1   # Nickel in olivine as an exploration indicator for magmatic Ni-Cu

2   # sulfide deposits: a data review and re-evaluation

3   # REVISION 2

4   Stephen J. Barnes[1], Zhuo-Sen Yao[2], Ya-Jing Mao[3], Ana P. Jesus[4], Shenghong Yang[5], Valentina

5   Taranovic[1,7], Wolfgang D. Maier[6].

6   [1]CSIRO Mineral Resources, 26 Dick Perry Ave., Kensington, WA 6151 Australia.

7   Steve.barnes@csiro.au [2]Department of Earth Sciences, Carleton University, Ottawa, Canada.

8   yaozhuosen@gmail.com [2]Key Laboratory of Mineral Resources, Institute of Geology and Geophysics,

9   Chinese Academy of Sciences (CAS), Beijing 100029, China. maoyajing@mail.iggcas.ac.cn.

10   [4]Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal. apjesus@fc.ul.pt [5]Oulu Mining

11   School, Univ. of Oulu, Finland. shenghong.yang@oulu.fi. [6]Dept. of Earth Sciences, Univ. of Cardiff,

12   Wales. maierw@cardiff.ac.uk. [7]tinatskg@gmail.com.

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.*

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.

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/)(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(ineralized), 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 IoGas 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.

Results

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).

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 gabbronorite, 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 km^2. 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 km^2 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-emplacement 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

458
459

460 As we have seen, intrusion-hosted olivines show wide and complex variability in Ni-Fo trends, even

461 within the same intrusion, indicating that sulfide melt equilibration is only one of a number of

462 factors influencing the Ni content of olivine. Some of these factors are considered and modelled in

463 the following section.

Range of variability of Ni in carrier magmas

464

465 The silicate magmas that form magmatic sulfide ores (carrier magmas) are known to have a wide

466 range of Ni contents, from ~1600 ppm in primitive komatiites to ~100 ppm in some mafic-hosted

467 systems (Barnes et al., 2016). The ability of relatively low-Ni mafic magmas to form deposits with

468 economic Ni contents arises from the very high partition coefficient D_{Ni} of Ni between sulfide and

469 olivine; this D_{Ni} value increases strongly with falling temperature and hence is considerably higher in

470 basalt than in komatiite (Kiseeva and Wood, 2015). The same effect applies to D_{Ni} between olivine

471 and silicate melt (Li and Ripley, 2010; Matzen et al., 2013; Matzen et al., 2017a; Matzen et al.,

472 2017b; Pu et al., 2021). The effect of this T dependence on olivine Ni contents gives rise to the

473 observed wide variability in the Ni contents of primary mantle melts, (Li and Ripley, 2010; Yao et al.,

474 2018) and basalt-hosted olivines (Sobolev et al., 2007; Herzberg et al., 2016), (Figure 1), a variability

475 that could be further enhanced by variability in the pyroxene:olivine ratio in mantle sources (Sobolev

476 et al., 2005). The presence of pyroxene-rich mantle-source regions has been proposed as a major

477 controlling factor on the range of olivine compositions in various Chinese deposits (Song et al.,

478 2011b; Song et al., 2011c; Lu et al., 2019), but remains a hotly debated topic beyond the scope of

479 this contribution.

480 We have carried out a series of model calculations on compositions of potential carrier magmas and

481 associated olivines generated at a variety of depths and primary water contents and undergoing

482 fractional crystallization, following the methods of Yao et al. (2018). A representative series of these

483 curves are shown in Figure 12, for conditions corresponding to sulfide undersaturation (i.e. no

484 sulfide liquid involved during melting or fractional crystallization) and appropriate values for the

485 crystallization pressure (1 kbar), water content (1 wt% H_2O) and oxygen fugacity (QFM-1). The

486 emplacement depths of most these mafic-ultramafic intrusions are probably shallow, resulting in a

487 relatively narrow pressure range varying from 0.5 to 2.5 kbar (Norilsk, (Yao and Mungall, 2021);

488 Bushveld, (Maier et al., 2013)), which has little influence on the trendlines of Ni in the crystallized

489 olivine grains (Appendix Fig. A1-a). The addition of water into the parental magma will decrease the

490 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 H_2O 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 S^{6+} rather

498   than S^{2-} 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 Fe^{3+}/Fe^{2+} 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.

Fractional crystallization of olivine + sulfide liquid

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

Figure 13

Recharge and magma mixing

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

Gleeson and Gibson (2019) point out that recharge and mixing provides a viable alternative hypothesis to the "pyroxenite source" model, which has been involved for some Ni deposits and camps, notably several of the Chinese deposits (Lu et al., 2019). Numerous other studies (Matzen et 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.

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 (Lesher, 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.*

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

607   NiO (olivine) + FeS (sulfide) = NiS (sulfide) + FeO (olivine)   (1)
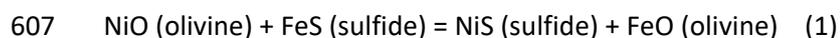
608   The distribution coefficient for this reaction K_D is given by

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

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; Lesher, 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.

Appendix 1. Modelling methods

728

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.*

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1060

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, fO2 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 (equns. 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

1174

1175

fig 1
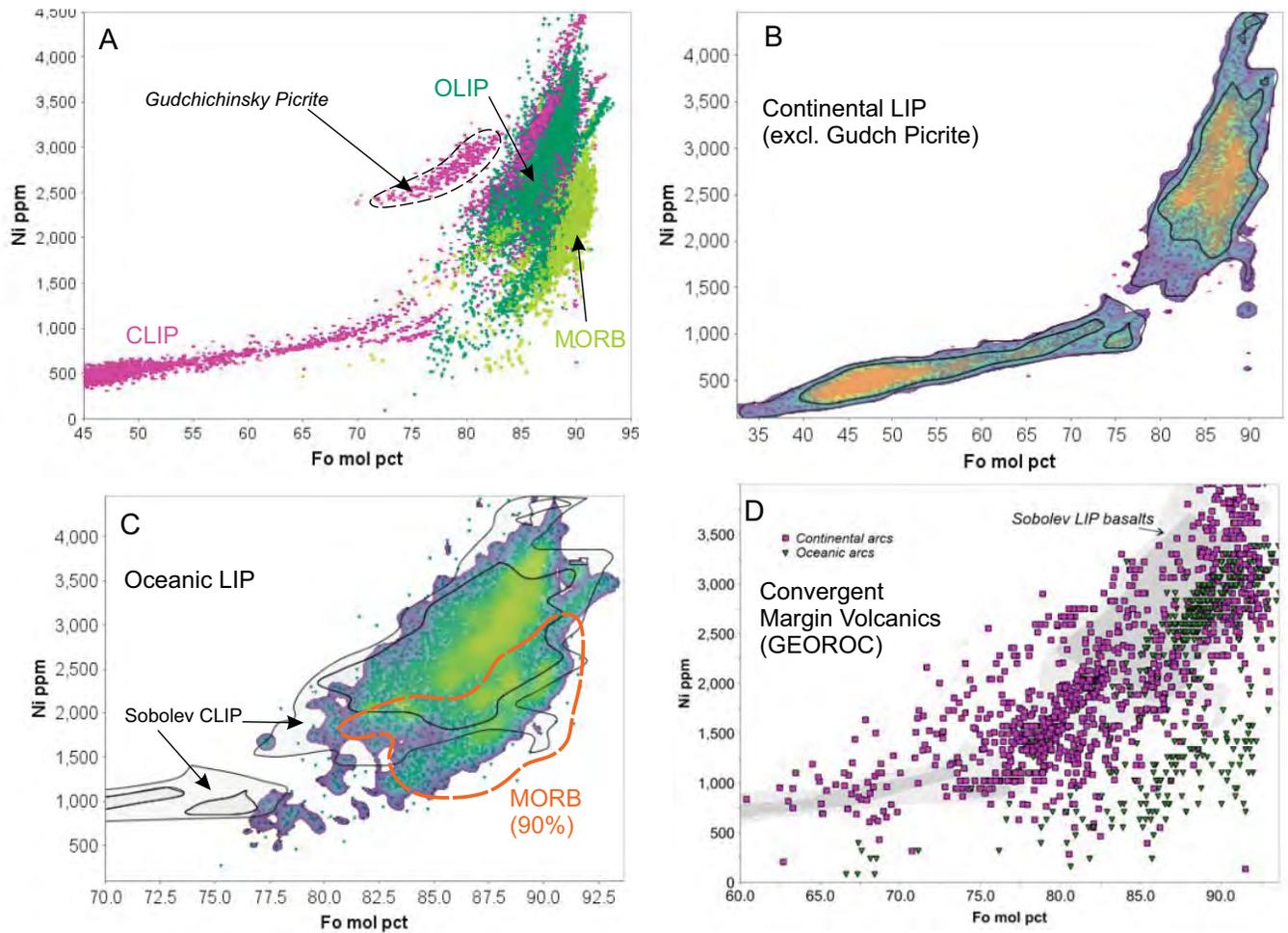
fig 2
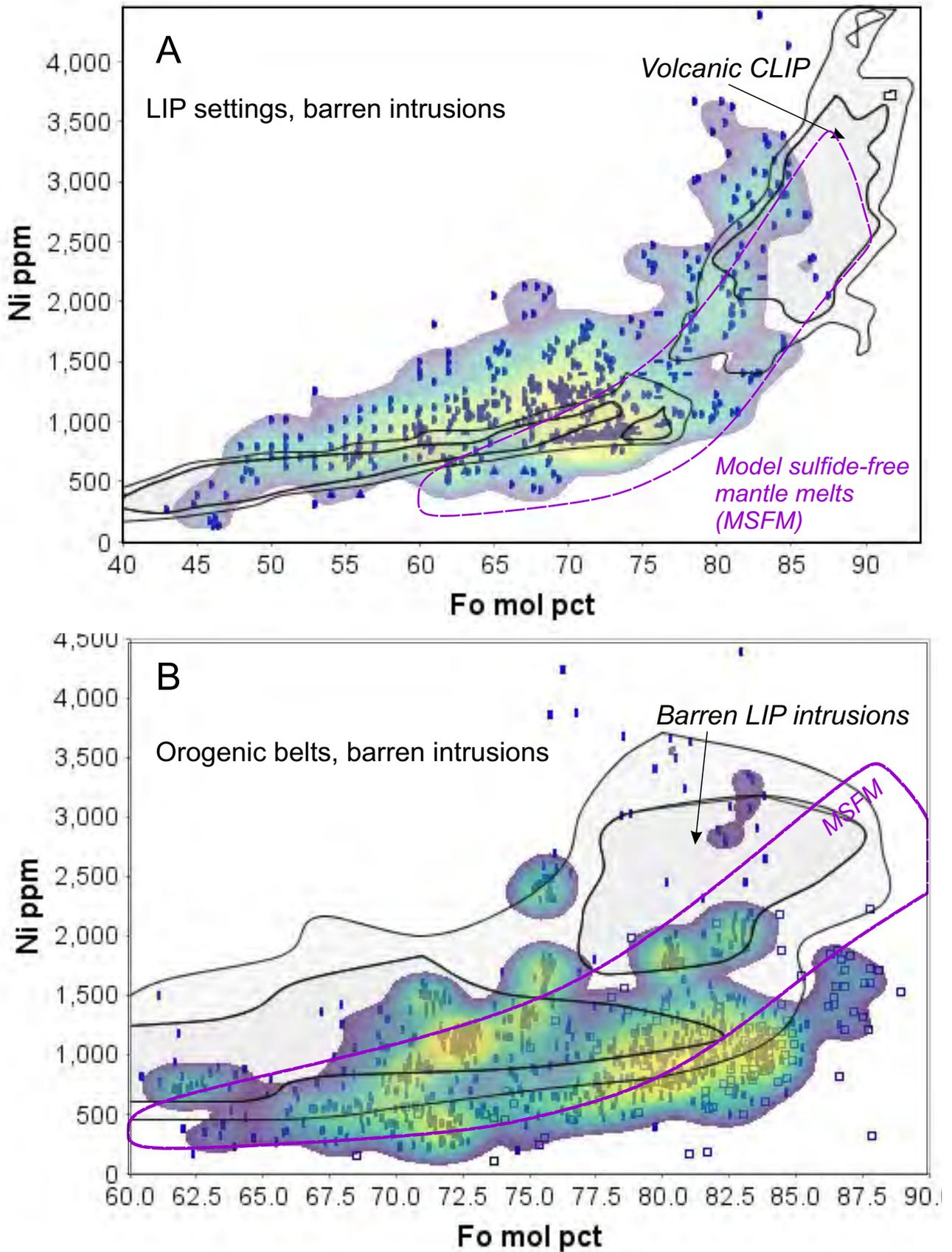
fig 3
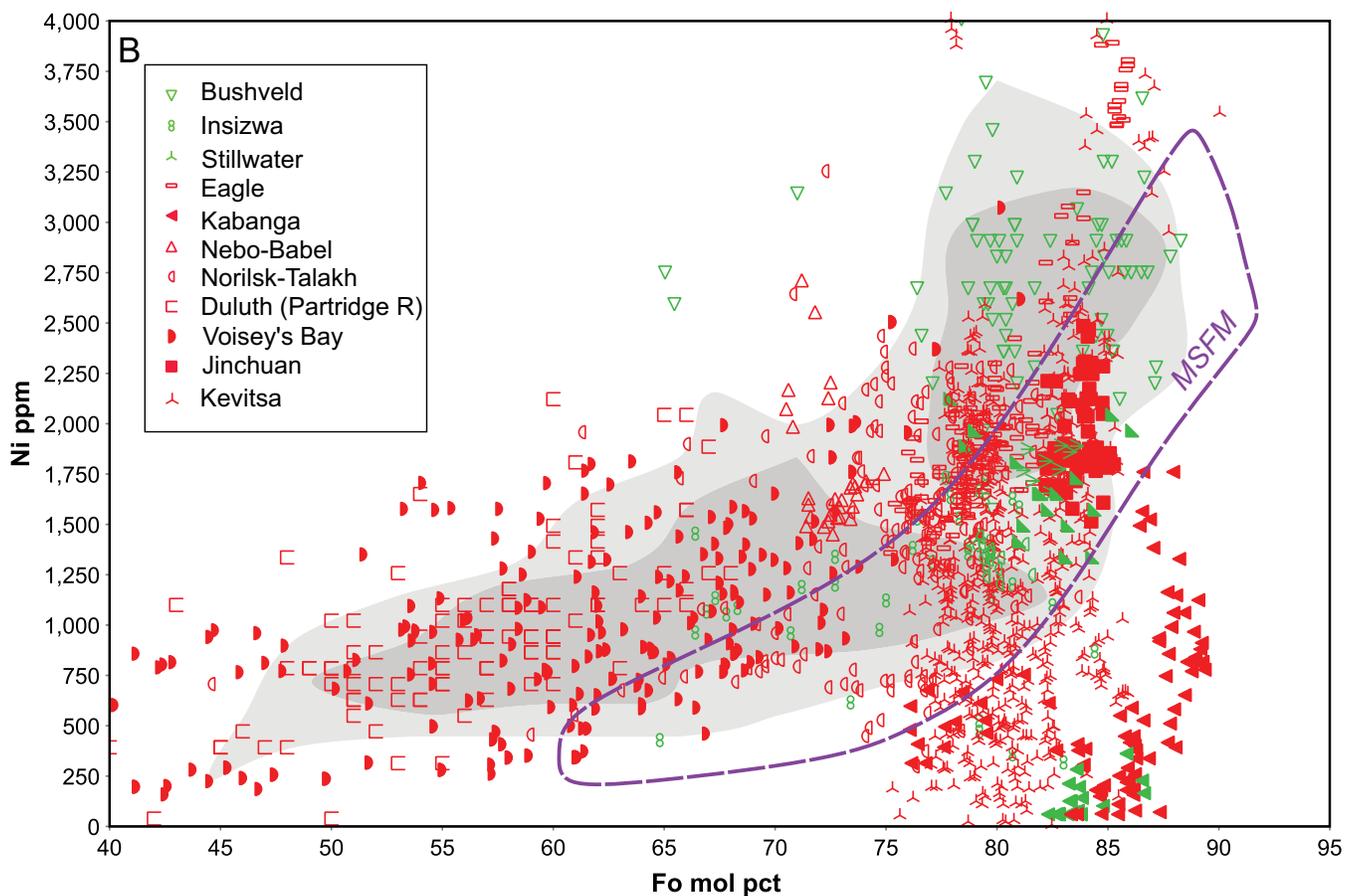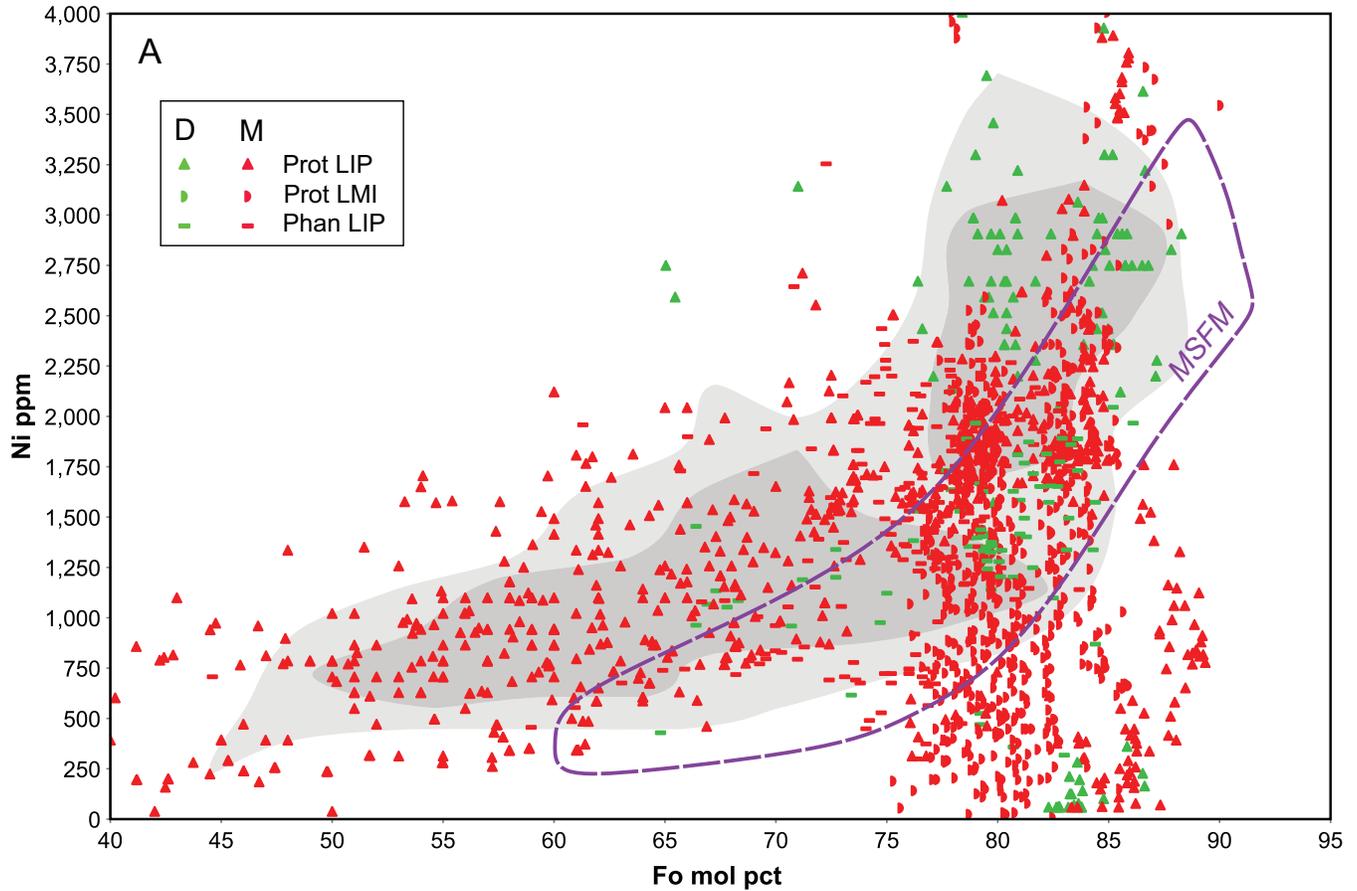
fig 4
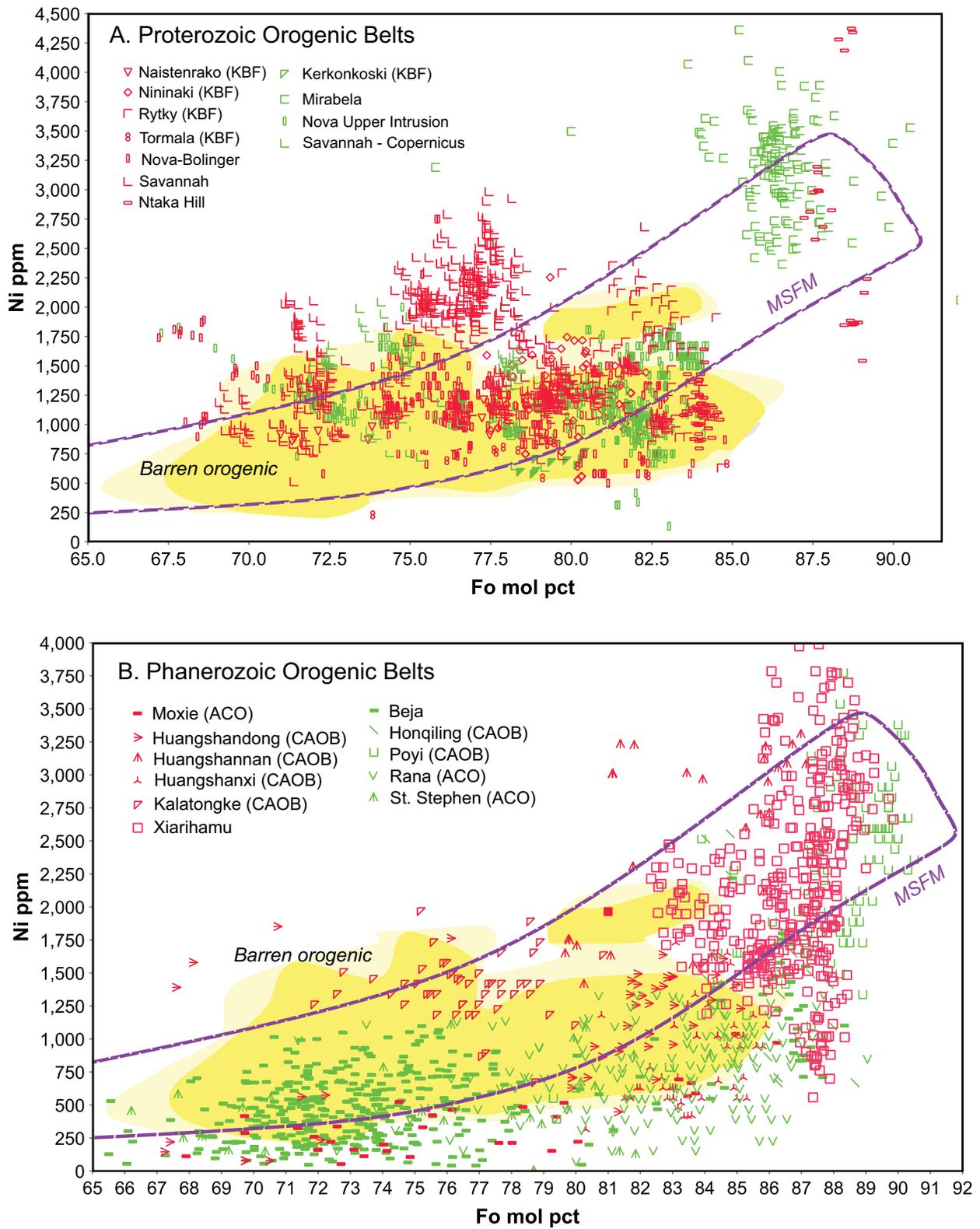
fig 5
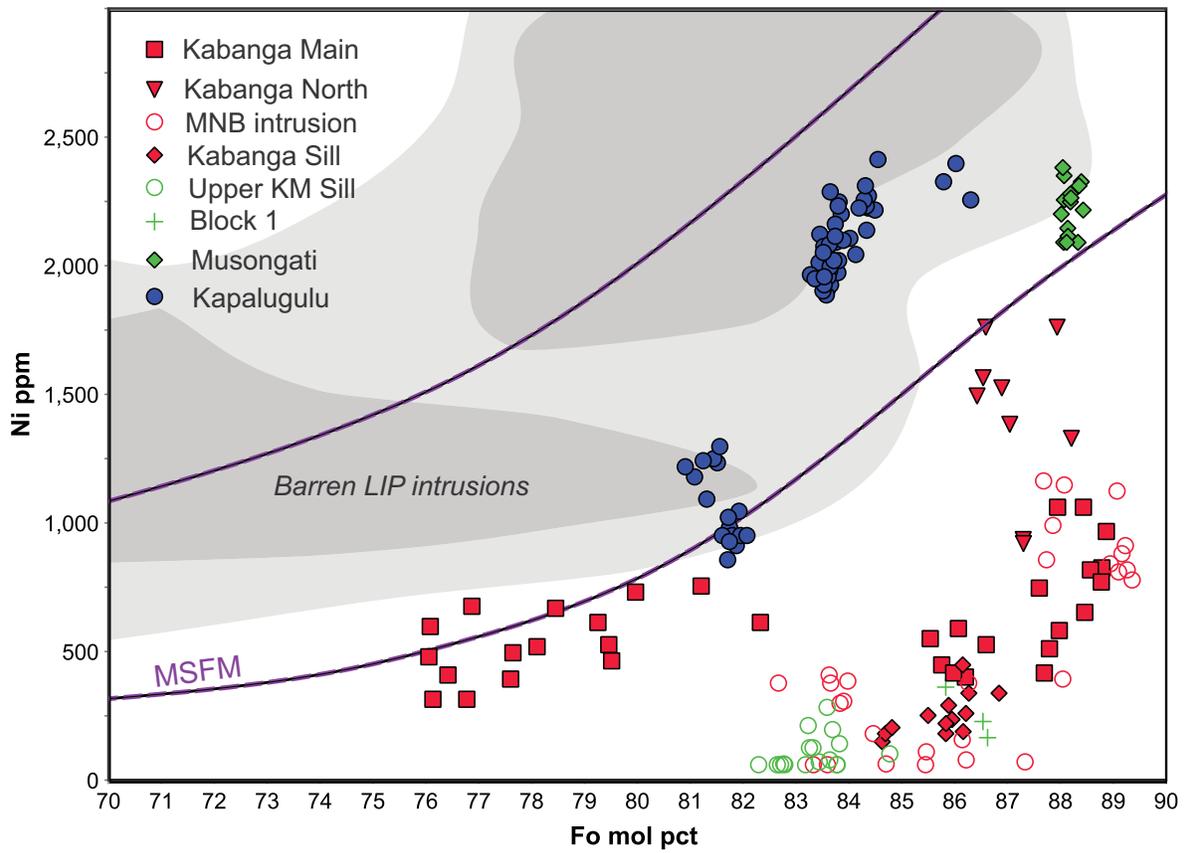
fig 6
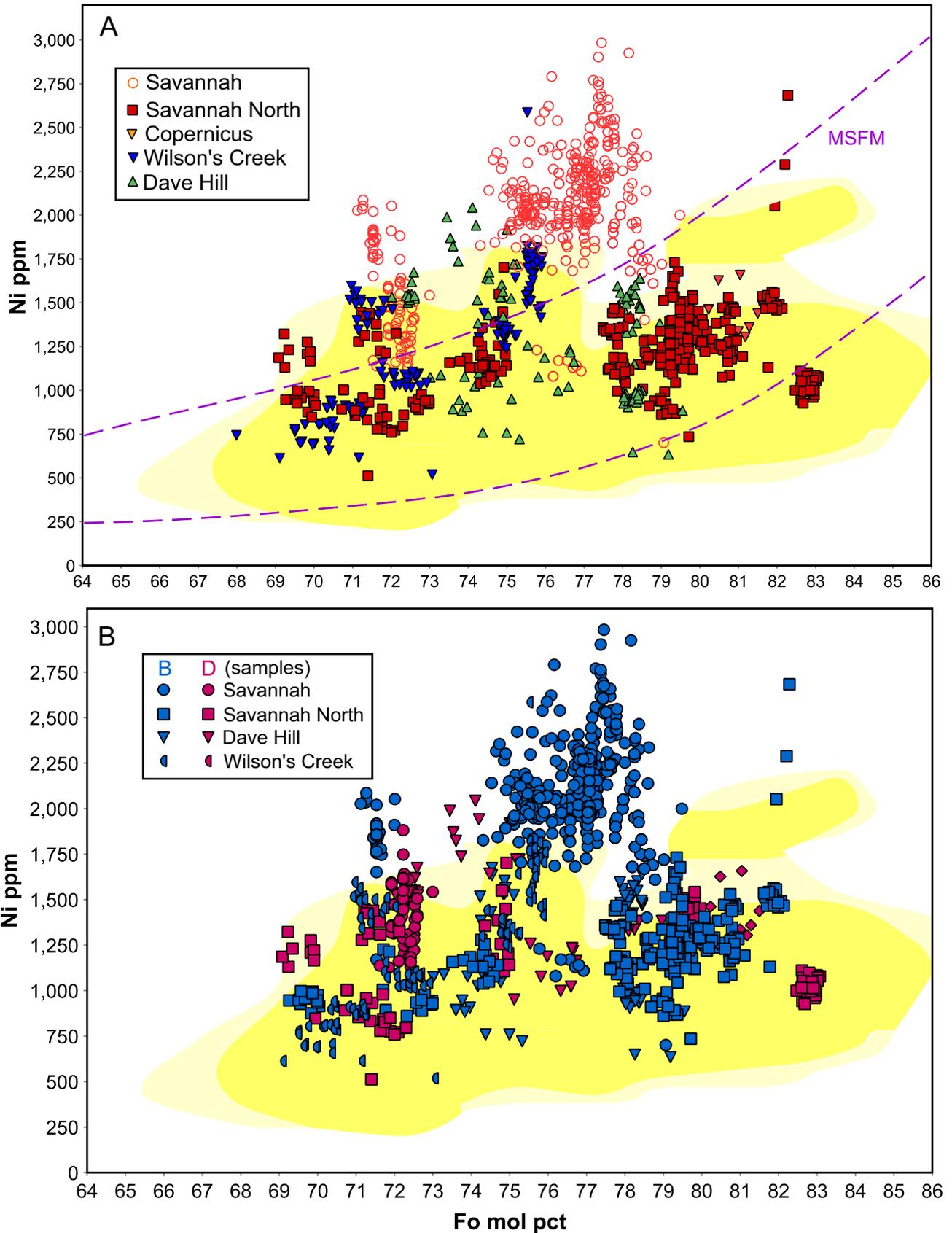
fig 7
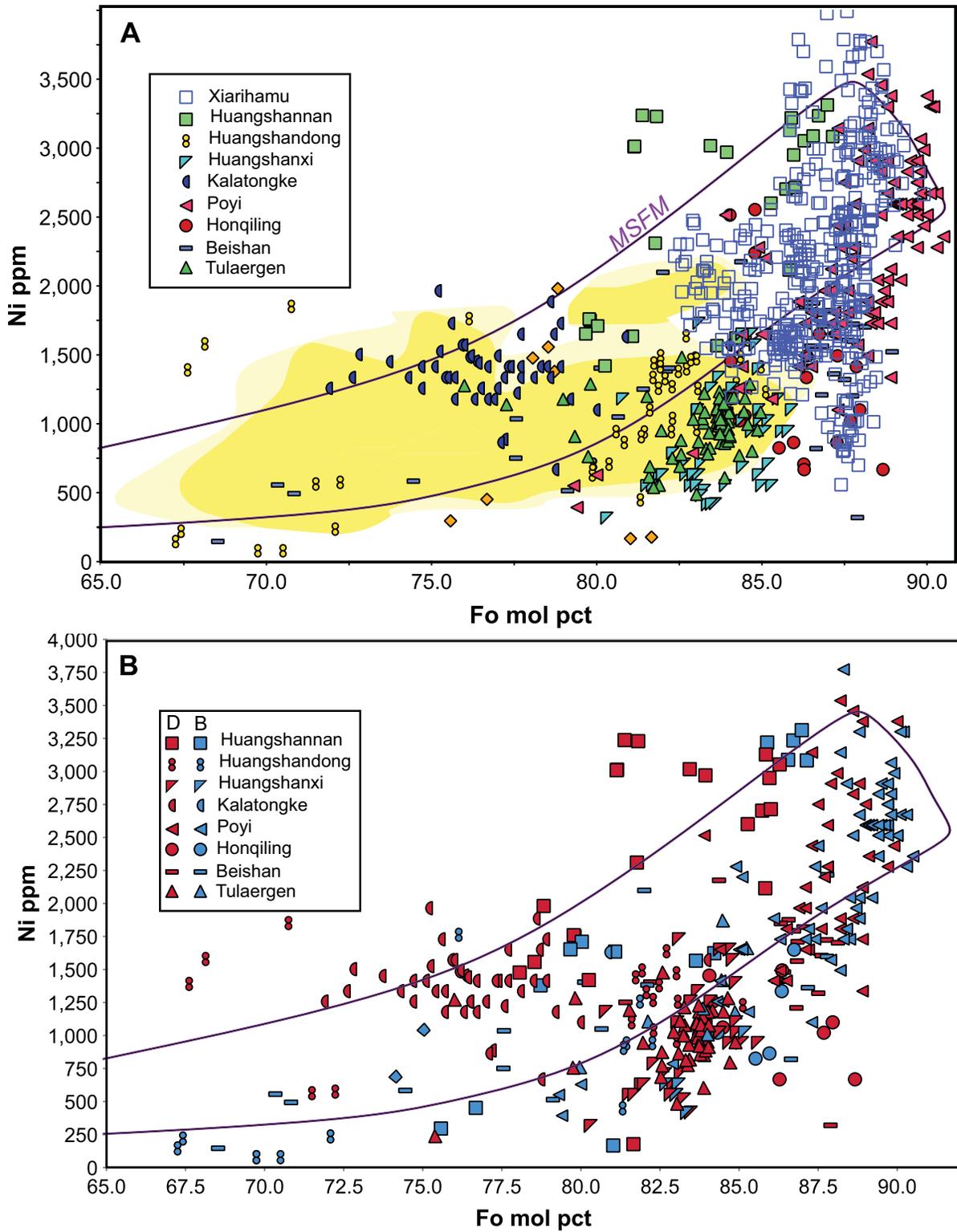
fig 8
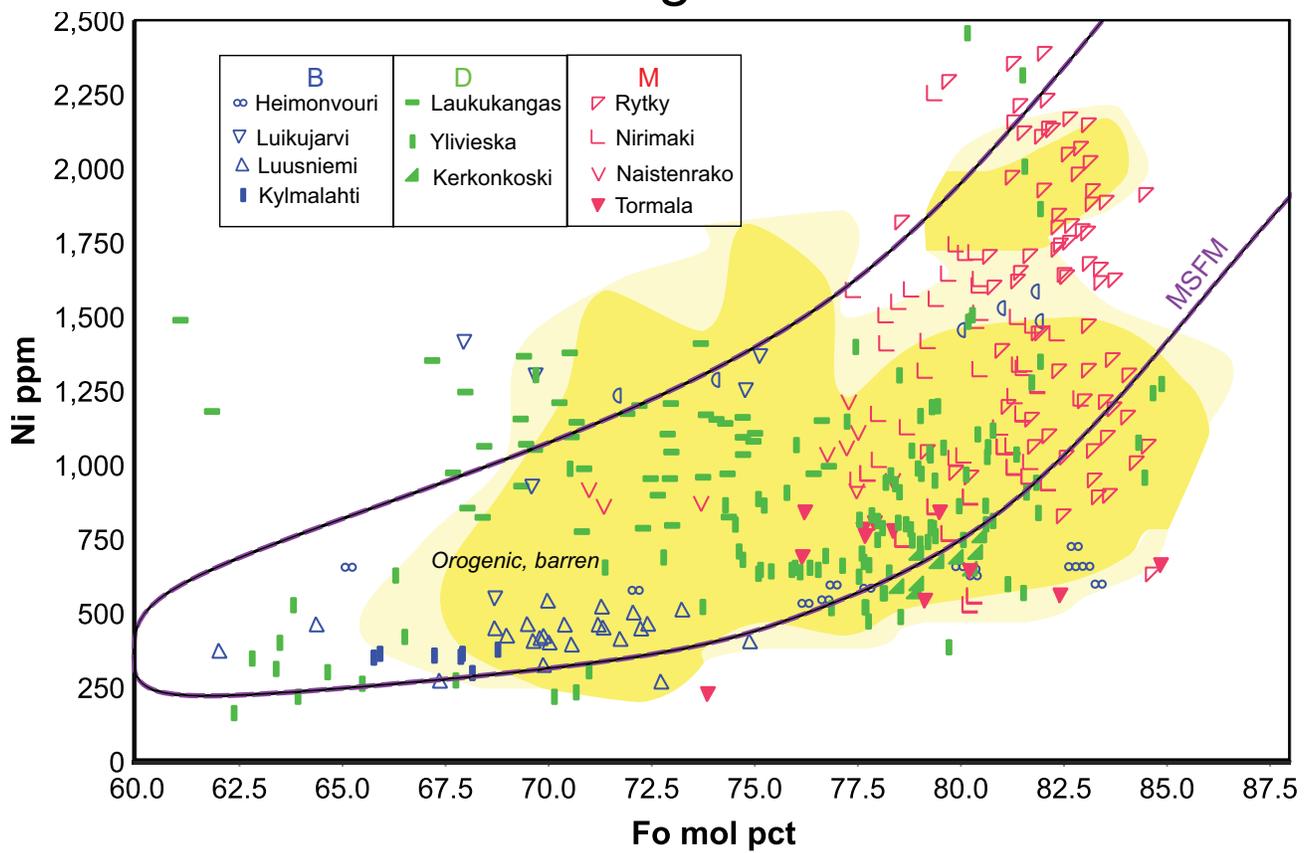
fig 9
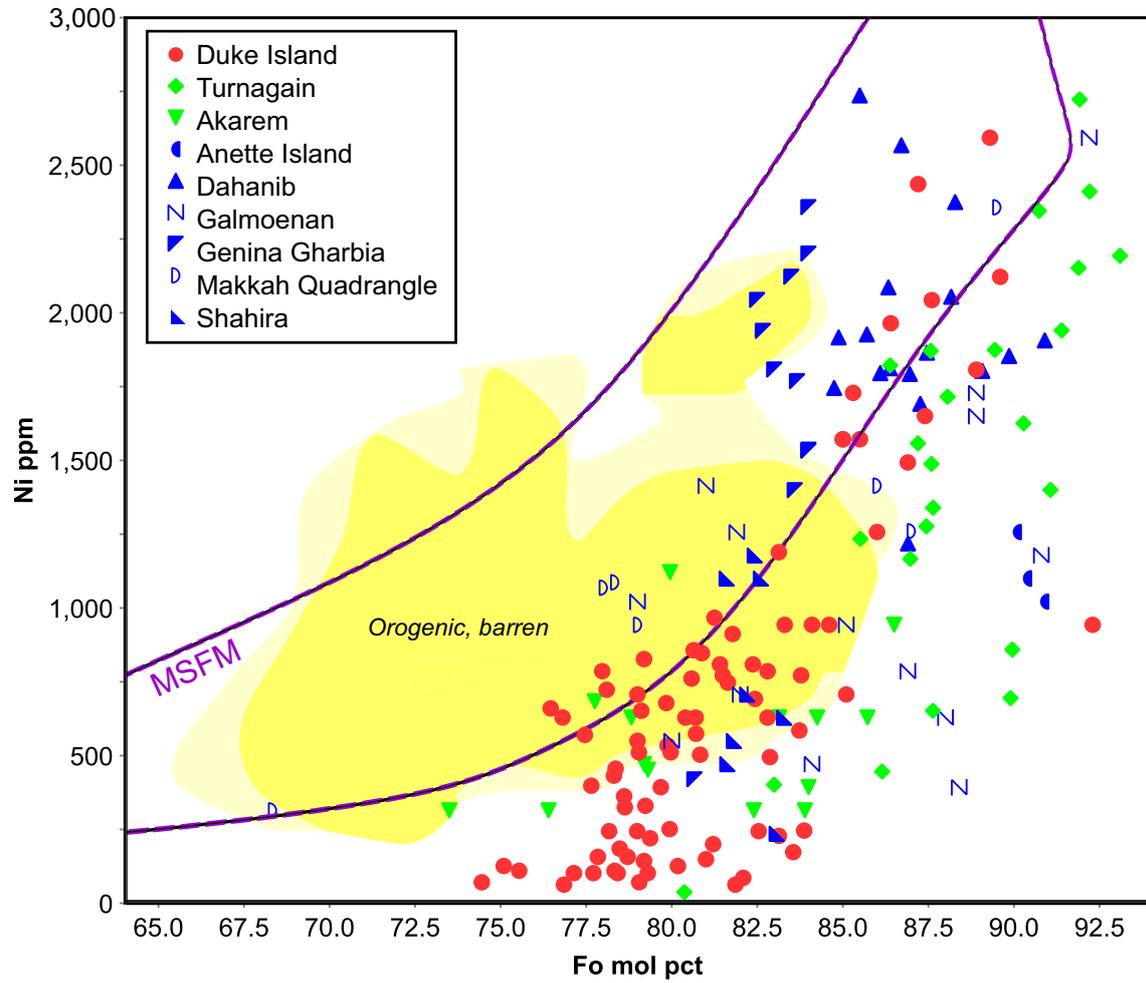
fig 10

fig 11

fig 13

fig 14

fig 15

Silicate melt
+ olivine, sulfide melt

Remove silicate melt

olivine + sulfide +
silicate melt mush

olivine - sulfide orthocumulate

A

B

C

*Accum-
ulate
olivine +
sulfide*

*Crystallise
interstitial
silicate
phases*

Silicate:sulfide mass ratio R
Silicate:olivine ratio F

Silicate:sulfide mass ratio R_1
Silicate:olivine ratio F_1

fig 16

fig 17

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

Sulfide liquid pool

Silicate melt + Fe-rich olivine

Sulfide liquid re-entrained

Fe rich olivine + sulfide liquid --> Ni-rich olivine

fig 18