | 0.78 | 0.86 | 2.31 | 1.47 | 1.89 | 1.61 | 1.24 | 0.35 | 0.12 | 0.75 | 0.84 | 0.16 | 0.62 | 0.35 | 1.26 | 0.50 | 0.56 | 1.81 |
| Tm169(MR) | 0.27 | 0.13 | 0.13 | 0.36 | 0.23 | 0.30 | 0.25 | 0.19 | 0.06 | 0.02 | 0.12 | 0.13 | 0.03 | 0.10 | 0.05 | 0.20 | 0.08 | 0.10 | 0.27 |
| Yb172(MR) | 1.63 | 0.83 | 0.85 | 2.28 | 1.38 | 1.88 | 1.55 | 1.15 | 0.46 | 0.13 | 0.76 | 0.84 | 0.18 | 0.65 | 0.35 | 1.28 | 0.51 | 0.64 | 1.62 |
| Lu175(MR) | 0.25 | 0.13 | 0.12 | 0.33 | 0.21 | 0.29 | 0.24 | 0.17 | 0.08 | 0.02 | 0.12 | 0.13 | 0.03 | 0.10 | 0.06 | 0.20 | 0.08 | 0.10 | 0.24 |
| Hf178(MR) | 5.16 | 0.34 | 0.31 | 1.25 | 1.01 | 1.40 | 0.92 | 0.80 | 0.22 | 0.08 | 0.61 | 0.58 | 0.08 | 0.43 | 0.15 | 0.82 | 0.47 | 0.28 | 5.15 |
| Ta181(MR) | 0.88 | 0.01 | 0.06 | 0.13 | 0.10 | 0.15 | 0.09 | 0.07 | 0.03 | 0.01 | 0.11 | 0.06 | 0.04 | 0.05 | 0.01 | 0.07 | 0.04 | 0.03 | 0.87 |
| Pb208(MR) | 37.77 | 0.58 | 0.81 | 4.10 | 1.99 | 2.76 | 1.29 | 1.18 | 2.71 | 0.41 | 1.39 | 1.00 | 0.37 | 1.00 | 0.83 | 1.97 | 1.13 | 1.70 | 38.09 |
| Th232(MR) | 6.26 | 0.15 | 1.44 | 1.02 | 0.72 | 0.95 | 1.06 | 0.18 | 0.29 | 0.09 | 1.67 | 0.11 | 0.24 | 0.10 | 0.13 | 0.51 | 0.93 | 0.24 | 6.40 |
| U238(MR) | 1.94 | 0.27 | 0.48 | 0.26 | 0.18 | 0.29 | 0.34 | 0.12 | 0.10 | 0.04 | 0.59 | 0.18 | 0.17 | 0.15 | 0.20 | 0.35 | 0.22 | 0.18 | 1.91 |

# Appendix H. Chromite LA-ICP-MS Analyses from Chromite-rich Meta-ultramafics

| Sample | HP-81-95 | HP-81-95 | HP-81-95 | HP-81-95 | HP-81-95 |
|---|---|---|---|---|---|
| Comments | rim | rim | core | rim | core |
| Mg | 79835.56 | 78098.28 | 77696.90 | 76403.33 | 75558.82 |
| Li | < d.l. | 0.01 | 0.19 | 1.20 | 2.49 |
| Al | 112727.82 | 97310.46 | 94401.73 | 105207.38 | 94675.20 |
| Ca | 2714.41 | 3202.03 | 3574.06 | 1764.92 | 2644.56 |
| Ti | 908.53 | 786.45 | 721.80 | 719.72 | 646.03 |
| V | 1145.64 | 1023.87 | 979.76 | 990.19 | 911.99 |
| Cr | 431910.40 | 454531.98 | 459188.66 | 447188.68 | 462419.96 |
| Mn | 7360.84 | 7114.75 | 7054.88 | 6554.64 | 6437.61 |
| Fe | 18138.64 | 17322.20 | 16821.38 | 16250.99 | 15504.67 |
| Co | 748.06 | 757.55 | 776.97 | 747.99 | 750.30 |
| Ni | 1487.34 | 1262.85 | 1033.37 | 1100.97 | 961.11 |
| Cu | 4.71 | 24.37 | 23.31 | 2.60 | 3.55 |
| Zn | 2906.01 | 2913.07 | 2820.40 | 2812.41 | 2868.21 |
| Ga | 52.37 | 46.86 | 42.03 | 45.23 | 40.50 |
| Ge | 174.04 | 203.84 | 172.49 | 155.86 | 129.96 |
| As | 5.51 | 8.04 | 4.04 | 3.90 | 1.51 |
| Se | 199.59 | 226.49 | 101.01 | 217.75 | 113.34 |
| Y | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Zr | 30.34 | 28.12 | 39.63 | 32.85 | 34.61 |
| Nb | 30.50 | 28.74 | 32.32 | 31.40 | 32.41 |
| Mo | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Ag | < d.l. | < d.l. | 0.19 | 0.62 | 0.03 |
| Cd | < d.l. | < d.l. | < d.l. | < d.l. | 0.54 |
| In | 0.21 | 0.14 | 0.19 | 0.17 | 0.03 |
| Sn | 22.99 | 22.65 | 19.50 | 30.56 | 29.62 |
| Sb | 1.28 | 1.56 | 1.40 | 1.05 | 1.19 |
| La | < d.l. | < d.l. | 0.70 | < d.l. | < d.l. |
| Ce | 3.03 | < d.l. | 0.78 | 0.74 | 2.49 |
| Nd | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Sm | 1.04 | 2.19 | 4.12 | 1.38 | < d.l. |
| Tb | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Ho | 0.89 | 2.34 | < d.l. | < d.l. | < d.l. |
| Tm | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Hf | < d.l. | 1.17 | < d.l. | < d.l. | 0.08 |
| Ta | 0.32 | < d.l. | < d.l. | < d.l. | 0.51 |
| W | < d.l. | 1.33 | 2.56 | 1.28 | < d.l. |
| Tl | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Pb | < d.l. | < d.l. | < d.l. | 0.17 | 0.20 |
| Bi | 0.03 | 0.15 | 0.16 | < d.l. | 0.02 |
| Th | < d.l. | < d.l. | < d.l. | 0.02 | < d.l. |
| U | < d.l. | < d.l. | < d.l. | 0.05 | 0.12 |
| | Analyses are in ppm | | | | |

| Sample | QC-81-19 | QC-81-19 | QC-81-19 | QC-81-19 | QC-81-19 | QC-81-19 | QC-81-19 | QC-81-19 | QC-81-19 |
|---|---|---|---|---|---|---|---|---|---|
| Comments | rim | core | rim | rim | rim | rim | rim | rim | core |
| Mg | 95263.34 | 98570.06 | 94406.98 | 92613.33 | 93364.87 | 91860.49 | 94310.91 | 93923.07 | 94495.83 |
| Li | 7.92 | 10.21 | 9.17 | 7.87 | 9.08 | 7.97 | 6.66 | 6.83 | 7.01 |
| Al | 116792.86 | 115721.25 | 112533.11 | 116044.50 | 117266.27 | 124746.55 | 117417.08 | 117967.37 | 113489.49 |
| Ca | 9.53 | < d.l. | 566.44 | 648.29 | 1157.72 | 3215.12 | 2536.96 | 2385.65 | 3118.36 |
| Ti | 1020.27 | 1009.36 | 1029.98 | 1079.87 | 1047.55 | 1012.30 | 962.91 | 957.08 | 940.23 |
| V | 1278.43 | 1235.08 | 1253.72 | 1296.59 | 1294.97 | 1262.16 | 1301.49 | 1298.02 | 1259.63 |
| Cr | 414014.49 | 411037.15 | 420111.04 | 417686.13 | 415473.65 | 407585.00 | 414307.81 | 414106.80 | 419561.48 |
| Mn | 7220.96 | 7205.47 | 7533.68 | 7686.91 | 7506.54 | 7367.21 | 7431.70 | 7466.88 | 7465.17 |
| Fe | 12612.87 | 13306.96 | 13047.04 | 12956.61 | 12706.96 | 12621.63 | 12590.51 | 12510.55 | 12152.16 |
| Co | 560.15 | 580.58 | 584.38 | 574.20 | 568.59 | 548.41 | 533.80 | 525.03 | 523.51 |
| Ni | 1091.72 | 1162.14 | 1268.83 | 1185.45 | 1171.73 | 1069.26 | 1114.75 | 1100.78 | 1100.88 |
| Cu | 3.04 | 2.76 | 0.28 | 2.32 | 1.40 | 3.12 | 3.26 | 4.11 | 4.35 |
| Zn | 1399.42 | 1459.82 | 1487.85 | 1449.40 | 1437.82 | 1435.78 | 1438.24 | 1448.29 | 1431.61 |
| Ga | 54.30 | 64.66 | 61.36 | 59.27 | 53.87 | 59.07 | 55.74 | 55.60 | 57.74 |
| Ge | 100.03 | 110.40 | 102.90 | 14.82 | 55.09 | 79.00 | 58.47 | 59.17 | 107.73 |
| As | 0.10 | < d.l. | 3.49 | 5.28 | 1.40 | < d.l. | < d.l. | < d.l. | 4.25 |
| Se | 28.58 | < d.l. | 160.49 | 175.97 | < d.l. | < d.l. | < d.l. | 93.92 | 151.19 |
| Y | < d.l. | < d.l. | 0.85 | < d.l. | 0.17 | 2.57 | < d.l. | 1.96 | 2.93 |
| Zr | 29.91 | 25.63 | 20.77 | 37.97 | 22.78 | 23.98 | 33.48 | 27.33 | 25.23 |
| Nb | 28.48 | 29.67 | 26.62 | 25.84 | 27.82 | 24.80 | 25.37 | 27.43 | 24.10 |
| Mo | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Ag | < d.l. | 0.24 | < d.l. | 0.06 | < d.l. | < d.l. | 0.12 | < d.l. | < d.l. |
| Cd | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| In | < d.l. | 0.17 | 0.10 | 0.07 | 0.06 | 0.11 | < d.l. | 0.12 | 0.09 |
| Sn | 26.29 | 26.61 | 24.07 | 27.78 | 30.72 | 27.93 | 29.33 | 28.46 | 26.93 |
| Sb | 0.29 | 1.38 | 0.02 | 0.55 | 0.26 | 0.81 | 1.64 | 1.43 | 1.42 |
| La | 0.58 | < d.l. | < d.l. | 0.74 | 1.40 | < d.l. | < d.l. | < d.l. | < d.l. |
| Ce | < d.l. | < d.l. | 0.76 | 1.57 | < d.l. | < d.l. | < d.l. | 0.08 | < d.l. |
| Nd | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Sm | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | 1.42 |
| Tb | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Ho | 0.09 | < d.l. | 0.42 | 0.02 | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Tm | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Hf | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | 0.06 | 0.53 |
| Ta | 1.41 | 1.58 | 1.24 | 0.42 | < d.l. | < d.l. | < d.l. | 0.13 | 1.02 |
| W | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Tl | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| Pb | 0.03 | 0.84 | 0.98 | 0.39 | 0.61 | 0.29 | 0.15 | < d.l. | 0.19 |
| Bi | < d.l. | < d.l. | < d.l. | < d.l. | 0.09 | 0.02 | 0.02 | < d.l. | 0.08 |
| Th | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| U | < d.l. | < d.l. | 0.69 | 0.37 | 0.12 | 0.12 | < d.l. | < d.l. | < d.l. |
| | Analyses are in ppm | | | | | | | | |

| Sample | Comments | Co | Fe | Ni | Cu | Zn | Ru101 | Ru102 | Rh103 | Pd105 | Ag | Re185 | Pt195 | Pt196 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HP-81-95 | rim full | 662.49 | 23114.38 | 1256.09 | 9.01 | 2619.50 | 0.01 | 0.00 | 0.16 | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| HP-81-95 | rim low | 682.55 | 23343.29 | 1179.45 | 4.98 | 2682.43 | 0.01 | 0.00 | 0.13 | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| HP-81-95 | mantle full | 665.89 | 22440.56 | 1092.06 | 31.96 | 2663.57 | 0.01 | 0.00 | 0.10 | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| HP-81-95 | mantle low | 695.38 | 22252.13 | 1063.93 | 5.22 | 2628.53 | 0.01 | 0.01 | 0.05 | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| HP-81-95 | core | 644.02 | 22218.65 | 998.23 | 7.41 | 2614.72 | 0.01 | 0.00 | 0.13 | 0.010 | < d.l. | 0.028 | < d.l. | < d.l. |
| HP-81-95 | rim full | 701.19 | 22690.45 | 1094.55 | 97.47 | 2888.19 | 0.01 | 0.00 | 0.28 | 0.004 | < d.l. | 0.004 | < d.l. | < d.l. |
| HP-81-95 | rim low | 723.98 | 23456.90 | 1038.19 | 8.25 | 2903.15 | 0.01 | 0.00 | 0.18 | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| HP-81-95 | mantle full | 693.69 | 21781.73 | 989.20 | 87.40 | 2894.06 | 0.01 | 0.00 | 0.36 | 0.005 | < d.l. | < d.l. | < d.l. | < d.l. |
| HP-81-95 | mantle low | 711.94 | 21949.04 | 956.13 | 12.60 | 2911.82 | 0.01 | 0.00 | 0.25 | < d.l. | < d.l. | < d.l. | < d.l. | < d.l. |
| HP-81-95 | core | 684.29 | 21555.07 | 864.26 | 80.06 | 2901.38 | 0.01 | 0.00 | 0.44 | 0.004 | 0.021 | < d.l. | < d.l. | 0.007 |
| QC-81-19 | bulk | 496.56 | 16585.08 | 1082.50 | 1.69 | 1360.57 | 0.01 | 0.01 | 0.25 | 0.006 | < d.l. | 0.009 | < d.l. | < d.l. |
| QC-81-19 | bulk | 513.33 | 16631.93 | 1139.60 | 2.05 | 1252.53 | 0.01 | 0.01 | 0.23 | 0.024 | < d.l. | < d.l. | < d.l. | < d.l. |
| QC-81-19 | bulk | 508.56 | 17138.43 | 1057.80 | 2.85 | 1327.34 | 0.01 | 0.00 | 0.18 | 0.016 | < d.l. | < d.l. | 0.865 | < d.l. |
| QC-81-19 | bulk | 515.05 | 16481.49 | 1040.39 | 1.75 | 1370.02 | 0.01 | 0.01 | 0.27 | 0.003 | < d.l. | < d.l. | < d.l. | < d.l. |
| | Amalyses are in ppm | | | | | | | | | | | | | |

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# Vita

Rachel Gnieski was born in Palm Beach Gardens, Florida. She attended Jupiter High School, graduating in 2014. She then attended Palm Beach State College graduating with an Associates of Arts degree in 2016. In 2016 she started at Louisiana State University and there she became interested in geology and pursued a degree in the subject. She graduated with a B.S. in geology from LSU in 2019 and, enthralled with Archean rocks she had studied as an undergraduate, decided to stay at LSU and pursue a MS degree with Dr. Darrell Henry on the subject.

Rachel was a TA at LSU and assisted with mineralogy, petrology, and introductory geology lab. She is a member of the Geological Society of America and the Mineralogical Society of America. In her spare time, she enjoys reading fantasy novels and playing nerdy card games. She plans on earning her MS degree in December 2022.