

# Genetic Link between Ilmenite and Kimberlite: Constrain from Ilmenite Compositions of Majhgawan Kimberlite Pipe, Panna, Madhya Pradesh

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**Abstract:** *We present, major element geochemical data for ilmenite grains obtained from heavy mineral concentrate of diamondiferous Majhgawan kimberlite clan diatreme in Central Indian Diamond Province (CIDP) in Panna District of Madhya Pradesh, India. The chemical composition of 148 ilmenite grains suggests different compositional trends when plotted over “Haggerty’s parabola” and as seen in MgO-Cr<sub>2</sub>O<sub>3</sub> bivariate plots. The study indicates that the ilmenite crystallized in three stages: the first stage where Cr - poor ilmenite is crystallized from protokimberlitic or kimberlitic melt and forms the base of Haggerty’s parabola on MgO-Cr<sub>2</sub>O<sub>3</sub> plots; the second stage ilmenite is rich in MgO and Cr<sub>2</sub>O<sub>3</sub> - represented by left branch of Haggerty’s parabola-might have formed by interaction between melt and lithosphere; the third stage ilmenite is formed by sub-solidus recrystallization in an evolved kimberlite melt due to oxidation and is reflected in the right branch of Haggerty’s parabola in MgO-Cr<sub>2</sub>O<sub>3</sub> plots. The various trends in the ilmenite composition from Majhgawan pipe are attributed to conditions prevailing during ilmenite crystallization in a kimberlite melt ascending through the lithospheric mantle. These geochemical features indicate a genetic link between ilmenite and the host kimberlite melt.*

**Keywords:** Ilmenite and Kimberlite

## I. INTRODUCTION

Picro-ilmenite or magnesian ilmenite is an important mineral in kimberlite and is extensively used in diamond exploration to identify primary deposits. Ilmenite occurs in all kimberlites of Group-I (Schulze et al., 1995; Griffin et al., 1997; Kostrovitsky et al., 2004; Wyatt et al., 2004) and more rarely in Group - II kimberlites or Orangeites (Mitchell, 1977). In kimberlites, ilmenite forms as monomineralic grains of megacryst, macrocryst and microphenocryst. At least, nine paragenetic types of ilmenites have been recognized (Mitchell, 1986) and same can be broadly summarized as (a) ilmenite occurring as megacryst and macrocryst (large rounded single crystals); (b) as primary groundmass or matrix ilmenite; (c) as an inclusion within olivine and phlogopite; (d) Intergrowth as lamellar with clinopyroxene; (e) Intergrowth with spinel as sub-solidus reduction; (f) Intergrowth with groundmass spinel and perovskite; (g) Intergrowth with ilmenite as exsolution; (h) Intergrowth with rutile and (i) Concentric overgrowth over olivine macrocryst.

The genesis of ilmenite (mainly megacryst and macrocryst) and its genetic relationship with kimberlite magma is still debated (Nixon and Boyd, 1973; Nowell et al., 2004; Kopylova et al., 2009). The possible theories for origin of megacryst and macrocryst ilmenite can be grouped as: (a) disaggregation of ilmenite bearing lithospheric mantle lithologies (Haggerty, 1975, 2016; Robles-Cruz et al., 2009); (b) crystallization within the asthenosphere (Boyd and Nixon, 1975; Harte & Gurney, 1981; De Bruin, 2005; Tappe et al, 2012, 2016); (c) crystallization from an asthenospheric melt within the lithosphere associated with kimberlite magmatism (Mitchell, 1986; Nowell et al, 2004; Kopylova et al., 2009; Giuliani et al., 2013; Kamenetsky et al., 2014); (d) formation in a “metasomatic aureole” surrounding the (proto-) kimberlite melt and / or previous pulses of failed (proto-) kimberlite melt, alongside other megacryst suite minerals (Moore and Lock, 2001; Moore and Belousova, 2005; Kargin et al., 2017).

The compositional trends in minerals of megacryst / macrocryst suite are commonly attributed to fractional crystallization as exemplified by decreasing NiO contents and Mg# in olivine and increasing FeOtotal and TiO2 contents in Ilmenite, olivine, garnet and clinopyroxene (Mitchell, 1986; Moore et al., 1992; Griffin et al., 1997).

The ascent of kimberlite melt from mantle is accompanied by a change in melt composition as a result of entrainment and assimilation of lithospheric material (Kamenetsky et al., 2008; Brett et al., 2009; Arndt et al., 2010; Russell et al., 2012; Ashchepkov et al., 2014; Soltys et al., 2016, 2018a, b) and changes in redox potential (Eggler, 1983; Mitchell, 1986). Ilmenite is sensitive to such changes (e.g., Green and Sobolev, 1975), and therefore variations in ilmenite composition can be used to elucidate both the genesis of this mineral, and changes in the host kimberlite melt during its ascent through the lithosphere.

In this study, we outline the relevant features of ilmenite compositions and study the genesis of megacrystic ilmenite and its genetic relationship with the kimberlite melt from Majhgawan pipe in Central Indian Diamond Province (CIDP). We have illustrated the compositional variations in the ilmenite through bivariate plots, as these plots are most informative for demonstration of variation in ilmenite composition from a kimberlite pipe (Haggerty, 1979; Mitchell, 1986; Moore et al., 1992).

## II. GEOLOGICAL SETTING

Central Indian Diamond Province (CIDP), is situated in the southern part of Bundelkhand Craton, which contains two kimberlite clusters (Majhgawan cluster and Saphrishi cluster). This also hosts the only diamond producing, Majhgawan Mine in India (Figure 1). Majhgawan cluster includes the Majhgawan pipe and Hinota pipe. These are intruded into the platformal Kaimur group of rocks, which forms a part of Vindhya Super Group (1400-1100 Ma). Based on the Rb-Sr, K-Ar dating of phlogopite and whole rock dating these pipes are Paleo - to Meso - proterozoic (close to 1100 Ma) in age (Paul, et.al., 1979; Smith, 1992; Anil Kumar and Gopalan, 1992). Majhgawan pipe has been classified as Lamproite by Scott Smith (1989, 1992a) and has termed it as olivine lamproite lapilli tuff of crater facies. However, other studies on Majhgawan pipe suggest that it resembles both lamproitic and kimberlitic character (Ravi Shankar, et.al., 2001 and reference therein). Based on combined petrological, geochemical and isotope characteristics, the Majhgawan pipe is termed as 'transitional kimberlite – orangeite - lamproite' (Chalapathi Rao, 2006).

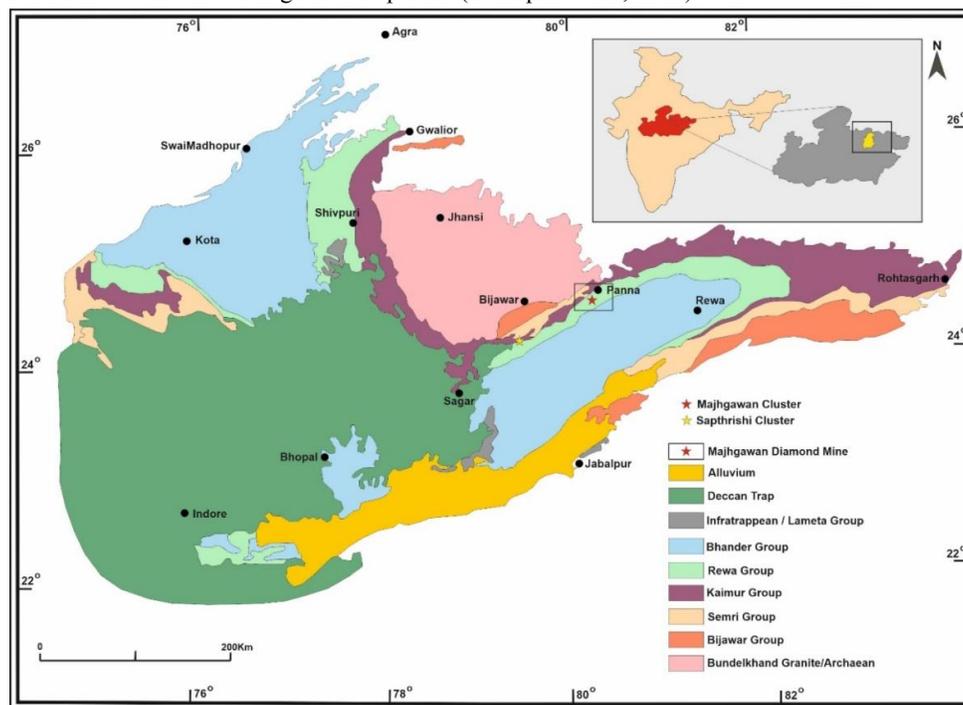


Figure 1: Location map of Majhgawan Diamond Mine and regional geology of the area

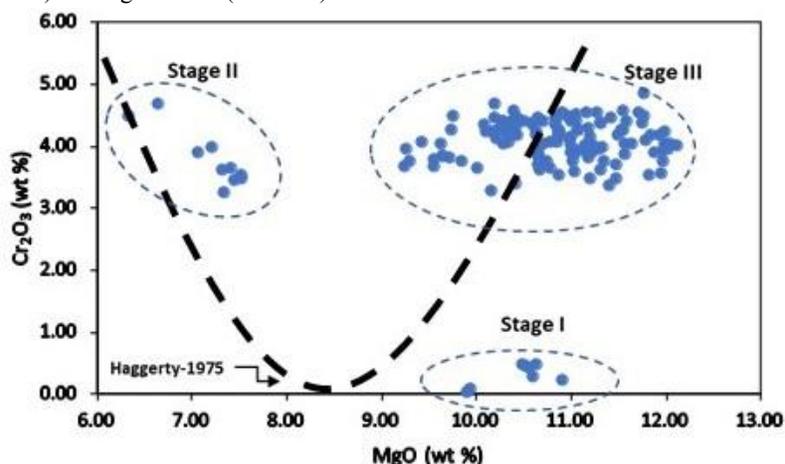
Petrographically, the Majhgawan pipe represents different varieties of magmaclastic agglomeritic tuff. These magmaclasts are macrocrystic in nature and contain olivine, ilmenites and pyroxenes. The Majhgawan pipe contains two generations of altered olivine, viz., large, anhedral and corroded macrocrysts (which could be xenocrysts) as well as subhedral to euhedral phenocrysts (representing primary olivines grown in the magma). The groundmass occasionally contains vesicles and juvenile lapilli tuffs. The pipe rock is also traversed by numerous veinlets of calcite and barite especially in the upper most portion.

### III. MATERIAL, SAMPLING AND ANALYTICAL METHODS

Kimberlitic ore is crushed and is reduced to a desirable size of 80mm to recover diamonds from the ore and the fines are stocked as tailings. This fines or material from the tailings were sampled to collect heavy mineral concentrates by utilizing jigging and heavy media separation, and ilmenite was subsequently separated from these concentrates by picking, under the microscope. The ilmenite grains are mounted in an epoxy for analysis using electron probe micro-analyzer (EPMA). Electron microprobe analysis is carried out on a 4-WDS Cameca SX100 Electron Microprobe instrument at CSIR-National Geophysical Research Institute, Hyderabad, India. This electron microprobe instrument is equipped with four wavelength dispersive spectrometer and analyses were performed at an acceleration voltage of 20 kV, a beam current of 20nA was used. The compositions of 148 ilmenite grains separated from the concentrate were determined. The average representative chemical compositions of analyzed ilmenite grains are provided as supplementary data of this article.

### IV. ILMENITE COMPOSITIONAL DISTRIBUTION

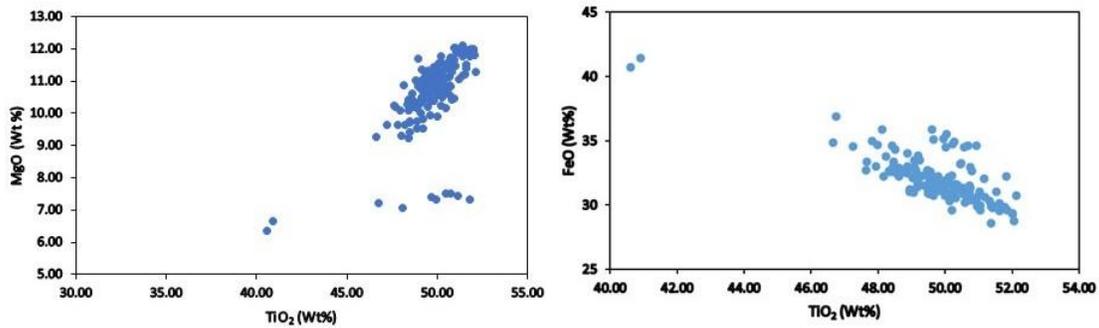
The compositional trend and distribution of ilmenite from Majhgawan pipe are illustrated in the MgO (wt%) vs Cr<sub>2</sub>O<sub>3</sub> (wt%) plots (Figure 2). In the variation diagram, TiO<sub>2</sub>-MgO-FeO, they display the trend of typical kimberlite (Wyatte, 2004). The trend of ilmenite from the studied pipe is characterized by variation in MgO and Cr<sub>2</sub>O<sub>3</sub> concentration. In terms of MgO and Cr<sub>2</sub>O<sub>3</sub>, the whole population of ilmenite can be categorized into three different trends: (1) a trend with intermediate MgO (10-11 wt%) and low Cr<sub>2</sub>O<sub>3</sub> (<1 wt%); (2) with low MgO (6-8 wt%) and high Cr<sub>2</sub>O<sub>3</sub> (3-5 wt%); (3) with high MgO (9-12 wt%) and high Cr<sub>2</sub>O<sub>3</sub> (3-5 wt%) content.



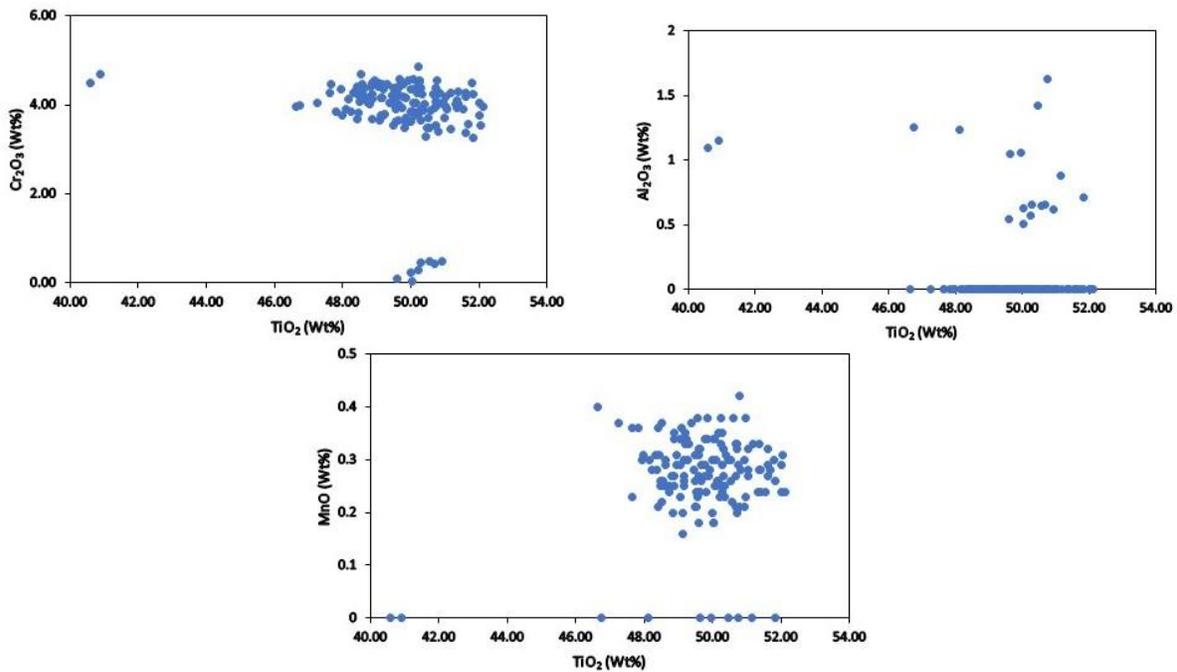
**Figure 2:** MgO vs. Cr<sub>2</sub>O<sub>3</sub> bivariate plot showing distribution of Ilmenite composition, crystallization stages and “Haggerty Parabola” from Majhgawan Kimberlite pipe, Panna, Madhya Pradesh.

In terms of “Cr<sub>2</sub>O<sub>3</sub> vs MgO Parabola diagram” of Haggerty - 1975, trend (1) corresponds to the base of the curve, trend (2) represents the left-hand side of the parabola and trend (3) right-hand side of the parabolic curve. The Cr<sub>2</sub>O<sub>3</sub> composition of the ilmenite, reflects a bimodal distribution i.e., one with high Cr<sub>2</sub>O<sub>3</sub> (3-5 wt%) and other with low Cr<sub>2</sub>O<sub>3</sub> (0-1 wt%). Distribution trends of TiO<sub>2</sub> vs MgO, FeO, Al<sub>2</sub>O<sub>3</sub>, MnO are illustrated in Figure 3.

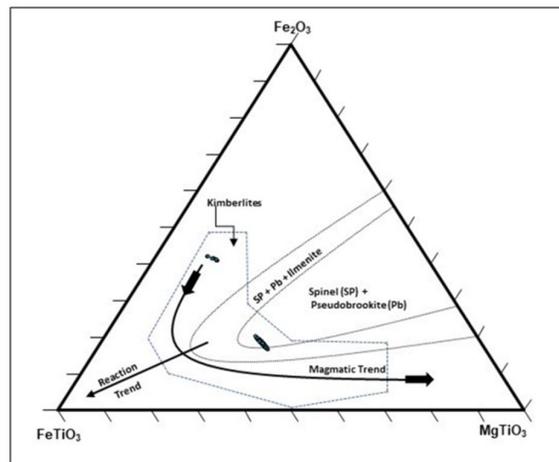
On the, Fe<sub>2</sub>O<sub>3</sub>-FeTiO<sub>3</sub>-MgTiO<sub>3</sub> diagram suggested by Haggerty et al.,1979, the majority of the ilmenites have picroilmenite composition and follow the magmatic trend, which could be related to the early evolution of kimberlite magma (Figure 4).



**Figure 3:** Variation diagram for Ilmenite from Majhgawan Kimberlite Pipe, Panna, Madhya Pradesh



**Figure 4:** Variation diagram for Ilmenite from Majhgawan Kimberlite Pipe, Panna, Madhya Pradesh.



**Figure 4:** Compositional evolution of Ilmenite from Majhgawan Kimberlite pipe on a ternary  $\text{Fe}_2\text{O}_3\text{-FeTiO}_3\text{-MgTiO}_3$  diagram (Haggerty et al., 1979)

## V. DISCUSSION

### 5.1 Generation of Ilmenite Compositional Trend

Ilmenite compositional trends for kimberlite are suggested to have been formed by fractionation (Griffin, 1997; Moore, et.al., 1992). The concentration of minor minerals is governed by other phases that crystallize together with ilmenite during fractionation of parental melt (i.e., Al<sub>2</sub>O<sub>3</sub> is controlled by presence of garnet and chromite, NiO by sulfides and olivine and Cr<sub>2</sub>O<sub>3</sub> by chromite) and these phases play different roles as assimilants and precipitates.

We assume that initially, ilmenite crystallization occurred together with other phase within the protokimberlitic or kimberlitic melt, which has endured fractional crystallization and was most likely characterized by relatively low Cr and high Fe-Ti contents (Boyd and Nixon, 1975). Ilmenite compositions with variable MgO and relatively low Cr<sub>2</sub>O<sub>3</sub> contents (i.e., <1–2 wt%) on MgO- Cr<sub>2</sub>O<sub>3</sub> plots (Figure 3) demonstrate this early phase of crystallisation and as this kimberlitic melt moves upward, it interact with other lithologies (lithospheric mantle) resulting, a change within melt composition and in response of this, another phase of ilmenite evolution occurred which is reflected by a trend of plots falling in the left side of “Haggerty’s Parabola” with depleted MgO and enriched Cr<sub>2</sub>O<sub>3</sub> contents. Later, the last phase evolved with high MgO and identical Cr<sub>2</sub>O<sub>3</sub> content, representing the, right side of “Haggerty’s Parabola” on MgO-Cr<sub>2</sub>O<sub>3</sub> plot.

During, the evolution of second phase of ilmenite crystallization, the melt was progressively got depleted in Mg but enriched in Cr (Figure 2). The lack of correlation between MgO and Cr<sub>2</sub>O<sub>3</sub> contents can likely be attributed to a high degree of heterogeneity of the melt, that assimilated various lithospheric mantle materials (e.g., clinopyroxene, garnet, Cr-bearing spinel). Further, the melt was possibly getting more oxidized resulting in heterogeneity of individual grains and is defined by the presence of ilmenite composition with high MgO and high Cr<sub>2</sub>O<sub>3</sub> contents (Figure 2).

The “Haggerty’s parabola” distribution is defined by the presence of two ilmenite groups, low- and high-Mg, with identical variation in Cr<sub>2</sub>O<sub>3</sub> contents (Figure 2). The process of secondary sub - solidus ilmenite recrystallization under changing redox potentials of the evolving kimberlite melt during ascent through the lithosphere, and possibly upto the crust could have resulted in increase of MgO content of ilmenite, while Cr<sub>2</sub>O<sub>3</sub> contents remained constant (stage II to stage III evolution). The right branch of this parabola reflects secondary sub - solidus ilmenite recrystallization under changing redox potentials.

## VI. CONCLUSIONS

The major element composition of ilmenite from diamondiferous Majhgawan pipe of CIDP was studied to establish a genetic link between ilmenite and kimberlite melt.

Based on ilmenite compositional distributions, we propose a three-stage formation and (re-) crystallization history of ilmenite: 1) primitive protokimberlitic / kimberlitic melt; 2) lithospheric contaminated melt and 3) re-equilibration with the host kimberlite during ascent through the lithosphere.

Initially, ilmenite crystallization occurred in an asthenospheric melt with other megacrystic minerals of the Cr-poor suite. It is assumed that, the primary mechanism for changing the composition of ilmenite (i.e., decreasing Cr concentrations), as well as assimilates minerals of Cr-poor megacryst suite, was fractional crystallization.

The second stage of ilmenite crystallization is inferred to have occurred within the lithosphere. This ilmenite displays a decrease in MgO but increase in Cr<sub>2</sub>O<sub>3</sub> contents, which reflects changes in the composition of the kimberlite melt during assimilation of lithospheric mantle material, forming the left branch of Haggerty’s parabola in MgO vs. Cr<sub>2</sub>O<sub>3</sub> bivariate plots.

The third stage of ilmenite re-crystallization (and re-equilibration) is recorded by the heterogeneity of individual grains. We propose recrystallisation of ilmenite under increasing fO<sub>2</sub> of the evolving kimberlite melt during ascent through the lithosphere (potentially continuing in the crust) caused the decreasing Fe and Mn contents, with corresponding increases in Mg content, yet Cr contents of remain unchanged. In our view, this process explains the production of the right branch of “Haggerty’s parabola”.



## VII. REPRESENTATIVE SUPPLEMENTARY DATA

Mineral	Ilmenite													
Data set point	2 / 1 .	15 / 1 .	25 / 1 .	35 / 1 .	46 / 1 .	61 / 1 .	75 / 1 .	88 / 1 .	101 / 1 .	115 / 1 .	130 / 1 .	140 / 1 .	141 / 1 .	148 / 1 .
SiO <sub>2</sub>	0.00	0.02	0.01	0.01	0.01	0.00	0.02	0.02	0.03	0.04	0.06	0.03	0.02	0.01
TiO <sub>2</sub>	49.18	49.13	49.59	49.05	50.30	49.32	50.69	50.26	51.63	48.16	50.93	50.96	49.27	51.53
Al <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.00	0.00	0.00
FeO	31.39	32.63	31.40	30.99	31.60	32.31	31.32	31.19	30.12	32.20	34.61	29.87	32.21	31.03
MnO	0.25	0.34	0.32	0.29	0.32	0.33	0.33	0.33	0.27	0.30	0.21	0.23	0.30	0.24
MgO	11.00	10.51	10.87	10.97	10.65	10.66	11.14	10.91	11.40	10.86	10.48	11.65	10.44	11.22
CaO	0.00	0.02	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.03	0.00	0.00	0.02
Na <sub>2</sub> O	0.03	0.00	0.02	0.00	0.05	0.03	0.00	0.02	0.00	0.01	0.02	0.05	0.00	0.00
K <sub>2</sub> O	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Cr <sub>2</sub> O <sub>3</sub>	4.40	4.41	4.20	4.49	3.89	4.45	3.92	4.55	3.37	4.14	0.49	4.04	4.43	3.89
Total	96.25	97.06	96.43	95.81	96.82	97.11	97.42	97.28	96.82	95.72	97.45	96.83	96.68	97.94

oxygen basis 3														
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	0.91	0.91	0.91	0.91	0.92	0.91	0.92	0.92	0.94	0.90	0.93	0.93	0.91	0.93
Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00
Fe <sup>2+</sup> all ferrous	0.64	0.67	0.64	0.64	0.64	0.66	0.63	0.63	0.61	0.67	0.70	0.60	0.66	0.62
Mn	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00
Mg	0.40	0.38	0.40	0.40	0.39	0.39	0.40	0.39	0.41	0.40	0.38	0.42	0.38	0.40
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
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.09	0.09	0.08	0.09	0.08	0.09	0.07	0.09	0.06	0.08	0.01	0.08	0.09	0.07
Total	2.05	2.05	2.05	2.05	2.04	2.05	2.04	2.04	2.03	2.06	2.05	2.04	2.05	2.03
MgTiO <sub>3</sub>	60.18	59.64	60.46	60.02	60.95	59.98	61.83	61.17	63.03	59.02	61.41	62.61	59.71	62.75
FeTiO <sub>3</sub>	80.57	81.76	80.99	80.04	81.90	81.63	82.01	81.45	81.75	80.36	85.54	80.83	81.48	82.56
Fe <sub>2</sub> O <sub>3</sub>	31.39	32.63	31.40	30.99	31.60	32.31	31.32	31.19	30.12	32.20	34.61	29.87	32.21	31.03
Total	172.14	174.03	172.85	171.05	174.45	173.92	175.16	173.81	174.90	171.58	181.56	173.31	173.40	176.34
MgTiO <sub>3</sub>	34.96	34.27	34.98	35.09	34.94	34.49	35.30	35.19	36.04	34.40	33.82	36.13	34.43	35.58
FeTiO <sub>3</sub>	46.80	46.98	46.86	46.79	46.95	46.94	46.82	46.86	46.74	46.84	47.11	46.64	46.99	46.82
Fe <sub>2</sub> O <sub>3</sub>	18.24	18.75	18.17	18.12	18.11	18.58	17.88	17.94	17.22	18.77	19.06	17.24	18.58	17.60
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

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