

1 **Fractionation of trace and platinum-group elements during metamorphism of komatiitic**
2 **chromites from the early Archean Gorumahishani greenstone belt, Singhbhum Craton**
3 **(eastern India)**

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16

17 **Abstract**

18 It is well established that the major and minor element contents of chromites are subject to
19 change during greenschist to amphibolite facies metamorphism. During upper amphibolite
20 facies metamorphism, chromite can be completely converted to chrome magnetite.

21 However, not all elements are affected to the same degree, the concentrations of +2 ions
22 (e.g. Zn, Co, Mn) being particularly vulnerable to modification. The degree to which trace
23 elements, particularly the platinum-group elements (PGE), are affected has not been closely
24 examined. The compositions and textures of chromites from komatiites of the

25 Gorumahishani greenstone belt of the Singhbhum Craton (India) have experienced a range
26 of metamorphic conditions from greenschist to amphibolite facies, providing the

27 opportunity to study the changes of trace and platinum-group element composition with

28 metamorphic grade. Five types of altered chromites are identified from the komatiitic suite

29 of rocks in the ~120 km long greenstone belt. The type-I chromites are non-porous and

30 characterized by the least modified cores. These chromites are mostly present in the

31 northern Maharajgunj-Tua Dungri section where rocks show metamorphism from

32 greenschist to greenschist-amphibolite transition facies. The type-II and type-III chromites

33 are porous and mostly found in the southern Kapili section of the greenstone belt where

34 rocks show metamorphism up to the mid-amphibolite facies. Type-IV and type-V chromites

35 are completely modified to ferritchromit and chrome magnetite, respectively and are

36 present in the komatiitic rocks from the entire greenstone belt. The central cores of the

37 type-I and type-II grains have relatively higher concentrations of mobile trace elements (e.g.

38 Zn, Co, and Mn) with higher Mg# [$Mg/(Mg+Fe^{2+})$], lower Cr# [$Cr/(Cr+Al)$] and lower Fe^{3+}/R^{3+}

39 ($R^{3+} = Fe^{3+}+Cr^{3+}+Al^{3+}$) ratios than their respective rims. Significantly higher concentrations of

40 the immobile trace elements (e.g. Ti and V) in the cores of the type-II grains relative to their

41 chrome magnetite rims from the Kapili section, and to the type-I varieties from other
42 sections might be due to the metamorphism of the komatiitic rocks under higher grade
43 conditions (amphibolite facies). *In situ* LA-ICPMS analysis for PGE reveal a relatively higher
44 concentration of Ru and Rh in the rims of the type-I chromites than in the cores which is due
45 to the diffusion of these elements from the normal spinel structure of the cores towards the
46 bivalent octahedral sites of the inverse spinel structure of the chrome magnetite rims during
47 metamorphic processes. The lower concentrations of Os, Ir, Ru, and Rh in the cores of the
48 type-II chromites from the Kapili section might be related to the metamorphism of the rocks
49 under higher grade conditions that facilitated the diffusion of these elements to associated
50 sulfide or platinum-group mineral or alloy phases. The calculated partition coefficients of Sc,
51 Ti, V, Mn, Ni, Ga, Os, Ir, Ru, and Rh from the least altered chromite cores assuming
52 equilibrium with the parental komatiitic melt also suggest the variable effects of
53 metamorphism when compared with global experimental and empirical values of the
54 natural samples.

55 **Keywords: komatiite . chromite . PGE and trace element . fractionation . metamorphism .**

56 **Singhbhum Craton**

57

58 **Introduction**

59 Chromite is an early crystallizing oxide phase in komatiites from greenstone belts. The Cr#
60 $[\text{Cr}/(\text{Cr}+\text{Al})]$, Ti, Al and V of chromites are used as petrogenetic indicators in massive
61 chromitites (e.g. Irvine 1967; Roeder 1994; Stowe 1997; Mondal et al. 2006; Mukherjee et al
62 2010) and in volcanic rocks (Kamenetsky et al. 2001; Canil 2002; Nicklas et al. 2016).
63 However in komatiitic rocks, chromites as well as the primary silicate phases are often
64 strongly affected by hydrothermal alteration and metamorphism (e.g. Barnes 1998, 2000,

65 2006). Such processes have led to textural variability and chemical modification of chromite
66 in many ultramafic-mafic rocks from widely varying geological settings (Evans and Frost
67 1975; Kimball 1990; Burkhard 1993; Proenza et al. 2004; González Jiménez et al. 2009, 2014;
68 Mukherjee et al. 2015; Colás et al. 2019) although studies of komatiitic chromites are
69 relatively scarce (e.g., Zhou and Kerrich 1992; Barnes 1998, 2000; Godel et al. 2013). Major
70 and minor element studies of komatiitic chromites (Barnes 1998, 2000) show that at low
71 metamorphic grades the core compositions may retain their primary magmatic character
72 (other than FeO content) and can be used to understand the crystallization environment.
73 Diverse opinions exist concerning the formation of the characteristic optical and chemical
74 zoning of ferritchromite and chrome magnetite rims in chromites e.g. (a) Such rims may
75 result from subsolidus elemental exchange with silicate minerals during prograde
76 metamorphism (Evans and Frost 1975; Wylie et al. 1987; Burkhard 1993; Barnes 2000;
77 González Jiménez et al. 2009; Merlini et al. 2009), (b) In ophiolitic chromitites these features
78 may reflect retrograde metamorphism during cooling from the eclogite facies (e.g. Proenza
79 et al. 2008; Gervilla et al. 2012; Colás et al. 2014). The trace element data obtained from LA-
80 ICPMS studies of chromites have been particularly useful in developing a more precise
81 understanding of how these zoned rims formed (e.g. Pagé and Barnes 2009; Mukherjee et
82 al. 2015; Colás et al. 2017; Yu et al. 2019). Such *in situ* techniques have also been used to
83 study trace and platinum-group element (PGE) partitioning between volcanic chromites and
84 co-existing high-Mg silicate melt from a variety of geological settings (Locmelis et al. 2011;
85 Pagé et al. 2012; Kamensky et al. 2015; Pagé and Barnes 2016; Arguin et al. 2016; Park et al.
86 2012, 2017).

87 In Eastern India, the ~120 km-long Archean Gorumahishani greenstone belt of the
88 Singhbhum Craton includes an entire komatiitic rock suite (lower dunite-peridotite

89 adaccumulate to upper komatiitic basalt) in the lower part of the supracrustal sequence.
90 Accessory chromite, chrome magnetite, and magnetite with textural and compositional
91 zoning are quite common in these rocks (e.g. Mondal et al. 2019a). In the current study, *in*
92 *situ* major, minor, trace, and PGE data, coupled with petrographic observations, are used to
93 characterize komatiitic chromites from this greenstone belt, and classify them into different
94 types. The characteristic trace and PGE concentration patterns in the compositionally
95 modified chromites, and the differences between chromite cores and rims, are explained in
96 terms of magmatic versus subsolidus processes. Our study is the first to discuss post
97 magmatic modification of PGE distribution in komatiitic chromites and to correlate the
98 patterns with degree of metamorphism of the rocks. Furthermore, we calculate apparent
99 trace element (Sc, Ti, V, Mn, Zn, Co, Ni, Ga) and PGE (Os, Ir, Ru, Rh) chromite-komatiite
100 partition coefficients using mass balance calculations based on the data of less altered
101 chromite cores (e.g. Pagé and Barnes 2009, 2016; Park et al. 2017). These data are
102 compared with other experimental and natural partitioning values to better discriminate
103 between magmatic and subsolidus processes. Our primary goal in this study is to look at PGE
104 and other trace elements hosted by the chromite itself but not at platinum-group mineral
105 microinclusions.

106

107 **Geological background**

108 The geological background of the Singhbhum Craton is described more fully in **Appendix 1**
109 **(Fig. 1a)**. The Archean granitic-gneissic nucleus of the craton is surrounded by greenschist to
110 amphibolite facies volcano-sedimentary rocks of the Iron Ore Group (IOG) supracrustals that
111 are present in three greenstone belts (e.g. Mondal 2009; **Fig. 1a**). This study concerns the
112 Gorumahishani-Badampahar greenstone belt (**Fig. 1b**) of the IOG supracrustals which also

113 include the Noamundi-Jamda-Koira and Tomka-Daitari greenstone belts (**Fig. 1a**). Komatiites
114 and komatiitic basalts are the main volcanic lithologies, and are intercalated with
115 sedimentary sequences of phyllite, tuffaceous shale, banded hematite jasper with iron ore,
116 quartzites, and dolomite (Sahu and Mukherjee 2001; Chaudhuri et al. 2015, 2017; Yadav et
117 al. 2015, 2017). U-Pb zircon ages of 3.5 and 3.4 Ga were determined respectively from
118 dacite of the Tomka-Daitari belt (Mukhopadhyay et al., 2008) and a tuff layer within the
119 Noamundi-Jamda-Koira belt (Basu et al., 2008), whereas a whole rock Sm-Nd isochron age
120 of ~3.6 Ga (Adhikari et al., 2021) was obtained from metabasalts and komatiites of the
121 Tomka-Daitari belt. The Gorumahishani schist belt follows an overall NW-SE trend, traceable
122 from south of Tatanagar (Jharkhand state) in the north to Badampahar (Orissa state) in the
123 south (**Fig. 1b**). The lower part of the greenstone sequence is composed of metamorphosed
124 ultramafic-mafic extrusive rocks while the upper part comprises volcanogenic sediments
125 and banded iron formation. Three parts of the belt, namely Maharajgunj-Chuka Pahar and
126 Tua Dungri in the north and Kapili in the south (**Fig. 1b-e**) have been sampled and the rock
127 types vary from dunite-peridotite (**Fig. 2a**) to spinifex-textured komatiite (**Fig. 2b-d**) to
128 komatiitic basalt (**Fig. 2e**). In the Maharajgunj-Chuka Pahar and Tua Dungri sections, the
129 dunite (~70 m) and the spinifex-textured komatiites (~100 m) are well exposed and thicker
130 than in the Kapili sector.

131

132 **Petrography**

133 **Dunite-peridotite cumulates (meta-dunite and meta-peridotite)**

134 Metamorphosed dunite-peridotites are present in the lower part of the komatiite
135 sequences (cumulate zone; **Fig. 2a**). Modal abundances of mineral phases (**Figs. 3, 4**) in
136 meta-dunite and meta-peridotite from the Maharajgunj-Chuka Pahar and Tua Dungri

137 sectors include, in decreasing order, serpentine, carbonates, tremolite, chlorite, and talc
138 (**Fig. 4**). In the Kapili sector, the decreasing order of mineral abundances changes to
139 serpentine, tremolite, chlorite, hornblende, and carbonate (**Figs. 3, 4**). A few micrometer-
140 sized olivine grains are observed in samples from the Kapili area (**Fig. 3a**). Interstitial spaces
141 between serpentines (pseudomorphic after olivine) are occupied by chlorite, tremolite,
142 hornblende, talc, and carbonates (**Fig. 3b, c**). Chromites are present as an accessory phase in
143 the metamorphosed dunite-peridotite (**Figs. 3, 4**). Sulfide minerals include pentlandite,
144 millerite, cobalt-rich violarite, chalcopyrite, and bornite and occur in disseminated form at
145 low modal abundances (Banerjee et al. 2021).

146 **Spinifex-textured komatiites (meta-peridotite)**

147 The metamorphosed komatiitic peridotites from the spinifex zone show platy, random,
148 and/or chevron spinifex textures (**Fig. 2b, d**). The spinifexes (~0.5 - 40 cm in length, and ~2 -
149 5 mm in width) are marked by deep cavities on the weathered surfaces of the rocks.
150 Microscopic study reveals that in the Maharajgunj-Chuka Pahar and Tua Dungri sections, the
151 modal abundances of serpentine are lower while modes of tremolite and chlorite are higher
152 in the spinifex zone relative to the cumulate zone (**Figs. 3d, 4**). Tremolite, chlorite,
153 hornblende and carbonate are the major minerals in the meta-peridotites of the spinifex
154 zone from the Kapili section (**Figs. 3e, 4**). The primary minerals in spinifex laths are replaced
155 by tremolite in Kapili, and to a lesser extent by serpentine in Tua Dungri (**Fig. 3d, e**).
156 Chromites are present as an accessory phase in the meta-peridotites (**Figs. 3, 4**). Sulfide
157 minerals are pentlandite, millerite, and cobalt-rich violarite which occur in the spinifex zone
158 in very low modal abundances and show a similar petrographic character to the sulfides
159 observed in the cumulate zone (Banerjee et al. 2021).

160 **Meta-basalts**

161 The komatiitic basalts are altered to meta-basalts and show schistose character (**Fig. 2e**). In
162 places, meta-basalts are interlayered with quartzites, indicating the top part of the
163 komatiitic litho-package (e.g. Arndt et al. 2008). The meta-basalts have higher modal
164 abundances of tremolite, chlorite, and actinolite in the Tua Dungri and Chuka Pahar
165 sections, whereas hornblende is more abundant in the Kapili section (**Figs. 3f, 4**). Oxide
166 mineralogy in the meta-basalts are represented by variable modes of fine-grained, anhedral
167 chrome magnetite, magnetite and ilmenite (**Fig. 3h**).

168 **Textural types of chromites in komatiitic rocks**

169 Chromite is present ubiquitously as an accessory mineral throughout the cumulate and
170 spinifex zones of the Gorumahishani komatiite sequences (**Figs. 3, 4**). Microscopic study and
171 back-scattered electron (BSE) imaging show that a few chromite grains are compositionally
172 zoned with different textures and variable reflectance (**Fig. 5**). The zoned grains typically
173 have a chromite core with a ferritchromite inner rim and chrome magnetite to magnetite
174 outer rim (**Fig. 5a, b**). However, multiple inner rims of different reflectance and composition
175 between chromite core and outer chrome magnetite rim are also observed (**Fig. 5c**).

176 Ilmenite grains are present along the outermost margin of some zoned chromites (**Fig. 5b,**
177 **c**). Based on petrographic observations and mineral chemistry the chromite grains are
178 classified into five broad types (**Table 1**). Type-I chromites in the meta-dunite-peridotite of
179 the cumulate zone from the Tua Dungri area, and type-II, type-III chromites in the meta-
180 peridotite of the spinifex zone from the Kapili area are optically and texturally
181 inhomogeneous (**Fig. 5**). In contrast, type-IV chromites in the meta-peridotite from the
182 Maharajgunj area and type-V chromites in the komatiitic sequences from all locations are
183 texturally homogeneous (**Fig. 3g, h**). Among the five types, type-V chromites have the
184 highest modal abundance in komatiitic rocks, while the lowest modal abundance is

185 displayed by the type-IV grains. The type-I and type-IV grains from the northern part of the
186 greenstone belt are present in komatiitic rocks that were metamorphosed under
187 greenschist to greenschist-amphibolite transition facies, whereas the type-II and type-III
188 grains from the southern greenstone belt are present in komatiitic rocks that were
189 metamorphosed under amphibolite facies. The type-V grains are present in the altered
190 komatiitic rocks of all metamorphic grades throughout the greenstone belt.

191

192 **Analytical methods**

193 Back-scattered electron (BSE) imaging and microanalysis of the mineral phases (oxides and
194 silicates) of 8 representative samples were carried out using a CAMECA SXFive EPMA
195 instrument at DST-SERB National Facility, Department of Geology, Banaras Hindu University
196 (India). Another 14 samples were analyzed by 4-WDX CAMECA SX-100 EPMA at the
197 Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur (India).
198 Fe_2O_3 and FeO concentrations of the silicate and oxide minerals were calculated following
199 the equation of Droop (1987). Trace and platinum-group element concentrations in
200 chromite, ferritchromit, and chrome magnetite were measured by laser ablation-inductively
201 coupled plasma mass spectrometry (LA-ICPMS) at the Korea Institute of Ocean Sciences and
202 Technologies, South Korea using an LA-ICPMS system consisting of a New Wave 193 nm ArF
203 excimer laser and an Agilent 7800 quadrupole ICP-MS. Analyses of bulk-rock major, trace,
204 and platinum-group elements, C and S for 2 representative komatiites were conducted by
205 Intertek Genalysis, Perth, Western Australia. See **Appendix 1** for details of all the analytical
206 methods.

207

208 **Results**

209 **Silicate and carbonate mineral chemistry**

210 All individual analyses of silicate and carbonate minerals are listed in **Appendix 3: Table S1**.

211 The forsterite content of one tiny olivine found in the Kapili peridotite is 88 while the
212 clinopyroxenes are augites in the Kapili and Maharajgunj komatiitic rocks (**Appendix 02: Fig.**

213 **S1a**). Serpentine shows a wide range of SiO₂ and MgO contents coupled with low Al₂O₃.

214 Amphiboles from the northern Maharajgunj and southern Kapili sections are mainly
215 tremolite whereas low modal abundances of magnesio-hornblende and actinolite are also

216 found in the southern Kapili section (**Appendix 2: Fig. S1**). Chlorites are Mg-rich with

217 variable Al₂O₃, and are identified as corundophilite and sheridanite (**Appendix 2: Fig. S1**).

218 Chlorite grains surrounding the type-II and type-III chromite grains in the Kapili area have

219 higher Cr₂O₃ (0.74 - 0.98 wt.%) than chlorite grains from other petrographic contexts (Cr₂O₃

220 = 0.21 - 0.69 wt.%). The carbonate minerals are mainly dolomite in the Tua Dungri komatiitic

221 rocks and calcite in Chuka Pahar (**Appendix 2: Fig. S1**).

222 **Oxide mineral chemistry**

223 Representative compositional ranges for chromites are tabulated in **Table 2**; all individual

224 analyses are presented in **Appendix 3: Table S2**. The cores of the type-I grains from Tua

225 Dungri have relatively higher MgO, Cr₂O₃, Al₂O₃, and lower Fe₂O₃ (higher Mg# and lower Cr#)

226 than in the outer ferritchromite and chrome magnetite rims (**Fig. 5a**). The non-porous cores

227 of the type-II chromites from the southern Kapili also have relatively higher Cr₂O₃ (higher

228 Mg# and lower Cr#) than the porous ferritchromite and chrome magnetite rims (**Fig. 5b**). In

229 both cases, the higher Cr# in the rims reflect the extremely low Al₂O₃ contents of these

230 zones rather than a high abundance of Cr₂O₃. The central zones of the type-III chromite

231 grains from the northern Kapili have similar concentrations of Al₂O₃, Cr₂O₃, MgO, and Fe₂O₃

232 (with a wide range of Mg# and Cr#) to those of the type-II grain cores, and are surrounded

233 by rims of various reflectance and porosity (**Fig. 5c**). These pores in the type-II and type-III
234 grains are filled with chrome-chlorite ($\text{Cr}_2\text{O}_3 \sim 1 \text{ wt.}\%$). The inner rims of variable reflectance
235 of the type-III grains that have metamorphosed under the amphibolite facies show lower
236 Fe_2O_3 and higher Al_2O_3 than the inner rims of the type-I and type-II grains (**Fig. 5c**). Outer
237 chrome magnetite rims show compositional similarity in the three types of zoned chromite
238 grains (**Figs. 5**). The type-IV oxides are compositionally similar to ferritchromite rims of the
239 type-I grains, whereas the type-V chrome magnetite grains have similar FeO , Fe_2O_3 to those
240 of the chrome magnetite rims (**Table 2**). The cores of both type-I and type-II chromites have
241 higher MnO and ZnO than the rims (**Fig. 5a, b**). The inner rims of the type-II chromites from
242 the northern Kapili have higher TiO_2 than the core (**Fig. 5a, b**), whereas the inner rims of the
243 type-III chromites from the southern Kapili have relatively higher TiO_2 , V_2O_5 , ZnO , and MnO
244 than the outer porous chrome magnetite rims or the central cores (**Fig. 5b, c; Table 2**). The
245 homogenous type-IV grains have similar TiO_2 concentrations, but higher MnO and ZnO than,
246 the ferritchromite rims of the type-I and type-II grains (**Table 2**). Type-V chrome magnetite
247 grains have low concentrations of ZnO ($<1 \text{ wt.}\%$) with variable TiO_2 and MnO (**Table 2**).

248 The compositions of the type-I cores are clustered in two different places in the $\text{Mg}\#$ vs.
249 $\text{Cr}\#$ plots where the smaller grains show higher Al depletion than the coarser grains (**Fig. 6a**).
250 This dichotomy is also evident in the $\text{Mg}\#$ vs. $\text{Fe}^{3+}/\text{R}^{+3}$ plot, where the smaller type-1 cores
251 show much greater Fe^{3+} enrichment than the larger ones (**Fig. 6c**). In the same figure, the
252 composition of chrome magnetite rims for all types of chromites and the independent type-
253 V oxide grains occupy the metamorphogenic chrome magnetite field of Barnes and Roeder
254 (2001; **Fig. 6c**). The altered rims for all chromites and the type-V grains define two negative
255 trends in the TiO_2 vs. $\text{Fe}^{3+}/\text{R}^{+3}$ plot (**Fig. 6d**). Almost all chromite rims, as well as type-IV and
256 V grains, also show two distinct negative correlations in the MnO vs. $\text{Fe}^{3+}/\text{R}^{3+}$ plot (**Fig. 6e**).

257 In contrast, the zoned chromites show a broad positive trend in the NiO vs. $\text{Fe}^{3+}/\text{R}^{3+}$ plot
258 (**Fig. 6f**). In a Cr-Al- Fe^{3+} ternary plot, the cores of the smaller type-I grains from Tua Dungri
259 and the type-IV, type-V grains, and most of the ferritchromit to chrome magnetite rims
260 show a variation along the Cr- Fe^{3+} join (**Fig. 6g**), and occupy the field of metamorphogenic
261 ferritchromit-magnetites of Barnes and Roeder (2001). In this ternary diagram the Al-rich
262 type-I cores plot closer to the Cr-Al join, while the cores of the type-II and type-III chromites
263 of the Kapili plot closer to the Cr apex (**Fig. 6g**).

264 **LA-ICPMS of chromite, ferritchromit, and chrome magnetite: trace elements**

265 *In situ* trace element analysis by LA-ICPMS of type-I, type-II and type-V oxides show
266 significant compositional variations across the grains (**Fig. 7; Table 3; Appendix 3: Table S3**).
267 Type-III and type-IV grains were not analysed because they are either highly porous (type-III)
268 or small and fractured (type-IV) (**Fig. 3g, 5c**). The type-I zoned chromite grains are from the
269 northern part, whereas the type-II grains are from the southern part of the greenstone belt.
270 The trace element distribution in these zoned chromites demonstrates the change from
271 lower to higher metamorphic grade towards the south. Except for Zn, the concentrations of
272 the minor elements (Sc, Ni, Co, Mn, Ga, and Ti) are higher in the type-II chromite cores than
273 in the type-I chromite cores (**Fig. 7; Table S3**). The cores of the type-I chromites in the Tua
274 Dungri komatiitic peridotite (northern sector) have higher concentrations of Sc, V, Zn, and
275 Ga than their corresponding rims whereas Ti, Mn, and Ni are higher in most ferritchromit
276 and chrome magnetite rims than in the cores (**Fig. 7a, b; Table 3**). The type-II chromite cores
277 in the Kapili peridotite (southern sector) have higher concentrations of Sc, Ti, V, Mn, Co, Ni,
278 Zn, and Ga than the chrome magnetite rim (**Fig. 7c, d; Table 3**). The type-V chrome
279 magnetite grains show highly variable concentrations of Ti, V, Mn, Co, Ni, Zn, Ga, and Sc
280 (**Table 3**). In Mg# vs. trace elements plots, Ga, Sc concentrations of the type-I chromites

281 cores show a positive correlation from outer to inner core, whereas Ni, Co, Mn, Zn, and Ti
282 show a negative trend (**Fig. 8**). Nevertheless, given the limited number of measurements
283 generalizations must be viewed with caution.

284 In the trace element spidergram (**Fig. 9a**) the average core compositions of the type-I (n
285 = 4) and type-II (n=2) chromites show a minor negative Sc anomaly ($0.79 - 0.86 \times$ EPR MORB
286 Cr-spinel) with high abundances of Zn, Co, and Mn ($6.70 - 41.47 \times$ EPR MORB Cr-spinel). The
287 ferritchromite and chrome magnetite rims of the type-I grains (n = 6) also show moderately
288 high abundances of Zn and Mn ($5.90 - 8.69 \times$ EPR MORB Cr-spinel) with a strong negative Sc
289 anomaly ($0.07 - 0.08 \times$ EPR MORB Cr-spinel). The M-shaped positive anomaly in the segment
290 Zn-Co-Mn (ZCM anomaly; Colás et al. 2014) is more prominent for the rims relative to the
291 cores of the type-I grains (**Fig. 9a**). Chrome magnetite rims of the type-II grains (n = 2) and
292 the average type-V grains (n = 15) have similar patterns, with negative anomalies of Sc (0.09
293 $- 0.10 \times$ EPR MORB Cr-spinel) and minor ZCM anomalies ($1 - 5.79 \times$ EPR MORB Cr-spinel)
294 (**Fig. 9a**). The least altered volcanic chromites from other occurrences do not have any such
295 ZCM anomalies and overall show a flat pattern (**Fig. 9b**).

296 **LA-ICPMS of chromite and chrome magnetite: PGE**

297 Platinum-group elements were determined *in situ* by LA-ICPMS in the cores and rims of
298 type-I and type-II zoned chromites, and type-V chrome magnetite grains (**Fig. 7; Table 3;**
299 **Appendix 3: Table S4**). Type-III and type-IV chromites were avoided for the reasons
300 explained above. Os, Ir, Ru (IPGE), and Rh concentrations were determined successfully,
301 whereas Pt and Pd were below the detection limits in all analysed grains. Despite the mostly
302 uniform count rates of IPGE + Rh, a few grains of the type-V chrome magnetite from the
303 Chuka Pahar (2 points) and Maharajgunj sections (3 points) show anomalous Ru, Rh signals
304 in the time-resolved LA-ICPMS spectra (**Fig. 10; Appendix 3: Table S4**), likely indicating the

305 presence of PGE rich micro-inclusions. The concentrations for these three points from
306 Maharajgunj are determined by averaging the data after excluding the Ru and Rh spikes.
307 However, the PGE spikes were more difficult to unambiguously identify in the two points
308 from Chuka Pahar, and so these spikes are not excluded from the average values (Ru = 128
309 and 140 ppb, Rh = 4.8 and 8.9 ppb, Os = 22.5 and 25.6 ppb, Ir = 20.8 and 23.8 ppb) given for
310 these two points (LA points 11 and 12) in **Table S4**. For this reason, these two points are not
311 used in the plots in figures 11 and 12. The type-V chrome magnetites in the komatiitic
312 sequence from the Maharajgunj-Chuka Pahar and Kapili sections have different PGE
313 abundances (**Table 4; Table S4**). The type-V grains from Kapili have Os, Ir, Rh below the
314 detection limit with Ru = 8 - 46 ppb except for one data point with Ru = 211 ppb, Rh = 14
315 ppb, Os = 7ppb, and Ir = 14 ppb compared to the type-V grains from the Maharajgunj-Chuka
316 Pahar section which have higher Os, Ir, Ru and Rh contents (**Appendix 2: Fig. S3**).

317 The cores of the analysed type-I chromites have lower Ru contents than those of their
318 respective ferritchromit and chrome magnetite rims (**Fig. 7a, b**). Rh content is also slightly
319 lower in the cores of the type-I grains than the rims (**Fig. 7a, b**). Osmium is detected in one
320 laser point of a type-I chromite core (Os = 8.8 ppb). In comparison with the type-I grains, the
321 type-II chromite cores have lower concentrations of Ru and Rh, and similar Ir and Os (**Fig. 7c,**
322 **d**). The chrome magnetite rims of the type-II grains have a lower concentration of Ru than
323 their respective cores with Rh, Os, and Ir below the detection limit (**Fig. 7c, d**). Overall, the
324 cores of the type-I and type-II zoned chromites from the Gorumahishani belt have lower
325 IPGE + Rh contents than the volcanic chromites of komatiites from Finland, Alexo mine, Pyke
326 Hill, and picrites from Greenland, Kamchatka, Troodos, and the Emeishan province, which
327 have ranges of Ru = 87 - 336 ppb, Rh = 7 - 95 ppb, Ir = 14 - 101 ppb, and Os = 5 - 64 ppb
328 (Puchtel et al. 2004; Park et al. 2017) (**Fig. 11b**).

329 Primitive mantle normalized plots of Ru, Rh, Os, and Ir show fractionated PGE patterns
330 for all three types of chromites with all being strongly enriched in Ru. In nearly all cases,
331 Ir_N/Os_N ratios are close to 1 (**Fig. 11a; Table 4**). Type-I chromite cores, ferritchromit, and
332 chrome magnetite rims are particularly enriched in both Ru and Rh (15 - 34 × PM). The cores
333 and ferritchromit rims of the type-I chromites tend to have less fractionated PGE ratios than
334 the type-I chrome-magnetite rims (**Table 4**), though given the small number of points it is
335 difficult to generalize. The type-II chromite cores show strong positive anomalies for Ru (16 -
336 21 × PM) with lower Rh abundances than the type-I grains (**Fig. 11a**). The type-V chrome
337 magnetites are enriched in Os and Ir ($Os = 2 - 8 \times PM$) compared to the other types of
338 chromites) (**Fig. 11a**). They also have low Rh abundances, similar to those of the type-II
339 chromite cores. The least altered volcanic chromites from Troodos, Greenland, Finland,
340 Emeishan picrite and Finland komatiite (Park et al. 2017) show similar PGE patterns of the
341 type-V chrome magnetite grains except Kamchatka picrite (**Fig. 11b**). They have higher Ru
342 anomaly (15 - 56 × PM) but similar abundance of Os, Ir, and Rh. No distinct relationships are
343 observed in V, Ni vs. Ru plots for the type-I, type-II, and type-V grains (**Fig. 12**).

344

345 **Discussion**

346 **Modification of chromite to ferritchromit and chrome magnetite during metamorphism**

347 Zones of various reflectances around chromite cores of all types mainly reflect
348 compositional variation in the rims between ferritchromit and chrome magnetite resulting
349 from prograde (Evans and Frost 1975; Burkhard 1993; Loferski 1986; Fleet, 1993; Barnes
350 2000; Mondal et al. 2006; Mukherjee et al. 2010, 2015) or retrograde metamorphism
351 (Proenza et al. 2004; Gervilla et al. 2012, 2019; Colás et al. 2014, 2017, 2019, 2020). The
352 ferritchromit formation is contemporaneous with modification of the primary mineral

353 assemblages of komatiitic peridotites (olivine, orthopyroxene, clinopyroxene) from
354 cumulate and spinifex zones to serpentine, tremolite, and chlorite. The H₂O and CO₂-rich
355 fluid at low metamorphic grade drives the formation of talc, tremolite, chlorite, and
356 carbonate minerals (e.g. Barnes 2006). The komatiitic chromites from the Gorumahishani
357 belt were also modified during metamorphism of the entire greenstone sequence and
358 became depleted in Mg, Al, Cr, and enriched in Fe³⁺ at the boundaries (**Figs. 5, 7**). Chrome-
359 chlorite was formed during this metamorphic process, incorporating Cr and Al released from
360 chromites (e.g. Evans and Frost 1975; Burkhard 1993; Barnes 2000). The enrichment of Fe³⁺
361 by the oxidation of Fe²⁺ during prograde metamorphism have produced the ferritchromit as
362 the inner rim and chrome magnetite as the outer rim in the modified chromites (type-I and
363 type-II grains; **Fig. 7**). The porous chrome magnetite rims of the type-II grains suggest
364 significant mass loss due to elemental exchange with silicates without any changes in grain
365 size during metamorphism associated with interaction with CO₂ and H₂O - rich fluids (**Fig.**
366 **5b**). The type-III chromites from the northern Kapili are different from type-I and type-II
367 grains, showing complex zoning patterns with a highly porous character (**Fig. 5c**). These
368 grains have broadly higher Cr# (0.87 - 0.92) and lower Mg# (0.08 - 0.17) in their cores
369 relative to type-I varieties (**Fig. 5c**). Lower Fe₂O₃ (2.1-14.88 wt.%) and Fe³⁺/R³⁺ in the type-I
370 and II inner rims relative to the outer rims suggest the slow progression of the oxidizing
371 fluids. The co-existing mineral assemblages associated with type-III and type-II grains are
372 similar except for the lower modal abundance of chlorite in the former. The higher Al₂O₃ in
373 the inner rims of the type-III grains might be due to the breakdown of chlorite under
374 amphibolite facies metamorphism (e.g. Loferski 1986). The type-IV grains from Maharajgunj
375 are intensely fractured small ferritchromit grains suggesting deformation during
376 metamorphism (**Fig. 3g**). The concentrations of major and minor elements in the type-IV

377 grains are mostly similar to those in the ferritchromit rims of the type-I and type-II grains.
378 The mineral assemblage of serpentine + chlorite + carbonate + talc ± tremolite from the
379 northern Tua Dungri indicates a low metamorphic grade close to the greenschist-
380 amphibolite transition (**Fig. 4**). The type-V chrome magnetite to magnetite grains have wide-
381 ranging major and minor element concentrations (**Fig. 6; Table S3**) and the geochemical
382 diversity reflects the differing degrees of metamorphism related to the development of the
383 chrome magnetite grains. Finer-grained type-V magnetite grains were formed during
384 modification of the primary ferromagnesian silicates during hydration of the komatiitic rocks
385 (e.g. Bach et al. 2004; Alt et al. 2007; Gahlan et al. 2006; Eslami et al. 2018).

386 Considering the olivine core (Fe_{88}) from the Kapili area (**Fig. 3a**) and the associated
387 chromite core, the geothermometers of Roeder et al. (1979) and Fabriès (1979) reveal re-
388 equilibration temperatures in the range of 409°-619°C, consistent with amphibolite facies
389 metamorphism. However this olivine grain is potentially of metamorphic origin because in
390 the amphibolite facies serpentine breaks down to form metamorphic olivine (e.g. Barnes
391 2006). Thermometric calculations are also performed using chrome magnetite-ilmenite
392 pairs of the Maharajgunj (1 pair) and Kapili area (3 pairs) following the method of Spencer
393 and Lindsley (1981) and Lepage (2003). The calculated temperature from the northern part
394 of the greenstone belt (Maharajgunj area) is 384°C suggesting greenschist facies
395 metamorphism at $X(CO_2) < 0.05$ in the stability field of serpentine, tremolite, chlorite, and
396 carbonate (e.g. Barnes 2006). On the other hand, the calculated temperatures from the
397 southern part of the greenstone belt (Kapili area) range from 443 to 502 °C suggesting
398 amphibolite facies metamorphism at $X(CO_2) < 0.05$ in the stability field of serpentine,
399 tremolite, chlorite, ± metamorphic olivine, which is consistent with our observations (e.g.
400 Barnes 2006).

401 ***In situ* LA-ICPMS study of the komatiitic chromites: Fractionation of trace elements**

402 Zoned chromites from the Gorumahishani belt show inter- and intra-grain major and minor
403 element variations, developed due to greenschist to amphibolite facies metamorphism.
404 Similar variations are apparent in trace element abundances determined by LA-ICPMS. The
405 positive relationships of Ga, Sc with Mg# for the non-porous cores of type-I chromites
406 indicate relatively pristine core compositions (**Fig. 8a, b**). However, the sum of Zn + Co + Mn
407 remains almost constant with decreasing Ga (**Fig. 8h**). This indicates a greater role for
408 metamorphism than for H₂O, CO₂ - rich fluid activity because hydrothermal re-equilibration
409 might have affected the Zn + Co + Mn content of type-I cores (e.g. Colás et al. 2014) but not
410 Ga. Ga and Sc are not compatible in olivine but may enter into the chlorite structure in
411 substitution for Al during metamorphic modification of the assemblage. Relatively abundant
412 chlorite in the Tua Dungri komatiitic peridotites thus justifies the lower contents of Ga and
413 Sc in the Fe³⁺-rich rims than in the cores of the type-I chromites (**Fig. 7a, b**).

414 The type-II porous chromites have a higher concentration of Ga and similar Sc
415 compared to the type-I grains (**Appendix 2: Fig. S2a; Table 3**). The higher concentrations of
416 Ga and lower modes of chlorite in the pores of chrome magnetite rims from Kapili suggest a
417 lower degree of substitution of Ga for Al in chlorite. Lower Al₂O₃ contents in the type-II
418 cores and rims than in the type-I variety support this observation as Al has migrated to
419 chlorite (**Table 3**). The concentrations of Zn in the type-II cores are similar but Co and Mn
420 are higher compared to the type-I cores (**Table 3; Fig. 9**). This is related to the higher
421 metamorphic grade i.e. amphibolite facies metamorphism suffered by the komatiitic rocks
422 of Kapili and therefore, higher diffusion rate of the trace elements (e.g. Sievwright et al.
423 2020). The ZCM anomaly in the type-I and type-II chromite cores (**Fig. 9**) was likely due to
424 modification during metamorphism when Zn, Co, and Mn were diffused into the chromite

425 structure from altered silicate minerals such as olivine, clinopyroxene, and the associated
426 carbonate phases (e.g. Colás et al. 2014).

427 The microprobe data are consistent with the LA-ICPMS data and show greater contrast
428 between core and rim in the type-III grains than in the type-II grains, with the inner rims of
429 the former having higher concentrations of Mn, Zn, Ni, Ti, and V than the cores (**Table 2**).
430 This transition from homogenized type-II cores towards enriched type-III inner rims
431 indicates the reverse diffusion of these elements from the core to the inner rims of the
432 type-III grains after complete homogenization of core composition under the amphibolite
433 facies conditions (e.g. Barnes 2000) (**Fig. 13**).

434 The LA-ICPMS data show that the type-II cores have higher concentrations of Ni (4513 -
435 10583 ppm) and Ti (20759 - 36413 ppm) at similar Mg# (0.13 - 0.16) and higher Fe^{3+}/R^{3+}
436 ratio (0.08 - 0.10) than the type-I cores (**Fig. 8; Table 3**). Ti^{4+} is less mobile to incorporate
437 into the spinel structure than the +2 ions (e.g. Barnes 2000), therefore, its higher
438 concentration in type-II cores indicates a homogenized character than the type-I cores under
439 a higher grade of metamorphism (**Fig. 13**). With increasing Fe^{3+}/R^{3+} ratio, bivalent ions begin
440 to occupy octahedral sites of the inverse spinel structure (e.g. Barnes 2000; Gervilla et al.
441 2012). As the homogenized type-II cores have higher Fe^{3+}/R^{3+} ratios, their higher Ni
442 concentrations may therefore result from the substitution of Ni^{2+} for the bivalent ions (Fe^{2+} ,
443 Mg^{2+}) in the divalent octahedral sites and Ti^{4+} for Fe^{3+} in the tetrahedral sites (e.g. Barnes
444 1998, 2000).

445 The type-V chrome magnetite grains show variable degrees of enrichment of Zn and Co
446 with lower Mg# and higher Fe^{3+}/R^{3+} ratios (**Fig. 8d, f; Table 3**), indicating different degrees of
447 involvement of metamorphism. However, the overall negative relationship between
448 Fe^{3+}/R^{3+} and Mn mainly from the type-V grains (**Fig. 6e**) indicates the bivalent tetrahedral

449 site occupancy of Mn was decreased in the inverse spinel structure. Fe³⁺ occupies the
450 tetrahedral site in the inverse spinel structure, limiting the possibility of Mn occupying this
451 site (e.g. Sack and Ghiorso 1991; González Jiménez et al. 2009; Gervilla et al. 2012). The
452 type-V chrome magnetite grains also show variable enrichment of Ni and Ti with Mg# and
453 Fe³⁺/R³⁺ (**Fig. 8b, g; Table 3**). This is due to different degrees of metamorphic modification
454 coupled with a variable Fe²⁺-Fe³⁺ re-ordering (e.g. Barnes 2000; Gervilla et al. 2012).

455 ***In situ* LA-ICPMS study of the Gorumahishani komatiitic chromites: Fractionation of PGE**

456 Previous studies using *in situ* LA-ICPMS analysis of natural Cr-spinels from volcanic
457 ultramafic-mafic rocks have documented higher concentrations of Rh, Os, Ir, and Ru that are
458 considered to be present as solid solutions in the spinel structure (Locmelis et al. 2011; Park
459 et al. 2012, 2017; Pagé et al. 2012; Pagé and Barnes 2016). Platinum-group elements were
460 also found to exist as micro-nuggets in chromite grains (Tredoux et al. 1995; Ballhaus and
461 Sylvester 2000; Park et al. 2012, 2017; Kamentsky et al. 2015; Arguin et al. 2016). Inclusions
462 of PGE-bearing phases, such as laurite (RuS₂), IPGE-alloys, and Pt-alloys are common in
463 chromites from mafic layered intrusions and ophiolitic complexes (Garuri et al. 2002; Ahmed
464 2007; Fonseca et al. 2009; Habtoor et al. 2017; Prichard et al. 2017; Mondal et al. 2019b and
465 references therein). Experimental studies considering silicate melt and chrome-spinel have
466 shown higher partition coefficients of Rh and IPGEs (Os, Ir, Ru) in chrome-spinels than Pt, Pd
467 (Capobianco and Drake 1990; Nell and O'Neill 1997; Righter and Downs 2001; Brenan et al.
468 2012).

469 *In situ* LA-ICPMS analysis of type-I, type-II, and type-V grains show high Ir, Os, Ru, and
470 Rh concentrations with strong positive Ru anomalies (**Fig. 11a**), as observed in other
471 volcanic chromites in a variety of contexts (**Fig. 11b**) (e.g. Park et al. 2017). However, the
472 concentrations of Rh, Ir, Os, and Ru differ between the types of altered chromite grains and

473 are also highly variable in different zones within a single grain (**Fig. 7; Table 4**). The type-I
474 chromite cores from Tua Dungri have lower Ru and similar Ir and Os to the ferritchromit and
475 chrome magnetite rims (**Fig. 7a, b**). The Rh concentrations are also slightly lower in the
476 cores of the type-I grains than in the corresponding outer ferritchromit and chrome
477 magnetite rims (**Fig. 7a, b; Table 4**). The petrological evidence reveals that the type-I
478 chromite grains were modified under greenschist-amphibolite transition facies conditions.
479 The modification of existing chromite to ferritchromit and chrome magnetite rims was
480 accompanied by the development of an inverse spinel structure surrounding the core.
481 Among the PGEs, Rh^{2+} might have diffused towards the ferritchromit and chrome magnetite
482 rims as these elements prefer to occupy divalent octahedral sites of inverse spinel (e.g.
483 Borisov and Palme 1995; Brenan et al., 2003; Park et al. 2017). However, such a process, if it
484 occurred, must have been quite limited as the difference between the Rh abundances of the
485 core and the rim are minimal (**Fig. 7a, b**).

486 Ru shows no relationship with Ni or V contents despite the fact that these trace
487 elements also tend to occupy the divalent octahedral sites in an inverse spinel structure
488 (**Fig. 12a, b**) (e.g. Barnes 2000; Park et al. 2017). Ruthenium exists both as Ru^{2+} and Ru^{3+}
489 depending on the fO_2 condition of the magma (e.g. Brenan et al., 2012; Park et al. 2012;
490 Locmelis et al. 2018). If Ru occupied the divalent octahedral site as Ru^{2+} , the type-I chromite
491 grains should have crystallized from a reduced parental melt. However, the Fe^{3+} enrichment
492 and development of an inverse spinel structure during formation of the ferritchromit and
493 chrome magnetite rims were due to post magmatic oxidation during metamorphism and
494 not a magmatic process. Therefore, it is possible that Ru was initially present as a 2^+ ion in
495 the reduced komatiitic melt of the early Archean Gorumahishani greenstone belt and thus
496 preferred to occupy the divalent octahedral sites (Ru^{2+}) in the primary magmatic chromites.

497 The enrichment of Ru²⁺ in the outer rims took place during metamorphic modification of the
498 grains when Ru²⁺ preferentially diffused to the octahedral sites in the inverse spinel
499 structure of the rims (**Fig. 7a, b**). Vanadium (V) is a redox sensitive element, and during
500 metamorphic modification of chromites the concentrations should be increased in the
501 altered outer rims, however, there is no such correlation of V with Ru concentrations in the
502 zoned chromites (**Fig. 12**). This suggests a reduced mantle source for the Gorumahisani
503 komatiites and consistent with the earlier observation of a global heterogeneity in mantle
504 redox conditions as inferred from the early Archean komatiitic melts (e.g. Nicklas et al.
505 (2019)).

506 As noted above, there may also be some IPGE-bearing phases present as inclusions (e.g.
507 laurite, erlichmanite, IPGE alloys; Kamensky et al. 2015) which result in the IPGE-
508 enrichment of chrome-spinels (e.g. chrome-spinels from komatiitic, ferropicritic, and
509 tholeiitic basalt from the Abitibi Greenstone belt; Fiorentini et al. 2004). A minor IPGE spike
510 (Rh, Ru rich inclusion) is observed from the LA spots in the type-I grains (**Fig. 10**), however,
511 only a limited number of spots were analysed and no specific platinum-group mineral phase
512 was identified during the SEM study. In addition, the observation of Ru (and Rh)
513 enrichments in the outer rims on both sides of the central cores of the type-I grains strongly
514 suggests that in the studied spots Ru is hosted as a solid solution in the spinel structure
515 rather than in IPGE bearing inclusions (**Fig. 7a, b**).

516 The type-II chromite cores have lower Os, Ir, Ru, and Rh than the type-I chromite cores
517 (**Fig. 7c, d; Table 4**). In addition, the chrome magnetite rims of the type-II grains have a
518 negligible amount of Ru with no traceable Rh, Os, and Ir (**Fig. 7c, d; Table 4**). The
519 petrological evidence reveals that the type-II chromite grains were modified under
520 amphibolite facies conditions. Therefore, enrichment of Ru and Rh in the thick chrome

521 magnetite rims relative to the cores should have been even higher than in the type-I grains.
522 The very low abundances of these elements in both type-II cores and rims are thus
523 surprising, and may reflect faster diffusion under the higher metamorphic grade (**Fig. 13**).
524 The chalcophile character of PGEs might have facilitated the partitioning of these elements
525 into the co-existing sulfide phases (e.g. chalcopyrite, pentlandite, millerite) or platinum-
526 group minerals (e.g. laurite, erlichmanite, IPGE alloy) that may be present in the komatiitic
527 rocks or as inclusions in Kapili chromites (Peach and Mathez 1996; Andrews and Brenan
528 2002; Fiorentini et al. 2004; Fonseca et al. 2009; Pagé and Barnes 2016; Park et al. 2012,
529 2017; Locmelis et al. 2018).

530 The isolated type-V chrome magnetite grains have higher Os, Ir, and lower Rh content
531 with a wider range of Ru concentration than the cores and rims of type-I and type-II grains
532 (**Table 4**). The IPGE and Rh concentrations of type-V grains vary spatially in the greenstone
533 belt (**Appendix 2: Fig. S3**). Only Ru is detected in type-V grains from the southern Kapili area
534 whereas higher IPGE and Rh contents are found in those from the northernmost
535 Maharajgunj and Chuka Pahar areas (**Table 4**). The overall enrichment of Os and Ir in the
536 type-V grains (**Fig. 11; Table 4**) is due to the stronger affinity of these elements towards the
537 VI-fold coordination of the inverse spinel structure (e.g. Brenan et al. 2012).

538 **Mass balance calculations and determination of empirical partition coefficients of trace elements** 539 **and PGE between chromite and komatiitic melt**

540 Chrome-spinel plays a significant role in controlling the budget of IPGE and Rh, and several
541 trace elements in plutonic and volcanic ultramafic-mafic rocks. Thus understanding the
542 partitioning of these elements between ultramafic-mafic silicate melt and co-existing
543 chrome-spinels during early magmatic processes is of great importance. This is a challenging
544 exercise for the Gorumahishani komatiitic chromites owing to their extensive alteration and

545 therefore, only the core compositions of the least altered chromites were considered for
 546 these calculations. We have considered the compositions of the Al-depleted meta-peridotite
 547 from Tua Dungri (sample MIC/16/44) and the Al-enriched meta-peridotite from Kapili
 548 (sample SHB/18/25) (values in **Appendix 3: Table S5**) to be equivalent to the parental
 549 komatiitic melt compositions of the type-I (Tua Dungri) and type-II (Kapili) chromites,
 550 respectively.

551 We first calculated the mass fraction of chromite in komatiitic rocks from the least
 552 altered chromite cores of type-I (sample MIC/16/39, meta-peridotite) and type-II grains
 553 (sample SHB/19-12/82, spinifex-textured meta-peridotite) following the equation proposed
 554 by Pagé and Barnes (2016):

$$555 \quad \% \text{ Cr-spinel in sample} = (\text{Cr}_2\text{O}_3^{\text{WR}} / \text{Cr}_2\text{O}_3^{\text{Cr-spinel}}) * 100 * 0.75$$

556 where $\text{Cr}_2\text{O}_3^{\text{WR}}$ = whole-rock Cr_2O_3 content in wt.% and $\text{Cr}_2\text{O}_3^{\text{Cr-spinel}}$ = Cr_2O_3 content of Cr-
 557 spinel in wt.%. The calculation assumes that 75% of Cr in the whole rock is hosted by
 558 chromite (e.g. Arguin et al. 2016), with the rest being hosted by silicate phases dominated
 559 by olivine with some pyroxene (e.g. Pagé et al. 2012; Pagé and Barnes 2016). Using the
 560 Cr_2O_3 abundances of the least altered chromite cores and the Cr_2O_3 contents of the
 561 corresponding rocks we find that the proportions of chromite in the komatiitic rocks ranged
 562 from 0.33% to 0.61% (**Appendix 3: Table S6, S7**) which is similar to the lower limit of
 563 chromite modal abundances obtained by Pagé and Barnes (2016) for volcanic samples. The
 564 weight fraction of chromite in the studied samples was used to estimate the fractions of
 565 trace elements and IPGE + Rh in the whole rock contributed by chromite, following the
 566 equation of Pagé and Barnes (2016):

$$567 \quad F_i^{\text{Cr-spinel}} (\%) = 100 * (C_i^{\text{Cr-spinel}} * F^{\text{Cr-spinel}}) / C_i^{\text{WR}}$$

568 where $F_i^{\text{Cr-spinel}}$ = contribution of element 'i' from chromite in the whole rock, $C_i^{\text{Cr-spinel}}$ =

569 element 'i' concentration in chromite, $F^{\text{Cr-spinel}}$ = proportion of Cr-spinel in our sample, and
570 C_i^{WR} = concentration of element 'i' in the whole-rock. The mass balance calculation for the
571 Tua Dungri komatiites indicates that chromite hosts mass fractions of Sc = 0.12 - 0.15%, Ti =
572 0.04%, Ni = 0.08 - 0.10%, V = 4.46%, Ga = 2.71 - 3.62%, Mn = 0.83 - 0.87% and Co = 3.7 -
573 3.92%. The proportions for the Kapili komatiites are: Sc = 0.09 - 0.16%, Ti = 3.89 - 7.05%, Ni =
574 2.88 - 6.97%, Ga = 6.58 - 11.41%, Mn = 9.62 - 16.78%, Co = 12.33 - 18.87% and V = 18.20 -
575 40.34% (**Appendix 3: Table S6, S7**). These values can be compared with the F_{Sc} , F_{Ni} , and F_{V}
576 values of the least modified komatiitic chromites ($F_{\text{Sc}} = 23.21\%$, $F_{\text{Ni}} = 47.98\%$) of Park et al.
577 (2017) and the bulk rock data of Törmänen et al. (2016). Assuming that our choices for the
578 bulk melt compositions are appropriate, the data show that low and variable fractions of the
579 considered minor and trace elements are hosted by chromites in the the Gorumahishani
580 komatiites, unlike the much higher fractions of these elements hosted by chromites in the
581 other komatiites (e.g., Park et al 2017). This suggests that the distribution of these elements
582 in the komatiitic rocks is mainly controlled by the modally abundant silicate or carbonate
583 minerals in combination with the metamorphic modification of the primary assemblages.

584 Calculations based on global komatiitic and ultramafic-mafic volcanic rocks (e.g. Pagé et
585 al. 2012; Pagé and Barnes 2016; Park et al. 2017) reveal that about 15 - 40% of the whole-
586 rock Os, Ir, Rh budgets and nearly 100% of the Ru budget are represented by accessory
587 chromites or the PGE-rich micro-inclusions they contain. In contrast, the type-I chromite
588 cores from the Gorumahishani komatiites account for 15-20% Ru, 11-12% Rh, 2% Os and 1-
589 2% Ir in the whole-rock budgets while the type-II chromite cores represent even lower
590 proportions of these elements (Ru ~8-10%, Rh ~2%, Os ~2%, and Ir ~1%; **Appendix 3: Table**
591 **S6, S7**) (**Fig. 11b**). The lower values from both types of grains relative to those calculated
592 from the global dataset partly reflect redistribution of PGEs during metamorphic

593 modification of the komatiitic chromites or Cr-spinel crystallization after sulfide saturation
594 of the komatiitic magma. In addition, part of the whole-rock PGE budget may be held by
595 micro-inclusions of PGE-alloys or PGE-minerals in the zoned chrome-spinels, although such
596 phases have not yet been identified in the laser spot analyses of our samples (Fiorentini et
597 al. 2004; Barnes and Fiorentini 2008; Park et al. 2012; Arguin et al. 2016). Metamorphic
598 redistribution may include diffusion of IPGE and Rh from chromites to co-existing sulfide
599 phases (e.g. chalcopyrite, pentlandite, millerite). Low chromite abundance in the
600 Gorumahishani komatiites can also be responsible for their low contribution to the whole-
601 rock IPGE + Rh budget as their proportion is similar to the lower limit of chrome-spinel
602 present in the rocks studied by Page and Barnes (2016).

603 We have calculated the empirical partition coefficients for trace elements and PGEs
604 considering the chromite core compositions and the bulk rock compositions of the selected
605 komatiitic rocks (Table S5). To obtain the composition of the melt with which the Cr-spinel
606 equilibrated, it is necessary to exclude the portion of each element hosted by this phase
607 from the bulk rock composition. To do this, we used the mass balance equation as
608 formulated by Pagé and Barnes (2016):

$$609 \quad C_i^{\text{Melt}} = [(C_i^{\text{WR}} * 100) - (C_i^{\text{Cr-spinel}} * \% \text{ Cr-spinel})] / (100 - \% \text{ Cr-spinel})$$

610 where C_i^{Melt} = content of element 'i' in the silicate melt. We then used these calculated melt
611 compositions to determine empirical partition coefficients ($D = C_i^{\text{Cr-spinel}} / C_i^{\text{Melt}}$) for Sc, Ti, V,
612 Mn, Co, Ni, Ga, IPGEs, and Rh for the least altered type-I and type-II cores. Type-I chromite
613 cores have values of $D_{\text{Sc}} = 0.37 - 0.45$, $D_{\text{Ni}} = 0.24 - 0.28$, $D_{\text{Ti}} = 0.12 - 0.13$, and $D_{\text{Co}} = 11.58 -$
614 **12.10 (Table 5)** similar to or lower than previous empirical values for volcanic chromites as
615 well as experimentally determined values e.g. $D_{\text{Sc}} = 0.36 - 0.57$, $D_{\text{Ni}} = 3.5 - 6.8$ and $D_{\text{Ti}} = 0.4 -$
616 3.5 , $D_{\text{Co}} = 3.1 - 29.6$ (Horn et al. 1994; Sattari et al. 2002; Righter et al. 2006; Pagé and

617 Barnes 2009; Park et al., 2012). The other trace elements from type-I chromite cores show a
618 restricted range of values: $D_V = 14.08 - 14.38$, $D_{Mn} = 2.51 - 2.69$, and $D_{Ga} = 8.44 - 11.04$ (**Table**
619 **5**). The type-II chromites have higher empirical partition coefficients for D_{Co} (23.52 - 37.66)
620 than the type-I values, and even higher than the volcanic chromites determined by previous
621 workers (Horn et al. 1994; Sattari et al. 2002; Righter et al. 2006; Pagé and Barnes 2009;
622 Park et al. 2012). The other trace elements, with the exception of Sc, also show higher
623 values than the type-I values (**Table 5**). Nevertheless, accessory chromites in komatiitic rocks
624 have re-equilibrated with co-existing modally abundant silicate minerals during
625 metamorphism, so the empirically determined partition coefficients should differ from the
626 true magmatic values.

627 Empirical partition coefficients calculated for IPGEs and Rh for type-I chromite cores are
628 $D_{Os} = 4.45$, $D_{Ir} = 2.54 - 4.18$, $D_{Ru} = 49.79 - 67.86$, and $D_{Rh} = 32.21 - 36.94$ (**Table 6**). Coefficients
629 for type-II chromite cores are $D_{Ir} = 2.23 - 3.1$, $D_{Ru} = 35.51 - 45.43$, and $D_{Rh} = 4.4 - 4.94$, which
630 are lower than the values obtained for the type-I grains except for $D_{Os} = 8.18 - 8.45$ (**Table**
631 **6**). Previous studies (e.g. Pagé et al. 2012; Park et al. 2017) of komatiitic chromites yielded
632 $D_{Os} = 9.6 - 18$, $D_{Ir} = 11 - 11.8$, $D_{Ru} = 5.64 - 100$, and $D_{Rh} = 13 - 18.1$. The calculated D_{Os} and D_{Ir}
633 from this study are somewhat lower while D_{Ru} falls within the wide range of published
634 values. D_{Rh} shows lower values in type-II cores but higher in type-I cores compared to the
635 published data. Experiments by Brenan et al. (2012) using synthetic iron-bearing basalt at
636 0.1 MPa and 2 GPa at 1400 - 1900 °C, $fO_2 = IW+1.6$ to $IW+2.1$ yielded lower partition
637 coefficient values for these elements ($D_{Ru} = 4$, $D_{Rh, Ir} = 0.04 - 1$). However, the values were
638 higher ($D_{Ir} = 186.9$, $D_{Ru} = 37.9$ and $D_{Rh} = 89$) under more oxidizing conditions, e.g. $fO_2 =$
639 $IW+3.1$ to $IW+7.2$. Other researchers (e.g. Capobianco and Drake 1990; Capobianco et al.
640 1994; Righter et al. 2004) determined the experimental partition coefficients under much

641 more oxidizing conditions (NNO to HM buffer), obtaining exceedingly high values of $D_{Ir} = 5 -$
642 22000 , $D_{Ru} = 20 - 4000$, and $D_{Rh} = 41 - 530$. Natural chrome-spinels crystallized from an
643 oxidized basaltic magma from Ambae volcano, Vanuatu at $fO_2 = QFM+2.5$ (Park et al. 2012)
644 yielded $D_{Os} = 288$, $D_{Ir} = 472$, $D_{Ru} = 2448$, and $D_{Rh} = 641$, which are comparable to the values
645 determined experimentally under highly oxidizing conditions. Brenan (2012) emphasized
646 that the high D (Ru Ir, Rh) values obtained for experiments performed under oxidizing
647 conditions were due to the presence of ferric iron in the spinels. In this light, it is significant
648 that some of the zoned chromites from the Gorumahishani belt have Fe^{3+} rich outer rims
649 with elevated Ru and Rh contents. Similarly, many of the type-V chrome magnetites have
650 high IPGE contents (**Table 4**). Although the fO_2 values of the Gorumahishani komatiite
651 parental melts are poorly constrained, the empirical partition coefficients ($D_{IPGE, Rh}$) of this
652 study and comparison with other natural or experimental values suggest that the accessory
653 chromites we studied might have crystallized from magma under relatively low fO_2
654 conditions. The low calculated D values for Os, Ir, Ru, and Rh are consistent with the low
655 Fe^{3+}/R^{3+} values of the type-I and type-II chromite cores, with both suggesting reducing
656 conditions. Global heterogeneity in early Archean mantle redox conditions and the change
657 of estimated fO_2 conditions for komatiitic melts from reducing to oxidizing since the early
658 Archean (3.48 Ga: $0.11 \pm 0.30 \Delta QFM$ log units to 1.87 Ga: $+1.22 \pm 0.31 \Delta QFM$ log units;
659 Nicklas et al. 2019) supports our observations. Finally, even though the cores are the least
660 altered chromite available, their trace element and PGE abundances may still have been
661 modified by metamorphism. So the calculated magmatic partition coefficients may
662 represent minimum values. This is particularly true for the type-II cores from the southern
663 area (Kapili), which experienced higher grade metamorphism and which are less likely to
664 represent magmatic compositions.

665

666 **Conclusions**

667 (1) Komatiitic rocks of the Gorumahishani greenstone belt were metamorphosed under
668 conditions close to the greenschist-amphibolite facies transition in the northern
669 Maharajgunj-Chuka Pahar-Tua Dungri sector and under amphibolite facies conditions in the
670 southern Kapili sector. Accessory komatiitic chromites were modified during metamorphism
671 in the presence of H₂O and CO₂-rich fluids by reaction with surrounding primary silicate and
672 oxide minerals. Three types of zoned chromites as well as homogenous grains of
673 ferritchromit and chrome magnetite were developed during this stage by release of Cr, Al,
674 and Mg, and re-ordering of Fe²⁺ - Fe³⁺ in the spinel structure.

675 (2) As the metamorphic grade increases from the northern to the southern part of the
676 greenstone belt, the type-II chromite cores, found only in the south, display greater extents
677 of diffusive equilibration of trace elements such as Zn, Co, Mn with associated silicate or
678 carbonate minerals than the type-I chromite cores, found only in the north. Increasing IPGE
679 (Os, Ir, Ru) and Rh concentrations from type-I cores to rims and lower concentrations of
680 these elements in type-II chromite cores to undetectable concentrations in type-II rims are
681 also related to the increasing metamorphic grade towards the south. The IPGEs and Rh may
682 also have diffused to the co-existing sulfide minerals such as chalcopyrite, pentlandite,
683 millerite, or platinum-group minerals (e.g. laurite, erlichmanite, IPGE alloy), if present.

684 (3) Mass balance calculation shows that the cores of the type-I chromite contribute < 1% Sc,
685 Ti, Ni, and Mn, and 2 - 5% V, Ga, and Co to the whole rock trace element budget. The type-II
686 chromite cores contribute <1 - 19% Sc, Ti, Ni, Mn, Ga, Co, and 18 - 40 % V indicating a major
687 control of the modally abundant silicate minerals on the whole rock budget of these trace
688 elements. In terms of IPGE + Rh, the type-I chromite cores contribute ≤ 20% and the type-II

689 chromite cores contribute $\leq 10\%$ of the whole rock IPGE + Rh budget indicating the effect of
690 metamorphism or equilibration with other PGE-bearing or sulfide phases.

691 (4) Calculation of empirical partition coefficients (D) of trace and platinum-group elements
692 based on the least altered cores of the type-I and type-II grains and komatiitic whole-rock
693 compositions yield values broadly comparable to natural and experimental values. These
694 values generally fall towards the low end of the experimental range, consistent with
695 partitioning under reducing conditions. The low D values of the type-I and type-II cores may
696 therefore indicate their crystallization from reduced komatiitic melts. These interpretations
697 should be viewed cautiously because of the limited number of *in situ* PGE and trace element
698 data and because the compositions of the chromite cores, particularly those of type-II, may
699 have been modified by metamorphism.

700

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976

977 **Figure captions**

978 **Fig. 1 (a)** Generalized geology of the Singhbhum Craton, India (after Saha 1994; Mondal et
979 al. 2006). Inset map of India shows the location of the Singhbhum Craton. 1 - Singhbhum
980 Granite Batholithic Complex, 2 - OMTG Tonalite-Granodiorite, 3 - OMG Supracrustals, 4 -
981 Iron Ore Group greenstone sequences with BIF, 5 - Ultramafic-Mafic rocks with chromite-
982 PGE deposits, 6 - Late Archean-Proterozoic sedimentary sequence, 7 - Late Archean-
983 Proterozoic volcanic sequence. **(b)** Geological map of the Gorumahishani-Badampahar
984 greenstone belt (modified from www.gsi.gov.in) showing the locations of Maharajgunj,
985 Chuka Pahar, Tua Dungri, and Kapili komatiite hillocks. **(c)** Lithological column of Tua Dungri
986 komatiite hill. The map in the right top corner shows the sample locations. **(d)** Geology of
987 the Kapili area showing the sample locations. **(e)** Lithological column of the komatiitic suite
988 of rocks from Maharajgunj and Chuka Pahar sections. The map in the middle shows the
989 sample locations.

990 **Fig. 2** Field photographs: **(a)** Meta-dunite from Tua Dungri (lower cumulate zone), **(b)**
991 Chevron spinifex-textured meta-peridotite from Kapili (spinifex zone), **(c)** Platy spinifex
992 textured meta-peridotite from Tua Dungri (spinifex zone), **(d)** Random spinifex-textured
993 meta-peridotite from Kapili (spinifex zone), **(e)** Schistose meta-basalt from Tiring, and **(f)**
994 Quartzite band interlayered with schists from Kapili.

995 **Fig. 3** Photomicrographs of komatiitic rocks in transmitted and reflected light: **(a)** Small
996 olivine (ol) core is surrounded by serpentine (srp) and associated with accessory chromite
997 (chr), **(b)** Serpentine shows pseudomorphic texture (after olivine) with accessory chromite.
998 Chlorite (chl) and tremolite (tr) form the interstitial assemblage, **(c)** Carbonate (cb) minerals
999 in the meta-peridotite, **(d)** Spinifex texture now represented by tremolite after pyroxene
1000 grains. Magnetite is present in between tremolite grains, **(e)** Spinifex texture now
1001 represented by serpentine after olivine grains. An assemblage of chlorite + tremolite +
1002 carbonate is present in between serpentine spinifexes, **(f)** Meta-basalt contains epidote (ep)
1003 after plagioclase along with chlorite and tremolite, **(g)** Photomicrograph of type-IV fractured
1004 chromite grain and completely altered to ferritchromit (fcmt), **(h)** Backscattered electron
1005 (BSE) image of type-V small to large anhedral grains completely altered to chrome
1006 magnetite.

1007 **Fig. 4** Comparison of modal abundances (in %) of mineral phases from the komatiitic
1008 suite of rocks between northern Maharajgunj, Chuka Pahar, Tua Dungri, and southern Kapili

1009 areas.

1010 **Fig. 5** Quantitative microprobe profiles of major and minor element oxides along with Mg#,
1011 Cr#, and $\text{Fe}^{3+}/\text{R}^{3+}$ across the (a) Type-I (sample: MIC/16/39), (b) Type-II (sample: SHB/18/24),
1012 and (c) Type-III (sample: SHB/18/36) zoned chromite grains showing variation from chromite
1013 cores to ferritchromit and chrome magnetite rims.

1014 **Fig. 6** Compositions of chromites from Gorumahishani komatiitic rocks: (a), (b) Mg# vs. Cr#
1015 and (c) Mg# vs. $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Cr}+\text{Al})$ variations of the type-I, II, III, IV, and, V Cr-spinels, (d), (e),
1016 (f) Variations of $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Cr}+\text{Al})$ plotted against TiO_2 , MnO, and NiO from all types of Cr-
1017 spinels, (g) Cr, Al, and Fe^{3+} variation of the type-I, II, III chromite cores, and rims along with
1018 type-IV and type-V grains.

1019 **Fig. 7** Quantitative *in situ* LA-ICPMS profiles of trace and platinum-group elements along
1020 with major elements Cr_2O_3 , Al_2O_3 , MgO, Fe_2O_3 , FeO and Mg#, Cr#, $\text{Fe}^{3+}/\text{R}^{3+}$ across the (a), (b)
1021 Type-I and (sample: MIC/16/39) (c), (d) Type- II (sample: SHB/19-12/82) zoned chromites. LA
1022 ponts: (a) Chr: 8, 9 and chrome magnetite: 7, 10; (b) Chr: 3, fcmt: 4, and chrome magnetite:
1023 5; (c) Chr: 25, chrome magnetite: 26; (d) Chr: 34, chrome magnetite: 33. Laser spots indicate
1024 data points showing variation from chromite core to ferritchromit and chrome magnetite
1025 rims.

1026 **Fig. 8** Compositional variations of the type-I, type-II, and type-V Cr-spinel grains from (a)-(g)
1027 Mg# vs. Ga, Ni, Sc, Co, Mn, Zn, and Ti plots, (h) Zn+Co+Mn vs. Ga plot.

1028 **Fig. 9** EPR MORB Cr-spinel (after Pagé and Barnes 2009) normalized spidergrams: (a)
1029 Average major, and trace elements compositional variation of the type-I, type-II, and type-V
1030 Cr-spinels and (b) Comparison of type-I, type-II, and type-V Cr-spinels with the least altered
1031 chromites from Finland komatiite and Greenland, Troodos, and Kamchatka picrite (Park et
1032 al. 2017).

1033 **Fig. 10** Representative time-resolved spectra of LA-ICPMS analyses on komatiitic chromites
1034 from (a) Sample MIC/16/39 (type-I chromite, Tua Dungri) showing homogenous PGE spectra
1035 (b) Sample SHB/19-12/35 (type-V chromite, Maharajgunj) with Rh, Ru spikes indicating the
1036 probable presence of Rh, Ru-bearing micro-inclusions.

1037 **Fig. 11** Primitive mantle normalized Rh and IPGE plot of (a) Type- I, type-II, and type-V Cr-
1038 spinel grains from the Gorumahishani komatiitic rocks and (b) Comparison of type-I, type-II,
1039 and type-V Cr-spinels with the least altered chromites from Finland komatiite and
1040 Greenland, Troodos, Finland, Emeishan, and Kamchatka picrites (Park et al. 2017). Primitive

1041 mantle values are from Barnes et al. (1988).

1042 **Fig. 12** Compositional variations of trace and platinum-group elements in the type-I, type-II,
1043 and type-V Cr-spinel grains. (a) V vs. Ru. (b) Ni vs. Ru.

1044 **Fig. 13** Schematic illustration of microstructural and chemical (major, minor, and trace
1045 element along with IPGE, Rh) changes in the five types of Cr-spinel grains during progressive
1046 metamorphism of komatiitic rocks from the Gorumahishani greenstone belt.

1047

1048 **Table captions**

1049 **Table 1** Classification of komatiitic chromites from the Gorumahishani greenstone belt.

1050 **Table 2** Major and minor element compositional ranges of the Cr-spinels (wt.%)

1051 **Table 3** Trace element compositional range of the Cr-spinels (ppm) measured by LA-ICP-MS.

1052 **Table 4** Platinum-group element (PGE) compositional range of the Cr-spinels (ppb)
1053 measured by LA-ICP-MS.

1054 **Table 5** Empirical partition coefficients of trace elements ($D^{\text{Cr-spinel/silicate melt}}$).

1055 **Table 6** Empirical partition coefficients of IPGEs and Rh ($D^{\text{Cr-spinel/silicate melt}}$).

1056 **Supplementary materials**

1057 **Appendix 1:** Detailed information on the geological background of the Singhbhum craton
1058 and analytical methods

1059 **Appendix 2:** Supplementary figures

1060 Fig. S1 (a) Classification of pyroxene (after Morimoto 1988), (b) amphibole (after Leake et al.
1061 1997), (c) carbonate, and (d) chlorite (after Hey 1954) from the komatiitic suite of rocks
1062 from the Gorumahishani greenstone belt.

1063 Fig. S2 Compositional variations of the type-I, type-II, and type-V chromite grains in Al_2O_3 vs.
1064 Ga plots.

1065 Fig. S3 Variation in platinum-group elements concentration (in ppb) of the type-V chrome
1066 magnetite grains from the northern and southern part of the Gorumahisani greenstone belt.

1067 **Appendix 3:** Complete set of analytical data

1068 Table S1 Major and minor element analyses of the silicate and carbonate minerals (wt.%).

1069 Table S2 Major and minor EMPA analyses of the oxide minerals (wt.%).

1070 Table S3 Trace element LA-ICPMS analyses of the oxide minerals (ppm).

1071 Table S4 Platinum-group element LA-ICPMS analyses of the oxide minerals (ppb).

1072 Table S5 Whole-rock major element (wt.%), trace element (ppm), and platinum-group

1073 element (PGE) (ppb) compositions of selected samples.

1074 Table S6 Empirical partition coefficients of trace elements ($D^{\text{Cr-spinel/silicate melt}}$). Calculated
1075 results also shown for mass fractions of chromite in komatiitic rocks, contribution of
1076 chromite to the whole rock budget of each element, silicate melt concentrations for each
1077 element.

1078 Table S7 Empirical partition coefficients of platinum-group elements ($D^{\text{Cr-spinel/silicate melt}}$).
1079 Calculated results also shown for mass fractions of chromite in komatiitic rocks, contribution
1080 of chromite to the whole rock budget of each element, silicate melt concentrations for each
1081 element.

Figure 01

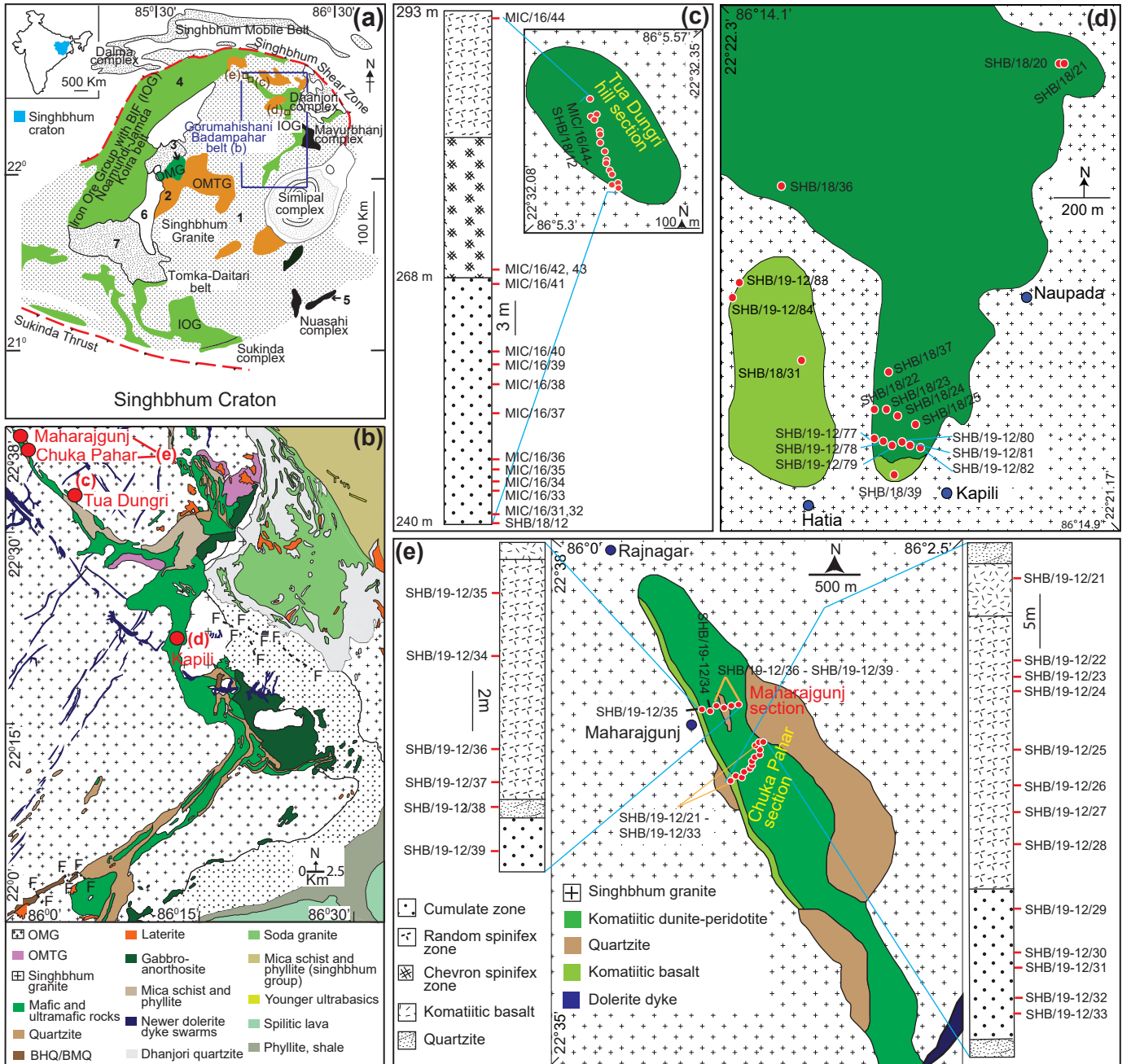


Figure 02



Figure 03

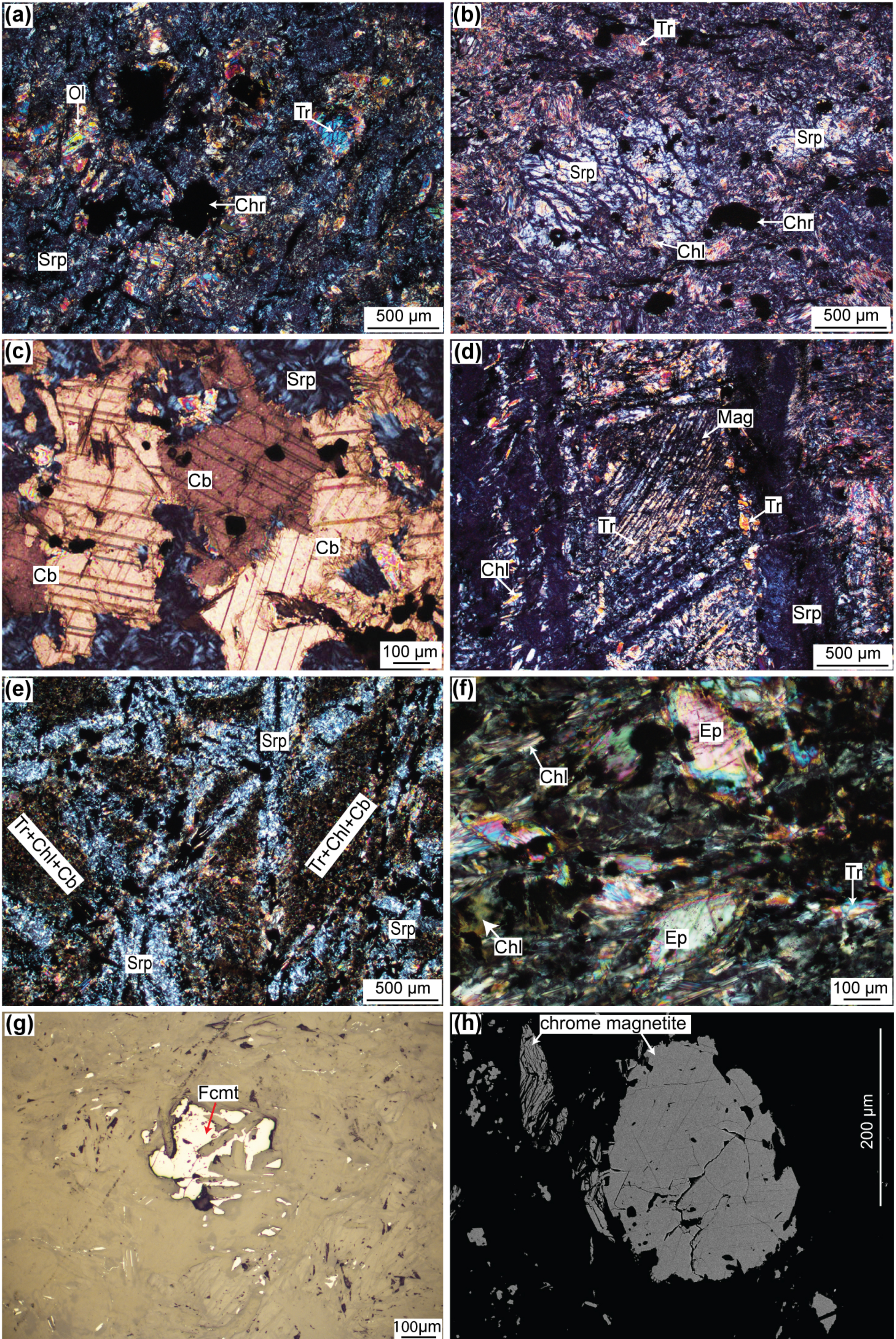


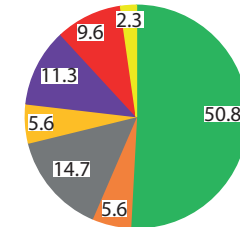
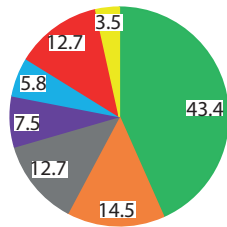
Figure 04

Northern Section Southern Section

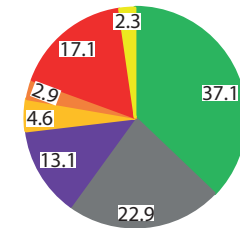
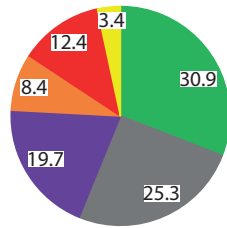
Maharajgunj
Chuka Pahar
Tua Dungri

Kapili

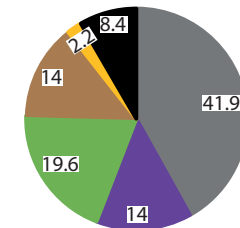
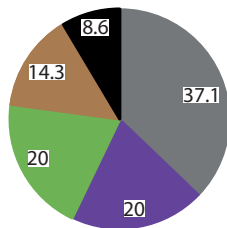
Meta-dunite and meta-peridotite



Spinifex-textured meta-peridotite



Meta-basalt



- serpentine ■ carbonate ■ tremolite
- hornblende ■ chlorite ■ talc
- actinolite ■ epidote ■ magnetite
- chromite ■ sulfide

Figure 05

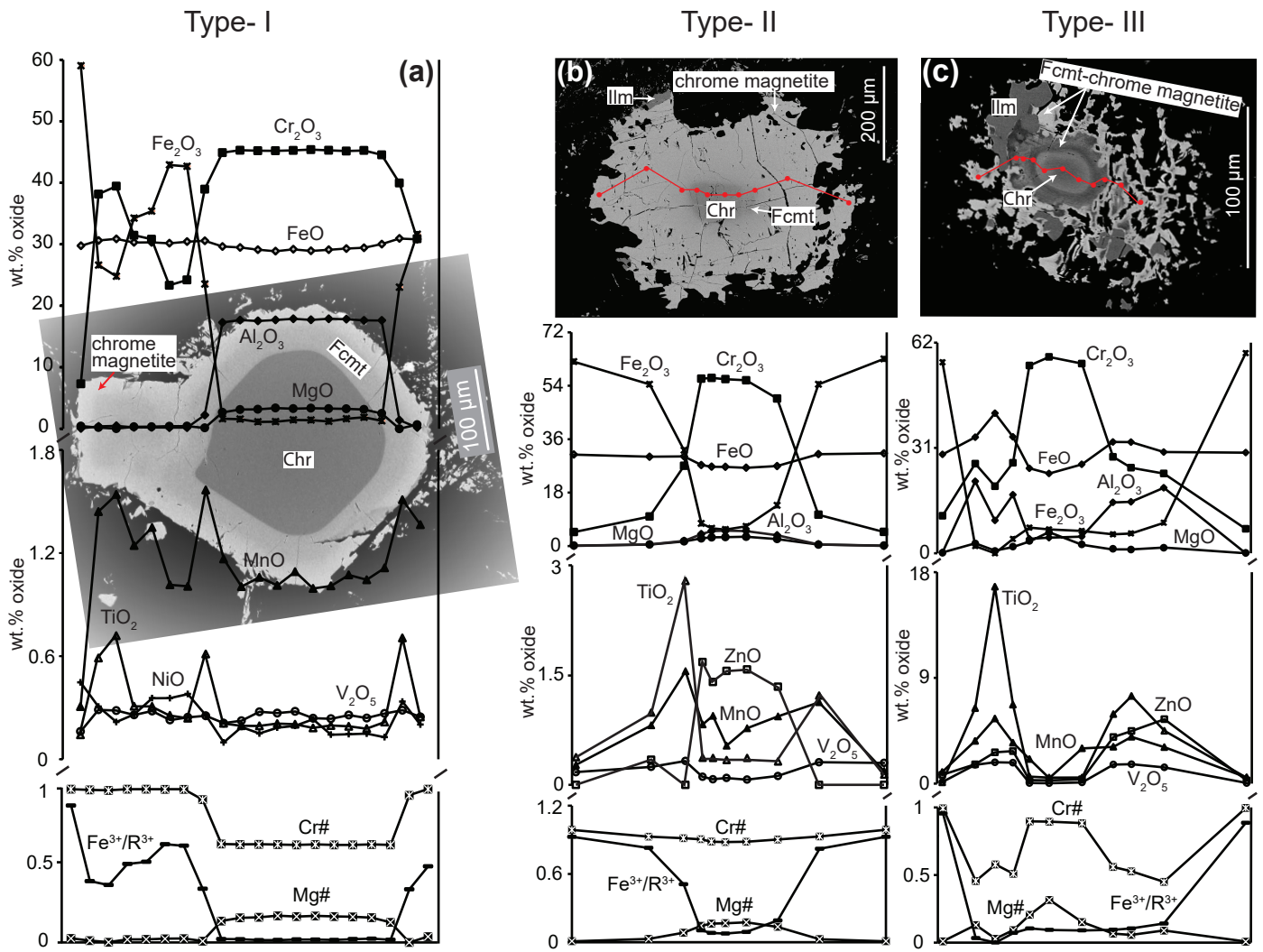


Figure 06

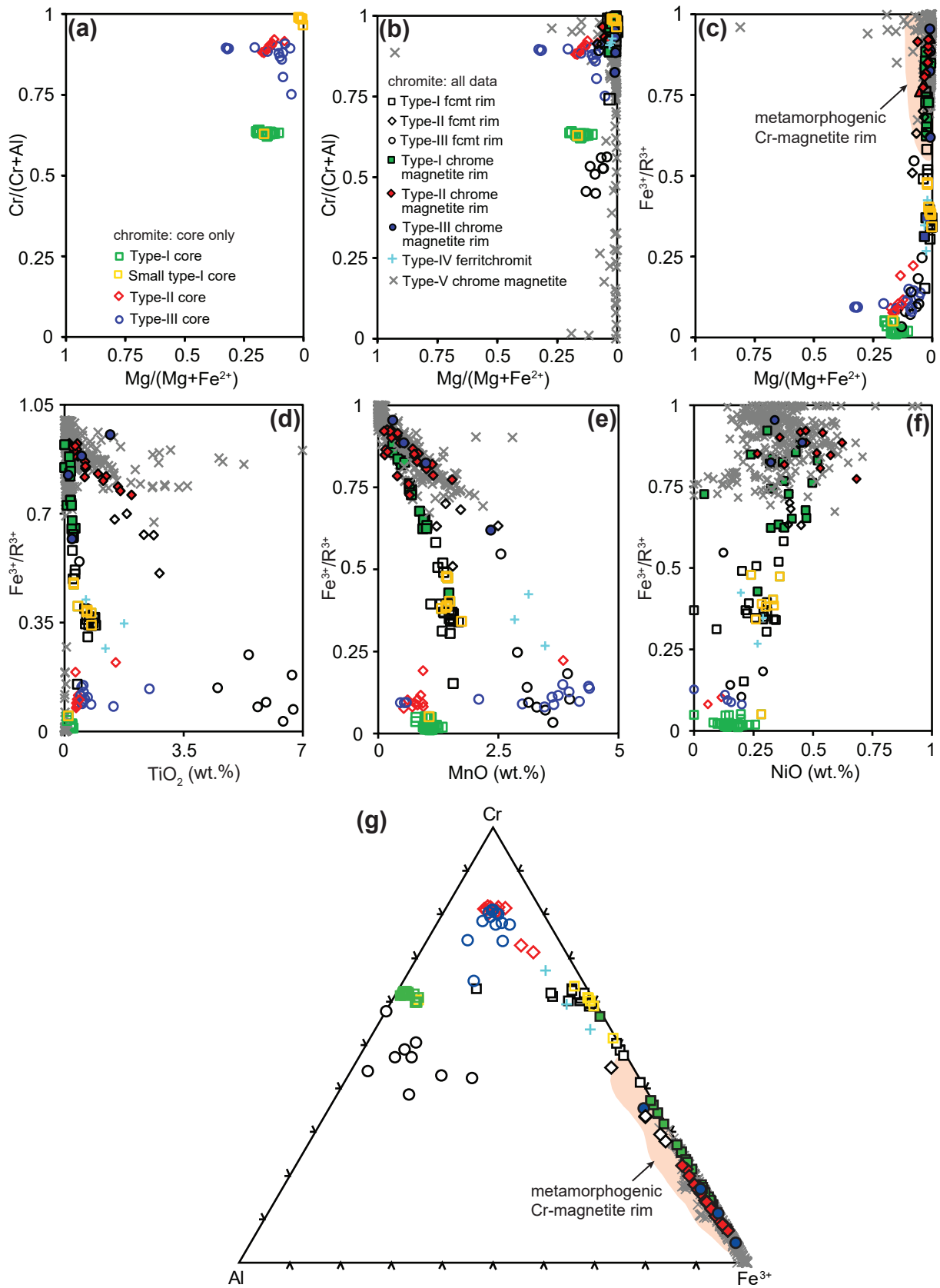


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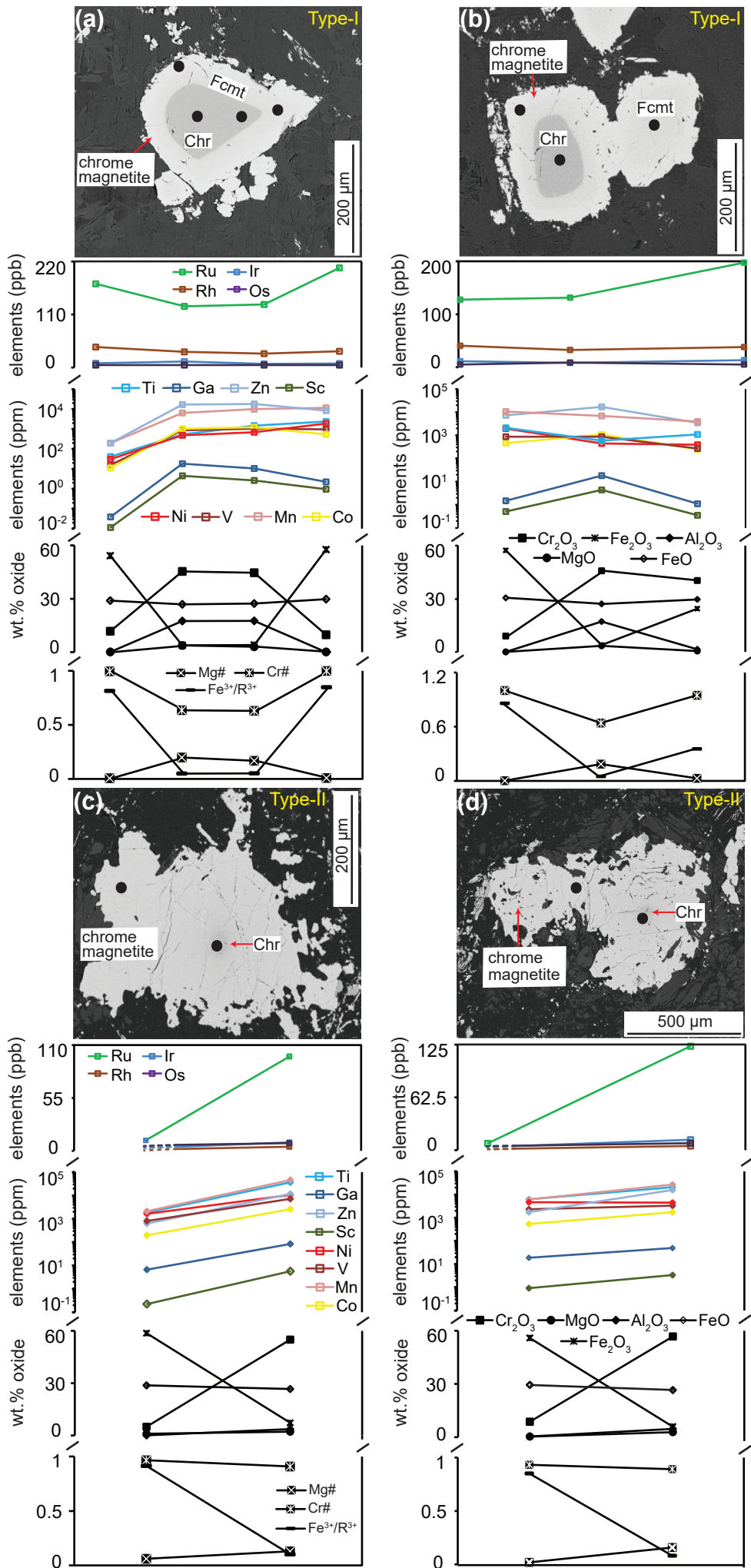


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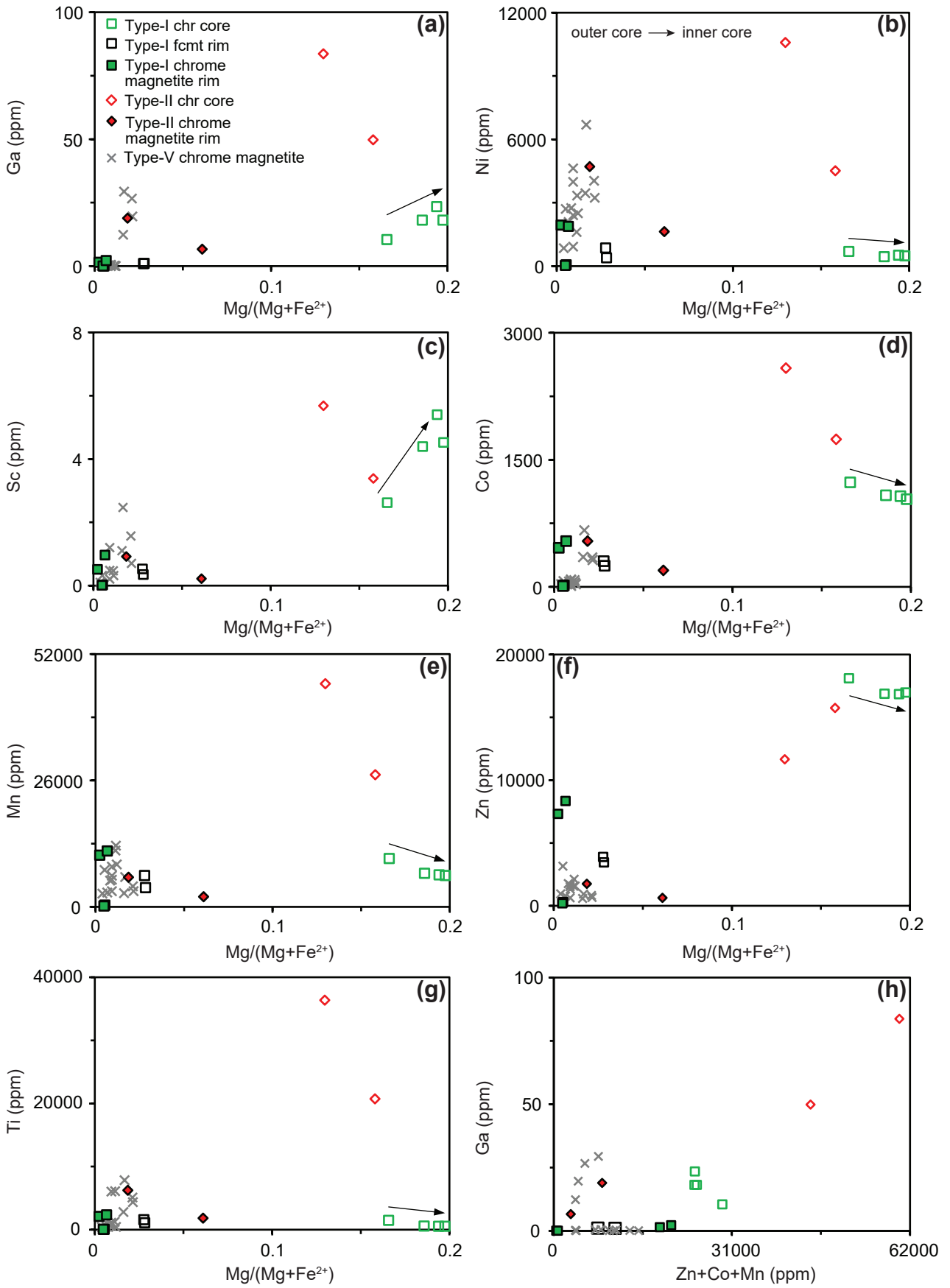


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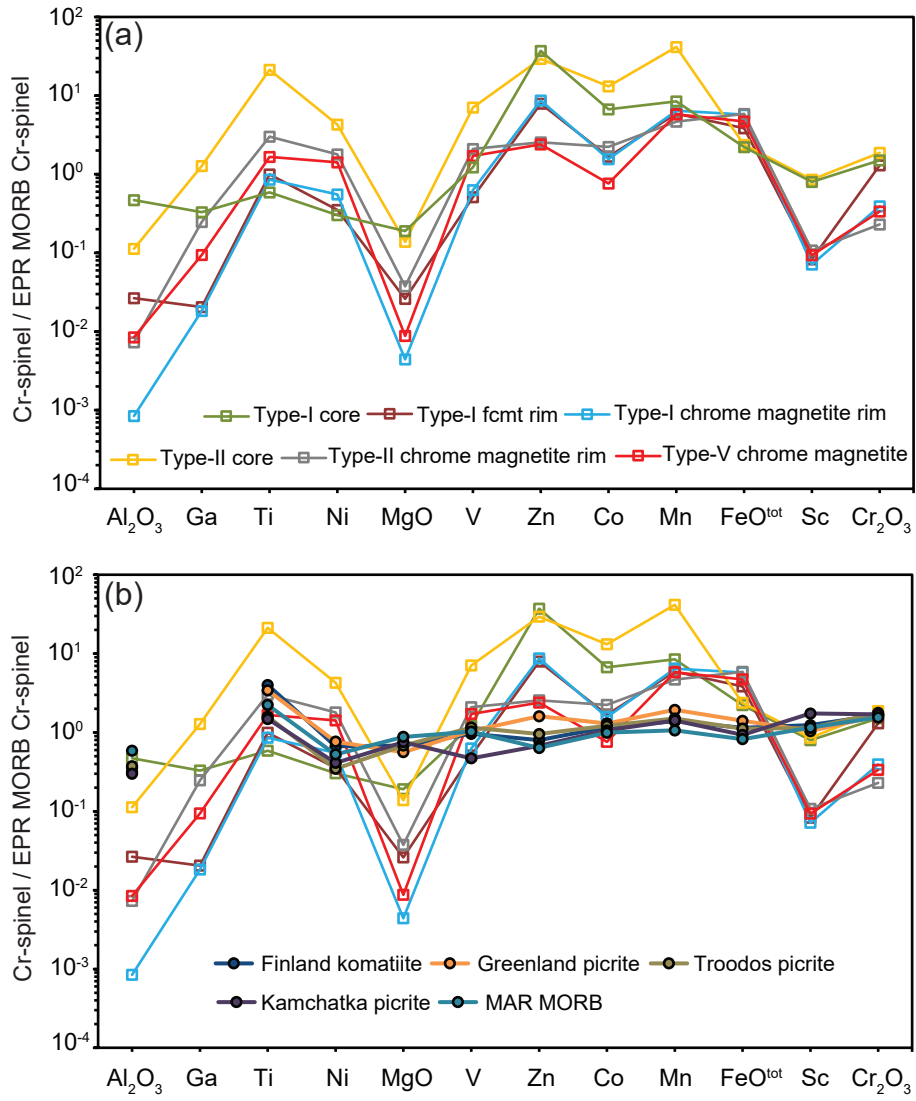


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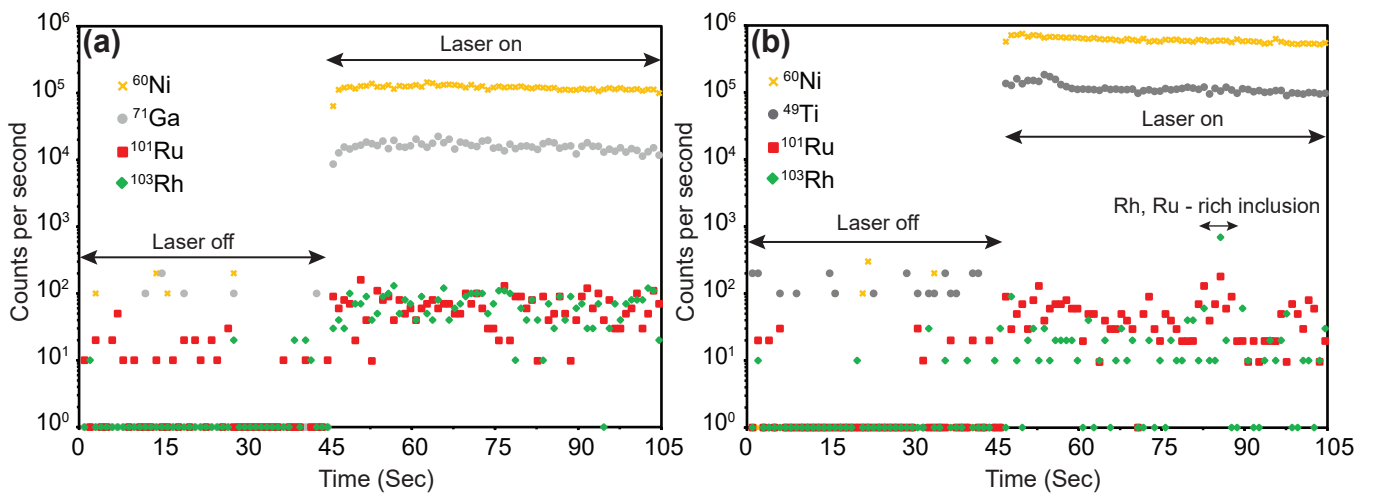


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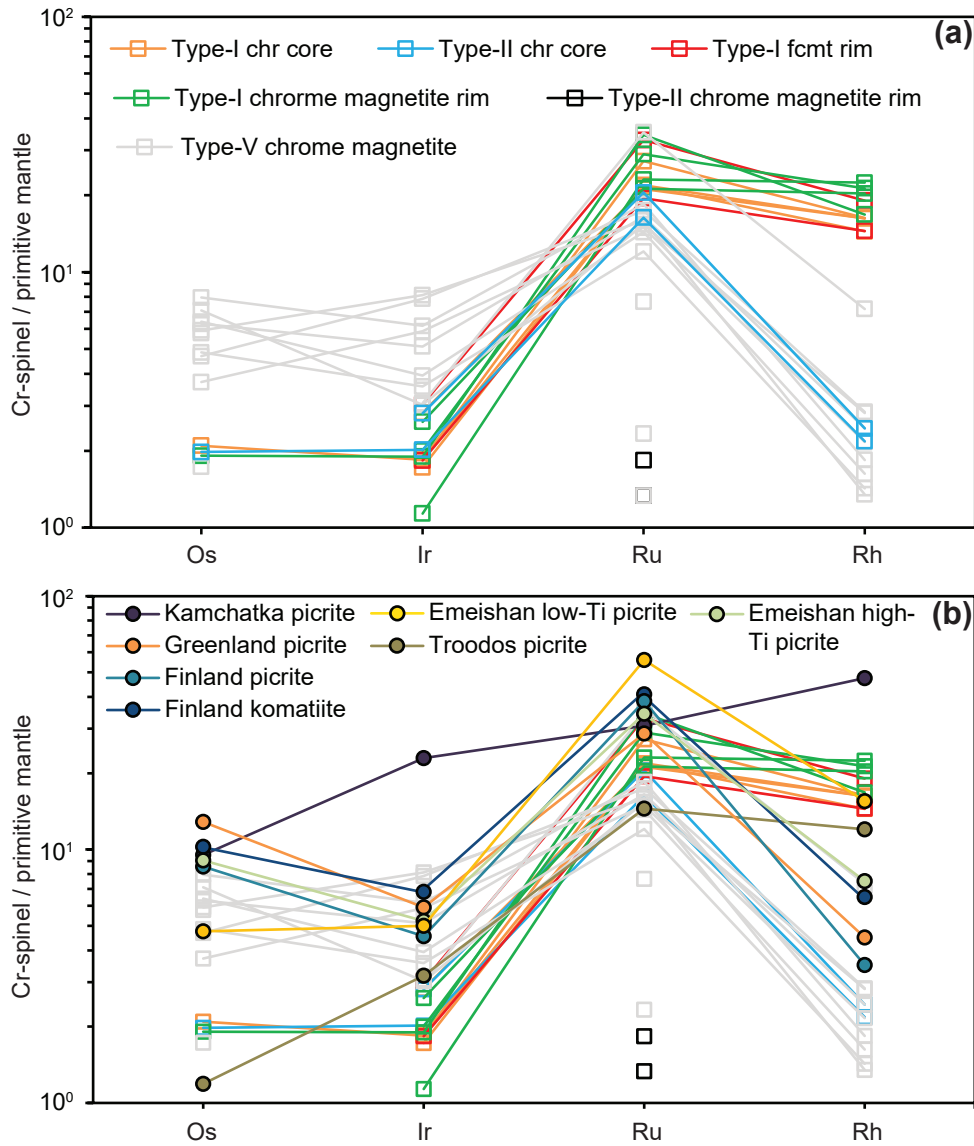


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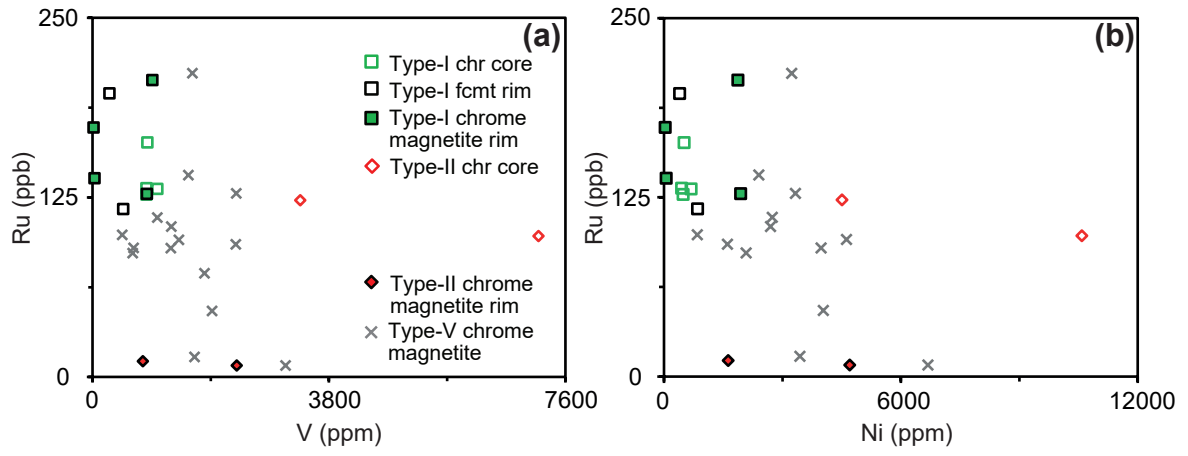


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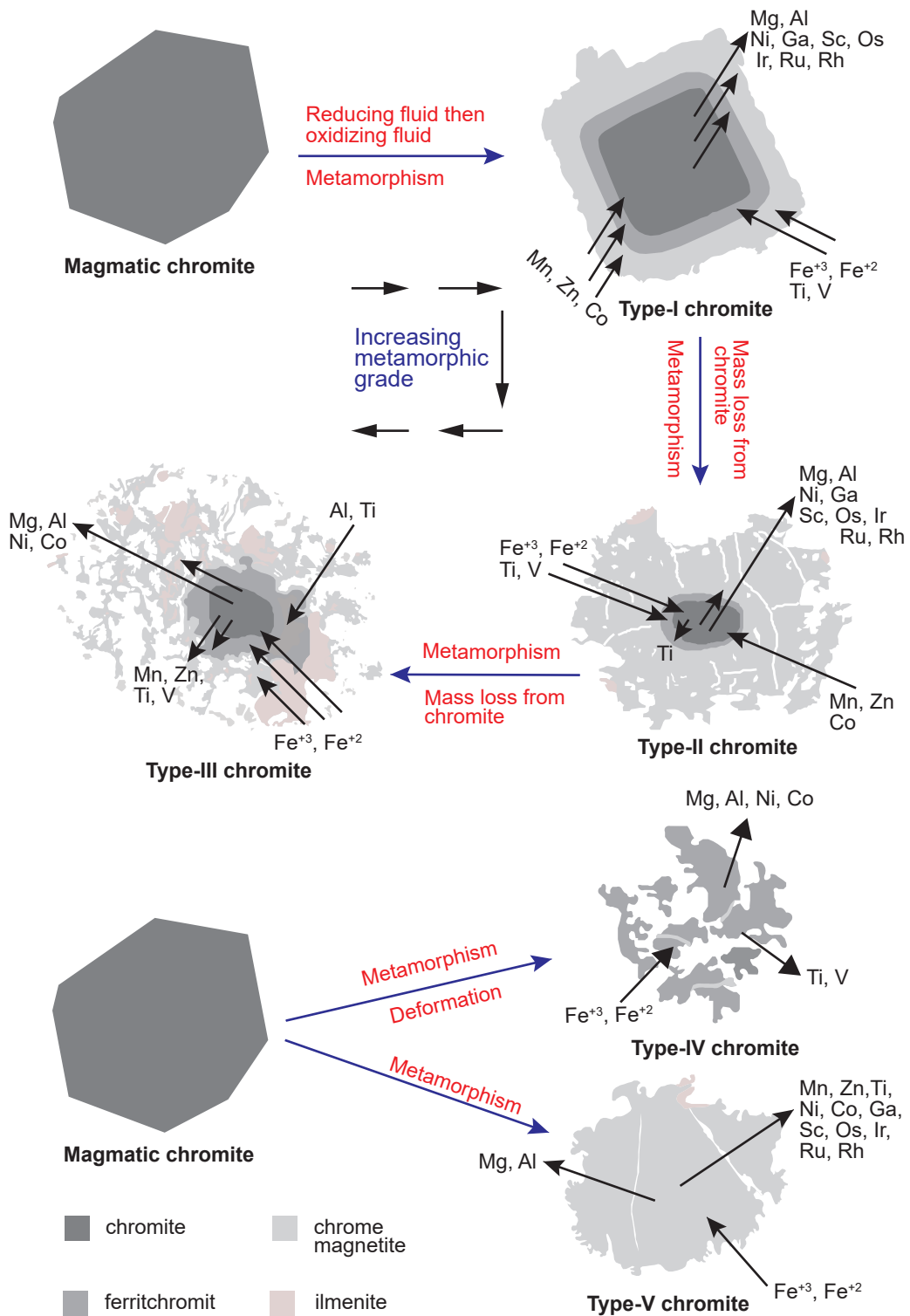


Table 1: Classification of komatiitic chromites from the Gorumahishani greenstone belt

Types of chromite	Study area	Host rock	Grain size	Textural and mineralogical character
Type-I	Tua Dungri	meta-dunite, meta-peridotite	~400 - 530 μm \times ~350 - 390 μm	Subhedral grain; non-porous low reflectance core and high reflectance ferritchromit to chrome magnetite rim with a sharp contact in between
Type-II	Southern part of Kapili	spinifex-textured meta-peridotite	~550 - 620 μm \times ~480 - 510 μm	Subhedral grain; low reflectance non-porous core with high reflectance thin ferritchromit rim, and wider, less porous chrome magnetite rim. Diffused contact in between cores and rims
Type-III	Northern part of Kapili	spinifex-textured meta-peridotite	~255 - 268 μm \times ~125 - 160 μm	Subhedral to anhedral grain; low and high reflectance inner rims with extensively porous outer chrome-magnetite envelope. Diffused contact in between cores and rims
Type-IV	Maharajgunj	meta-dunite, meta-peridotite	~30 - 50 μm \times ~70 - 100 μm	Anhedral grain; small fractured ferritchromit with almost homogeneous character. Occasionally, thin high reflectance magnetite rims are observed along the fracture planes
Type-V	Maharajgunj, Chuka Pahar, Tua Dungri, Kapili	meta-peridotite, spinifex-textured meta-peridotite, meta-basalt	~40 - 60 μm \times ~25 - 50 μm	Subhedral to euhedral grain. Optically and compositionally homogenous chrome-magnetite and magnetite with non-porous character

Table 2: EPMA major and minor elements compositional range (wt%) of komatiitic chromites from the Gorumahishani greenstone belt

Location	TD	TD	KL	KL	TD	KL	KL	TD	KL	KL	MG	All
Mineral	Chr	Chr	Chr	Chr	Fcmt	Fcmt	Al rich Chr	Chr mag	Chr mag	Chr mag	Fcmt	Chr mag
Type	T-I Core	S T-I core	T-II core	T-III core	T-I R1	T- II R1	T-III R1	T-I R2	T-II R2	T-III R2	T-IV	Type-V
Data (n)	36	8	11	13	22	5	8	25	16	5	3	21
wt.%												
Al ₂ O ₃	17.23-18.38	0.23-0.96	2.8-5.16	3.55-9.14	0.15-9.95	0.88-1.72	12.65-21.15	0-0.19	0.03-0.71	0.01-1.09	1.74-2.56	0-1.61
MnO	0.78-1.25	1.41-1.74	0.54-3.85	0.47-4.4	1.1-1.68	1.41-2.50	2.90-3.99	0.13-1.02	0.19-1.54	0.31-2.35	2.84-3.48	0-2.8
TiO ₂	0.08-0.25	0.26-0.79	0.32-1.51	0.47-2.5	0.23-0.92	1.47-2.79	4.50-7.46	0-0.31	0.13-1.65	0.11-1.34	0.63-1.75	0-7.67
Cr ₂ O ₃	44.45-46.84	33.04-44.62	45.59-56.79	41.19-58.06	26.89-42.54	16.92-27.03	23.47-28.96	5.03-24.20	4.69-13.26	2.83-22.73	34.2-42.1	0.92-19.57
MgO	2-3.75	0.04-0.35	1.25-3.13	0.84-6.24	0-0.68	0.51-1.55	0.81-2.86	0.04-0.52	0.15-1.05	0.13-0.18	0.32-0.54	0.02-5.68
SiO ₂	0.09-0.30	0.23-0.27	0.08-0.17	0.05-0.15	0.08-1.46	0-0.04	0.03-0.12	0-0.47	0-0.77	0.07-0.12	0.03-0.12	0-4.45
Fe ₂ O ₃	0.84-4.04	22.96-32.24	5.54-14.94	6.2-10.82	26.89-42.54	32.26-44.71	2.1-14.88	41.8-62.28	50.15-63.03	41.63-62.62	17.61-28.47	42.79-66.14
FeO	26.42-30.65	29.80-30.94	25.51-27.62	22.91-27.91	29.25-31.29	28.33-30.33	29.8-34.26	29.17-30.55	28.76-31.25	27.9-31.57	27.68-29.02	27.06-34.03
V ₂ O ₃	0.12-0.29	0.24-0.30	0.05-0.16	0.03-0.67	0.08-0.3	0.33-0.37	1.23-1.79	0.05-0.28	0.17-0.33	0.05-0.24	0.55-0.92	0-0.54
NiO	0-0.28	0.24-0.34	0.06-0.12	0-0.16	0-0.38	0.4-0.45	0.15-0.29	0.04-0.52	0.27-0.68	0.32-0.46	0.2-0.29	0-0.71
ZnO	1.63-2.11	0	1-2.41	0.28-3.03	0.52-0.88	0-1.45	1.64-5.48	0-0.38	0-0.63	0-1.16	1.29-1.61	0-0.62
CoO	0.02-0.23	0	0	0.02-0.23	0-0.16	0.12-0.27	0-0.32	0-0.14	0-0.16	0-0.07	0-0.11	0-0.31
Cation												
Al	5.387-5.867	0.084-0.343	0.989-1.747	1.231-3.108	0.055-3.408	0.323-0.618	4.260-6.617	0-0.067	0.010-0.223	0.005-0.397	0.623-0.908	0-0.589
Mn	0.175-0.311	0.365-0.446	0.130-0.976	0.110-1.092	0.280-0.431	0.313-0.654	0.702-0.952	0.034-0.263	0.049-0.400	0.080-0.616	0.736-0.885	0-0.750
Ti	0.017-0.061	0.022-0.181	0.070-0.339	0.107-0.541	0.053-0.208	0.347-0.637	0.936-1.581	0-0.072	0.031-0.379	0.025-0.311	0.143-0.402	0-1.825
Cr	9.456-9.651	8.026-9.735	10.783-12.882	9.396-12.718	6.456-9.780	4.146-6.499	5.138-6.350	1.249-5.786	1.153-3.214	0.689-5.575	8.193-10.004	0.231-4.829
Mg	0.820-1.484	0.019-1.159	0.559-1.333	0.360-2.575	0.002-0.310	0.233-0.701	0.343-1.132	0.020-0.236	0.068-0.494	0.059-0.082	0.145-0.248	0.009-2.517
Si	0.026-0.081	0.071-0.084	0.019-0.050	0.015-0.042	0.024-0.447	0-0.013	0.008-0.020	0-0.148	0-0.242	0.022-0.036	0.008-0.038	0-1.323
Fe ³⁺	5.238-7.452	0.764-7.452	1.198-3.364	1.361-2.343	2.366-9.067	7.385-10.431	0.420-3.198	9.683-14.713	11.575-14.584	9.719-14.530	3.983-6.493	9.803-15.624
Fe ²⁺	7.655-7.843	5.978-7.935	6.296-6.763	5.304-6.735	7.341-7.923	7.329-7.763	6.901-7.870	7.616-7.970	7.486-8.034	7.238-8.142	7.014-7.420	6.722-9.045
V	0.021-0.053	0.049-0.060	0.010-0.031	0.005-0.127	0.015-0.059	0.066-0.075	0.232-0.324	0.010-0.057	0.036-0.067	0.011-0.049	0.111-0.182	0-0.112
Ni	0-0.061	0.059-0.083	0.013-0.027	0-0.037	0-0.092	0.099-0.110	0.034-0.066	0.011-0.130	0.067-0.169	0.080-0.115	0.048-0.071	0-0.180
Zn	0.320-0.414	0	0.217-0.531	0.027-0.645	0.116-0.196	0-0.330	0.322-1.121	0-0.086	0-0.142	0-0.265	0.290-0.360	0-0.143
Co	0.004-0.050	0	0-0.043	0.004-0.050	0-0.038	0.028-0.067	0-0.072	0-0.034	0-0.037	0-0.018	0-0.026	0-0.079
Mg#	0.10-0.20	0-0.02	0.08-0.17	0.09-0.33	0-0.04	0.03-0.08	0.04-0.13	0-0.03	0.01-0.06	0.01	0.02-0.03	0-0.27
Cr#	0.62-0.64	0.97-0.99	0.88-0.91	0.75-0.91	0.74-0.99	0.91-0.93	0.45-0.56	0.99-1	0.92-0.99	0.93-1.00	0.91-0.93	0.69-1
Fe ³⁺ /R ³⁺	0.01-0.05	0.34-0.48	0.08-0.22	0.09-0.15	0.15-0.58	0.51-0.7	0.03-0.25	0.62-0.92	0.77-0.93	0.62-0.95	0.27-0.42	0.67-0.98

TD: Tua Dungri, KL: Kapili, MG: Maharajgunj, All: All locations i.e., Maharajgunj, Chuka Pahar, Tua Dungri, and Kapili; Chr: Chromite, Fcmt: Ferritchromit, Chr mag: Chrome magnetite, Cr-Spl: Chrome spinel; T-I, II, III, IV, V: Type-I, II, III, IV, V; S T-I: Small type-I; R1: Inner rim, R2: Outer rim.

Table 3: *In situ* LA-ICPMS trace elements compositional range (ppm) of komatiitic chromites from the Gorumahishani greenstone belt

Location	Tua Dungri	Kapili	Tua Dungri	Tua Dungri	Kapili	Kapili	Maharajgunj	Chuka Pahar
Mineral	Chromite	Chromite	Ferritchromit	Chr mag	Chr mag	Chr mag	Chr mag	Chr mag
Type	T-I core	T-II core	T-I inner rim	T-I outer rim	T-II outer rim	T-V	T-V	T-V
Data (n)	4	2	2	4	2	4	6	5
ppm								
Sc	2.62 - 5.40	3.39 - 5.68	0.35 - 0.53	0.01 - 0.96	0.22 - 0.92	0.70 - 2.47	0.10 - 0.32	0.10 - 1.20
Ti	534.70 - 1474.71	20758.92 - 36412.50	1097.34 - 1576.23	41.20 - 2369.50	1845.19 - 6247.98	2822.38 - 7855.66	450.83 - 2112.30	2899.36
V	863.76 - 1040.39	3337.90 - 7165.42	270.13 - 489.53	15.77 - 958.93	807.58 - 2316.46	1602.08 - 3102.78	477.59 - 1388.39	456.03 - 6110.31
Mn	6447.34 - 9946.79	27180.70 - 45891.24	3950.50 - 6453.32	196.29 - 11521.59	2107.26 - 6121.52	2834.59 - 6158.82	2761.42 - 7608.79	660.52 - 2307.15
Co	1037.17 - 1234.52	1744.47 - 2585.57	248.19 - 304.79	11.12 - 539.76	195.86 - 541.47	318.45 - 668.12	32.41 - 86.16	12.45 - 77.06
Ni	447.66 - 688.55	4512.85 - 10582.87	394.70 - 851.14	30.94 - 1944.89	1627.49 - 4705.06	3233.99 - 6688.57	847.92 - 4623.81	922.90 - 3328.77
Cu	0.09 - 2.38	0.23 - 3.13	0.04 - 0.34	<0.03 - 2.06	0.17 - 0.32	0.03 - 0.22	0.03 - 0.07	0.03 - 0.20
Zn	16865.87 - 18124.18	11664.55 - 15757.30	3454.17 - 3898.71	196.33 - 8346.21	627.38 - 1746.30	580.29 - 938.86	775.48 - 3159.17	626.47 - 2126.8
Ga	10.44 - 23.48	49.83 - 83.7	1.04 - 1.11	0.04 - 2.25	6.64 - 18.88	12.32 - 29.39	0.17 - 0.52	0.05 - 0.12
Cr ₂ O ₃	44.16 - 45.77	55.00 - 56.79	37.50 - 40.27	8.98 - 16.31	5.02 - 8.69	5.34 - 7.47	11.22 - 13.71	15.08 - 16.91
Al ₂ O ₃	17.14 - 17.61	3.69 - 4.68	0.49 - 1.48	0 - 0.06	0.12 - 0.42	0.21 - 0.37	0.38 - 0.93	0.13 - 0.23
MgO	3.04 - 3.71	2.23 - 2.79	0.46 - 0.48	0.04 - 0.11	0.31 - 1.05	0.27 - 0.36	0.07 - 0.16	0.15 - 0.20
FeO	26.42 - 27.30	26.54 - 26.69	29.03 - 29.69	28.97 - 30.50	28.76 - 29.43	29.45 - 29.66	29.57 - 29.85	28.27 - 28.91
Fe ₂ O ₃	3.82 - 4.00	5.92 - 7.27	24.45 - 27.44	50.11 - 57.70	55.93 - 58.60	57.48 - 60.31	50.72 - 55.1	48.75 - 50.11
Mg#	0.17 - 0.20	0.13 - 0.16	0.02 - 0.03	0 - 0.01	0.02 - 0.06	0.02	0 - 0.01	0.01
Fe ³⁺ /R ³⁺	0.05	0.08 - 0.10	0.35 - 0.41	0.74 - 0.86	0.85 - 0.91	0.87 - 0.91	0.77 - 0.81	0.73 - 0.76
Cr#	0.63 - 0.64	0.89 - 0.91	0.95 - 0.98	0.99 - 1.00	0.93 - 0.97	0.92 - 0.95	0.90 - 0.96	0.98 - 0.99

Chr Mag: Chrome magnetite; T-I, II, V: Type-I, II, and V; Mg#: Mg/(Mg+Fe²⁺), R³⁺: Fe³⁺+Cr+Al, Cr#: Cr/(Cr+Al); type-I, type-II, and type-V grains are analyzed from Korea Institute of Ocean Sciences and Technologies, South Korea (29 data points)

Table 4: *In situ* LA-ICPMS Platinum-Group Elements (PGEs) compositional range of komatiitic chromites from the Gorumahishani greenstone belt

Location	Tua Dungri	Kapili	Tua Dungri	Tua Dungri	Kapili	Kapili	Maharajgunj	Chuka Pahar	^a Global data
Mineral	Chromite	Chromite	Fcmt	Chr mag	Chr mag	Chr mag	Chr mag	Chr mag	Chromite
Type	T-I core	T-II core	T-I R1	T-I R2	T-II R2	T-V	T-V	T-V	
Data (n)	4	2	2	4	2	4	6	5	63
ppb									
Os	<5 - 8.8	8 - 8.3	<5	<5	<5	<5 - 7.3	15.6 - 33.4	19.7 - 29.8	5 - 54
Ir	7.6 - 12.4	8.9 - 12.3	8.1 - 13.4	5 - 11.4	<3	<3 - 13.5	17.3 - 35.7	12.4 - 23.8	14 - 101
Ru	127 - 163.2	98.1 - 123.1	116.9 - 197.4	127.5 - 206.7	8 - 11	8 - 211.5	86.2 - 110.9	72.2 - 140.6	87 - 336
Rh	28.9 - 32.6	4.4 - 4.9	29 - 38.1	33.6 - 44.8	<1	<1 - 14.4	2.7 - 5.7	2.9 - 8.9	7 - 95
Pt	<2	<12	<2	<2	<12	<12	<12	<12	<3 - <5
Pd	<14	<14	<14	<14	<14	<14	<14	<14	<1 - <4
Rh _N /Os _N	7.79	1.10		7.83 - 19.72		1.90	0.08 - 0.22	0.10 - 0.35	2.94 - 3.69
Rh _N /Ir _N	5.77 - 8.84	0.87 - 1.08	6.28 - 7.92	8.19 - 20.28		2.34	0.17 - 0.48	0.40 - 0.93	1.10 - 2.07
Rh _N /Ru _N	0.60 - 0.77	0.12 - 0.13	0.58 - 0.74	0.49 - 0.97		0.07	0.03 - 0.05	0.03 - 0.07	0.24 - 0.85
Ru _N /Os _N	12.99	8.27		18.00		29.11	2.86 - 5.52	2.43 - 6.25	4.36 - 12.18
Ru _N /Ir _N	7.52 - 14.75	7.31 - 8.10	10.64 - 10.84	8.19 - 20.28		11.48	1.96 - 3.65	3.38 - 5.32	2.44 - 4.56
Ir _N /Os _N	0.88	1.02		0.99		1.86	0.84 - 1.31	0.53 - 0.93	1.79 - 2.67
Cr ₂ O ₃	44.16 - 45.77	55.00 - 56.79	37.50 - 40.27	8.98 - 16.31	5.02 - 8.69	5.34 - 7.47	11.22 - 13.71	15.08 - 16.91	41.20 - 56.70
Al ₂ O ₃	17.14 - 17.61	3.69 - 4.68	0.49 - 1.48	0 - 0.06	0.12 - 0.42	0.21 - 0.37	0.38 - 0.93	0.11 - 0.23	8.60 - 18.80
MgO	3.04 - 3.71	2.23 - 2.79	0.46 - 0.48	0.04 - 0.11	0.31 - 1.05	0.27 - 0.36	0.07 - 0.16	0.15 - 0.20	9.90 - 14.10
FeO	26.42 - 27.30	26.54 - 26.69	29.03 - 29.69	28.97 - 30.50	28.76 - 29.43	29.45 - 29.66	29.57 - 29.85	28.27 - 28.91	12.70 - 19.30
Fe ₂ O ₃	3.82 - 4.00	5.92 - 7.27	24.45 - 27.44	50.11 - 57.70	55.93 - 58.60	57.48 - 60.31	50.72 - 55.10	48.75 - 50.11	4.50 - 10.70
Mg#	0.17 - 0.20	0.13 - 0.16	0.03	0 - 0.01	0.02 - 0.06	0.02	0 - 0.01	0.01	0.48 - 0.66
Fe ³⁺ /R ³⁺	0.05	0.08 - 0.10	0.35 - 0.41	0.74 - 0.86	0.85 - 0.91	0.87 - 0.91	0.77 - 0.81	0.73 - 0.76	0.06 - 0.13
Cr#	0.63 - 0.64	0.89 - 0.91	0.95 - 0.98	0.99 - 1.00	0.93 - 0.97	0.92 - 0.95	0.90 - 0.96	0.98 - 0.99	0.60 - 0.82

Fcmt: Ferritchromit, Chr mag: Chrome magnetite; T-I, II, V: Type-I, II, V; R1: inner rim, R2: outer rim; Mg#: Mg/(Mg+Fe²⁺), R³⁺: Fe³⁺+Cr+Al, Cr#: Cr/(Cr+Al);

^aGlobal dataset for chromites from Finland komatiite and picrite, and Greenland, Kamchatka, Troodos, and Emeishan picrites (Data from Park et al. 2017)

Table 5: Empirical partition coefficient of trace elements ($D^{Cr\text{-spinel-silicate melt}}$)

Sample	MIC/16/39			SHB/19-12/82	
Type	T-I C	T-I C	T-I C	T-II C	T-II C
Location	Tua Dungri	Tua Dungri	Tua Dungri	Kapili	Kapili
D_{Sc}	0.37	0.45	0.38	0.26	0.15
D_{Ti}	0.13	0.12	0.12	12.28	6.77
D_V	14.21	14.34	14.08	109.52	37.21
D_{Mn}	2.69	2.57	2.51	32.65	17.81
D_{Co}	12.10	11.99	11.58	37.66	23.52
D_{Ni}	0.24	0.28	0.26	12.13	4.95
D_{Ga}	8.46	11.04	8.44	20.87	11.78

T-I C: Type-I core, T-II C: Type-II core

Table 6: Empirical partition coefficient of IPGEs and Rh ($D^{Cr\text{-spinel-silicate melt}}$)

Sample	MIC/16/39				SHB/19-12/82	
Type	T-I C	T-I C	T-I C	T-I C	T-II C	T-II C
Location	Tua Dungri	Tua Dungri	Tua Dungri	Tua Dungri	Kapili	Kapili
D_{Ru}	67.86	51.73	49.79	51.74	35.51	45.43
D_{Rh}	36.94	36.66	36.71	32.21	4.40	4.94
D_{Os}		4.45			8.18	8.45
D_{Ir}	2.72	2.73	4.18	2.54	2.23	3.10

T-I C: Type-I core, T-II C: Type-II core

Fractionation of trace and platinum-group elements during metamorphism of komatiitic chromites from the early Archean Gorumahishani greenstone belt, Singhbhum Craton (eastern India)

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Detailed information on the geological background of the Singhbhum craton and analytical methods

Geological background

The Singhbhum Craton in eastern India is bounded by the Singhbhum mobile belt to the north, the Satpura metamorphic belt to the northwest, the granulite facies Eastern Ghat mobile belt in the southeast with a tectonic contact marked by the Sukinda thrust, and the alluvium of the Bengal basin to the east (Saha 1994) (**Fig. 1a**). The Archean granitic-gneissic nucleus of the craton is surrounded by the greenschist to amphibolites facies volcano-sedimentary supracrustal rocks of the greenstone belts (**Fig. 1a**). Among the supracrustal rocks, the Older Metamorphic Group (OMG: 3.55 Ga zircon age, Mishra et al. 1999) shows the metamorphic events clustering at 3.4, 3.35, and 3.2 Ga (Goswami et al. 1995; Mishra et al. 1999; Upadhyay et al. 2014, 2019). The OMG is consisting of pelitic schist, arenite, para-amphibolite, and ortho-amphibolite (e.g. Saha 1994) that were intruded by Older Tonalite-Trondhjemite-Granodiorite (OMTG) rocks consist of thin compositionally layered, tonalitic to granodioritic gneisses along with granites (e.g. Saha 1994). Voluminous granitic rocks constitute the Singhbhum Granite Batholithic Complex (SGBC) with their emplacement in three successive phases (I, II, and III; Saha 1994) along with the OMTG rocks at 3.45 - 3.44 Ga and 3.35 - 3.32 Ga (Upadhyay et al. 2014) (**Fig. 1a**). Chaudhuri et al. (2018) reported a U-Pb age of 4.24 - 4.03 Ga of xenocrystic zircons from the OMTG rocks. The volcano-sedimentary rocks of the greenstone belts belonging to the Iron Ore Group (IOG) supracrustal sequences are distributed in the Gorumahisani-Badampahar, Noamundi-Jamda-Koira, and Tomka-Daitari belts (e.g. Acharyya 1993; Mondal 2009) (**Fig. 1a**). Komatiites and komatiitic basalts are the main volcanic sequences that are intercalated with the sedimentary sequences of phyllite, tuffaceous shale, banded hematite jasper with iron ore, quartzites, and dolomite (Sahu and Mukherjee 2001; Chaudhuri et al. 2015, 2017; Yadav et al. 2015, 2017; Mondal et al. 2019) (**Fig. 1b-e**). Mukhopadhyay et al. (2008) have

determined a U-Pb zircon age of 3.5 Ga from the dacitic lavas of the Tomka-Daitari belt and Basu et al. (2008) have determined a U-Pb zircon age of 3.4 Ga from a tuff layer within the Noamundi-Jamda-Koira belt. Adhikari et al. (2021a) have determined the Sm-Nd isochron age of ~ 3.6 Ga for the metabasaltic rocks of the Tomka-Daitari greenstone belt.

Mesoarchean to late Archean Dhanjori-Jagannathpur-Malangtoli-Simlipal volcano-sedimentary belts surround the rocks of the older greenstone belts (OMG and IOG) and granite-gneiss complexes of the OMTG and the SGBC (e.g. Mondal 2009) (**Fig. 1a**). Adhikari et al. (2021b) have determined the Sm-Nd isochron age of 2799 ± 67 Ma for the basaltic rocks from the Jagannathpur-Malangtoli belt. Mesoarchean to late Archean Nuasahi-Sukinda-Mayurbhanj complexes with chromite, Ni-Cu-sulfides, PGE and Ti-V-magnetite deposits are the major ultramafic-mafic plutonic suites in the craton (e.g. Mondal et al. 2007; Manikyamba et al. 2020; Bhattacharjee and Mondal 2021; Mondal et al. 2021) (**Fig. 1a**). The mafic dyke systems of Mesoarchean to late Proterozoic ages are exposed within the SGBC of the craton (e.g. Mazumder and Chaudhuri 2019; Srivastava et al. 2019; Dey and Mondal 2021) (**Fig. 1b**).

Analytical methods

Back-scattered electron (BSE) imaging and microanalysis of the mineral phases (oxides and silicates) of a total of 8 representative samples were carried out using a CAMECA SXFive EPMA instrument at DST-SERB National Facility, Department of Geology, Banaras Hindu University (India). Another 14 samples were analyzed by 4-WDX CAMECA SX-100 EPMA at the Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur (India). The CAMECA SXFive EPMA was operated by SXFive Software at a voltage of 15 kV and beam current of 10 nA whereas the 4-WDX CAMECA SX-100 EPMA was controlled by a

beam current of 15 nA and acceleration voltage of 20 kV. Natural mineral standards fluorite, apatite, albite, halite, periclase, peridotite, corundum, wollastonite, orthoclase, rutile, chromite, rhodonite, celestite, barite, hematite, crocoite, pyrite, and synthetic Ag₂Te, InAs, InSb, Ni, Co, Cu, Zn metal supplied by CAMECA-AMETEK were used for routine calibration and quantification during analysis. Routine calibration, acquisition, quantification, and data processing were carried out using SxSAB version 6.1 and SX-Results software of CAMECA. ZAF matrix corrections were performed by the CAMECA-supplied PAPSIL software. Representative data of mineral compositions are presented in **Table 1** (silicates and carbonates), and **Table 2** (oxides), and the complete data sets are also available in **Appendix 03: Table S1-S2**.

Trace element and PGE contents in chromite, ferritchromite, and chrome-magnetite were also measured by an LA-ICP-MS system for selected elements (Sc, Ti, V, Mn, Co, Ni, Cu, Zn, Ga, Os, Ir, Ru, Rh, Pt, Pd) consisting of a New Wave 193 nm ArF excimer laser and an Agilent 7800 quadrupole ICP-MS at Korea Institute of Ocean Sciences and Technologies, South Korea. The ablation conditions were a 10 Hz repetition rate, an 80-100 μm beam size and ~ 5 J/cm² energy density. The NIST 610 glass was used as a primary standard and Al contents measured by a microprobe was an internal standard element for calculating trace element. Representative data of trace elements from chromite are presented in **Table 3** and the complete data set is available in **Appendix 03: Table S3**. The sulfide reference material UQAC-FeS-1 was used as a primary standard and Fe contents as an internal standard element for platinum-group elements (PGE). The data reduction was conducted by Lolite software (Paton et al. 2011). The isobaric interference by metal oxides (MO+) and metal argides (MAR+) were checked by analyses of pure Cu metal (C-430, Fisher Scientific Company) and PGE-free synthetic Ni-sulphide. The expected isobaric interferences are ~1

ppb Ru per 1000 ppm Ni and ~7 ppb Rh per 1000 ppm Cu in Cr-spinels, which result in negligible isobaric interferences of $^{61}\text{Ni}^{40}\text{Ar} +$ and $^{63}\text{Cu}^{40}\text{Ar} +$ on ^{101}Ru and ^{103}Rh (<2 %) for most samples. Any micro inclusions, identified as spikes in time-resolved spectra data, were excluded when calculating the concentrations. Multiple analyses (n=7) of Cr-spinels from Kamchatka picrite (Ty24) were performed using the UQAC-FeS-1 reference material to externally monitor the quality of the PGE data. Our results are consistent with the values reported in Park et al. (2017) within 1 standard deviation as reported in **Appendix 03: Table S4**. Representative data of PGE are also presented in **Table 4**.

For whole-rock analysis, samples were cleaned, crushed, and pulverized to a 200-mesh size in the Department of Geological Sciences, at Jadavpur University. The crushing and pulverization work was carried out by single bowl RO milling systems (Model MBM 07, Insmart systems). The grinding was carried out by high energy frequent impact of agate (99.9% SiO₂, 7.0Mohs hardness, and 2.65 g/cc density) balls. At 600 rpm, 100 g of the sample was crushed by the machine in 45 min. Whole-rock major, trace, and platinum-group elements alongside C and S were conducted from Intertek Genalysis, Perth, Western Australia. For major elements, approximately 0.7g was catch weighed into a platinum crucible and this was mixed with a pre-weighed amount of flux which was comprised of a mixture of lithium tetraborate and lithium metaborate. An oxidant was added and the sample was fused to produce a homogeneous melt which was cast into a platinum mould to produce a fusion disk. The fusion disk was analysed on a Panalytical Axios sequential wavelength-dispersive X-ray fluorescence spectrometer. Calibration was affected by standard glass beads of known composition. Corrections were made for the catch weights, instrumental drift, line overlaps and inter-element enhancement/absorption matrix effects as well as moisture (done by the TGA). Standard OREAS 24b was used as reference material

for this case. LOI was analyzed using a TGA or thermo gravimetric analyzer. The instrument weighed the inert crucible. Approximately 1 g of sample was added to the crucible. The instrument weighed the crucible and sample. The mass of the sample taken was determined by difference. The sample was then heated to constant mass at 105°C and weighed. The mass lost as a fraction of the mass taken was the moisture. The sample was then heated to constant mass at 1000°C and weighed. The mass lost as a fraction of the dry mass was the loss on ignition or LOI. For trace elements, the pulped samples are catch weighed at 0.20g ± 0.02g into a Teflon tube. The tube was placed in a rack and the digesting acids are added sequentially with nitric acid pre-oxidation of sulphides. The rack was placed on a “hot block” which provides even heat to decompose the sample and ensure to ensure maximum dissolution. The perchloric (HClO₄) acid was evaporated and the residue leached by boiling in HCl. The solution was transferred to a polystyrene tube where it was volumed and mixed. A further dilution of the digest solution was required before reading on the Agilent 7900 ICPMS with collision cell technology. Calibration was affected using solution standards of known concentration. Standard OREAS 45h is used for trace elements analysis. For platinum-group elements (PGE) analysis the pulped samples were catch weighed at 25grams and mixed with a flux and fired in a furnace. When fired, the flux sample mixed forms a nickel sulphide matte and an immiscible slag which separate owing to density differences. The precious metals were collected in the nickel sulphide matte (button). The button was separated from the slag, weighed and pulverized. A portion of the pulverized button was catch weighed and dissolved in boiling HCl. The addition of various reagents to the boiling HCl solution and careful observation of the dissolution process ensures that the platinum group elements and gold were quantitatively recovered by filtration as insoluble residues. These residues were dissolved in aqua regia. The solution was diluted and read on an ICP

mass spectrometer with collision cell technology to remove polyatomic interferences, especially first-row transition element argide species. Internal standards are used to correct for drift and plasma fluctuations. The results are corrected for the various catch weights and the button weight by the LIMS system. Standard OREAS 13b was used for PGE+Au analysis. Carbon (C) and Sulfur (S) analysis was performed in an Eltra CS800 Carbon–Sulphur Analyser. The pulped sample was weighed out and placed in a ceramic crucible. An accelerant was added to act as a flux and improve fluidity and oxidation of the carbon and sulphur. Heating was accomplished in a high-frequency induction furnace as this provides both speed and accuracy. Any sulphur or carbon was converted to gaseous oxides. These gases absorb infrared radiation at specific wavelengths which were proportional to the concentration of the C or S in the sample. Any water in the sample was removed by passing the gases produced through magnesium perchlorate as water interferes with the analysis. Calibration was affected by the standard of known C and S concentration. Standard OREAS 600b was used here as reference material. The complete whole-rock data set is presented in

Appendix 03: Table S5.

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Fractionation of trace and platinum-group elements during metamorphism of komatiitic chromites from the early Archean Gorumahishani greenstone belt, Singhbhum Craton (eastern India)

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Supplementary online material for figures

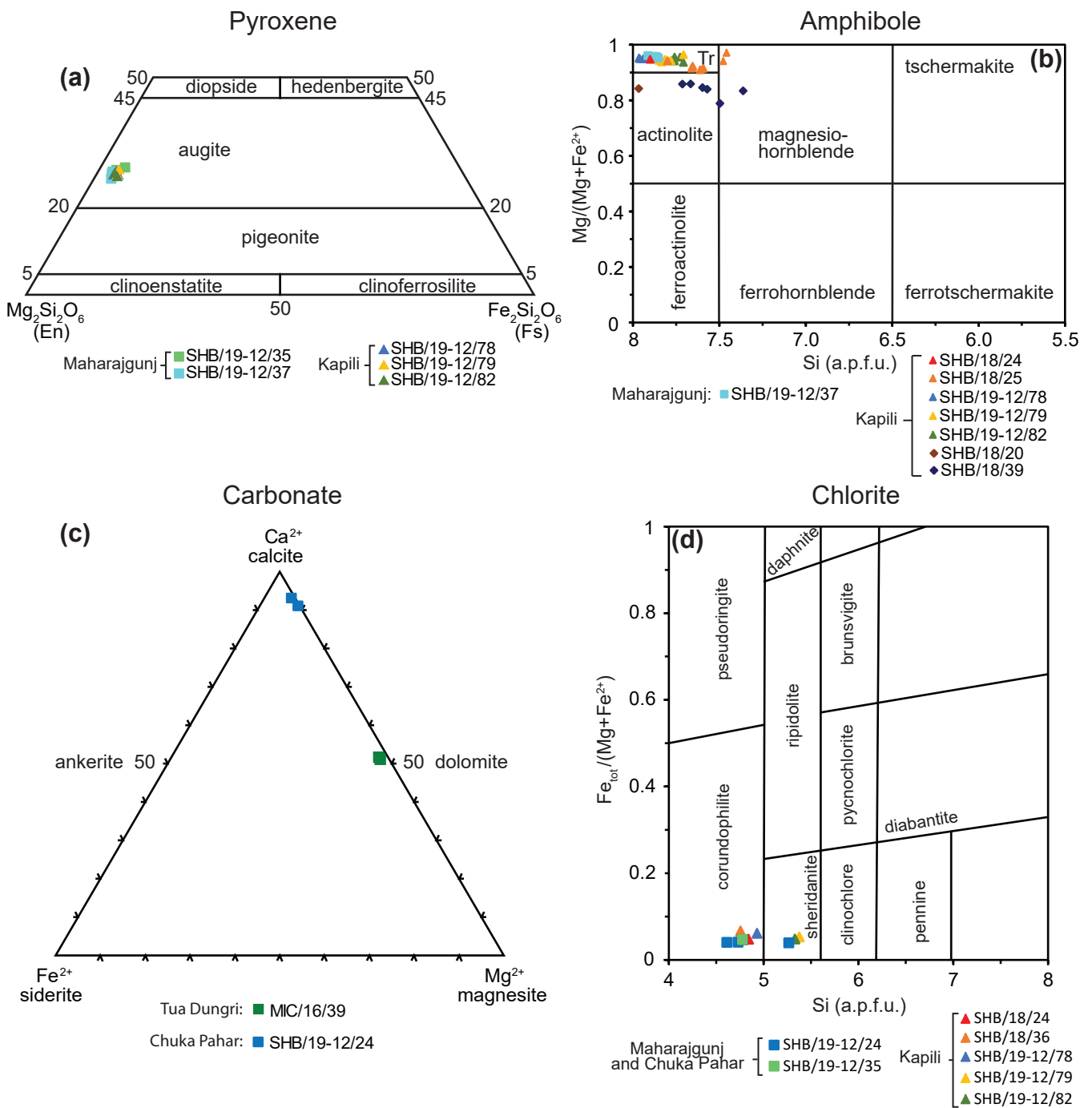


Fig. S1 (a) Classification of pyroxene (after Morimoto 1988), (b) amphibole (after Leake et al. 1997), (c) carbonate, and (d) chlorite (after Hey 1954) from the komatiitic suite of rocks from the Gorumahishani greenstone belt.

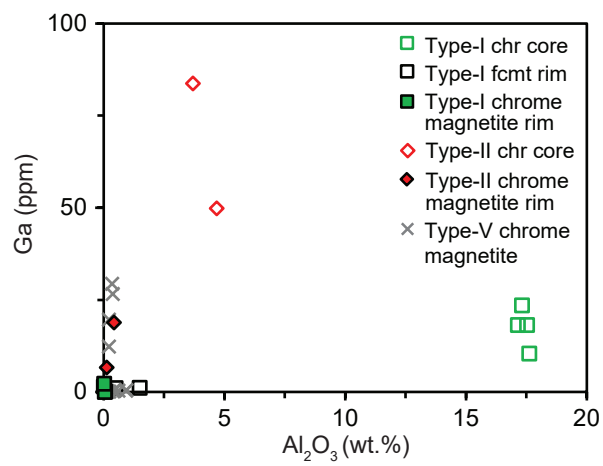


Fig. S2 Compositional variations of the type-I, type-II, and type-V chromite grains: Al₂O₃ vs Ga plot.

Type-V chrome magnetite

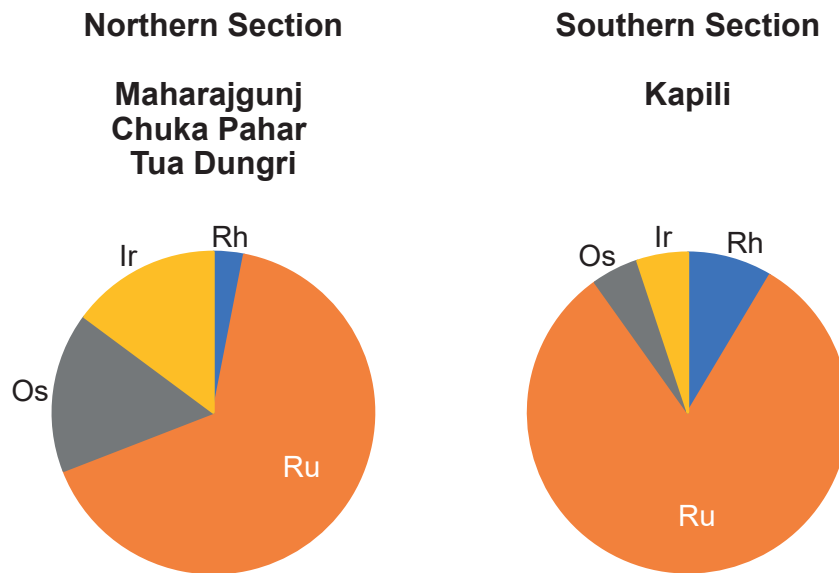


Fig. S3 Variation in platinum-group elements concentration (in ppb) of the type-V chrome magnetite grains from the northern and southern part of the Gorumahisani greenstone belt.

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