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Title: Nickel in olivine as an exploration indicator for magmatic Ni-Cu sulfide deposits: a data review and re-evaluation.

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1 **Nickel in olivine as an exploration indicator for magmatic Ni-Cu**
2 **sulfide deposits: a data review and re-evaluation**

3 **REVISION 1**

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13 **Abstract**

14 Nickel contents of olivine have been widely used as petrogenetic indicators and as fertility indicators
15 for magmatic sulfide potential of mafic-ultramafic intrusions, on the assumption that olivines
16 crystallized from magmas that had equilibrated with sulfide liquid should be relatively depleted in Ni
17 compared with a sulfide-free baseline. This has given rise to a large accumulation of data that is
18 brought together here, along with data on volcanic olivines, to critically evaluate the effectiveness of
19 the approach. We identify multiple sources of variance in Ni content of olivine at given Fo content,
20 including: variability in mantle melt composition due to depth, water content (and possibly source);
21 subsequent fractional crystallization with and without sulfide; recharge and magma mixing; batch
22 equilibration between olivine and sulfide at variable silicate-sulfide ratio (R) and olivine/liquid ratio;
23 and subsequent equilibration during trapped liquid crystallization in orthocumulates. Baselines for Ni
24 in olivine in relation to Fo content are somewhat lower in orogenic belt settings relative to intrusions
25 in continental Large Igneous Provinces (LIPs). This is probably related to differences in initial parent
26 magma compositions, with plume magmas generally forming deeper and at higher temperatures. No
27 clear, universal discrimination is evident in Ni in olivine between ore-bearing, weakly mineralized
28 and barren intrusions even when tectonic setting is taken into account. However, sulfide-related
29 signals can be identified at intrusion scale in many cases. Low-R factor, low-tenor sulfides are
30 associated with low-Ni olivines in a number of examples and these cases stand out clearly.

31 Anomalously high-Ni olivines are a feature of some mineralized intrusions, in part due to trapped
32 liquid reaction effects. However, in some cases, this mechanism cannot account for the magnitude
33 of enrichment. In these cases, enrichment may be due to re-entrainment of “primitive” Ni-rich
34 sulfide by a more evolved Fe-rich magma, driving the olivine to become Ni-enriched due to Fe-Ni
35 exchange reaction between sulfide and olivine during transport. An extreme case of this process
36 may account for ultra-Ni enriched olivine at Kevitsa (Finland), but more subtle signals elsewhere
37 could be positive indicators. A lack of clear mineralized/barren distinction in specific groups of
38 related intrusions, e.g. the deposits of NW China or the Kotalahti Belt in Finland, may well be due to
39 “false negatives” where undiscovered mineralization exists in specific intrusions or in their feeder
40 systems, or may also be due to a multiplicity of confounding factors. Wide variability of both Fo and
41 Ni between related intrusions at regional scale may be a useful regional prospectivity indicator,
42 more than an intrusion-scale discriminant, and is certainly informative as a petrogenetic indicator. In
43 general, the use of Ni-olivine as a fertility tool is more likely to generate false negatives than false
44 positives, but both are possible, and the technique should be used as part of a broader weight-of-
45 evidence approach.

46 *Keywords: magmatic sulfides, nickel deposits, mantle melting.*

47 Introduction

48 The Ni content of olivine has been used over several decades as an indicator of potential host rocks
49 to magmatic Ni-Cu sulfide deposits (Häkli, 1971; Naldrett et al., 1984; Li and Naldrett, 1999; Barnes
50 et al., 2004; Makkonen et al., 2008; Barnes and Fiorentini, 2012; Le Vaillant et al., 2016). More
51 generally, Ni in olivine has been widely used as a petrogenetic indicator to infer mantle magma
52 sources (Sobolev et al., 2005; Sobolev et al., 2007; Li and Ripley, 2010) and deep-seated petrogenetic
53 processes (Hart and Davis, 1978; Zhang et al., 2005; Herzberg et al., 2016; Matzen et al., 2017b;
54 Gleeson and Gibson, 2019). Its potential usefulness as a prospectivity indicator arises from the
55 compatible and chalcophile character of Ni, which has a strong tendency to partition both into
56 olivine and much more strongly into sulfide liquid from coexisting silicate melt (Duke, 1979; Naldrett
57 et al., 1984; Kiseeva and Wood, 2015; Yao et al., 2018). Consequently, competition for Ni between
58 co-precipitating sulfide and olivine should produce olivine depleted in Ni relative to olivines that
59 have never “seen” sulfide liquid. This effect was modelled in detail in the only previous global review
60 of the topic (Li et al., 2007). However, more recent experimental data on the strong dependency of
61 partitioning behaviour of Ni into olivine with temperature (Li and Ripley, 2010; Matzen et al., 2017a;
62 Matzen et al., 2017b; Pu et al., 2021) together with effects of recharge and magma mixing (Gleeson
63 and Gibson, 2019) introduce important confounding factors into the interpretation. Furthermore,

64 olivine compositions may be modified considerably by post-cumulus processes (Barnes, 1986) which
65 can generate Ni enrichment in some circumstances (Barnes and Naldrett, 1985; Li and Naldrett,
66 1999; Ding et al., 2010). These multiple factors, among others considered here, have not been fully
67 considered in previous studies,

68 In this contribution, we combine an empirical data-driven approach with quantitative modelling of
69 the various factors controlling olivine compositions in sulfide-saturated and undersaturated
70 magmas. We employ a large compilation of data on Ni in olivine from volcanic and intrusive rocks,
71 including all the published data we have been able to locate on mineralized and unmineralized
72 mafic-ultramafic intrusive rocks over a wide range of ages and tectonic settings. From this dataset,
73 we assess whether systematic differences exist that would enable reliable discrimination of
74 mineralized intrusions. Such a tool would potentially be applicable in target selection at the early
75 stage of regional exploration campaigns and also in vectoring towards mineralization in well-
76 explored terranes. This approach has already been investigated for komatiite-hosted magmatic
77 sulfide systems and shown to be effective at prospect scale in some cases, such as the Agnew-
78 Wiluna Belt of the Yilgarn Craton (Barnes and Fiorentini, 2012; Le Vaillant et al., 2016), although
79 signals are commonly confounded by flushing of mineralized lava channels post ore formation
80 (Barnes et al., 2013b). Here we focus primarily on application to mineralization within small mafic-
81 ultramafic intrusions in continental large igneous provinces (LIPs) and orogenic belts.

82 Method

83 Olivine chemistry data has been compiled from large number of literature sources listed in
84 Supplemental Table 1 and from the GEOROC online database ([http://georoc.mpch-
85 mainz.gwdg.de/georoc/](http://georoc.mpch-mainz.gwdg.de/georoc/))(Lehnert et al., 2000; Sarbas, 2008). Data plotting and data density
86 contouring was done with the ioGas geochemical plotting software. In all cases data are from
87 electron microprobe microanalysis, which typically reports Ni contents down to hundreds of ppm
88 with precisions around 5-10% of measured abundance. Tabulation of individual precision estimates
89 for the many dozens of different data sources was not attempted, but readers are referred to
90 original sources (Supplementary Table 1) for further details. A full listing of data compilation used in
91 this study is available at <https://zenodo.org/record/5787901> or via the CSIRO Data Access Portal at
92 doi: *(to be advised)*.

93 Samples were classified on the basis of volcanic/intrusive status (volcanic, small intrusions and large
94 layered intrusions); combined tectonic setting and age (large igneous provinces and convergent
95 margins, Phanerozoic and Proterozoic) and for intrusion samples, three categories of mineralization
96 status of the host intrusion: M(inedralized), containing economic accumulations of Ni-Cu sulfide;

97 (D)isseminated, containing economic or sub-economic disseminated Ni-Cu sulfide mineralization
98 only; and (B)arren, either no sulfide mineralization at all as far as is known, or only minor
99 disseminations. These distinctions are inevitably somewhat arbitrary and based on best available
100 data. In many of the plots, summary “data clouds” for particular groupings are represented as
101 smoothed kernel data density contours determined in the loGas plotting software. In most cases
102 except where stated contours enclose the 50th and 90th percentiles on data point density.
103 Modelling calculations follow the procedures and assumptions of Yao et al. (2018). These are
104 described in appendix 1.

105 Results

106 Background olivine compositions in Phanerozoic basalts

107 Compositions of olivine phenocrysts in basalts provide a useful baseline for comparison, in that they
108 are least likely to have been modified by the processes that affect cumulate rocks in intrusions. A
109 dataset of over 20,000 analyses, assembled by Sobolev and co-workers (Sobolev et al., 2007), is
110 shown in summary form in Figure 1 along with additional data from convergent margin basalts from
111 the GEOROC database (Sarbas, 2008). Wide variability was noted by Sobolev et al. (2007) in relation
112 to tectonic setting, such as basalts from continental large igneous provinces (CLIPS) and from intra-
113 oceanic plumes associated with old, thick oceanic lithosphere. This gives rise to distinctly different
114 baseline ranges for CLIPS, oceanic LIPs and hotspot chains (OLIP) and MORBs, which are distinctly
115 lower in olivine Ni than the other two categories for given Fo content. Since many of the potential
116 target intrusions for magmatic sulfide deposits occur within mid-plate LIPs, the CLIP basalt dataset
117 (Figure 1B) makes a useful baseline for comparison for these cases. The approximate 75th percentile
118 data density contour on the CLIP data (black outline on Figure 1 B,C) (with the outlying
119 Gudchichinsky Picrite suite from Siberia excluded) is reproduced in some of the diagrams that follow.

120 *Figure 1*

121 Volcanic olivine compositions from convergent margins (Figure 1D) show a somewhat contrasting
122 pattern with the LIP data cloud. The bulk of the data sets overlaps with the LIP data, but clusters of
123 points fall both well above and well below. Oceanic arc olivines have a distinctly bimodal
124 distribution, whereby a distinct group of primarily oceanic arc-associated olivines falls well below the
125 LIP cloud at the higher Fo end (Fig. 1D).

126 Comparison of intrusion hosted olivines between tectonic settings

127 Modelling of olivine compositions from variably hydrated and variable depth sources (see below)
128 indicates that we would expect significantly different baseline trends for magmas from deep-

129 sourced continental LIPs relative to magmas formed by shallow flux melting in arcs. The effect of
130 melting depth (melting beneath thick and thin lithosphere) was pointed out by (Sobolev et al., 2005,
131 2007). For this reason we combine continental LIP and intracratonic layered intrusions such as
132 Bushveld together as one category, and orogenic belts with likely arc associations as another (Figure
133 2) in establishing baselines for comparison of mineralized versus unmineralized intrusions. A caveat
134 is needed here in that in some cases “orogenic belt” localities may be sampling plume magmas
135 emplaced along craton margins and caught up in collisional events; this is particularly an issue in
136 highly deformed Proterozoic orogens such as the Albany-Fraser Orogen in Western Australia. For
137 purposes of this study, we include all such occurrence in the Orogenic Belt category but
138 acknowledge the strong possibility of misclassification. Data for unmineralized intrusions only are
139 plotted in Figure 2. Layered intrusions containing stratiform PGE Reef mineralization are considered
140 unmineralized for this purpose, on the grounds that the magmas parental to the reefs could not
141 have interacted previously with large proportions of sulfide liquid.

142 A major problem in empirical comparisons of this type is a sampling bias towards mineralized
143 intrusions; they tend to be more common subjects of academic study than barren intrusions and
144 exploration companies drill more holes into sulfide-bearing bodies. Furthermore, there may well be
145 a false negative bias in that where an intrusion is known to contain sulfides its classification is clear,
146 whereas “barren” intrusions may simply contain as yet undiscovered mineralization. As an
147 additional baseline for comparison, we have therefore included a field for expected olivine
148 compositions derived by fractional crystallization from the plausible range of mantle-derived basaltic
149 magmas generated by 10% or more partial melting, based on the modelling of Yao et al. (2018). This
150 field is labelled “MSFM” for “model sulfide free mantle melts” in Figure 2 and subsequent Ni vs Fo
151 plots. The derivation of these model values is discussed in detail below.

152 *Figure 2.*

153 The data clouds shown in Figure 2 are clearly distinct between the continental LIP (CLIP+LMI) and
154 Orogenic Belt (OB) categories, with the latter having consistently lower Ni for the same Fo content.
155 We therefore need to consider different baselines for these two different tectonic settings.
156 Furthermore, the data set for CLIP-associated intrusions shows a considerably broader spread than
157 the field for volcanic olivines, particularly at low Fo contents.

158 In the following sections, we compare olivine compositions for mineralized and unmineralized
159 intrusions from CLIP and OB settings. Implicit in this comparison is the major uncertainty of “false
160 negatives” as noted above, which should be borne in mind through the discussion.

161 Mineralized vs barren, CLIP settings

162 Figure 3 shows a comparison of data points for olivines in variably mineralized mafic-ultramafic
163 intrusions in intraplate continental Large Igneous Province (CLIP) settings (including large
164 intracratonic layered intrusions), plotted over the data density cloud for unmineralized CLIP-
165 associated intrusions. In this plot and those that follow, intrusions hosting economic sulfide-rich
166 mineralization are plotted as red symbols, with symbol shapes indicating locality, while green
167 symbols denote intrusions containing disseminated and/or minor subeconomic mineralization only.
168 The bulk of the data fall within the “unmineralized” data cloud, with three localities as major
169 exceptions. Kabanga (Tanzania) shows consistently strong Ni depletion in the main ore-hosting
170 intrusion (Maier et al., 2010; Maier et al., 2011). Voisey’s Bay (Labrador, Canada, red circles) defines
171 a field of widely varying Ni and Fo with Fe-rich olivine compositions extending to below Fo45. Nickel
172 contents vary by a factor of up to 7 over the same Fo. In the Kevitsa Intrusion (northern Finland) the
173 range of variability is a factor of 20 over a limited range in Fo. As well as a cluster of strongly
174 depleted olivines, the Kevitsa dataset includes some extreme examples of Ni enrichment (Yang et al.,
175 2013) falling outside the scale limits of this plot; these are discussed further below in the case-study
176 section below. The main conclusion at this stage is that there is no universal evidence for consistent
177 Ni depletion in mineralized compared with unmineralized intrusions, but distinct signals can be
178 recognized in some specific cases. Wide variability for limited range in Fo appears to be the most
179 consistent signal in mineralized intrusions. It is noteworthy that a large portion of the data cloud falls
180 above the theoretical field (MSFM field on Figure 3) for olivines derived from sulfide-free mantle
181 melts.

182 Figure 3.

183 Mineralized vs barren, orogenic belt settings

184 An exactly equivalent comparison to that in Figure 3 is shown in Figure 4 for combined Phanerozoic
185 and Proterozoic orogenic settings (bearing in mind that some of the localities included in this
186 category could be misallocated plume associations). The same conclusion applies: there is no clear
187 evidence for consistent Ni depletion in mineralized compared with unmineralized intrusions.
188 However, as in the CLIP category, mineralized intrusions occupy a wider range, with Ni falling both
189 above and below the unmineralized baseline and show a wide variability of Ni for similar Fo
190 contents. The most clearly anomalous mineralized intrusions are the Savannah intrusions in the Halls
191 Creek orogen that show localized strong enrichment, and a group of intrusions (Moxie, Maine; St
192 Stephen, New Brunswick and Rana, Northern Norway) within the Appalachian-Caledonide orogen
193 that shows consistently Ni depleted olivine (Figure 4B). The Beja intrusion, Portugal, host to minor

194 disseminated sulfides (Jesus et al., 2020), straddles the 90th percentile “barren” contour but
195 contains a high proportion of significantly Ni-depleted olivines at low Fo. We consider some of these
196 localities further below as case studies. The Xiarihamu deposit in the East Kunlun orogenic belt in
197 Tibet shows a distinctive signal of widely variable Ni at a restricted range of high Fo contents,
198 somewhat similar to the Poyi intrusion in the Central Asia Orogenic Belt in China. Comparing
199 Phanerozoic and Proterozoic settings, Phanerozoic intrusions appear to be more likely to show
200 recognisable Ni depletion, as noted by Jesus et al. (2020). This may be an association with depth of
201 emplacement, noting that several of the Proterozoic intrusions (Savannah, Kotalahti Belt, Nova)
202 were emplaced at mid to lower crustal depths.

203 Compared with the theoretical model field for olivines derived from sulfide-free basalts (MSFM
204 outline), evidence for Ni depletion is seen in the localities mentioned above, along with some
205 samples from Xiarihamu, Ntaka Hill, Nova and several of the Chinese CAOB deposits. Samples from
206 Savannah plot well above the MSFM field.

207 *Figure 4.*

208 **Comparison within individual magmatic provinces**

209 In this section, we consider some specific examples from both orogenic and CLIP categories where
210 multiple intrusions co-exist within a restricted province with and without significant mineralization.

211 LIP related: Kabanga–Musongati–Kapalagulu Belt, Tanzania

212 The Kabanga deposit is located in a relatively small chonolith-style intrusion within the 1.4 Ga
213 Kabanga–Musongati–Kapalagulu (KMK) mafic–ultramafic belt that extends for >500 km from Uganda
214 to Lake Tanganyika in the Great Lakes region of East Africa (Deblond and Tack, 1999; Evans et al.,
215 2000; Duchesne et al., 2004; Maier et al., 2007; Maier et al., 2010). This belt is considered to form
216 part of a LIP developed along the NW margin of the Tanzanian Craton (Mäkitie et al., 2014). The belt
217 contains both relatively large, mafic-ultramafic layered intrusions of several km thickness and tens of
218 square km in surface and subsurface outcrop (e.g., Musongati and Kapalagulu) and numerous sills
219 and chonolith bodies consisting largely of harzburgite, pyroxenite and gabbro, with
220 thicknesses on the order of m to hundreds of m (e.g., Kabanga).

221 The Kabanga North-MNB body, one of the smallest intrusions in the belt, has a tubular chonolith
222 morphology measuring up to 150 m in diameter. The body has been delineated by drilling for ~1.4
223 km in a NE–SW direction. The Kabanga Main intrusion is a sill-like body with a relatively narrow
224 (2km), trough-like lower portion and an upper segment of greater width (~4km). Its thickness may
225 be on the order of 500m. The ~500-m-thick MNB body was discovered in 2001 while drilling for
226 extensions of the Kabanga North body. The MNB extends over >2 km strike length and bears

227 considerable similarity to the Kabanga Main body. It may thus represent the extension of Kabanga
228 Main at depth. The Block 1 intrusion, 4 to 5 km to the SW of Kabanga Main, consists of a thick (~
229 800m) pile of mafic-ultramafic cumulates containing abundant disseminated low-tenor sulfides.

230 The heavily mineralized intrusions of the Kabanga locality stand out clearly as having strongly Ni
231 depleted olivines, with the most advanced depletion being in the Upper KM Sill, Block 1 and the
232 MNB body (Figure 5). This is the clearest example in the entire dataset of strong Ni depletion
233 associated with high degrees of crustal contamination and abundant sulfides having low Ni tenors.
234 Kabanga sulfides have low Ni (<1–3 wt%), Cu (~0.1–0.4 wt%), and PGE contents (\ll 1 ppm), high
235 Ni/Cu (5–15), and low Ni/Co (10–15) and Pd/Ir (2–20). Sulfides with higher metal contents (up to
236 ~5% Ni, 0.8% Cu, 10 ppm PGE) are found in only one unit from Kabanga North, which significantly
237 has markedly less Ni depleted olivine, albeit still depleted relative to the CLIP “Barren” baseline. The
238 observed metal contents of the Kabanga sulfides are consistent with segregation of magmatic
239 sulfides from fertile to strongly metal-depleted magmas, at intermediate to very low mass ratios of
240 silicate to sulfide liquid (R factors) of approximately 10–400.

241 The Kapalugulu intrusion, approximately 300 km south of Kabanga, is a large layered intrusion
242 containing chromitite and associated PGE concentrations. It contains sulfide mineralization only in a
243 proposed feeder zone and shows undepleted olivines in samples from the unmineralized layered
244 cumulate sequence.

245

246 *Figure 5.*

247 **Proterozoic Orogenic Belt: Halls Creek Orogen, Australia.** The Savannah (formerly Sally Malay) and
248 Savannah North deposits, along with the smaller Copernicus deposit, are located within a belt of 1.8
249 Ga mafic and mafic-ultramafic intrusions, the Sally Malay Suite, within the Halls Creek Orogen of
250 Western Australia (Mole et al., 2018; Le Vaillant et al., 2020). The magmatism is thought to be
251 related to a slab break-off event during the collision of the North Australian and Kimberley Craton
252 (Kohanpour et al., 2017). The Savannah deposit occupies the lower edge of a now rotated bladed
253 dyke (Barnes and Mungall, 2018) and the adjacent Savannah North deposit occupies a basal contact
254 position within a separate small layered intrusion with probable funnel geometry. A group of
255 petrographically similar intrusions within about 10 km of Savannah has been sampled by regional
256 scale exploratory drilling, which has located only minor occurrences of disseminated sulfide. On this
257 basis, Savannah and Savannah North samples represent the mineralized category while the
258 remainder are considered barren.

259 Most of the olivines analysed from this suite fall within the “barren” baseline for orogenic settings
260 (Figure 6), and Savannah North is indistinguishable in olivine chemistry from the barren Dave Hill and
261 Wilson’s Creek bodies, aside from one data cluster at high Fo and low Ni that probably does reflect
262 sulfide-related depletion. The notable exception is the Savannah Intrusion, which contains
263 substantially more Ni enriched olivines within the layered peridotite and olivine norite layers that
264 occupy the interior of the dyke. These rocks are primarily mesocumulates, and no systematic
265 difference in olivine composition is recognisable with sulfide or olivine mode, such that the
266 displacement from the cluster of Savannah North olivines cannot simply be explained by trapped
267 liquid equilibration. The Savannah Intrusion evidently formed from a more Ni rich carrier magma
268 than the other components of the Sally Malay suite. However, this contrast is not evident in the Ni
269 tenors of the Savannah and Savannah North sulfide rich ores, which are 3.5-5 wt% and 2-3.5 wt%
270 respectively. Both orebodies are strongly PGE depleted (Le Vaillant et al., 2020) implying prior
271 extraction of sulfide liquid.

272 For this data set, we have also investigated the extent to which Fo-Ni variability is distinguishable on
273 the basis of the sulfide content of individual samples (Figure 6B). Most of the analysed samples from
274 the Savannah intrusion are sulfide-free, from the interior of the intrusion, showing the distinctive Ni
275 enrichment characteristic of this body, but some mineralized samples are also Ni enriched. There is
276 an almost complete overlap (with the exception of the highest Fo sample) between sulfide-bearing
277 and sulfide-free samples in the Savannah North intrusion. This confirms that recognition of indicative
278 Fo-Ni signals does not rely on sampling sulfide-bearing rocks.

279 *Figure 6.*

280 **Phanerozoic Orogenic Belt, Central Asian Orogenic Belt, NW China.** About a dozen economic
281 magmatic Ni-Cu sulphide deposits occur at the southern margin of the Central Asian orogenic belt
282 (CAOB) in NW China (Mao et al., 2008; Lu et al., 2019), with a few deposits occur in the
283 southeasternmost part of CAOB, such as the Hongqiling deposit in NE China (Wei et al., 2013; Lu et
284 al., 2019). These NW China deposits could be classified into four groups by spatial distribution: the
285 Beishan, Central Tianshan, Eastern Tianshan, and south Chinese Altai groups from south to north.
286 over a total distance of close to 1000 kilometres. They were predominately formed in the Permian
287 (Qin et al., 2011; Su et al., 2011). The host rocks of these NW China deposits are enriched in hydrous
288 phases and show arc-like geochemical characteristics, suggesting that the related magmas were
289 derived from metasomatized mantle sources which have been modified by the subduction events
290 prior to the Permian. Most researchers propose that the Permian magmatism in the south (Beishan,
291 Central Tianshan, and Eastern Tianshan) of NW China was associated with the partial melting of
292 metasomatized mantle driven by either the coeval Tarim mantle plume (Qin et al., 2011; Su et al.,

293 2011) or asthenosphere upwelling induced by lithosphere delamination (Song et al., 2011a; Zhang et
294 al., 2011). The Permian magmatism in the Chinese Altai is thought to be triggered by a slab break-off
295 event (Zhang et al., 2009; Li et al., 2012). Ore-hosting magmatic bodies of these deposits come in a
296 variety of shapes, i.e. elongated rhomboid, kernel-shaped flares, tube-like or dyke-like, and have
297 surface areas less than 2 km². Several have been interpreted as variants on the theme of “blade-
298 shaped dykes” (Barnes and Mungall, 2018). Sulphide mineralization mainly occurs at the bases of
299 these magmatic bodies, with few exceptions locating at the central to upper zones, such as the
300 Huangshandong mafic body and the Tulaergen deposit.

301 Olivine-rich cumulates are the predominant host to the sulphides in the NW China deposits.
302 Lherzolite and olivine websterite are the most prevalent rock types in the intrusions, such as the
303 Tianyu and Baishiquan deposits in the Central Tianshan, Huangshandong, Huangshanxi,
304 Huangshannan, Xiangshanzhong, Tudun, Tulaergen, and Hulu deposits in the Eastern Tianshan.
305 Dunite is one of the main rock types of the intrusions from the Beishan, such as the Poyi and Poshi
306 intrusions (Xue et al., 2016). The Kalatongke deposit comprises 14 small mafic intrusions, with the
307 orebodies mostly hosted by the Y1 and Y2 intrusion. Olivine grains are common in the Y1 intrusion,
308 where olivine norite is the main rock type, but rarely found in the others. (Zhang et al., 2009; Gao
309 and Zhou, 2013; Mao et al., 2021). The olivine from the NW China deposits has variable Fo values
310 (from 70 to 90 mol%) (Figure 7). Generally, the Ni content in olivine decreases with decreasing Fo
311 value (Figure 7), as expected for simple fractional crystallization. For each deposit, the Ni variation
312 cannot be adequately produced by fractional crystallization alone. For instance, the Poyi olivines
313 show wide Ni variation (from 1500 to 3500 ppm) but subtle Fo variation (88-89 mol%).

314 The intrusions of this province show no clear discrimination on the basis of olivine chemistry
315 between mineralized and weakly or unmineralized intrusions (Figure 7). The mineralized
316 Huangshanxi intrusion shows a wide range in Ni, 400-1750 ppm, over a restricted range in Fo, but
317 similar ranges are seen in unmineralized and weakly mineralized bodies also. Huangshandong
318 contains both Ni-depleted and Ni-enriched olivine at relatively low Fo contents, whereas Kalatongke
319 shows a grouping of relatively Ni-enriched olivines at around Fo75 compared with the rest of the
320 CAOB data set, although less enriched than the olivines at Savannah (Figure 6). Notably, these
321 Kalatongke samples are primarily sulfide-bearing orthocumulates, whereas the more Fo-rich samples
322 from Poyi and others are adcumulate to mesocumulates. Huangshannan stands out as having
323 strongly Ni-enriched olivines relative to the rest of the province, and to orogenic-setting intrusions
324 generally, over a range of Fo contents. The distinctive character of the Huangshannan and
325 Kalatongke olivines may be related to trapped liquid effects, as discussed below. With reference to

326 the modelled sulfide-free olivine (MSFM) field, distinct depletion is seen in Tulaergen (most
327 samples), Huangshanxi, Hunangshandong, Honqiling, Xiarihamu, and Poyi.

328 Also included in this comparison is the Xiarihamu deposit, a small ultramafic-dominated intrusion of
329 Paleozoic age in the East Kunlun orogenic belt in Tibet, containing a large accumulation of
330 disseminated sulfides (Li et al., 2015; Song et al., 2016; Song et al., 2020), entirely unrelated to the
331 CAOB suite. It is marked by a very wide range of Ni contents at a relatively high and narrow range of
332 Fo contents, similar to Poyi.

333 As in the previous section for the Savannah area intrusions, sufficient data are available to subdivide
334 individual samples on their sulfide content (Figure 7B). Depletion signals are present in sulfide-free
335 as well as sulfide-bearing samples from the same intrusion (e.g. Poyi, Honqiling), although Ni-
336 enriched olivines (Kalatongke and Huangshandong) tend to be restricted to sulfide-bearing samples.
337 This can be taken as evidence for Ni enrichment being due to trapped liquid equilibration effects,
338 discussed further below.

339 *Figure 7.*

340 **Proterozoic orogenic belt: the Svecofennian (Raahe-Ladoga) Orogenic Belt, Finland.** The
341 Svecofennian Orogenic Belt (also known as the Raahe-Ladoga Belt, or the Kotalahti Nickel Belt) is a
342 Paleoproterozoic (1.88 Ga) belt of polydeformed gneisses and amphibolites extending through
343 central Finland (Makkonen et al., 2008; Makkonen, 2015). It is co-eval and probably correlative with
344 the Vammala Nickel Belt in the south west of Finland. The belt contains over a dozen distinct mafic
345 and mafic-ultramafic intrusions, several of which – Rytky, Kotalahti, Hitura and Enankoski – contain
346 mined or subeconomic Ni-Cu sulfide deposits (Makkonen et al., 2008; Makkonen, 2015), along with a
347 suite of mafic metavolcanic rocks at least some of which are considered to be co-magmatic with
348 these intrusions (Barnes et al., 2009). Most of these intrusions are deformed and in some cases
349 dismembered and are considered to have been emplaced during the peak of metamorphism in the
350 belt (Makkonen et al., 2015). The weakly differentiated, dominantly ultramafic Vammala-type
351 intrusions consist almost entirely of olivine cumulates and represent magma conduits. The more
352 strongly differentiated, mafic and mafic-ultramafic, Kotalahti type intrusions consist of olivine
353 cumulates, pyroxene cumulates, and plagioclase-bearing cumulates. The parental magma was
354 basaltic with MgO contents mostly around 10–12 wt%. The mineralized intrusions show chemical
355 evidence for crustal contamination. Makkonen et al. (2008) identified Ni-depleted olivine in the
356 mineralized intrusions. Some of the mineralized intrusions contain complexly zoned cumulus and
357 poikilitic pyroxenes, features not observed in similar rock types from the unmineralized bodies
358 (Schoneveld et al., 2020).

359 A new compilation of olivine data drawing on Makkonen et al. (2008) and Lamberg (2005) is shown
360 in Figure 8. There is no clear-cut discrimination between the mineralized and barren intrusions, but
361 some indicative features are present. Distinct depletion is evident at low Fo contents in the weakly
362 mineralized Ylivieska intrusion; the mineralized Rytky intrusion shows a wide range in Ni from 600 to
363 2400 ppm for a restricted range of 81-84 mol % Fo; the Nirimaki intrusion shows a similar trend to
364 Rytky but displaced to lower Fo; and the weakly mineralized Laukukangas body shows a grouping of
365 high-Ni, low Fo olivine similar to those seen at Kalatongke in the CAOB (Figure 7). Data for several of
366 the intrusions (Luusniemi, Ylivieska, Heimonvouri) fall to the lower Ni end of the range of Ni in this
367 tectonic setting, and well below the data cloud for plume-related settings.

368 *Figure 8.*

369 **Ural-Alaskan Complexes.** Ural-Alaskan Complexes are a rare but widely distributed component of
370 orogenic belts in the Phanerozoic and Proterozoic, and in some cases contain sub-economic Ni-Cu
371 sulfide mineralization, usually in the form of disseminated sulfides (Thakurta et al., 2008). Examples
372 of this are the Duke Island Intrusion in Alaska (Li et al., 2013; Thakurta et al., 2014) and the
373 Turnagain Complex in British Columbia (Clark, 1980). Olivine data from these intrusions are
374 compared with the data contours on barren orogenic belt intrusions in Figure 9. Duke Island and
375 some samples from Turnagain, along with the Akarem Complex in Egypt, which also contains
376 disseminated mineralization (Helmy and Mogessie, 2001) contain distinctly Ni-depleted olivines
377 falling well below the reference field and showing wide variability in Ni for limited Fo.

378 *Figure 9.*

379 **The Kevitsa intrusion, Finland.** The 2.058 Ga Kevitsa intrusion (Mutanen, 1997; Santaguida et al.,
380 2015; Luolavirta et al., 2017; Luolavirta et al., 2018) is located in the Central Lapland greenstone belt
381 in northern Finland. It is part of a suite of small to medium sized mafic-ultramafic intrusions,
382 including the large Koitelainen layered intrusion as well as the neighbouring Sakatti intrusion hosting
383 the Cu-Ni Sakatti deposit. These intrusions range in age from 2.1 Ga to 1.8 Ga (Huhma et al., 2013).
384 They are emplaced into a volcanic suite containing komatiites. The Kevitsa intrusion occupies a
385 surface area of approximately 16 km² and consists of a lower ultramafic unit up to 2 km in thickness,
386 overlain by a mafic unit over several hundred metres thick. The ultramafic unit is composed of
387 interlayered olivine pyroxenite and websterite, with local development of cyclic units, but for the
388 most part lacking obvious internal layering (Santaguida et al., 2015), but showing inward-dipping
389 cryptic layering defined by variations in the sulfide tenors (Le Vaillant et al., 2017). The Kevitsa Ni-Cu-
390 (PGE) deposit occurs in the middle part of the ultramafic unit, associated with variably layered
391 olivine pyroxenites and websterites. The deposit consists entirely of disseminated sulfides with
392 widely varying Ni, Cu and PGE tenors, with a published combined resource of 237 Mt at 0.28% Ni,

393 0.41% Cu and 0.6 ppm 3E (Pt + Pd + Au) (Geological Survey of Finland website, 2016) with Ni grades
394 up to around 0.6% (99th percentile on all assays in the database). The mineralization has been
395 separated into different ore types, mainly on the basis of their Ni-PGE tenors showing a broadly
396 layered distribution with higher tenors generally at higher levels within the stratigraphy (Le Vaillant
397 et al., 2017). Low tenor disseminated but locally net-textured ores form near the base of the
398 intrusion and along the margins of the Cu-Ni mineralization are classified as “false ore”. This
399 pyrrhotite-rich mineralization has Ni tenors less than 1% and is typically associated with abundant
400 country rock xenoliths. The “regular” or “normal” ore represents the bulk (>90%) of the economic
401 resource and is characterized by 2–6 vol% of sulfides (pyrrhotite, pentlandite, and chalcopyrite) and
402 average Ni and Cu ore-grades of 0.3 and 0.4 wt% respectively (Santaguida et al., 2015) with a range
403 of Ni tenors between 1 and 10 % and PGE tenors between about 1 and 5 ppm. The volumetrically
404 minor “Ni–PGE ore” has a similar sulfide content to that of the Normal ore, but the sulfides are
405 predominantly pentlandite, pyrite and millerite. These ores have higher and more variable Ni grades,
406 lower Cu grades (Ni/Cu = 1.5–15), and extreme Ni tenors ranging as high as 30%, attributed to high R
407 factors in olivine-rich suspensions (Barnes et al., 2013a) with a likely, possibly assimilated komatiitic
408 component (Yang et al., 2013). Pockets of Ni-PGE ore are developed throughout the orebody but the
409 main development is in the upper part of the section (Le Vaillant et al., 2017).

410 The Kevitsa occurrence provides a useful case study in the variability of olivine compositions (Figure
411 10) within a single extensively mineralized intrusion that shows a wide range in nickel tenors. The
412 most striking feature of the dataset is the presence of a group of ultra-Ni-rich olivines within the Ni-
413 PGE ores (Yang et al., 2013), but the dataset is also characterized by strongly Ni-depleted olivines
414 associated with the very low Ni-tenor False Ores (Luolavirta et al., 2017). The False Ores are
415 interpreted to be the opposite case to the Ni-PGE rich ores: the result of very restricted equilibration
416 between abundant assimilated sulfide and a poorly-stirred, high viscosity crystal mush (Le Vaillant et
417 al., 2017), or alternatively as the result of extensive pre-emplacment fractional extraction of sulfide
418 (Luolavirta et al., 2018). Within the strongly Ni-enriched part of the data set, distinct linear arrays are
419 developed at sample scale where Ni correlates negatively with Fo (Figure 10B): this is a hallmark of
420 sample-scale trapped liquid equilibration, as discussed further below.

421 *Figure 10.*

422 **Nova-Bollinger.** The Mesoproterozoic Nova – Bollinger Ni-Cu – sulfide ore deposit is located in the
423 Albany-Fraser Orogen in Western Australia (Maier et al., 2016). The host-rocks are mafic - ultramafic
424 intrusive cumulates subdivided into two connected intrusions, designated Upper and Lower (Figure
425 11). The Upper Intrusion is bowl-shaped and modally layered with alternating peridotite and norite
426 mesocumulate layers, with a basal series of dominantly orthocumulate mafic lithologies. The Lower

427 is a much thinner semi-conformable chonolith (flattened tube-shaped intrusion) comprising mostly
428 unlayered mafic to ultramafic orthocumulates (Taranovic et al., 2021). The Lower Intrusion hosts all
429 the high-grade mineralization and most of the disseminated ores. A distinctive plagioclase-bearing
430 lherzolite containing both orthopyroxene and olivine as cumulus phases is a characteristic of the
431 Lower Intrusion and the basal series of the Upper. The intrusions were emplaced under peak
432 metamorphic conditions at around 20-25 km depth into granulite facies paragneisses which
433 underwent partial melting during extensive infiltration of sulfides into the footwall (Barnes et al.,
434 2020). The geometry of the intrusions and the disposition of the sulfides suggest that the Lower
435 intrusion formed as an apophysis off the base of the Upper, propagating westward into the footwall
436 rocks (Taranovic et al., 2021). Nova-Bollinger ores contain Ni tenors in the 5-9% range (Barnes et al.,
437 2021).

438 *Figure 11.*

439 A wide spread of Ni and Fo contents is present. The most Ni-depleted Fo rich olivines are located
440 within the upper part of the Upper Intrusion, and also within the Lower intrusion where the two
441 intrusions diverge. Less Fo rich olivines with trends towards Ni enrichment are in the Lower (ore-
442 bearing) intrusion (Figure 11). The Lower Intrusion rocks are distinctly more orthocumulate such that
443 the trend towards lower Fo and higher Ni can be attributed to trapped liquid effects, as discussed
444 further below. This is particularly clear in the purple diamond symbols in Figure 11A. However, the
445 most significant feature of the Nova data set is the presence of a widespread group of low-Ni, high-
446 Fo samples located predominantly in the Upper Intrusion, and particularly in the entirely
447 unmineralized layered ultramafic cumulates higher in the sequence (Figure 11B). This is significant
448 from an exploration viewpoint in that the Lower Intrusion is entirely blind to the surface; recognition
449 of Ni depletion in these ostensibly barren upper cumulate layers would be a pathfinder to the
450 orebodies.

451 The choice of baseline for Nova is problematic. While the setting is undoubtedly a convergent
452 margin orogenic belt (Spaggiari et al., 2015), the Fraser Zone magmatic complex to which Nova
453 belongs is a large volume mafic suite with a restricted age range and trace element characteristics
454 that could be interpreted as plume-like, indicative of a LIP affinity (Taranovic et al., 2021). If the
455 Fraser Zone is indeed a LIP, then the low-Ni, high Fo olivines of the Upper intrusion are definitively
456 depleted. Regardless, the Ni in olivine signal of the Nova-Bollinger intrusions is clearly positive for
457 mineralization.

Discussion: controls on olivine Fo-Ni variations in sulfide-bearing magmatic systems

As we have seen, intrusion-hosted olivines show wide and complex variability in Ni-Fo trends, even within the same intrusion, indicating that sulfide melt equilibration is only one of a number of factors influencing the Ni content of olivine. Some of these factors are considered and modelled in the following section.

Range of variability of Ni in carrier magmas

The silicate magmas that form magmatic sulfide ores (carrier magmas) are known to have a wide range of Ni contents, from ~1600 ppm in primitive komatiites to ~100 ppm in some mafic-hosted systems (Barnes et al., 2016). The ability of relatively low-Ni mafic magmas to form deposits with economic Ni contents arises from the very high partition coefficient D_{Ni} of Ni between sulfide and olivine; this D_{Ni} value increases strongly with falling temperature and hence is considerably higher in basalt than in komatiite (Kiseeva and Wood, 2015). The same effect applies to D_{Ni} between olivine and silicate melt (Li and Ripley, 2010; Matzen et al., 2013; Matzen et al., 2017a; Matzen et al., 2017b; Pu et al., 2021). The effect of this T dependence on olivine Ni contents gives rise to the observed wide variability in the Ni contents of primary mantle melts, (Li and Ripley, 2010; Yao et al., 2018) and basalt-hosted olivines (Sobolev et al., 2007; Herzberg et al., 2016), (Figure 1), a variability that could be further enhanced by variability in the pyroxene:olivine ratio in mantle sources (Sobolev et al., 2005). The presence of pyroxene-rich mantle-source regions has been proposed as a major controlling factor on the range of olivine compositions in various Chinese deposits (Song et al., 2011b; Song et al., 2011c; Lu et al., 2019), but remains a hotly debated topic beyond the scope of this contribution.

We have carried out a series of model calculations on compositions of potential carrier magmas and associated olivines generated at a variety of depths and primary water contents and undergoing fractional crystallization, following the methods of Yao et al. (2018). A representative series of these curves are shown in Figure 12, for conditions corresponding to sulfide undersaturation (i.e. no sulfide liquid involved during melting or fractional crystallization) and appropriate values for the crystallization pressure (1 kbar), water content (1 wt% H₂O) and oxygen fugacity (QFM-1). The emplacement depths of most these mafic-ultramafic intrusions are probably shallow, resulting in a relatively narrow pressure range varying from 0.5 to 2.5 kbar (Norilsk, (Yao and Mungall, 2021); Bushveld, (Maier et al., 2013)), which has little influence on the trendlines of Ni in the crystallized olivine grains (Appendix Fig. A1-a). The addition of water into the parental magma will decrease the olivine saturation temperature and enhance the olivine stability during crystallization (dropping to a

491 lower Fo number), but the partition coefficient of Ni between olivine and melt has been shown to
492 have a negligible dependence on water content (Pu et al., 2021). The combined effects of water
493 content on the Ni trendlines of olivine grains is confirmed to be slight when the initial H₂O in the
494 parent magma varies from 0 to 3 wt% (Appendix Fig. A1B). The oxygen fugacity of plume-associated
495 magmatism may mostly vary from QFM-2 to QFM, while the parental magma derived by flux-melting
496 of mantle wedge can have a higher oxygen fugacity that can even reach QFM+2. These most oxidized
497 conditions are within the range where most of the S in the magma would be dissolved as S⁶⁺ rather
498 than S²⁻ such that sulfide formation is inhibited (Jugo et al., 2005), so can be disregarded in this
499 context. In both settings, for fO_2 below QFM+1, the variation of fO_2 simply drives a limited horizontal
500 movement of the trendlines of Ni contents (Appendix Fig. A1C, D) because a higher fO_2 results in the
501 increase of Fe³⁺/Fe²⁺ in melt, which further elevates the Fo content of olivine. Hence, the variations
502 of crystallization conditions have only a limited impact on the modelled Ni trendlines. The reader is
503 referred to Appendix 1 for more detailed discussion of the modelling.

504 These curves are used to define a range for model olivine compositions that can be derived from
505 plausible mantle partial melts, taking the upper limit as the uppermost plume model curve at any Fo
506 and the lower as the 10% partial melt in the depleted MORB mantle (DMM) flux model. This range is
507 plotted as a reference field on the data plots shown above.

508 Aside from this reference field, the main conclusions from the modelling are

- 509 1. the curve for olivine fractionation in plume magmas changes over a factor of about 50%
510 (2400 to 3600 ppm) between pyroxenite-free and 30% pyroxenite sources, but converges to
511 similar values with fractionation. The range between sources gives model trends that match
512 reasonably well with the CLIP basalt data array, but fall to the low end compared with
513 intrusion-hosted olivines.
- 514 2. Models involving flux melting from hydrated depleted mantle generate lower Ni in olivine
515 for the same Fo, but also (probably for the same reason) fall at the lower Ni side of the field
516 for intrusion hosted olivines. Natural olivines from convergent margin lavas show a wide
517 spread of Ni at high Fo contents.

518 *Figure 12*

519 The consistent difference between olivine Ni contents in LIP relative to orogenic belt settings above
520 probably arises largely from these primary controls on the compositions of the carrier magmas.
521 More generally, it provides a major confounding effect on the ability to discern sulfide extraction
522 history in magma suites from olivine compositions alone, reinforcing the need to use different
523 baselines when comparing LIP settings with convergent margin settings.

524 Fractional crystallization of olivine + sulfide liquid

525 In most models of olivine evolution in sulfide-saturated systems, sulfide is assumed to be segregated
526 from the carried magma along with the fractional crystallization of olivine in some defined
527 proportion. In the models shown in Figure 13, olivine compositions are shown for fractional
528 crystallization of two starting liquids: a plume melt including a 50% contribution from a “pyroxenite”
529 mantle corresponding to the uppermost curve in Figure 12A, and from a melt generated by flux
530 melting of depleted mantle (Figure 12B) as the proportion ratios of olivine and sulfide in each
531 crystallization increment are assumed as 50, 100, 200 and 500. The partition coefficient of Ni
532 between sulfide and melt is from the formulation of Kiseeva and Wood (2015). As expected,
533 variation in the proportion of olivine to sulfide from 50 to 500 produces a change over a factor of 4-5
534 in Ni in olivine. Various estimates of the proportion of sulfide to olivine under cotectic conditions
535 (i.e. fractionation of olivine plus sulfide liquid exactly along the sulfide saturation surface) have been
536 made, using various parameterizations of the sulfide content at sulfide liquid saturation (SCSS) as a
537 function of melt chemistry and temperature (Ariskin and Barmina, 1999; Li and Ripley, 2005; Barnes,
538 2007; Ariskin et al., 2013; Godel et al., 2013) with a general consensus of values around 100-200 for
539 olivine saturated magmas. Hence cotectic fractionation should result in Ni depletion by factors of
540 around 3-4.

541 *Figure 13*

542 Recharge and magma mixing

543 Recharge and magma mixing of derivative fractionated magmas with primitive parental magmas has
544 been identified in MORBs and other mafic suites and has been proposed by Gleeson and Gibson
545 (2019) as a mechanism for generating anomalous Ni enrichment in olivine. This follows from the
546 convex-upward form of curves for Ni vs Fo in olivine during fractional crystallization (Figure 12,
547 Figure 13). This type of process may account for otherwise unexplained Ni-enriched olivine trends
548 such as in the Gudchichinsky Picrites of the Siberian LIP (Figure 1A), and also the high Ni in Hawaiian
549 picrite olivines reported by Sobolev et al. (2007). Where magmatic sulfides are generated within
550 multiply recharged sill-dyke networks, as proposed by Barnes et al. (2016), this process has good
551 potential to obscure Ni depletion signals and indeed to generate enrichment. Presence of sulfide in
552 the system may enhance this tendency, as discussed further below.

553 Gleeson and Gibson (2019) point out that recharge and mixing provides a viable alternative
554 hypothesis to the “pyroxenite source” model, which has been involved for some Ni deposits and
555 camps, notably several of the Chinese deposits (Lu et al., 2019). Numerous other studies (Matzen et
556 al., 2017b; Yao et al., 2018) have pointed out other combinations of melting depth and mechanism

557 that avoid the need for pyroxenitic sources. Full discussion of this issue requires consideration of
558 trace elements and isotopic signals that are out of scope of this contribution, but we note that of the
559 deposits represented in this compilation, only a few (Mirabela, Poyi, Xiarihamu, Eagle and Kevitsa)
560 contain olivines in the high Fo (>85 mol pct) and high Ni (>3000) ppm that are claimed by Sobolev et
561 al (2007) as evidence for pyroxenitic mantle sources.

562 R factor effects

563 The term “R-factor” refers to the widely used equation (Campbell and Naldrett, 1979) describing the
564 composition of silicate and sulfide melt during closed-system batch equilibration, where R is defined
565 as the mass ratio of silicate to silicate liquid at equilibrium during a closed-system batch
566 equilibration event. The equation can readily be adapted to also include olivine as a third component
567 in the reaction (Barnes et al., 2013a). It is particularly applicable to the situation where a sulfide
568 xenomelt (Leshner, 2017) is incorporated into a magma body by assimilation of crustal rocks and
569 equilibrates with a fixed mass of magma. Olivine and sulfide compositions can be modelled by a one-
570 stage three-way batch equilibrium calculation, involving equilibrium between olivine, sulfide liquid
571 and silicate liquid using experimental values for partition and distribution coefficients (Barnes et al.,
572 2013a). Figure 14 shows the results of these calculations for variable R and four hypothetical silicate
573 melt compositions (Table 1): komatiite (“kom”), a high-Mg plume basalt (“Plume bas 18”), a
574 ferropicrite and a MORB, using typical values taken from data compilations of Barnes and Fiorentini
575 (2012) and Barnes et al. (2015). The main conclusion from the model results in Figure 14 is that
576 much of the spread of Fo and Ni concentrations in olivine found between individual deposits can
577 theoretically be explained by the combination of initial melt composition and R factor. Variations in
578 R within a single deposit, as for example in the Kevitsa intrusion noted above, can generate the
579 observed spread in olivine Ni for a limited range of Fo, and this variability would be expected to
580 correlate with sulfide tenor, as indeed it does at Kevitsa. The prime cause of strongly Ni depleted
581 olivine is equilibration with silicate and sulfide liquid at low R values, a process which generates
582 correspondingly low-Ni tenor sulfides, as seen in the Kabanga example above (Figure 5) and
583 modelled in Figure 14.

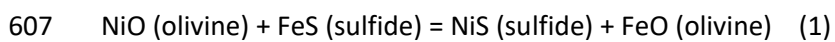
584 It is commonly concluded that depletion of Ni in olivine necessarily implies that the silicate
585 component has been depleted by some previous “upstream” sulfide extraction event prior to the
586 crystallization of the assemblage being studied; i.e. that the depletion implies the existence of an
587 additional sulfide body or bodies elsewhere in the intrusion network. Figure 14 shows that this is not
588 a necessary conclusion: a single stage batch equilibration event can produce a wide range in degrees
589 of Ni depletion depending on the R factor. Low R factor, low Ni-tenor sulfide necessarily coexists
590 with low-Ni olivine at equilibrium.

591 *Figure 14.*

592 *Table 1.*

593 **Trapped liquid effects**

594 One of the factors affecting cumulus mineral compositions is the effect of equilibration between
595 olivine and trapped intercumulus liquid (Barnes, 1986). The principle is illustrated in Figure 15. The
596 original orthocumulate consists of a mixture of olivine, sulfide and silicate liquid, assumed to be in
597 equilibrium (Figure 15A), with the composition of the three phases determined by the three-way
598 equilibration at a given R factor (mass ratio of silicate to sulfide) and proportion of silicate to olivine
599 (F). In the illustrative calculations shown here, the proportion of olivine participating in this initial
600 bulk equilibrium is assumed to be small, 5%. Olivine and sulfide then accumulated mechanically in
601 different proportions along with a component of trapped interstitial silicate melt to form a partially
602 solid mush (Figure 15B). For simplicity we assume that the resulting component has 40% trapped
603 liquid and 5% sulfide (at and above this proportion of sulfide, the change in composition of sulfide
604 during the trapped liquid reaction is minor). As the olivine then re-equilibrates with the evolving
605 trapped liquid during solidification (Figure 15C), it becomes more Fe-rich, and consequently is
606 constrained to also become more Ni rich due to the exchange reaction



608 The distribution coefficient for this reaction K_D is given by

$$609 K_D = (X_{\text{NiS}}/X_{\text{FeS}})_{\text{sulfide liquid}} / (X_{\text{NiO}}/X_{\text{FeO}})_{\text{olivine}}, \quad (2)$$

610

611 which has a value independent of temperature but dependent on fO_2 and the sulfide
612 composition (Brenan 2003; Barnes et al., 2013a; Mao et al., 2017).

613 The sulfide is the dominant reservoir of Ni in the rock for abundances of more than about 5%, such
614 that its composition is only slightly affected by the trapped liquid reaction. Consequently, as the FeO
615 content of the olivine increases, the NiO content must also increase to satisfy the K_D . This gives rise
616 to a negative correlation between Fo and Ni, first recognized in the JM Reef of the Stillwater
617 Complex (Barnes and Naldrett, 1985) and identified subsequently at Voisey's Bay (Li and Naldrett,
618 1999). Hints of such correlations are present in several of the data sets presented in this study,
619 notably Kevitsa (Figure 10).

620 *Figure 15.*

621 The effect has been quantified for a variety of different starting compositions and assumptions
622 (Figure 16), using an iterative solution method based on that of Barnes et al. (2013a). The calculation

623 procedure involves (1) calculation of olivine, sulfide and liquid compositions for each starting liquid
624 (Table 1) as a function of silicate:sulfide mass ratio R, corresponding to stage A in Figure 15; and (2)
625 calculation of new olivine and sulfide composition following complete equilibrium crystallization of a
626 mixture of 55% olivine, 5% sulfide and 40% trapped silicate liquid (Figure 15 b-c).

627 *Figure 16.*

628 The calculation shows that trapped liquid reaction can have a significant effect on Ni content of
629 olivine, most evident in sulfide-bearing orthocumulates where the change in olivine Fo content is
630 greatest. For komatiites, the effect is enhanced by the composition dependence of the K_D on the Ni
631 content of the sulfide, which becomes a significant factor where the Ni content of the sulfide is in
632 the 20-30% Ni range (Barnes et al., 2013a), but it is present for all assumptions about parent melts.
633 The range of Ni variation is comparable to that produced by changes in R over factors of up to an
634 order of magnitude.

635 Sulfide “cannibalization” and Ni enrichment

636 It is likely that the trapped liquid effect contributes considerably to the “noise” in the data and may
637 well explain the observation of anomalously Ni rich olivines in some deposits such as Kalatongke,
638 Savannah, Nova-Bollinger and Kevitsa. However, in a number of cases high Ni is not specifically
639 associated with sulfide-bearing orthocumulates so another explanation is called for.

640 The sequence of events may be more complex than the simple scenario modelled in Figure 16. For
641 example, fluid dynamic considerations predict that pools of Ni-enriched magmatic sulfide liquid may
642 commonly be “cannibalized” and entrained as droplets in a flowing slurry of silicate magma, liquid
643 sulfide and olivine (Barnes and Robertson, 2019; Leshner, 2019). In this case (Figure 17), we have a
644 starting scenario similar to Figure 15A, except that rather than starting out as a Ni-free Fe-sulfide
645 xenomelt, the sulfide component in the slurry is re-entrained magmatic sulfide that already has high
646 Ni. For example, if the slurry has 5% of sulfide with 10% Ni, 5% olivine with 0.1 % Ni and the silicate
647 melt has 250 ppm Ni (realistic assumptions for a typical mafic-hosted deposit), the sulfide
648 component contains 95% of the total Ni budget and will effectively buffer the Ni contents of both
649 silicate melt and olivine. In contrast, the silicate melt is the predominant reservoir of Fe and Mg and
650 buffers the olivine Fo content. Where this olivine is relatively Fe-rich, the Fe-Ni exchange reaction
651 will cause it to gain Ni from the re-entrained sulfide, without greatly affecting the Ni content of that
652 sulfide component. In a more extreme case, where the sulfide has 30% Ni (towards the upper end of
653 sulfides associated with komatiites), an olivine with an initial composition of Fo84 would react
654 towards a Ni content in excess of 10,000 ppm for a typical Ni/Fe K_D of around 8, provided that
655 equilibrium was attained between the three phases during flow. Further trapped liquid reaction

656 post-deposition could then push this value even higher, to the extreme values of 10,000-15,000 ppm
657 Ni seen in the Ni-PGE ores at Kevitsa. The effect is further amplified as the K_D value increases with
658 increasing Ni in the sulfide. This is consistent with the suggestion of Yang et al. (2013) that these
659 unusual ores could be the result of assimilation of komatiite-derived sulfide, and with the
660 explanation offered by Burnham et al. (2003) for anomalously Ni-rich olivines in the komatiite-
661 associated William Lake intrusion in the Thompson Nickel Belt, Manitoba (Burnham et al., 2003).
662 More generally, the process of re-entrainment of pre-formed magmatic sulfide by magma-olivine
663 mixtures with variable composition could explain the apparent paradox that several deposits
664 mentioned above, and also Ntaka Hill (Barnes et al., 2019) and William Lake, show signals of Ni
665 enrichment rather than depletion in olivine. In particular the presence of a strong Ni enrichment
666 signal in sulfide-free rocks in the Savannah intrusion (Figure 6B) is attributed to this effect. (It is also
667 possible that the same effect could operate in reverse: an Mg-rich olivine reacting with sulfide
668 formed initially in equilibrium with a relatively Mg-poor olivine could have its Ni content reduced).

669 *Figure 17.*

670 Multi-stage emplacement and sulfide re-entrainment in predominantly vertical sill-dyke-conduit
671 complexes (Barnes et al., 2016) could provide an additional set of confounding factors for the
672 interpretation of Ni in olivine data. On a more positive note, the presence of anomalously Ni-
673 enriched olivines within a suite of otherwise similar intrusions may be as much of a positive indicator
674 for mineralization as depletion.

675 **Summary of sources of variation of Ni in olivine.**

676 Multiple sources of variance in Ni content of olivine at given Fo content could be operative at
677 multiple stages in the formation of a mineral system. Some of these processes are summarized on
678 Figure 18.

- 679 • Variability in mantle melt composition due to depth, water content (and possibly source).
680 Baselines for Ni in olivine in relation to Fo content are somewhat lower in orogenic belt
681 settings relative to intrusions in continental LIPs. This is probably related to differences in
682 initial parent magma compositions, with plume magmas generally forming deeper and at
683 higher temperatures (Yao et al., 2018).
- 684 • Subsequent fractional crystallization with and without sulfide (Figure 18);
- 685 • Recharge and magma mixing (Gleeson and Gibson, 2019) (Figure 18);
- 686 • Batch equilibration between olivine and sulfide at variable R and olivine/liquid ratio (Figure
687 14);

- 688 • Subsequent equilibration during trapped liquid crystallization in orthocumulates (Figure 18;
689 Figure 15);
- 690 • Reaction of olivine with sulfide during “cannibalization”/re-entrainment; olivine could
691 become anomalously enriched or depleted during such events depending on the sequence
692 of emplacement and relative change in melt composition and olivine Fo content.

693 *Figure 18.*

694 Implications and application to exploration

695 While there is no clear, universal discrimination evident in Ni in olivine between ore-bearing, weakly
696 mineralized and barren intrusions in either CLIP or orogenic categories, sulfide-related signals of
697 both enrichment and depletion can be detected at intrusion scale in many cases, in both sulfide-
698 bearing and sulfide-free samples. Low-R factor, low-tenor sulfides are associated with low-Ni olivines
699 in a number of examples such as Kabanga, and these cases stand out clearly; to put it another way,
700 Ni depletion is a very effective tool for finding low tenor deposits. A lack of clear mineralized/barren
701 distinction in specific groups of related intrusions, e.g. the deposits of NW China or the Kotalahti Belt
702 in Finland, may well be due to “false negatives” where undiscovered mineralization exists in specific
703 intrusions or in their feeder systems, or may also be due to a multiplicity of confounding factors as
704 summarized in Figure 18. In these cases, wide variability of high and low Ni at similar Fo may be
705 more useful as a fertility indicator than simple depletion signals. Wide variability of both Fo and Ni
706 between related intrusions at regional scale may be a useful regional prospectivity indicator, more
707 than an intrusion-scale discriminant. Anomalously high Ni in sulfide-free samples may in some cases
708 be an indicator of prospectivity. In general, the use of Ni-olivine as a fertility tool is more likely to
709 generate false negatives than false positives, but both are possible, and the technique should be
710 used as part of a broader weight-of-evidence approach.

711 The increasing availability of laser ablation – ICPMS trace element data potentially opens new
712 opportunities for practical applications. A small number of existing data sets, e.g. from Savannah (Le
713 Vaillant et al., 2020) and Nova (Taranovic et al., 2021), show that the presence of positive
714 correlations between Ni and Co in olivine may be a useful indicator of reaction with sulfide, and
715 further work is warranted to test this association.

716 More broadly, Ni in olivine is certainly informative as a petrogenetic process indicator in magmatic
717 sulfide mineral systems. The question of whether “pyroxenite” components in plume sources
718 contribute to higher Ni olivines remains open and, given the large number of confounding variables,
719 is probably not resolvable on olivine data alone.

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720

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Appendices/Supplementary

726

727 **Supplementary Table 1.** Data source table and references.

728 Appendix 1. Modelling methods

729 Mafic-ultramafic magmas in continental LIPs are derived from decompression melting of mantle
730 beneath the rigid lithosphere. The geochemical characteristics of these mantle-derived magmas are
731 mostly dependent on geochemical features, mineralogy and potential temperature) of the mantle
732 source, as well as the melting degree which is determined by the thickness of lithosphere because
733 the upwelling of mantle ceases at the base of rigid lithosphere. Given that the continental
734 lithosphere is rarely thinned to below 80-100 km during the LIP event, the representative mantle-
735 derived magma in the CLIP is adopted as the melt that is generated by the adiabatic decompression
736 melting of the primary mantle (McDonough and Sun, 1995) with a hot potential temperature
737 (1550 °C), and extracted from the source at 3 GPa (~100 km). This melt contains ~25 wt% MgO, 14
738 wt% FeO_t (total Fe expressed as FeO) and 1040 ppm Ni based on the model from Yao et al. (2018),
739 and is used for a further model of fractional crystallization at the assumed condition. In order to
740 account for the effect of mantle heterogeneity, this peridotite-derived melt is also mixed with the
741 melt generated by a MORB-like pyroxenite mantle with the same decompression melting path
742 (potential temperature, 1550 °C; terminal melting pressure, 3 GPa). The proportions of pyroxenite-
743 derived melt in the mixed magmas are assumed as 10, 30 and 50%, respectively. The partition
744 coefficient of Ni between the olivine and melt is calculated via the new equation that is calibrated on
745 many 1-bar experiments spanning a wide range of melt and olivine compositions (Pu et al., 2017; Pu
746 et al., 2021). The partition coefficients of Ni within the clinopyroxene-melt and orthopyroxene-melt
747 pairs follow the equations from Matzen et al. (2017b). The olivine grains crystallized from the mixed
748 magmas (especially contain 30-50% pyroxenite-derived melt) contain a higher Ni content than that
749 of peridotite-derived melt at the high-Fo regime, but all modelled Ni trendlines become overlapped
750 when the Fo value drops below 78 (Figure 12A). In general, the modelling results coincide with the

751 trends and distributions of CLIP olivine dataset (Fig. 12A) and can be considered as the baseline to
752 trace the influence of post-cumulus processes on the Ni content of olivines.

753 The petrogenesis of ultramafic-mafic intrusions in orogenic belts is extremely complex, and the
754 associated magmatism may be generated in subduction, collision and post-collision periods. Hence,
755 the partial melting process occurred in orogenic belt may involve the flux-melting of mantle wedge
756 during subduction, the upwelling of asthenosphere due to slab break off or lithospheric
757 delamination in syn- or post-collisional setting, and even the possible contributions of adiabatic
758 decompression melting of hot plume material. In the models presented here (Fig. A1), partial
759 melting processes in orogenic belt are simplified as the flux-melting of mantle wedge above the
760 subducted slab. The details of this melting model can be found in Yao et al. (2018). The mantle
761 source is simplified as the depleted MORB mantle (DMM) (Workman and Hart, 2005). We also set a
762 relatively high temperature (1300 °C) that is close to the anhydrous solidus of mantle wedge
763 peridotite at the crust-mantle boundary (~ 1 GPa), which corresponds to the subduction of a young
764 oceanic lithosphere with slow convergence rate and low subduction angle. The melting products
765 generated at different melting degree (5-25%) are adopted as the representative parental magmas
766 in orogenic belt to model the subsequent fractional crystallization at 1 kbar pressure. The melts
767 derived by flux-melting contain the relatively lower Ni contents (~245-273 ppm), and the melting
768 degrees here show a slight influence on the Ni trendlines of olivine (Figure 12B).

769 *Appendix Figure A1.*

References

- 771 Ariskin, A.A., and Barmina, G.S. (1999) An empirical model for the calculation of spinel-melt
772 equilibria in mafic igneous systems at atmospheric pressure: 2. Fe-Ti oxides. *Contributions to*
773 *Mineralogy and Petrology*, 134, 251- 263.
- 774 Ariskin, A.A., Danyushevsky, L.V., Bychkov, K.A., McNeill, A.W., Barmina, G.S., and Nikolaev, G.S.
775 (2013) Modeling solubility of Fe-Ni sulfides in basaltic magmas: the effect of Ni in the melt.
776 *Economic Geology*, 108.
- 777 Barnes, S.J. (1986) The effect of trapped liquid crystallization on cumulus mineral compositions in
778 layered intrusions. *Contributions to Mineralogy and Petrology*, 93, 524-531.
- 779 Barnes, S.J. (2007) Cotectic precipitation of olivine and sulfide liquid from komatiite magma, and the
780 origin of komatiite-hosted disseminated nickel sulfide mineralization at Mt Keith and
781 Yakabindie, Western Australia. *Economic Geology*, 102, 299-304.
- 782 Barnes, S.J., Cruden, A.R., Arndt, N.T., and Saumur, B.M. (2016) The mineral system approach
783 applied to magmatic Ni-Cu-PGE sulphide deposits. *Ore Geology Reviews*, 76, 296-316.
- 784 Barnes, S.J., and Fiorentini, M.L. (2012) Komatiite magmas and nickel sulfide deposits: a comparison
785 of variably endowed Archean terranes. *Economic Geology*, 107, 755-780.
- 786 Barnes, S.J., Godel, B., Gürer, D., Brenan, J.M., Robertson, J., and Paterson, D. (2013a) Sulfide-olivine
787 Fe-Ni exchange and the origin of anomalously Ni-rich magmatic sulfides. *Economic Geology*,
788 108, 1971-1982.
- 789 Barnes, S.J., Heggie, G.J., and Fiorentini, M.L. (2013b) Spatial variation in platinum group element
790 concentrations in ore-bearing komatiite at the Long-Victor deposit, Kambalda Dome,
791 Western Australia: enlarging the footprint of nickel sulfide orebodies. *Economic Geology*,
792 108, 913-933.
- 793 Barnes, S.J., Hill, R.E.T., Perring, C.S., and Dowling, S.E. (2004) Lithogeochemical exploration for
794 komatiite-associated Ni-sulfide deposits: strategies and limitations. *Mineralogy and*
795 *Petrology*, 82, 259-293.
- 796 Barnes, S.J., Makkonen, H.V., Dowling, S.E., Hill, R.E.T., and Peltonen, P. (2009) The 1.88 Ga Kotalahti
797 and Vammala Nickel Belts, Finland: geochemistry of the mafic and ultramafic metavolcanic
798 rocks. *Bulletin of the Geological Society of Finland*, 81, 103-141.
- 799 Barnes, S.J., Mole, D.R., Hornsey, R., and Schoneveld, L.E. (2019) Nickel-copper sulfide mineralization
800 in the Ntaka Hill Ultramafic Complex, Nachingwea region, Tanzania. *Economic Geology* 114,
801 1135-1158.
- 802 Barnes, S.J., and Mungall, J.E. (2018) Blade shaped dykes and nickel sulfide deposits: a model for the
803 emplacement of ore-bearing small intrusions. *Economic Geology*, 113, 789-798.
- 804 Barnes, S.J., Mungall, J.E., and Maier, W.D. (2015) Platinum group elements in mantle melts and
805 mantle samples. *Lithos*, 232, 395-417.
- 806 Barnes, S.J., and Naldrett, A.J. (1985) Geochemistry of the JM (Howland) Reef of the Stillwater
807 Complex, Minneapolis Adit area. I. Sulfide chemistry and sulfide-olivine equilibrium.
808 *Economic Geology*, 80, 627-645.
- 809 Barnes, S.J., and Robertson, J.C. (2019) Time scales and length scales in magma flow pathways and
810 the origin of magmatic Ni-Cu-PGE ore deposits. *Geoscience Frontiers*, 10, 77-87.
- 811 Barnes, S.J., Stanley, C.R., and Taranovic, V. (2021) Compositions and Ni-Cu-PGE tenors of Nova-
812 Bollinger ores with implications for the origin of Pt anomalies in PGE-poor massive sulfides.
813 *Economic Geology*, in press.
- 814 Barnes, S.J., Taranovic, V., Miller, J.M., Boyce, G., and Beresford, S.W. (2020) Sulfide emplacement
815 and migration in the Nova-Bollinger Ni-Cu-Co deposit, Albany-Fraser Orogen, Western
816 Australia. *Economic Geology*, 115, 1749-1776.
- 817 Brenan, J.M., (2003) Effects of fO_2 , fS_2 , temperature and melt composition on Fe-Ni exchange
818 between olivine and sulfide liquid: implications for natural olivine-sulfide assemblages .
819 *Geochimica et Cosmochimica Acta*, 64, 307-320.

820 Burnham, O.M., Halden, N., Layton-Matthews, D., Leshner, C.M., Liwanag, J., Heaman, L., Hulbert, L.,
821 Machado, N., Michalak, D., Pacey, M., Peck, D., Potrel, A., Theyer, P., Toope, K., and Zwanzig,
822 H. (2003) *Geology, Stratigraphy, Petrogenesis, and Metallogensis of the Thompson Nickel*
823 *Belt, Manitoba: Final Report for CAMIRO Project 97E-02*, p. 410 pp. Mineral Exploration
824 Research Centre, Sudbury.

825 Campbell, I.H., and Naldrett, A.J. (1979) The influence of silicate:sulphide ratios on the geochemistry
826 of magmatic sulphides. *Economic Geology*, 74, 1503-1506.

827 Clark, T. (1980) Petrology of the Turnagain ultramafic complex, northwestern British Columbia.
828 *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre*, 17(6), 744-
829 757.

830 Deblond, A., and Tack, L. (1999) Main characteristics and review of mineral resources of the
831 Kabanga-Musongati mafic-ultramafic alignment in Burundi. *Journal of African Earth Sciences*,
832 29, 313- 328.

833 Ding, X., Li, C., Ripley, E.M., Rossell, D., and Kamo, S. (2010) The Eagle and East Eagle sulfide ore-
834 bearing mafic-ultramafic intrusions in the Midcontinent Rift System, upper Michigan:
835 Geochronology and petrologic evolution. *Geochemistry, Geophysics, Geosystems*, 11(3).

836 Duchesne, J.-C., Liégeois, J.-P., Deblond, A., and Tack, L. (2004) Petrogenesis of the Kabanga-
837 Musongati layered mafic-ultramafic intrusions in Burundi (Kibaran belt): Geochemical, Sr-
838 Nd isotopic constraints and Cr-Ni behaviour. *Journal of African Earth Sciences*, 39, 133-145.

839 Duke, J.M. (1979) Computer simulation of the fractionation of olivine and sulfide from mafic and
840 ultramafic magmas. *Canadian Mineralogist*, 76, 507-514.

841 Evans, D.M., Boadi, I., Byemelwa, L., Gilligan, J., Kabete, J., and Marcet, P. (2000) Kabanga magmatic
842 nickel sulphide deposits, Tanzania: Morphology and geo-chemistry of associated intrusions.
843 *Journal of African Earth Sciences*, 97, 651-674.

844 Gao, J.-F., and Zhou, M.-F. (2013) Magma mixing in the genesis of the Kalatongke dioritic intrusion:
845 Implications for the tectonic switch from subduction to post-collision, Chinese Altay, NW
846 China. *Lithos*, 162, 236-250.

847 Gleeson, M.L.M., and Gibson, S.A. (2019) Crustal controls on apparent mantle pyroxenite signals in
848 ocean-island basalts. *Geology (Boulder)*, 47(4), 321-324.

849 Godel, B., Barnes, S.J., and Barnes, S.-J. (2013) Deposition mechanisms of magmatic sulphide liquids:
850 evidence from high-resolution X-ray computed tomography and trace element chemistry of
851 komatiite-hosted disseminated sulphides. *Journal of Petrology*, 54, 1455-1481.

852 Häkli, T.A. (1971) Silicate nickel and its application to the exploration of nickel ores. *Bulletin of the*
853 *Geological Society of Finland*, 43, 247-263.

854 Hart, S.R., and Davis, K.E. (1978) Ni partitioning between olivine and silicate melt. *Earth and*
855 *Planetary Science Letters*, 40, 203-219.

856 Helmy, H.M., and Mogessie, A. (2001) Gabbro Akarem, Eastern Desert, Egypt; Cu-Ni-PGE
857 mineralization in a concentrically zoned mafic-ultramafic complex. *Mineralium Deposita*,
858 36(1), 58-71.

859 Herzberg, C., Vidito, C., and Starkey, N.A. (2016) Nickel-cobalt contents of olivine record origins of
860 mantle peridotite and related rocks. *The American Mineralogist*, 101(9), 1952-1966.

861 Jesus, A., Mateus, A., Benoit, M., Tassinari, C., and Bento dos Santos, T. (2020) The timing of sulfide
862 segregation in a Variscan synorogenic gabbroic layered intrusion (Beja, Portugal):
863 Implications for Ni-Cu-PGE exploration in orogenic settings. *Ore Geology Reviews*.

864 Jugo, P.J., Luth, R.W., and Richards, J.P. (2005) Experimental data on the speciation of sulfur as a
865 function of oxygen fugacity in basaltic melts. *Geochimica et Cosmochimica Acta*, 69(2), 497-
866 503.

867 Kiseeva, E.S., and Wood, B.J. (2015) The effects of composition and temperature on chalcophile and
868 lithophile element partitioning into magmatic sulphides. *Earth and Planetary Science Letters*,
869 424, 280-294.

870 Kohanpour, F., Gorczyk, W., Lindsay, M.D., and Occhipinti, S.A. (2017) Examining tectonic scenarios
871 using geodynamic numerical modelling: Halls Creek Orogen, Australia. *Gondwana Research*,
872 46, 95-113.

873 Lamberg, P. (2005) From genetic concepts to practice – lithogeochemical identification of Ni-Cu
874 mineralised intrusions and localization of the ore. *Geological Survey of Finland Bulletin*, 402,
875 1-266.

876 Le Vaillant, M., Barnes, S.J., Mole, D.R., Fiorentini, M.L., LaFlamme, C.K., Denyszyn, S., Austin, J.,
877 Patterson, B., Godel, B., Neaud, A., Hicks, J., Shaw-Stuart, A., and Mao, Y.J. (2020)
878 Multidisciplinary study of a complex magmatic system: The Savannah Ni-Cu-Co Camp,
879 Western Australia. *Ore Geology Reviews*, 117, 103292.

880 Le Vaillant, M., Fiorentini, M.L., and Barnes, S.J. (2016) Review of lithogeochemical exploration tools
881 for komatiite-hosted nickel sulphide deposits. *Journal of Geochemical Exploration*, 168, 1-19.

882 Le Vaillant, M., Hill, E.J., and Barnes, S.J. (2017) Simplifying drill-hole domains for 3D geochemical
883 modelling: an example from the Kevitsa Ni-Cu-(PGE) deposit. *Ore Geology Reviews*, 90, 388-
884 398.

885 Lehnert, K., Su, Y., Langmuir, C.H., Sarbas, B., and Nohl, U. (2000) A global geochemical database
886 structure for rocks. *Geochemistry Geophysics Geosystems*, 1, 1012.

887 Leshner, C.M. (2017) Roles of residues/skarns, xenoliths, xenocrysts, xenomelts, and xenovolatiles in
888 the genesis, transport, and localization of magmatic Fe-Ni-Cu-PGE sulfides and chromite. *Ore*
889 *Geology Reviews*, 90, 465-484.

890 Leshner, C.M. (2019) Up, down, or sideways: emplacement of magmatic Fe-Ni-Cu-PGE sulfide melts
891 in large igneous provinces. *Canadian Journal of Earth Science*, 56, 756-773.

892 Li, C., and Naldrett, A.J. (1999) Geology and petrology of the Voisey's Bay intrusion: reaction of
893 olivine with sulfide and silicate liquids. *Lithos*, 47, 1- 31.

894 Li, C., Naldrett, A.J., and Ripley, E.M. (2007) Controls on the Fo and Ni Contents of Olivine in Sulfide-
895 bearing Mafic/Ultramafic Intrusions: Principles, Modeling, and Examples from Voisey's Bay.
896 *Earth Science Frontiers*, 14, 177-183.

897 Li, C., Ripley, E.M., Thakurta, J., Stifter, E.C., and Liang, Q. (2013) Variations of olivine Fo-Ni contents
898 and highly chalcophile element abundances in arc ultramafic cumulates, southern Alaska.
899 *Chemical Geology*, 351, 15-28.

900 Li, C., Zhang, M., Fu, P., Qian, Z.Z., Hu, P., and Ripley, E.M. (2012) The Kalatongke magmatic Ni-Cu
901 deposits in the Central Asian Orogenic Belt, NW China: product of slab window magmatism?
902 *Mineralium Deposita*, 47(1-2), 51-67.

903 Li, C., Zhang, Z., Li, W., Wang, Y., Sun, T., and Ripley, E.M. (2015) Geochronology, petrology and Hf-S
904 isotope geochemistry of the newly-discovered Xiarihamu magmatic Ni-Cu sulfide deposit in
905 the Qinghai-Tibet Plateau, western China. *Lithos (Oslo)*, 216-217, 224-240.

906 Li, C.S., and Ripley, E.M. (2005) Empirical equations to predict the sulfur content of mafic magmas at
907 sulfide saturation and applications to magmatic sulfide deposits. *Mineralium Deposita*, 40,
908 218-230.

909 Li, C.S., and Ripley, E.M. (2010) The relative effects of composition and temperature on olivine-liquid
910 Ni partitioning: Statistical deconvolution and implications for petrologic modeling. *Chemical*
911 *Geology*, 275(1-2), 99-104.

912 Lu, Y., Leshner, C.M., and Deng, J. (2019) Geochemistry and genesis of magmatic Ni-Cu-(PGE) and
913 PGE-(Cu)-(Ni) deposits in China. *Ore Geology Reviews*, 107, 863-887.

914 Luolavirta, K., Hanski, E., Maier, W., Lahaye, Y., O'Brien, H., and Santaguida, F. (2018) In situ
915 strontium and sulfur isotope investigation of the Ni-Cu-(PGE) sulfide ore-bearing Kevitsa
916 Intrusion, northern Finland. *Mineralium Deposita*, 53(7), 1019-1038.

917 Luolavirta, K., Hanski, E., Maier, W., and Santaguida, F. (2017) Whole-rock and mineral compositional
918 constraints on the magmatic evolution of the Ni-Cu-(PGE) sulfide ore-bearing Kevitsa
919 intrusion, northern Finland. *Lithos*, 296-299, 37-53.

920 Maier, W.D., Barnes, S.-J., and Groves, D.I. (2013) The Bushveld Complex, South Africa; formation of
921 platinum-palladium, chrome- and vanadium-rich layers via hydrodynamic sorting of a
922 mobilized cumulate slurry in a large, relatively slowly cooling, subsiding magma chamber.
923 *Mineralium Deposita*, 48(1), 1-56.

924 Maier, W.D., Barnes, S.-J., and Ripley, E.M. (2011) The Kabanga Ni Sulfide Deposits, Tanzania: A
925 Review of Ore-Forming Processes. *Reviews in Economic Geology*, 17, 217-234.

926 Maier, W.D., Barnes, S.J., Sarkar, A., Ripley, E.M., Li, C., and Livesey, T. (2010) The Kabanga Ni sulfide
927 deposit, Tanzania: I. Geology, petrography, silicate rock geochemistry, and sulfur and oxygen
928 isotopes. *Mineralium Deposita*, 45, 419-441.

929 Maier, W.D., Peltonen, P., and Livesey, T. (2007) The ages of the Kabanga north and Kapalagulu
930 intrusions, western Tanzania: A reconnaissance study. *Economic Geology*, 102, 147-149.

931 Maier, W.D., Smithies, R.H., Spaggiari, C.V., Barnes, S.J., Kirkland, C.L., Yang, S., Lahaye, Y., Kiddie, O.,
932 and MacRae, C.M. (2016) Petrogenesis and Ni-Cu sulphide potential of mafic-ultramafic
933 rocks in the Mesoproterozoic Fraser Zone within the Albany-Fraser Orogen, Western
934 Australia. *Precambrian Research*, 281, 27-46.

935 Mäkitie, H., Data, G., Isabirye, E., Mänttäri, I., Huhma, H., Klausen, M.B., Pakkanen, L., and
936 Virransalo, P. (2014) Petrology, geochronology and emplacement model of the giant 1.37 Ga
937 arcuate Lake Victoria dyke swarm on the margin of a large igneous province in eastern
938 Africa. *Journal of African Earth Sciences*, 97, 273– 296.

939 Makkonen, H.V. (2015) Nickel deposits of the 1.88 Ga Kotalahti and Vammala Belts. In W.D. Maier, R.
940 Lahtinen, and H. O' Brien, Eds. *Mineral Deposits of Finland*, p. 253-287. Elsevier.

941 Makkonen, H.V., Makinen, J., and Kontoniemi, O. (2008) Geochemical discrimination between
942 barren and mineralized intrusions in the Svecofennian (1.9 Ga) Kotalahti nickel belt, Finland.
943 *Ore Geology Reviews*, 33(1), 101-114.

944 Mao, J.W., Pirajno, F., Zhang, Z.H., Chai, F.M., Wu, H., Chen, S.P., Cheng, L.S., Yang, J.M., and Zhang,
945 C.Q. (2008) A review of the Cu-Ni sulphide deposits in the Chinese Tianshan and Altay
946 orogens (Xinjiang Autonomous Region, NW China): Principal characteristics and ore-forming
947 processes. *Journal of Asian Earth Sciences*, 32(2-4), 184-203.

948 Mao, Y.J., Barnes, S.J., Godel, B., Schoneveld, L.E., Qin, K.Z., Tang, D.M., Williams, M.J., and Kang, Z.
949 (2021) Sulfide ore formation of the Kalatongke Ni-Cu deposit as illustrated by sulfide
950 textures. *Economic Geology*, in revision.

951 Mao, Y.J., Qin, K.Z., Barnes, S.J., Ferraina, C., Iacono-Marziano, G., Verrall, M.R., Tang, D.M., and Xue,
952 S.C. (2017) A revised oxygen barometry in sulfide-saturated magmas and application to the
953 Permian magmatic Ni–Cu deposits in the southern Central Asian Orogenic Belt. *Mineralium
954 Deposita*, 53, 731-755.

955 Matzen, A.K., Baker, M.B., Beckett, J.R., and Stolper, E.M. (2013) The temperature and pressure
956 dependence of nickel partitioning between olivine and silicate melt. *Journal of Petrology*, 54,
957 2521-2545.

958 Matzen, A.K., Baker, M.B., Beckett, J.R., Wood, B.J., and Stolper, E.M. (2017a) The effect of liquid
959 composition on the partitioning of Ni between olivine and silicate melt. *Contributions to
960 Mineralogy and Petrology*, 172(1), 3.

961 Matzen, A.K., Wood, B.J., Baker, M.B., and Stolper, E.M. (2017b) The roles of pyroxenite and
962 peridotite in the mantle sources of oceanic basalts. *Nature Geoscience*, 10(7), 530-535.

963 McDonough, W.F., and Sun, S.-S. (1995) The composition of the Earth. *Chemical Geology*, 120, 223-
964 253.

965 Mole, D.R., Barnes, S.J., Le Vaillant, M., Martin, L.A.J., and Hick, J. (2018) Timing, geochemistry and
966 tectonic setting of intrusion-hosted Ni-Cu sulfide deposits of the Halls Creek Orogen,
967 Western Australia. *Lithos*, 314-315, 425-446.

968 Mutanen, T. (1997) Geology and ore petrology of the Akanvaara and Koitelainen mafic layered
969 intrusions and the Keivitsa-Satovaa layered complex, northern Finland. *Bulletin of the
970 Geological Survey of Finland*, 395.

- 971 Naldrett, A.J., Duke, J.M., Lightfoot, P.C., and Thompson, J.F.H. (1984) Quantitative modelling of the
972 segregation of magmatic sulphides: an exploration guide. *Canadian Institute of Mining and*
973 *Metallurgy Bulletin*, 77, 46-56.
- 974 Pu, X., Lange, R.A., and Moore, G. (2017) A comparison of olivine-melt thermometers based on D
975 (sub Mg) and D (sub Ni) ; the effects of melt composition, temperature, and pressure with
976 applications to MORBs and hydrous arc basalts. *American Mineralogist*, 102(4), 750-765.
- 977 Pu, X., Moore, G.M., Lange, R.A., Touran, J.P., and Gagnon, J.E. (2021) Experimental evaluation of a
978 new H (sub 2) O-independent thermometer based on olivine-melt Ni partitioning at crustal
979 pressure. *American Mineralogist*, 106(2), 235-250.
- 980 Qin, K.-Z., Su, B.-X., Sakyi, P.A., Tang, D.M., Li, X.H., Sun, H., Xiao, Q.H., and Liu, P.P. (2011) Sims
981 zircon U-Pb geochronology and Sr-Nd isotopes of Ni-Cu-bearing mafic-ultramafic intrusions
982 in Eastern tianshan and Beishan in correlation with flood basalts in Tarim basin (NW china):
983 Constraints on a Ca. 280 Ma mantle plume. *American Journal of Science*, 311(3), 237-260.
- 984 Santaguida, F., Luolavirta, K., Lappalainen, M., Ylinen, J., Voipio, S., and Jones, S. (2015) The Kevitsa
985 Ni-Cu-PGE deposit in the Central Lapland Greenstone Belt in Finland. In W.D. Maier, R.
986 Lahtinen, and H. O' Brien, Eds. *Mineral Deposits of Finland*, p. 195-210. Elsevier.
- 987 Sarbas, B. (2008) The GEOROC database as part of a growing geoinformatics network. In S.R. Brady,
988 A.K. Sinha, and L.C. Gunderson, Eds. *Geoinformatics 2008 - data to knowledge*, Proceedings.
989 US Geological Survey Scientific Investigations Report 2008-5172, p. 42-43.
- 990 Savov, I.P., Ryan, J.G., D'Antonio, M., and Fryer, P. (2007) Shallow slab fluid release across and along
991 the Mariana arc-basin system; insights from geochemistry of serpentinized peridotites from
992 the Mariana fore arc. *Journal of Geophysical Research*, 112(B9), B09205.
- 993 Schoneveld, L.E., Barnes, S.J., Makkonen, H.V., Le Vaillant, M., Paterson, D.J., Taranovic, V., Wang, K.-
994 Y., and Mao, Y.-J. (2020) Zoned Pyroxenes as Prospectivity Indicators for Magmatic Ni-Cu
995 Sulfide Mineralization. *Frontiers in Earth Science*, 8(256).
- 996 Sobolev, A., Hoffman, A., Kuzmin, D., Yaxley, G., Arndt, N., Chung, S.-L., Danyushevsky, L., Elliott, T.,
997 Frey, F., Garcia, M., Gurenko, A., Kamenetsky, V., Kerr, A., Krivolutskaya, N., Matvienkov, V.,
998 Nikogosian, I., Rocholl, A., Sigurdson, I., Sushchevskaya, N., and Teklay, M. (2007) The
999 amount of recycled crust in sources of mantle-derived melts. *Science*, 316, 412-417.
- 1000 Sobolev, A.V., Hofmann, A.W., Sobolev, S.V., and Nikogosian, I.K. (2005) An olivine-free mantle
1001 source of Hawaiian shield basalts. *Nature (London)*, 434(7033), 590.
- 1002 Song, X.-Y., Xie, W., Deng, Y.-F., Crawford, A.J., Zheng, W.-Q., Zhou, G.-F., Deng, G., Cheng, S.-L., and
1003 Li, J. (2011a) Slab break-off and the formation of Permian mafic-ultramafic intrusions in
1004 southern margin of Central Asian Orogenic Belt, Xinjiang, NW China. *Lithos*, 127(1-2), 128-
1005 143.
- 1006 Song, X., Wang, Y., and Chen, L. (2011b) Magmatic Ni-Cu-(PGE) deposits in magma plumbing
1007 systems; features, formation and exploration. *Geoscience Frontiers*, 2(3), 375-384.
- 1008 Song, X., Xie, W., Deng, Y., Crawford, A.J., Zheng, W., Zhou, G., Deng, G., Cheng, S., and Li, J. (2011c)
1009 Slab break-off and the formation of Permian mafic-ultramafic intrusions in southern margin
1010 of Central Asian orogenic belt, Xinjiang, NW China. *Lithos (Oslo)*, 127(1-2), 128-143.
- 1011 Song, X., Yi, J., Chen, L., She, Y., Liu, C., Dang, X., Yang, Q., and Wu, S. (2016) The giant Xiarihamu Ni-
1012 Co sulfide deposit in the East Kunlun orogenic belt, northern Tibet Plateau, China. *Economic*
1013 *Geology and the Bulletin of the Society of Economic Geologists*, 111(1), 29-55.
- 1014 Song, X.Y., Wang, K.Y., Barnes, S.J., Yi, J.-N., and Schoneveld, L.E. (2020) Petrogenetic insights of
1015 chromite in ultramafic cumulates: Implications from the Xiarihamu intrusion, northern Tibet
1016 Plateau, China. *American Mineralogist*, 105, 479-497.
- 1017 Spaggiari, C.V., Kirkland, C.L., Smithies, R.H., Wingate, M.T.D., and Belousova, E. (2015)
1018 Transformation of an Archean craton margin during Proterozoic basin formation and
1019 magmatism: the Albany-Fraser Orogen, Western Australia. *Precambrian Research*, 266, 440-
1020 466.

1021 Su, B.-X., Qin, K.-Z., Sakyi, P.A., Li, X.-H., Yang, Y.-H., Sun, H., Tang, D.-M., Liu, P.-P., Xiao, Q.-H., and
1022 Malaviarachchi, S.P.K. (2011) U–Pb ages and Hf–O isotopes of zircons from Late Paleozoic
1023 mafic–ultramafic units in the southern Central Asian Orogenic Belt: Tectonic implications
1024 and evidence for an Early-Permian mantle plume. *Gondwana Research*, 20(2-3), 516-531.

1025 Taranovic, V., Barnes, S.J., Beresford, S.W., Williams, M.J., MacRae, C., and Schoneveld, L.E. (2021)
1026 Nova – Bollinger Ni – Cu Sulfide Ore Deposits, Fraser Zone, Western Australia: Petrogenesis
1027 of the Host Intrusions. *Economic Geology*, in press.

1028 Thakurta, J., Ripley, E.M., and Li, C. (2014) Platinum group element geochemistry of sulfide-rich
1029 horizons in the Ural-Alaskan-type ultramafic complex of Duke Island, southeastern Alaska.
1030 *Economic Geology and the Bulletin of the Society of Economic Geologists*, 109(3), 643-659.

1031 Thakurta, J., Ripley, E.M., and Li, C.S. (2008) Pre-requisites for Sulphide-poor PGE and Sulphide-rich
1032 Cu-Ni-PGE Mineralization in Alaskan-type Complexes. *Journal of the Geological Society of
1033 India*, 72(5), 611-622.

1034 Wei, B., Wang, C.Y., Li, C., and Sun, Y. (2013) Origin of PGE-Depleted Ni-Cu Sulfide Mineralization in
1035 the Triassic Hongqiling No. 7 Orthopyroxenite Intrusion, Central Asian Orogenic Belt,
1036 Northeastern China. *Economic Geology*, 108(8), 1813-1831.

1037 Workman, R.K., and Hart, S.R. (2005) Major and trace element composition of the depleted MORB
1038 mantle (DMM). *Earth and Planetary Science Letters*, 231(1-2), 53-72.

1039 Xue, S., Qin, K., Li, C., Tang, D., Mao, Y.-J., and Qi L. (2016) Geochronological, Petrological, and
1040 Geochemical Constraints on Ni-Cu Sulfide Mineralization in the Poyi Ultramafic-Troctolitic
1041 Intrusion in the Northeast Rim of the Tarim Craton, Western China. *Economic Geology*, 111,
1042 1465-1484.

1043 Yang, S.-H., Maier, W.D., Hanski, E.J., Lappalainen, M., Santaguida, F., and Maatta, S. (2013) Origin of
1044 ultra-nickeliferous olivine in the Kevitsa Ni-Cu-PGE-mineralized intrusion, northern Finland.
1045 *Contributions to Mineralogy and Petrology*, 166(1), 81-95.

1046 Yao, Z.-s., and Mungall, J.E. (2021) Linking the Siberian Flood Basalts and Giant Ni-Cu-PGE Sulfide
1047 Deposits at Norilsk. *Journal of Geophysical Research: Solid Earth*, 126(3), e2020JB020823.

1048 Yao, Z., Qin, K.Z., and Mungall, E. (2018) Tectonic controls on Ni and Cu contents of primary mantle-
1049 derived magmas for the formation of magmatic sulfide deposits. *American Mineralogist*,
1050 online AM-18-106392.

1051 Zhang, M., Li, C., Fu, P., Hu, P., and Ripley, E. (2011) The Permian Huangshanxi Cu–Ni deposit in
1052 western China: intrusive–extrusive association, ore genesis, and exploration implications.
1053 *Mineralium Deposita*, 46(2), 153-170.

1054 Zhang, Z.C., Ma, J.W., Wang, F.S., Hao, Y.L., and Mahoney, J.J. (2005) Mantle Plume Activity and
1055 Melting Conditions: Evidence From Olivines in Picritic-Komatiitic Rocks From the Emeishan
1056 Large Igneous Province, Southwestern China. *Episodes*, 28(3), 171-176.

1057 Zhang, Z.C., Mao, J.W., Chai, F.M., Yan, S.H., Chen, B.L., and Pirajno, F. (2009) Geochemistry of the
1058 Permian Kalatongke Mafic Intrusions, Northern Xinjiang, Northwest China: Implications for
1059 the Genesis of Magmatic Ni-Cu Sulfide Deposits. *Economic Geology*, 104(2), 185-203.

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1061

1062 **Figure captions**

1063 Figure 1 Sobolev et al. (2008) and GEOROC basaltic olivine data set. A, Sobolev data, for continental
1064 and oceanic LIPs (CLIP, OLIP) and MORB. B, Sobolev CLIP data, excluding the outlying Gudchichinsky
1065 Picrites (Siberia) with 90th and 50th percentile data density contours. C Density shaded data cloud
1066 for Oceanic LIPs only (individual points are 95th percentile outliers) shown over the CLIP contours
1067 and with 90th percentile data contour on MORB olivines. D, Comparison of convergent margin data:
1068 data points are olivines from GEOROC data compilation for tholeiitic and picritic
1069 volcanic/subvolcanic rocks from continental (pink) and oceanic (green) convergent margin settings
1070 including active arcs, compared with Sobolev CLIP data density fields (grey).

1071 Figure 2. Comparison of olivine from unmineralized intrusions, small intrusions and large LMIs
1072 combined, between LIP settings (A – 550 data points) and orogenic belt settings (B – 844 data
1073 points), both showing data points and contoured data density. A shows data points for LIP intrusions
1074 over outline for CLIP basalts from Sobolev et al. (Figure 1), B shows orogenic belt intrusions over
1075 50th and 90th density contours for barren LIP intrusions. Field labelled MSFM is for olivines formed
1076 as fractional crystallization products of modelled sulfide-free mantle melts, based on computational
1077 modelling described in detail below.

1078 Figure 3. Proterozoic plus Phanerozoic CLIP-LMI settings. A, Data points for mineralized intrusions
1079 over cloud for barren intrusions from Figure 2A. B, same dataset, mineralized only, subdivided by
1080 locality. Note that scale is trimmed to exclude extreme Ni enriched olivines from Kevitsa discussed
1081 below. In this and most following plots, red symbols indicate Mineralized, green indicated
1082 Disseminated or minor mineralization – see Methods section for definitions. Curve labelled MSFM is
1083 modelled outline for olivines derived from variably fractionated model sulfide free mantle melts
1084 (MSFM). Grey fields are data cloud for unmineralized LIP-related intrusions.

1085 Figure 4. Orogenic belt settings – Proterozoic (A) + Phanerozoic (B). Data points for mineralized
1086 intrusions over cloud (yellow) for barren orogenic belt intrusions from Figure 2B and modelled
1087 outline for olivines derived from variably fractionated model sulfide free mantle melts (MSFM).
1088 CAOB = Central Asia Orogenic Belt in China; ACO = Appalachian-Caledonian Orogen; KBF = Kotalahti
1089 Belt (Svecofennian Orogen), Finland.

1090 Figure 5. Ni-Fo plot for samples from the Kabanga–Musongati–Kapalagulu Belt. Contours on data
1091 densities for barren intrusions from CLIP and LMI grouping.

1092 Figure 6. A) Olivines from the Sally Malay suite of intrusions in the Halls Creek Orogen, over data
1093 cloud for barren intrusions from orogenic belts (yellow). Savannah, Savannah North and Copernicus

1094 host the known economic deposits, Dave Hill and Wilsons contain sparse localized disseminated
1095 sulfides. MSFM is theoretical range for olivines from sulfide-free mantle melts. B) Same data set,
1096 coloured by sulfide content of individual samples – B= barren (no visible sulfide, and/or less than
1097 0.1% S), D=containing disseminated sulfide.

1098 Figure 7. A, Olivines from small intrusions in the Central Asian Orogenic Belt in NW China and the
1099 Xiarihamu intrusion, Tibet. All intrusions are mineralized to varying degrees. Field for data from
1100 barren intrusions from orogenic belts (Figure 2). MSFM is model field for sulfide-free olivines from
1101 mantle melts. Note that: “Beishan” here represents a summary of the olivine data from the mafic-
1102 ultramafic intrusions located in the Beishan area, except the Poyi intrusion; the olivine data of
1103 Honqiling and Tulaergen deposits is collected from the disseminated mineralization. B, Same data
1104 set excluding Xiarihamu, subdivided by sulfide content of sample (B = <100 ppm Cu, D = >100 ppm
1105 Cu).

1106 Figure 8. Ni vs Fo plot of olivines from intrusions in the Svecofennian (Kotalahti) Belt of central
1107 Finland. Contours are on data from barren intrusions in orogenic settings. MSFM is model field for
1108 sulfide-free olivines from mantle melts.

1109 Figure 9. Ural-Alaskan Type Complexes. MSFM is model field for sulfide-free olivines from mantle
1110 melts.

1111 Figure 10. Olivine compositions from the Kevitsa intrusion. Ni-PGE = High Ni-PGE tenor orezone, Ni
1112 tenors up to 30%. A, all data, subdivided by ore type. Xenolith is a sample of an ultramafic xenolith
1113 within this zone. “Normal” includes disseminated ores with a wide range of Ni tenors. Most Ni
1114 depleted samples are from zones of “False Ore”, pyrrhotite-rich disseminated sulfides associated
1115 with country rock metasediment xenoliths. Ni-PGE ores are defined on the basis of high Ni and PGE
1116 tenors in sulfide (Yang et al., 2013). B, Ni-PGE oretype only, data subdivided by sample for all
1117 samples with >6 individual spot analyses. Note the strong negative correlation between Ni and Fo
1118 content within samples. MSFM is model field for sulfide-free olivines from mantle melts.

1119 Figure 11. Olivine compositions in the Nova-Bollinger system. A, Ni vs Fo plot, shapes indicate host
1120 intrusion, colours are arbitrary indications of range of Ni-Fo. Fields for barren orogenic belt
1121 intrusions (yellow) and 90th percentile outline for barren LIP intrusions (grey dashed lines). Arrows
1122 indicate locations of different composition types on (B), projected long section in vertical plane,
1123 looking north, through entire system. Note the most Ni-depleted Fo rich olivines are located within
1124 the upper part of the Upper Intrusion, more Fe rich with trends towards Ni enriched olivine are in
1125 the Lower (ore-bearing) intrusion.

1126 Figure 12 – model curves for olivine compositions generated by low-pressure fractional
1127 crystallization from various starting magmas (see Appendix)

1128 Figure 13 Low-pressure fractional crystallization (FC) trends for the indicated pressure, fO_2 and
1129 magma water content. The proportion ratios of olivine and sulfide in each crystallization increment
1130 are assumed as 50, 100, 200 and 500. The partition coefficient of Ni between sulfide and melt is
1131 calculated by the recent comprehensive model from Kiseeva and Wood (2015). In (B), the mantle
1132 source in flux melting is assumed to enrich in Ni (~3050 ppm), because the slab-metasomatized
1133 mantle wedge can show extreme enrichment of Ni and fluid mobile elements (Savov et al., 2007).

1134 Figure 14. Model single-stage batch equilibrium calculations for olivine and sulfide Ni contents as a
1135 function of silicate melt/sulfide melt mass ratio R factor for the four idealized silicate melt
1136 compositions indicated in Table 1. Sulfide equilibrates with mixture of 95% silicate melt, 5% olivine.
1137 See Barnes et al. (2013) for details of calculation procedure.

1138 Figure 15. Cartoon of olivine-trapped liquid reaction. A. Flowing slurry of silicate + sulfide melts and
1139 olivine. B, accumulation of olivine, sulfide in different proportions to form a cumulate mush with
1140 ~40% silicate melt. Phases assumed to have the same compositions as A. C, cooling and equilibrium
1141 crystallization of the trapped intercumulus liquid causes olivine to evolve towards more Fe rich
1142 composition, hence also becoming more Ni rich due the Fe-Ni exchange reaction (eqns. 1,2).

1143 Figure 16. Calculation showing theoretical effect of trapped liquid equilibration in olivine-sulfide
1144 orthocumulates (olivine-plagioclase orthocumulate in the basaltic case) with 5% modal % sulfide, for
1145 various silicate liquid compositions. Dash lines join points for the same R factor. “Original”
1146 compositions, corresponding to stage A in Figure 15, are olivines in equilibrium with sulfide and
1147 silicate liquid (95% liquid, 5% olivine) for different values of R and different starting silicate melt
1148 compositions (Table 1) corresponding to komatiite with 30% MgO, plume “picrite” basalt with 18%
1149 MgO, Ferropicrite with 14% MgO and MORB basalt (8% MgO), all being representative
1150 compositions from the modelling results described above. Note that a larger shift in olivine Fo is
1151 assumed for the cumulate from the low-Mg mafic magma owing to a lower modal proportion of
1152 olivine in the cumulus assemblage – see Barnes (1986).

1153 Figure 17. Model for generation of Ni-enriched olivine by “cannibalization” of previously formed
1154 sulfide. A, initial formation of Ni-rich sulfide liquid pool from an Mg-rich magma. B, flushing of flow
1155 pathway by more evolved magma carrying relatively low-Fo, Fe-enriched olivine. Reaction of this
1156 olivine with stage-A Ni-rich sulfide causes Ni content of olivine to increase due to the Fe-Ni exchange
1157 reaction (equation 1).

1158 Figure 18. Schematic diagram showing the multiple factors influencing final olivine compositions.
 1159 Single dashed lines indicate olivine-only fractional crystallization (FX) from idealized primitive mantle
 1160 melts from deep plume source and from flux melting of hydrated mantle. FX(ol-sul) indicates effect
 1161 of fractional crystallization/liquation of a cotectic olivine-sulfide assemblage from primitive plume
 1162 melt. TL = effect of re-equilibration during solidification of trapped intercumulus liquid, with and
 1163 without presence of cumulus sulfide. Recharge and mixing indicates effect of mixing fractionated
 1164 and primitive magmas (Gleeson & Gibson, 2019). Batch sulfide extraction indicates effect of addition
 1165 of xenomelt sulfide and batch equilibration with melt and olivine (Figure 14).

1166 Appendix Figure A1. The influences of crystallization environments (A. crystallization pressure; B.
 1167 initial H₂O content; and C-D. oxygen fugacity) on the Ni contents of olivine grains that are
 1168 crystallized from parental magma derived by the adiabatic decompression melting in plume (A-C)
 1169 and the flux melting of DMM in subduction zone (D).

1170

1171 Table 1.

1172 Starting compositions for batch equilibrium - trapped liquid reaction model in Figure 16. (eqm)
 1173 indicates composition of olivine or sulfide liquid at R>10,000

	Kom	Plume bas 18	Ferropicrite 14	MORB 8
Ni sil	1600	660	350	100
FeOsil	10.0	12	14.0	8.5
MgOsil	30.0	18.0	14.0	8.0
Cu sil	50	100	100	200
NiOl (eqm)	3191	3430	2444	1505
FoOl (eqm)	93.8	88.8	84.4	85.4
Sul liq (eqm)	37.9	24.9	13.6	6.9
T	1600	1380	1280	1140

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1175

fig 1

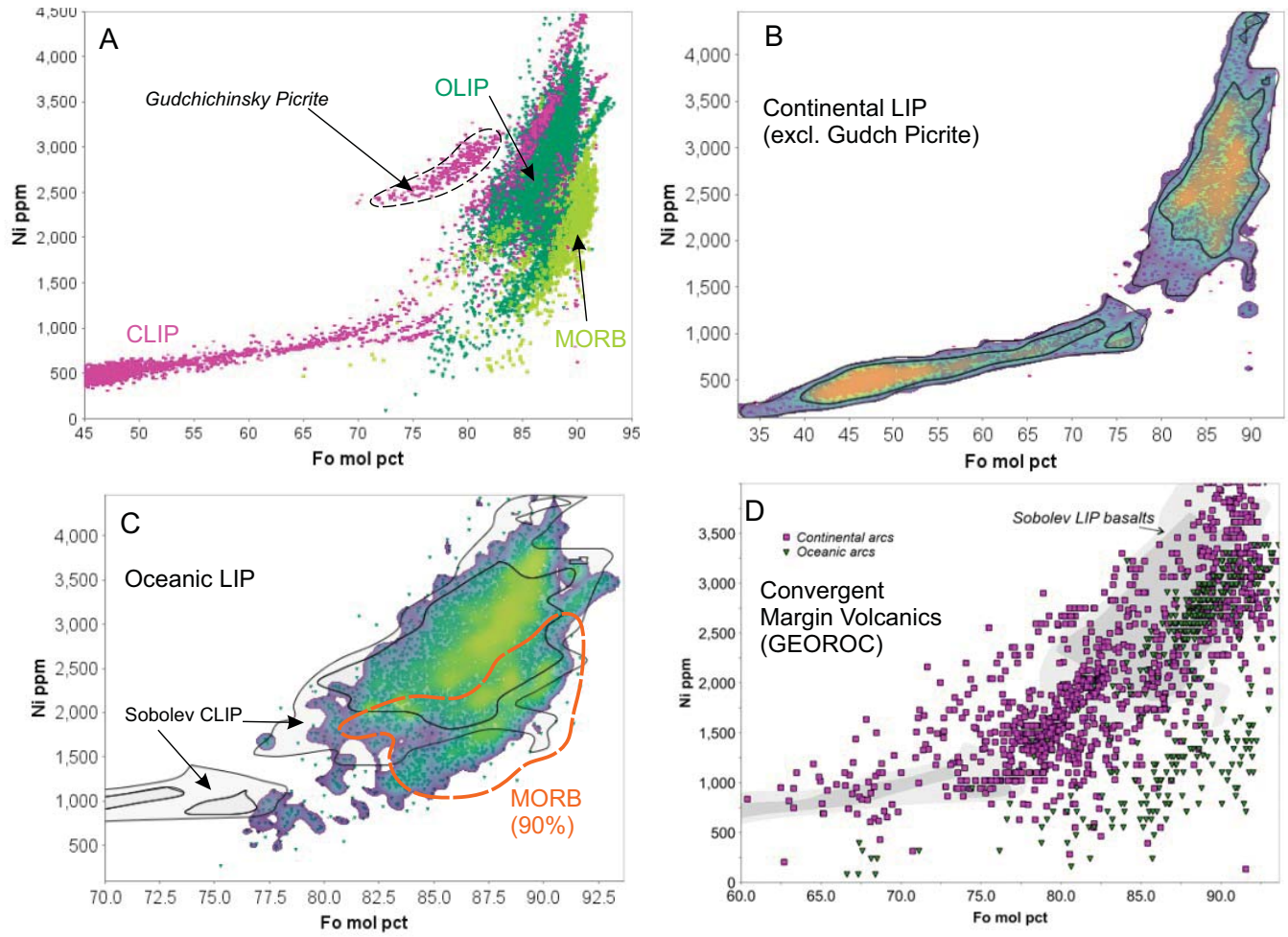


fig 2

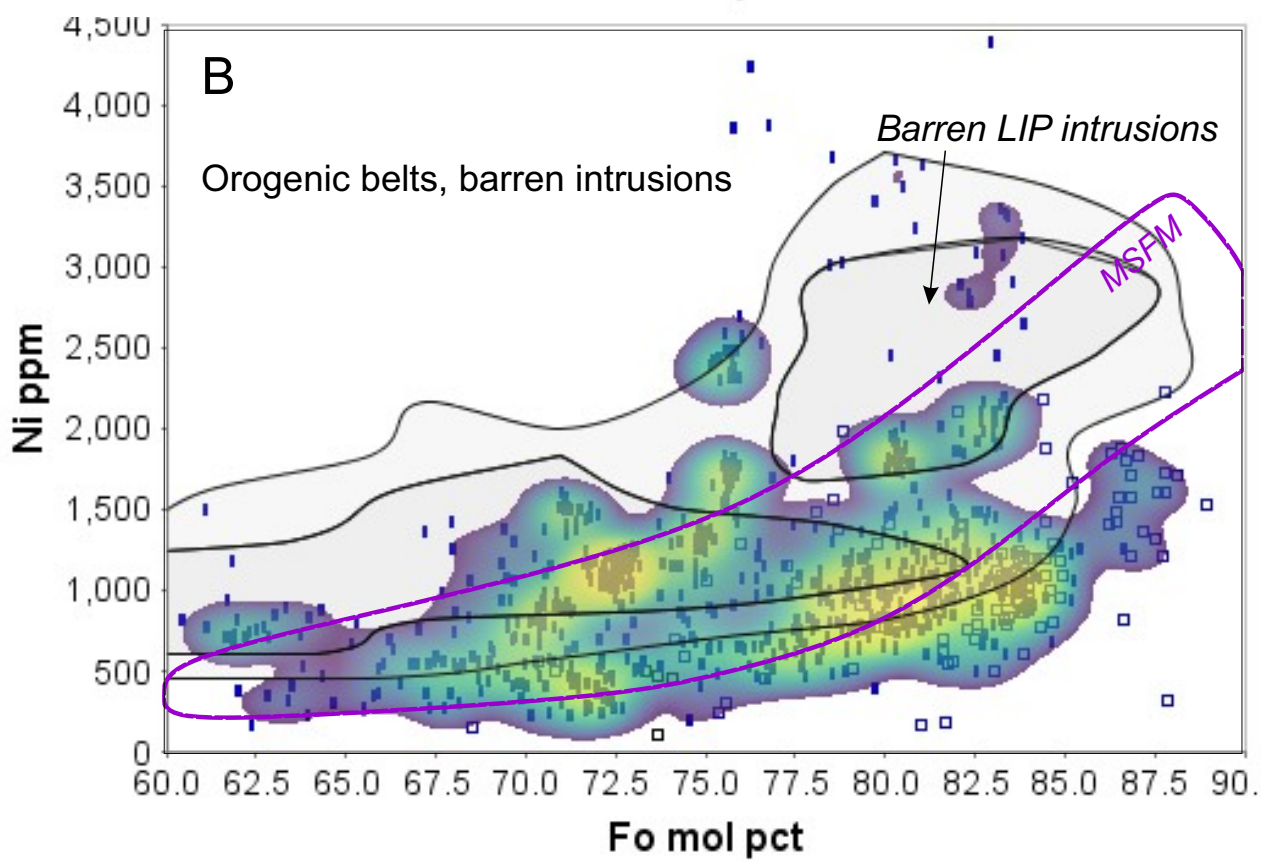
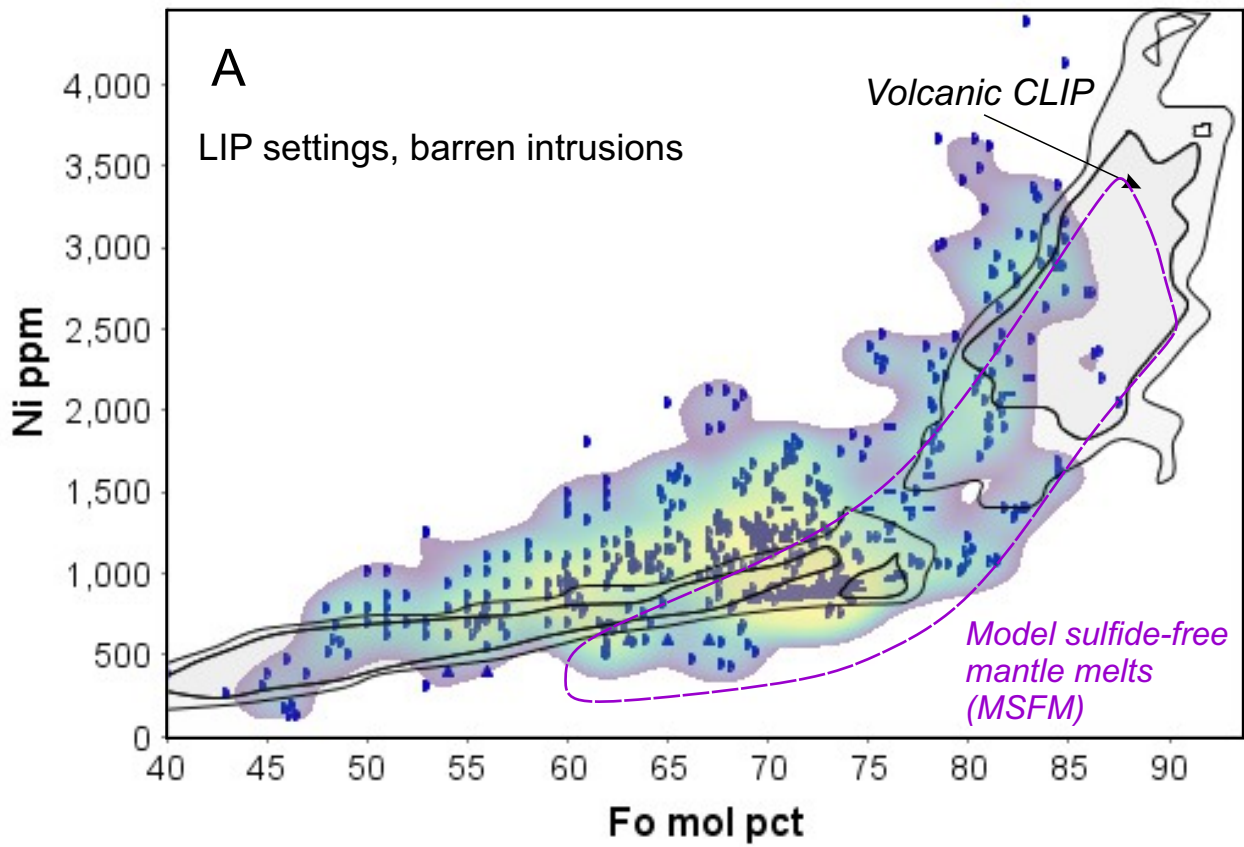


fig 3

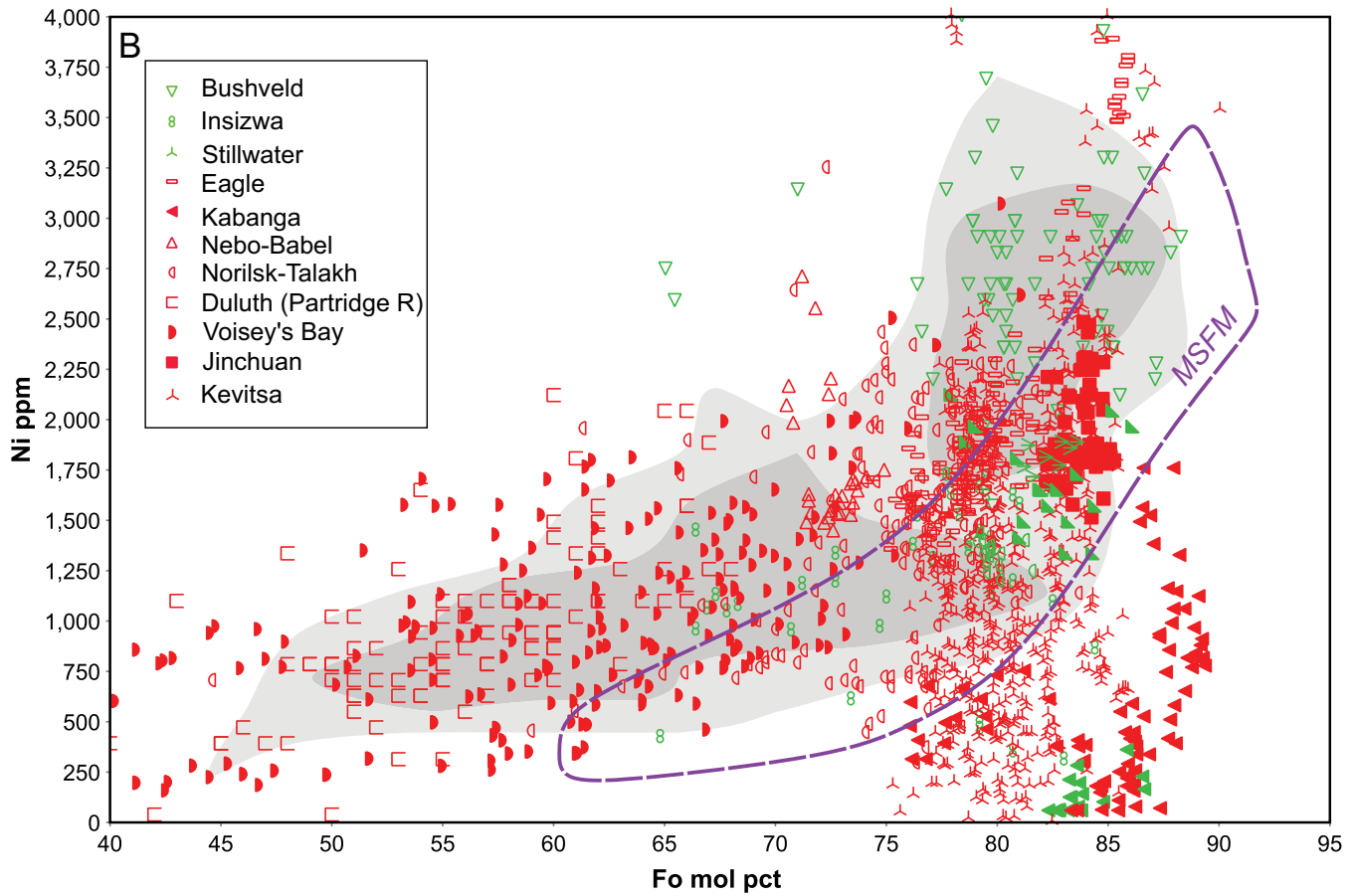
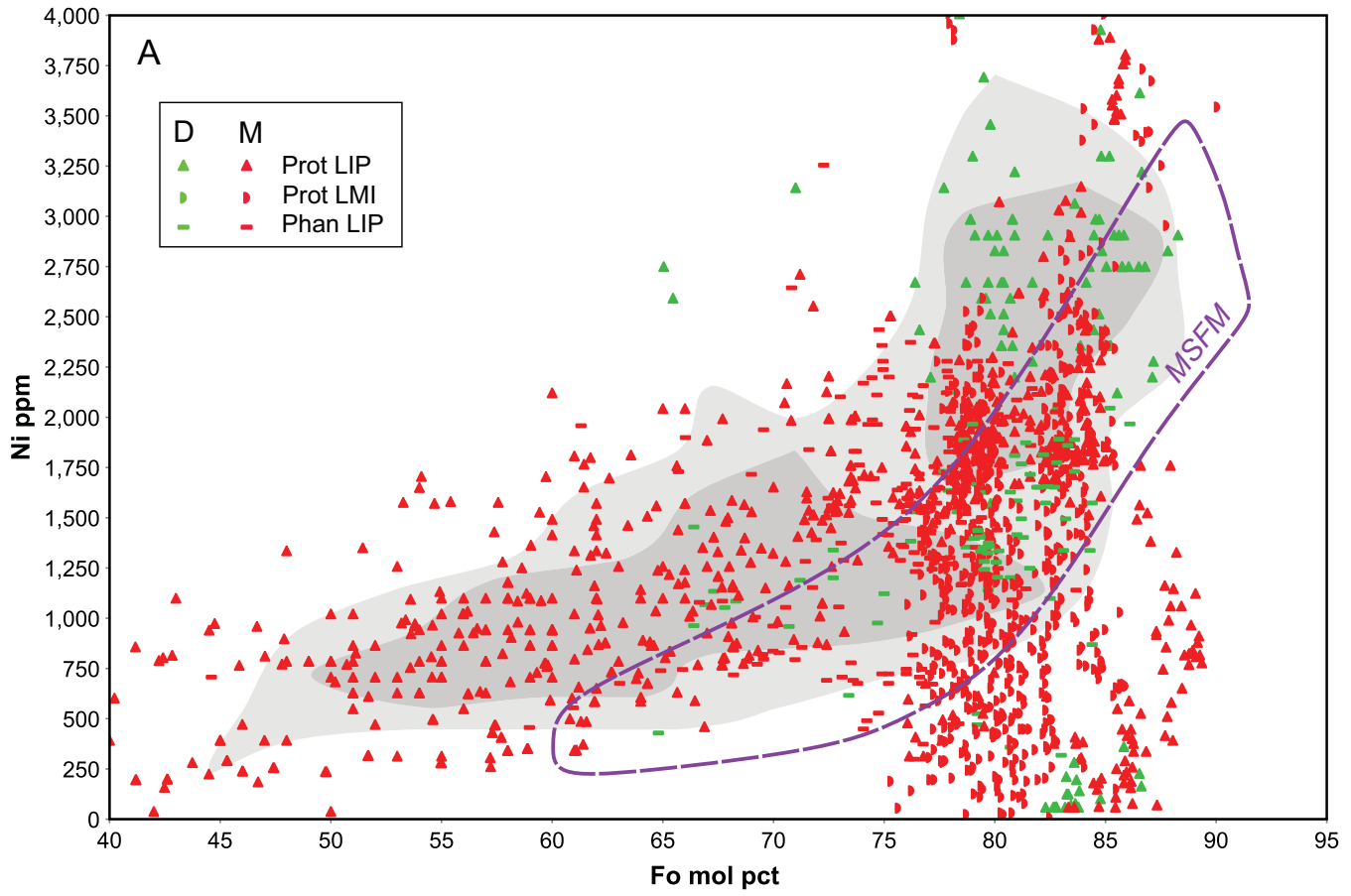


fig 4

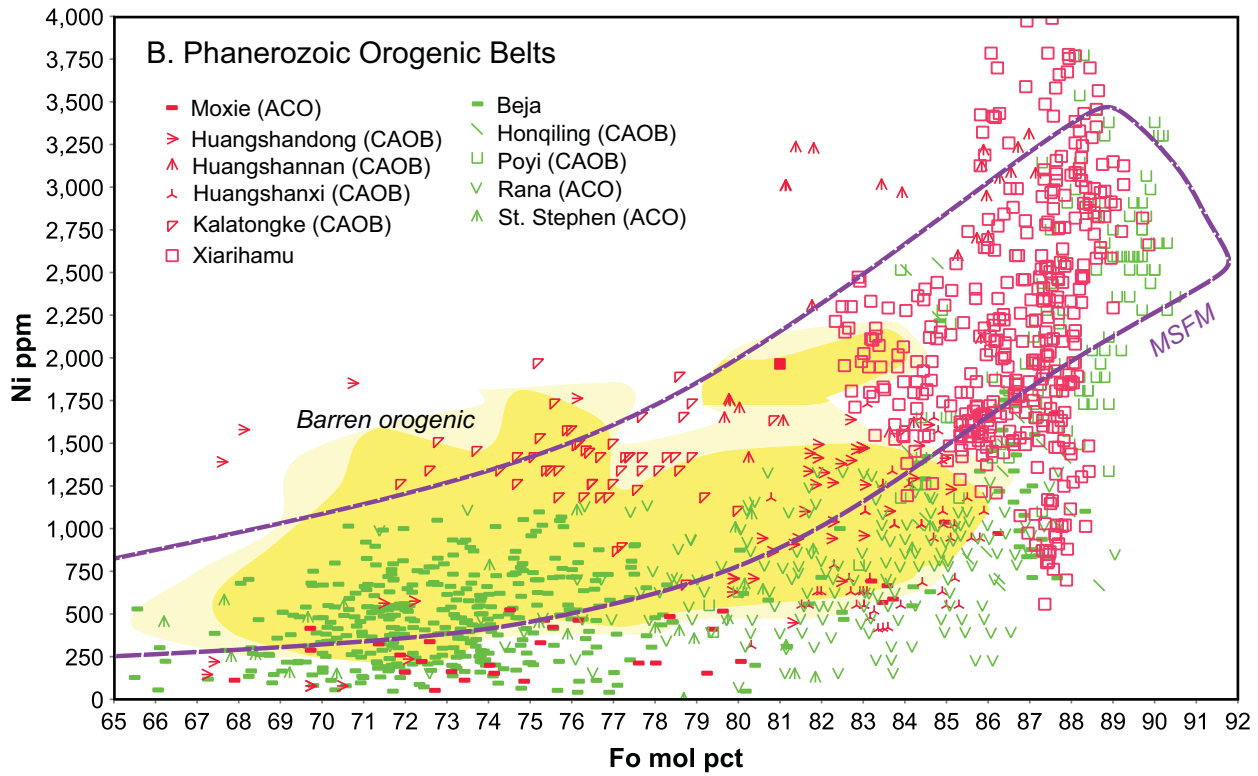
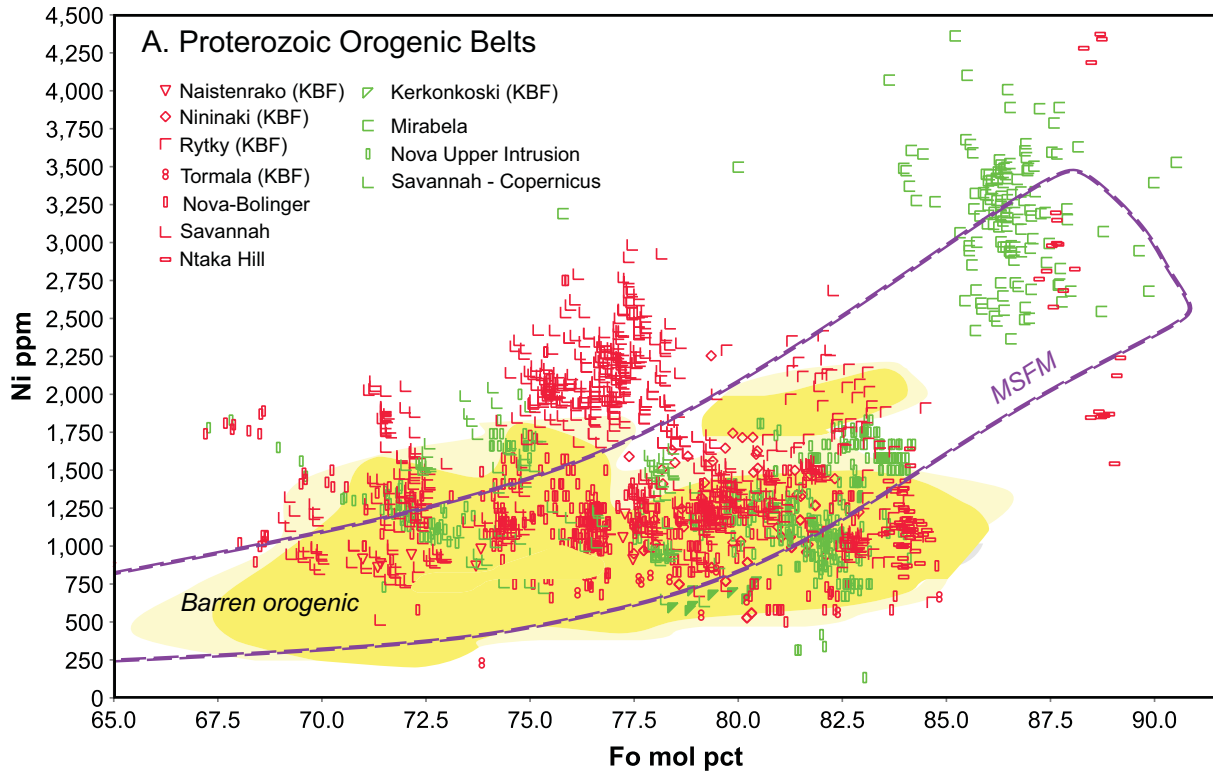


fig 5

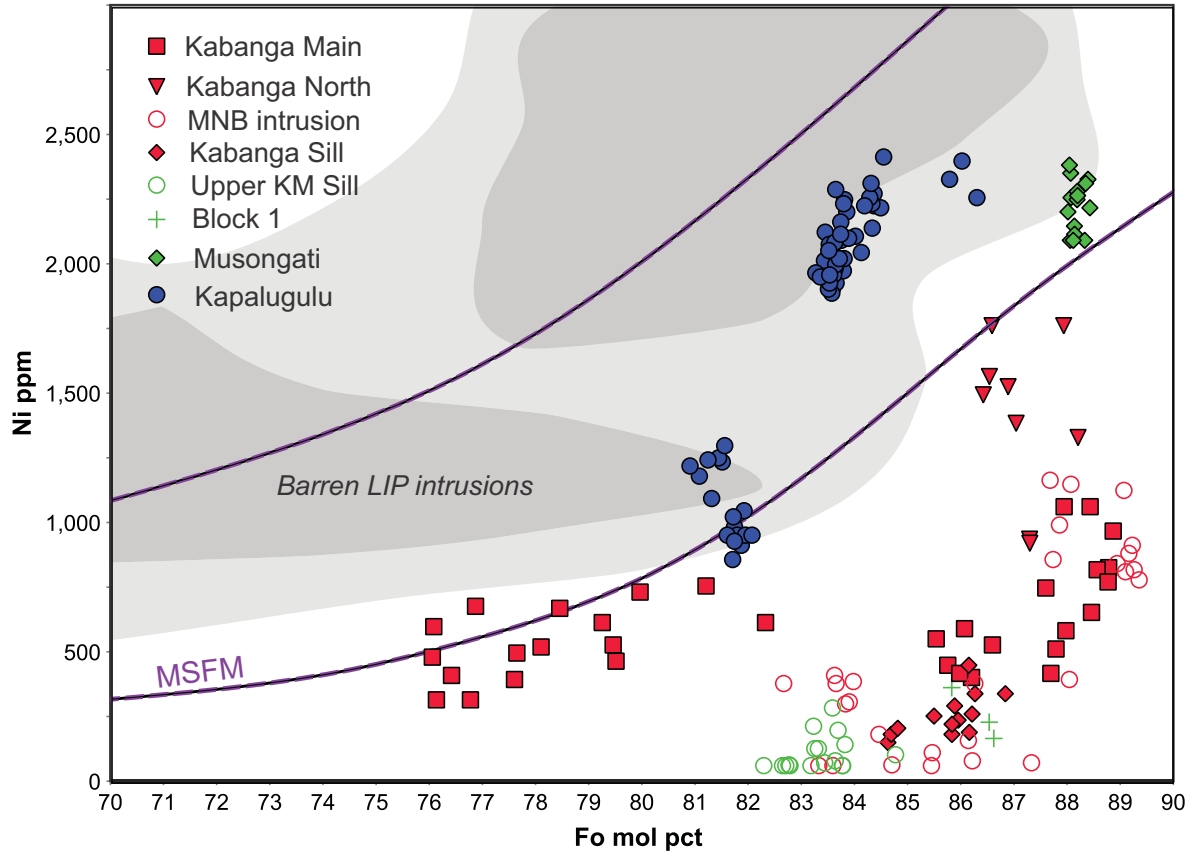


fig 6

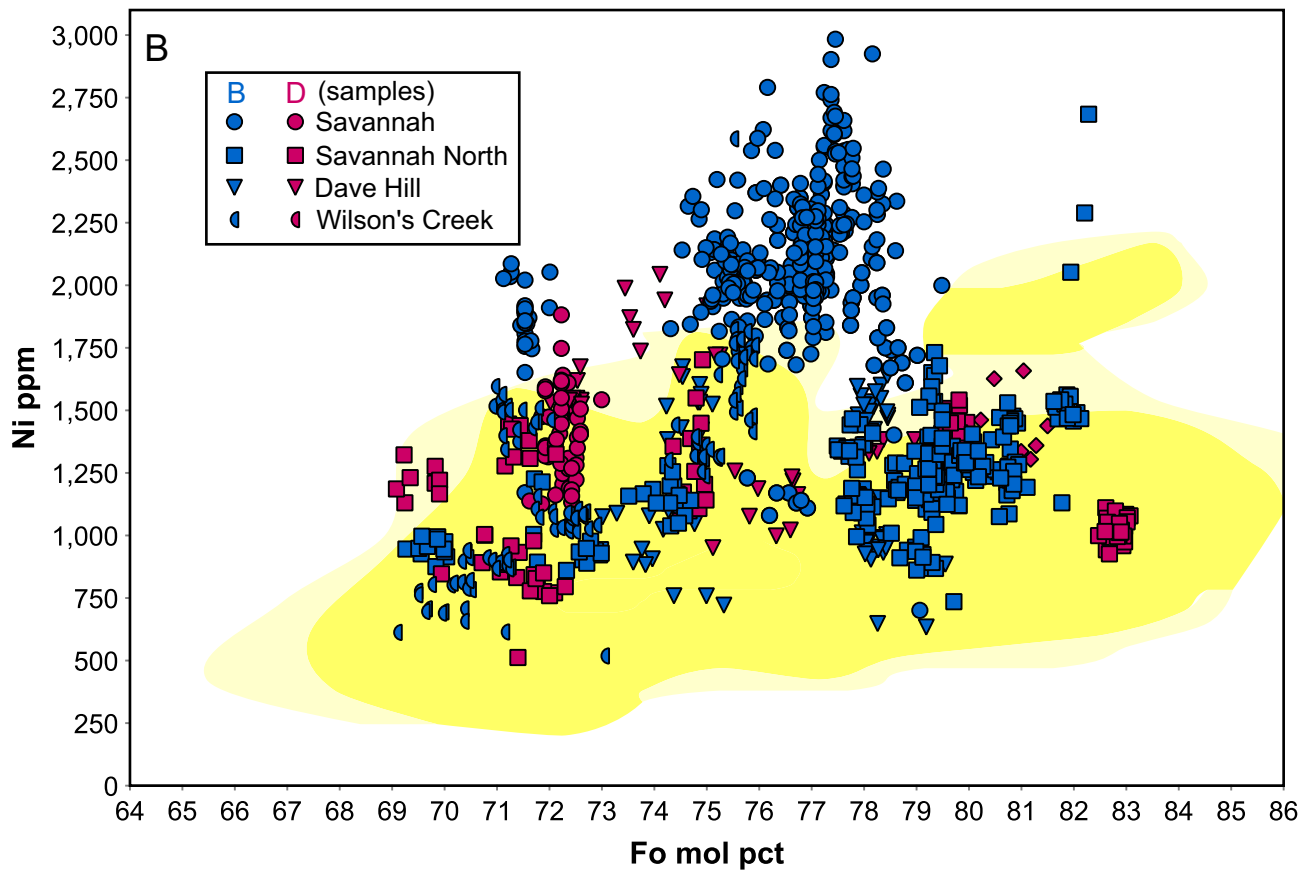
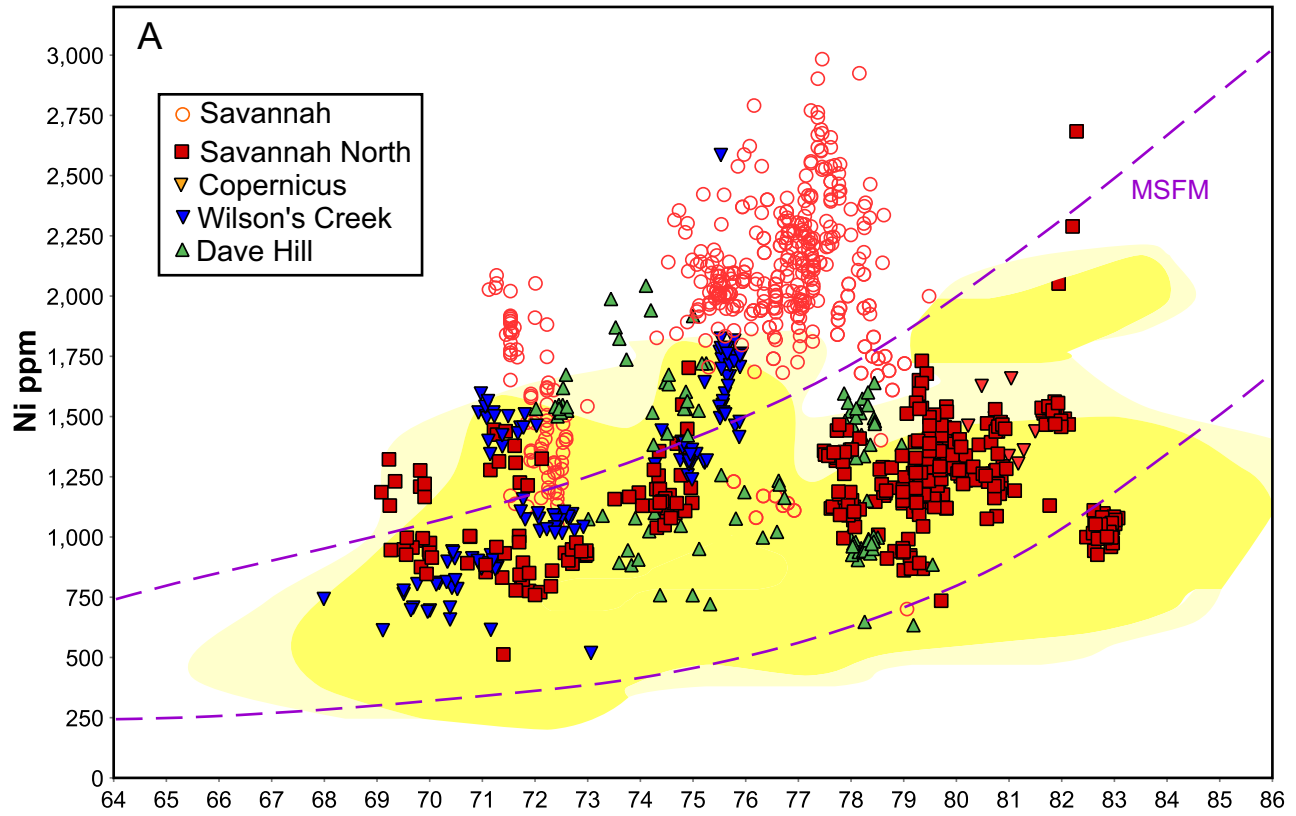


fig 7

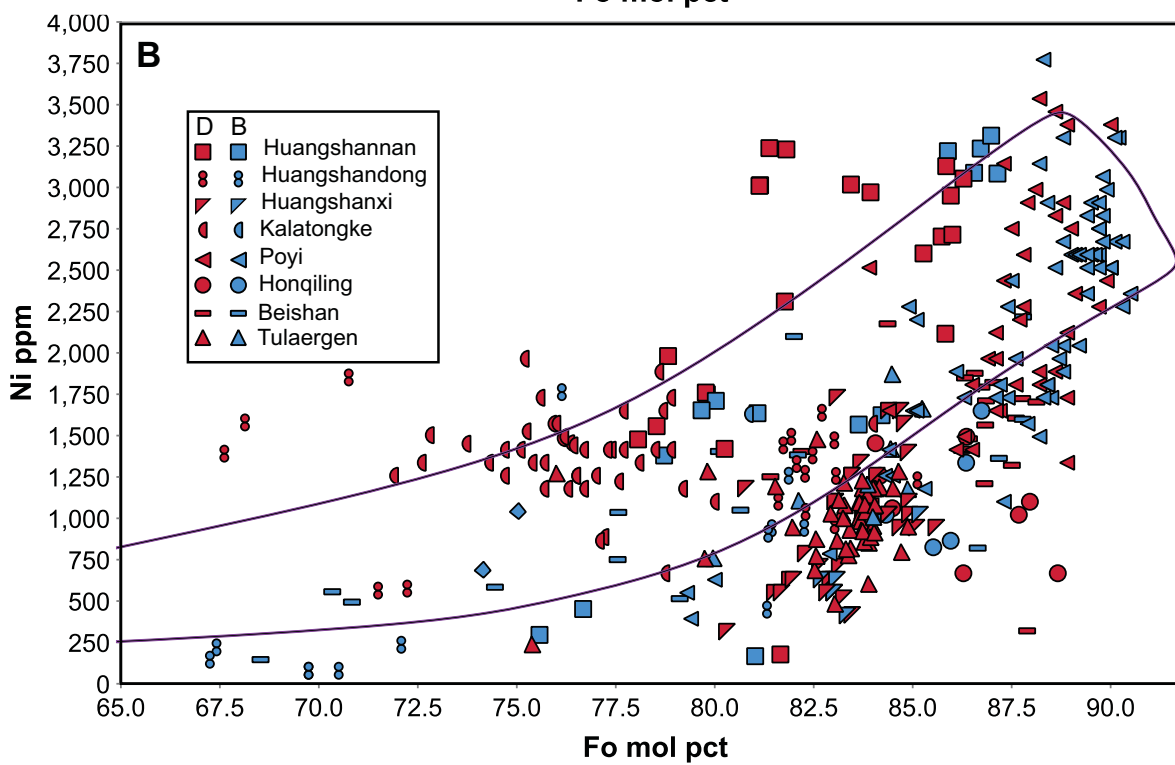
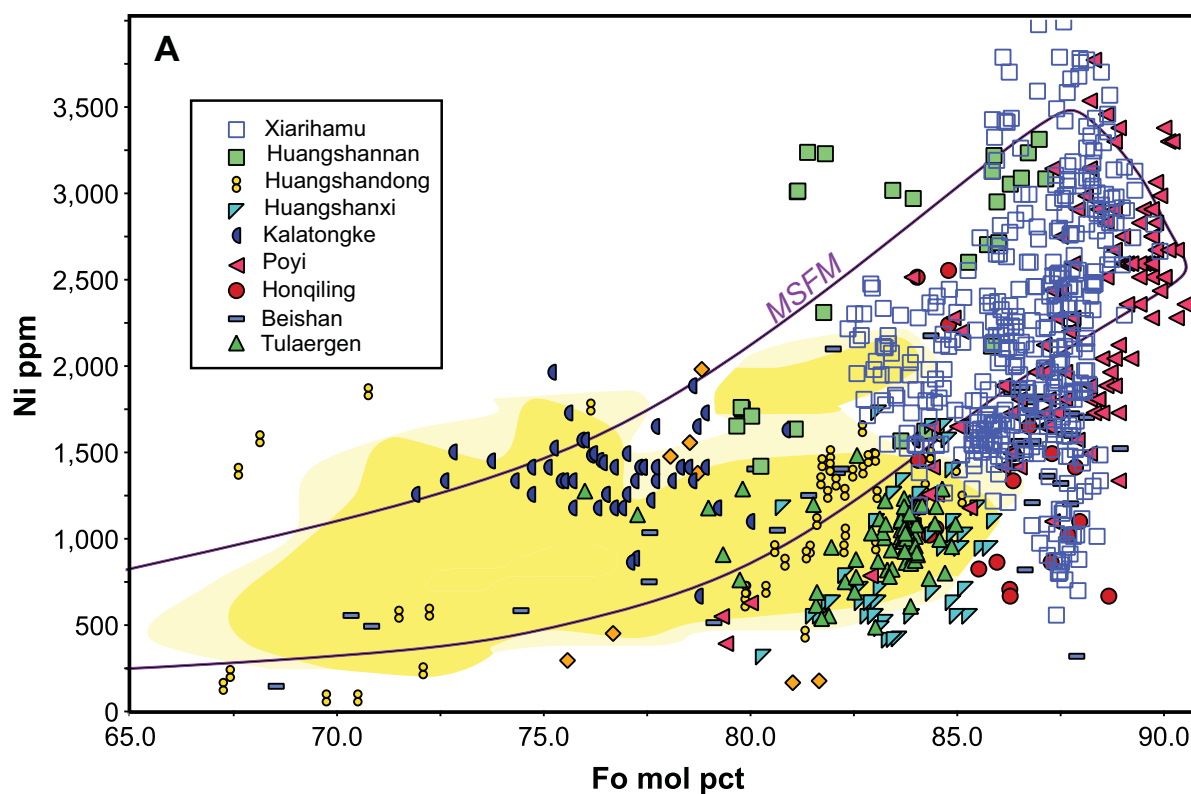


fig 8

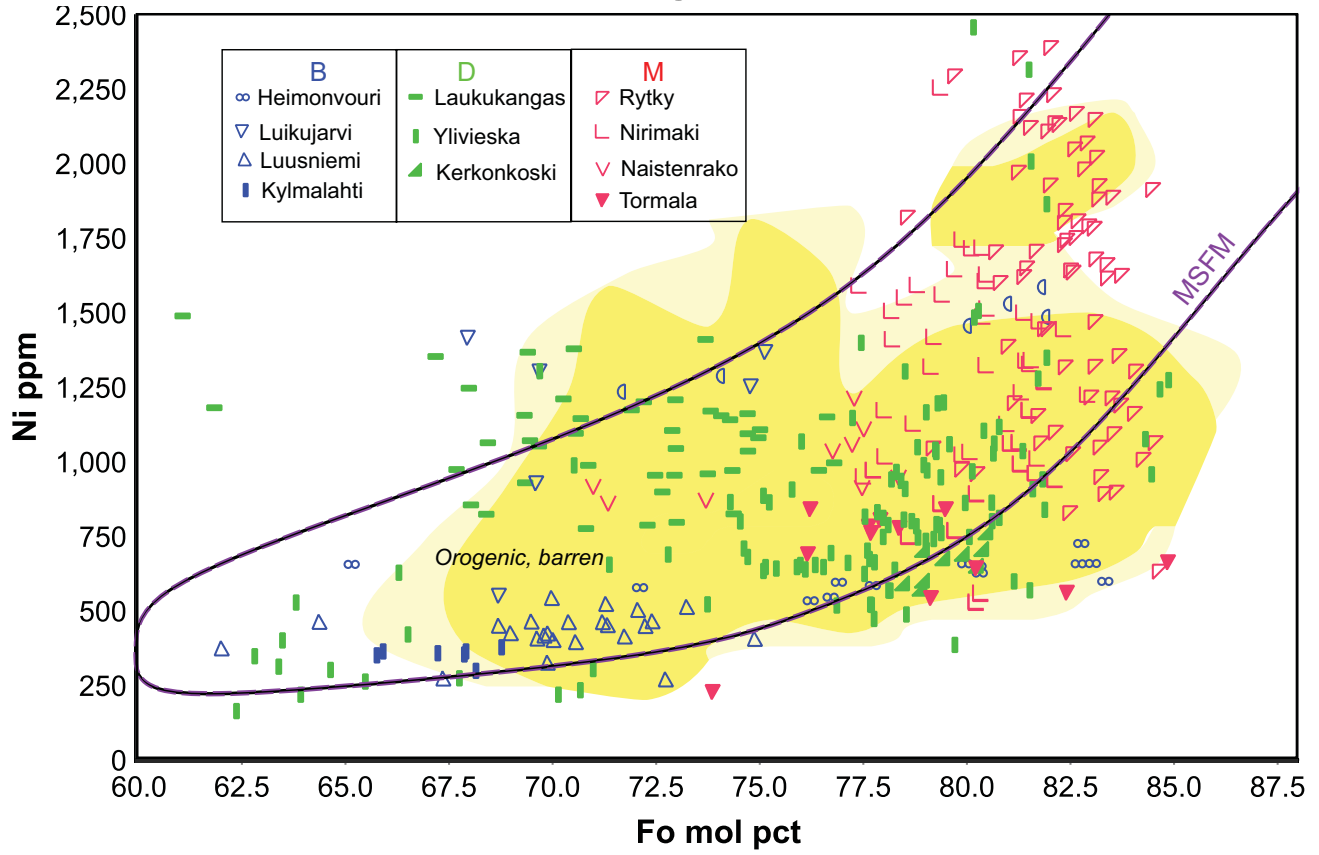


fig 9

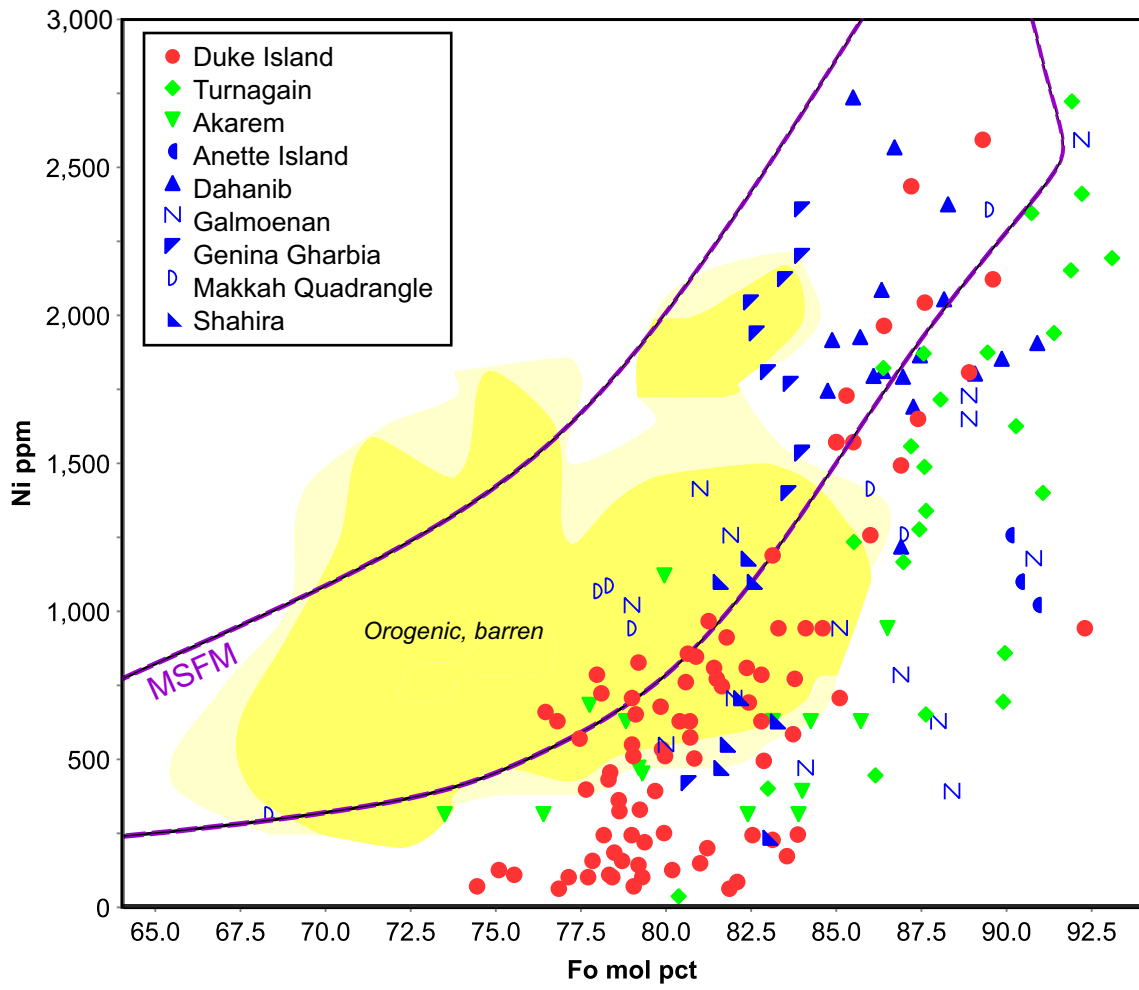


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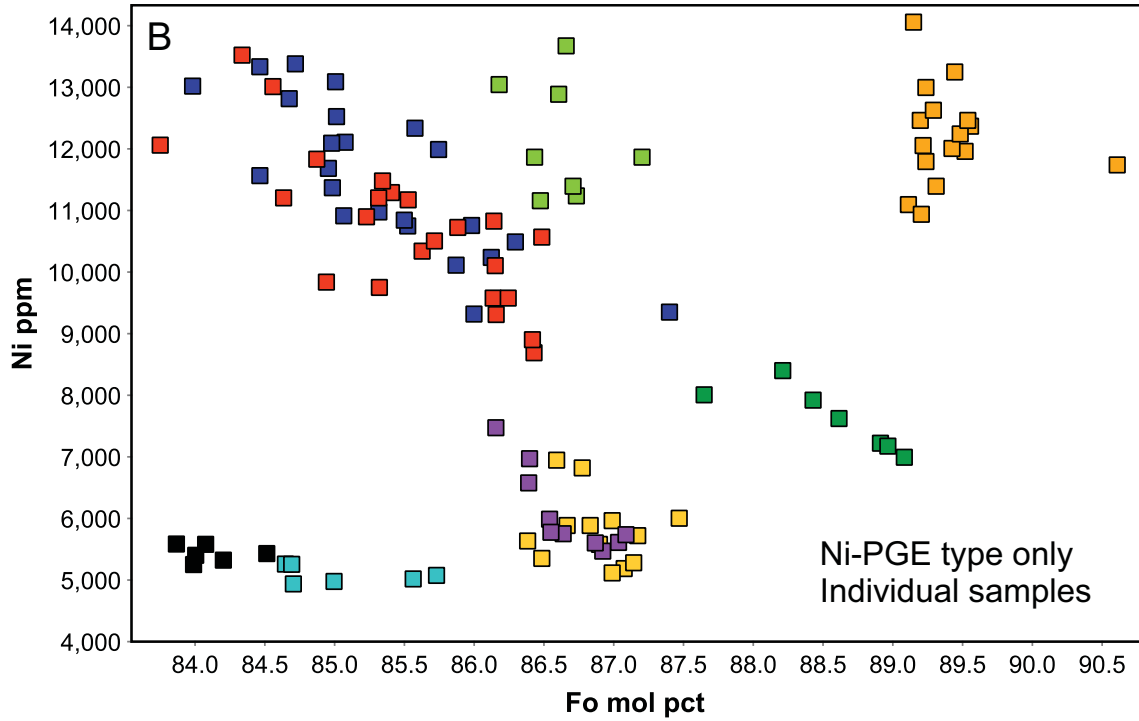
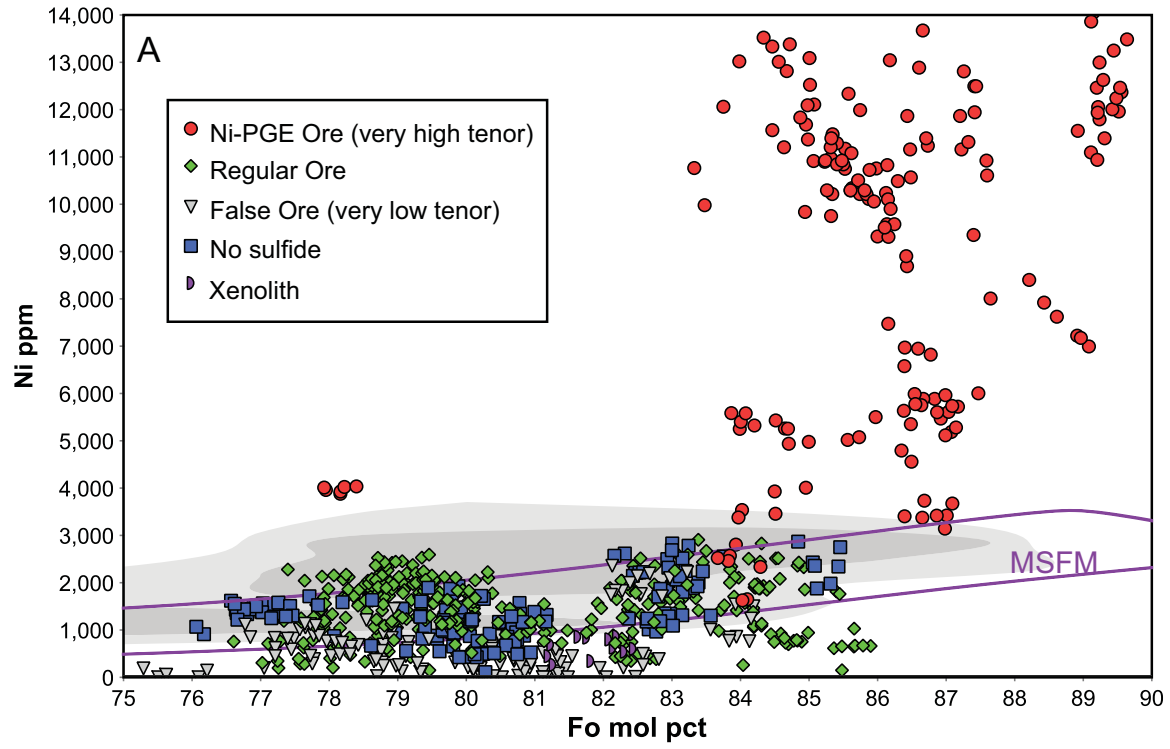
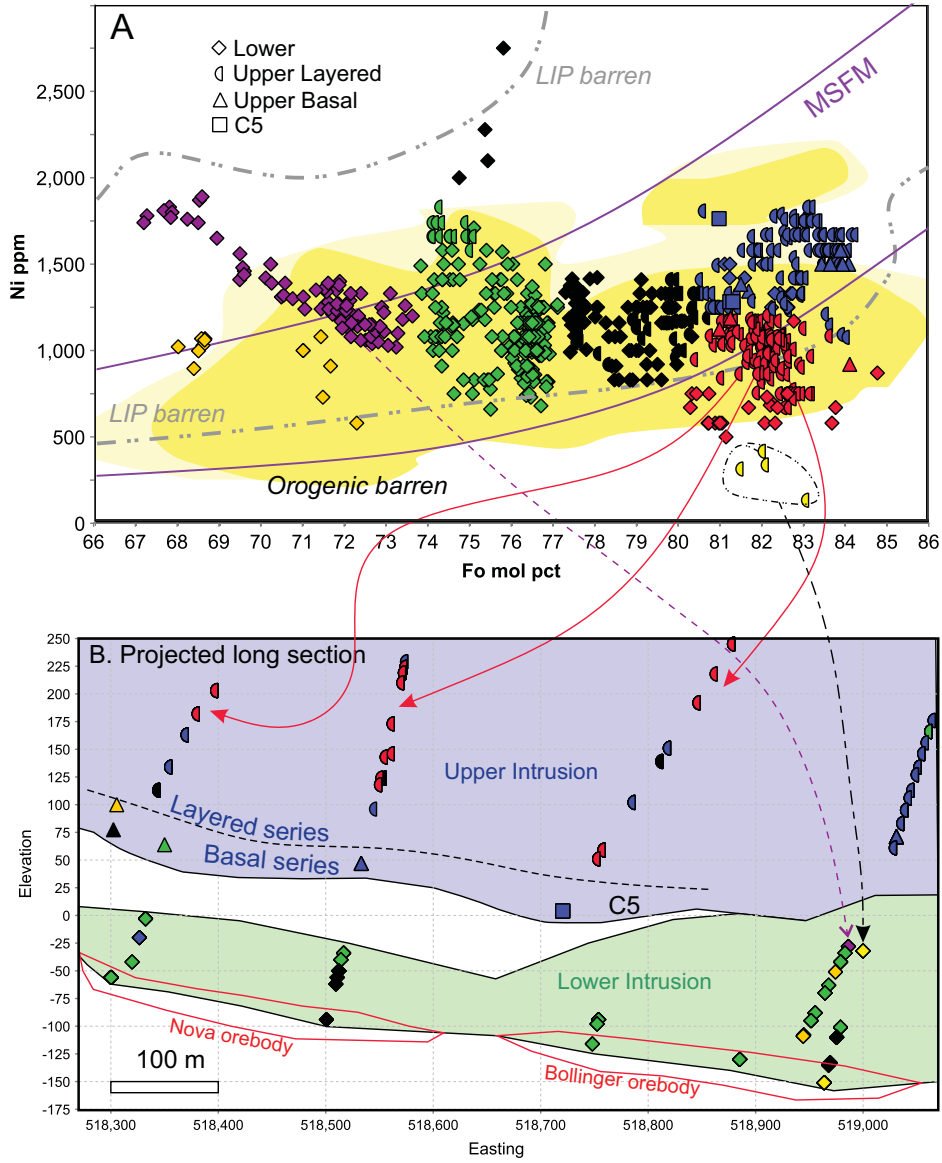


fig 11



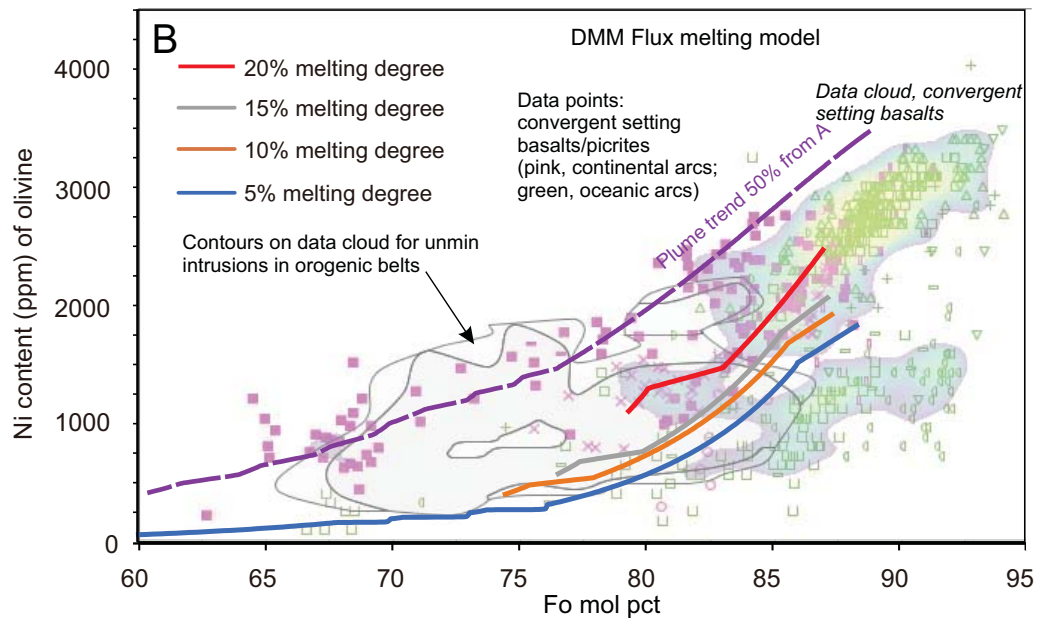
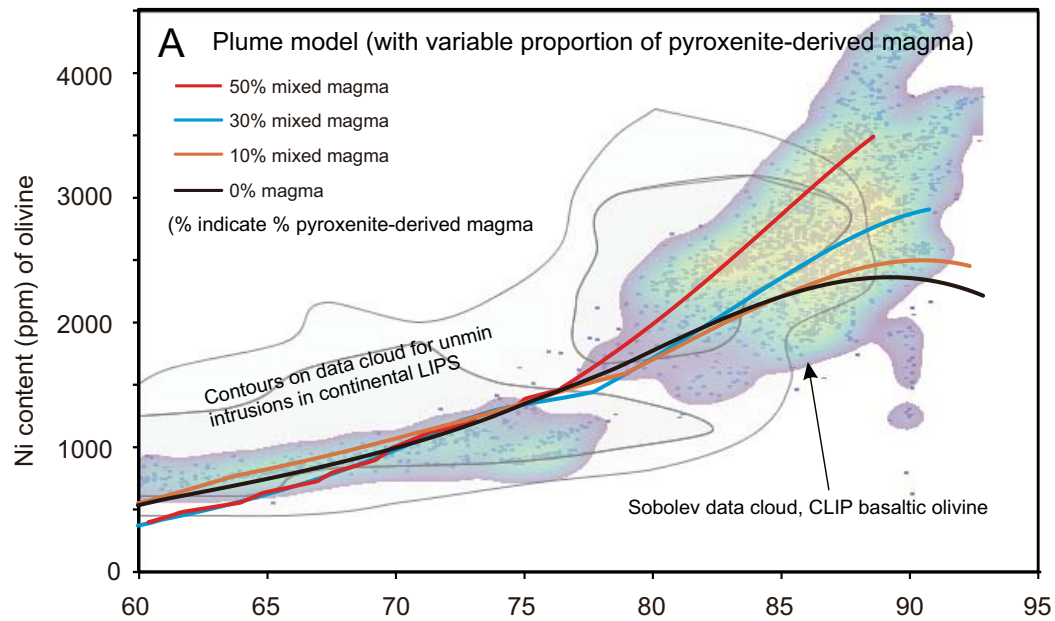


fig 13

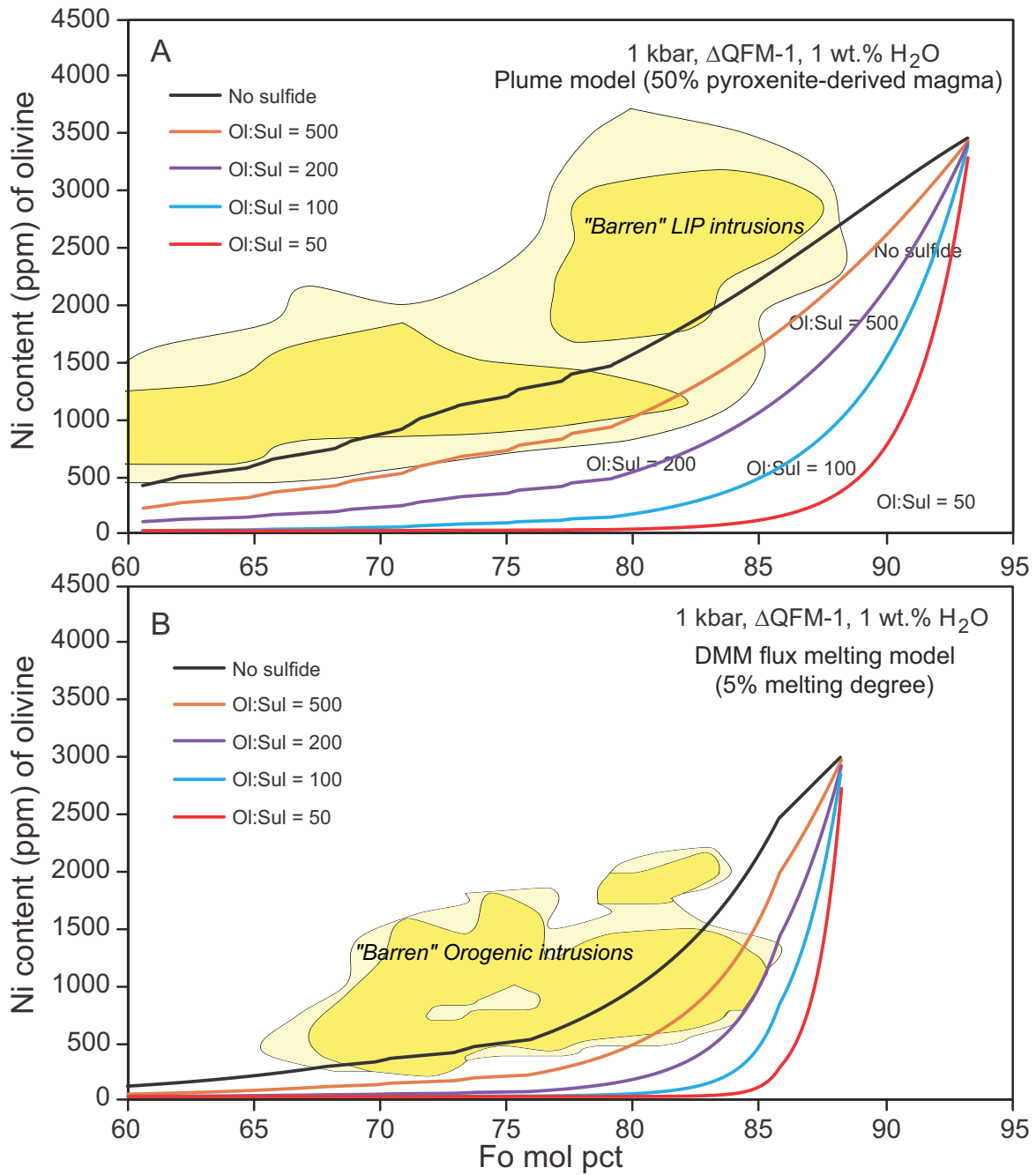


fig 14

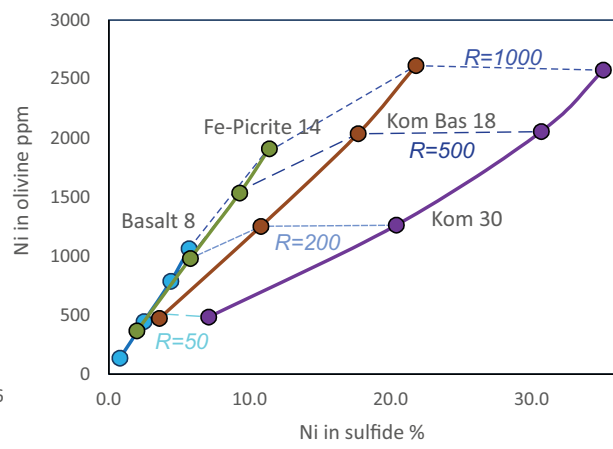
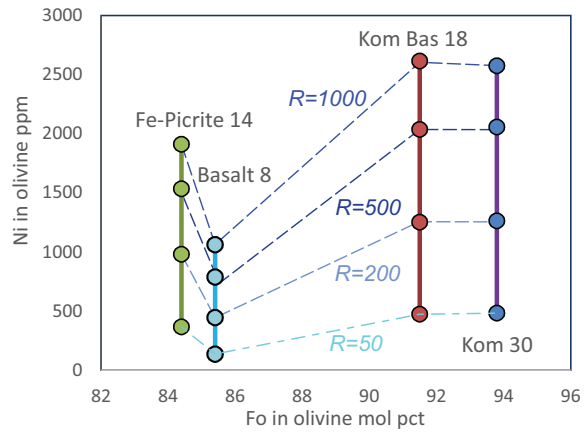


fig 15

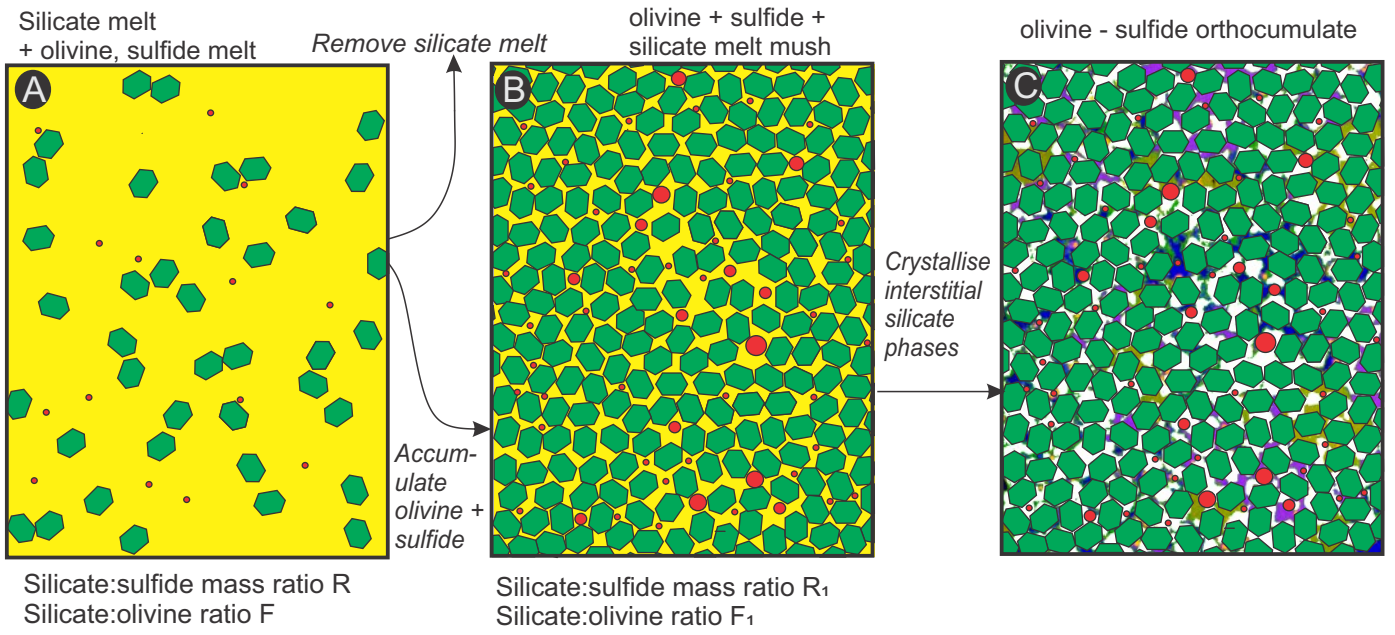


fig 16

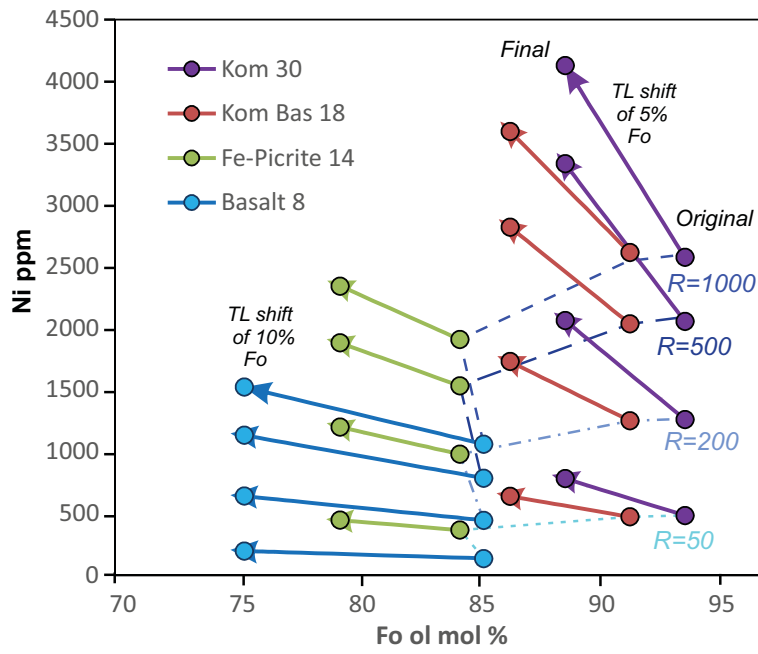
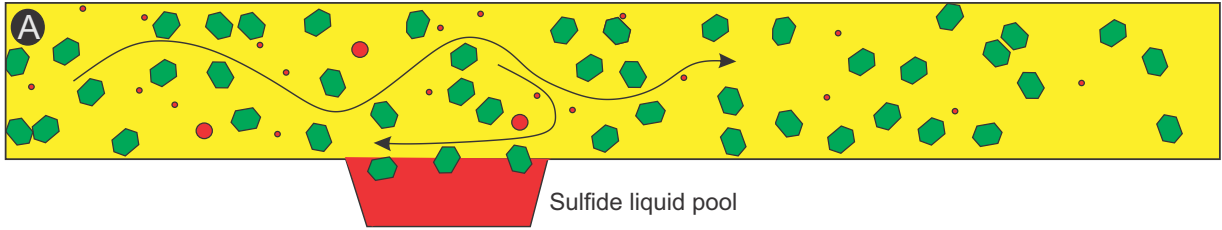


fig 17

Silicate melt + Mg-rich olivine, Ni-rich sulfide melt



Silicate melt + Fe-rich olivine

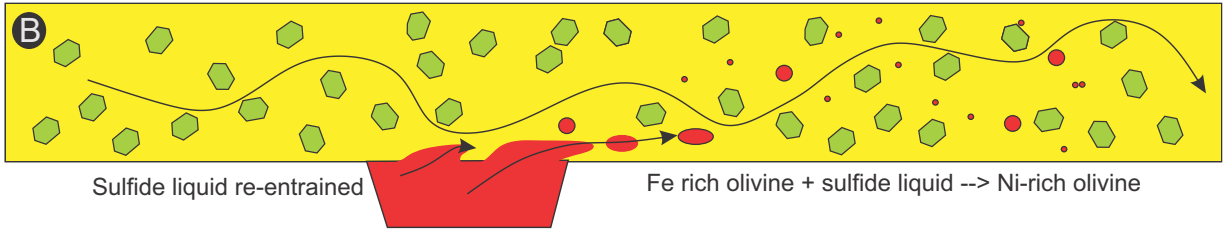


fig 18

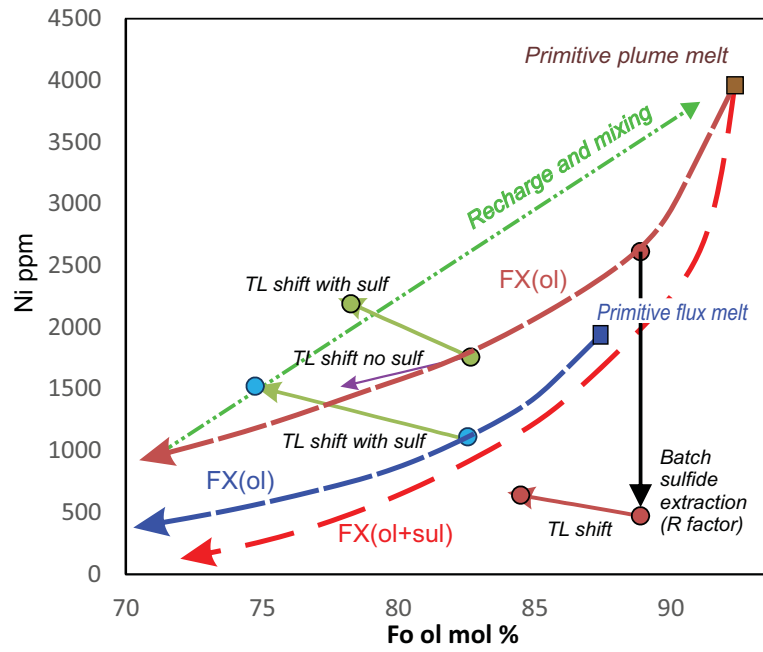


fig A1-1

