

1 **Sulfide-silicate textures in magmatic Ni-Cu-PGE sulfide ore**
2 **deposits. 1. Disseminated and net-textured ores.**

3 **(Revision 1)**

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Abstract

15 A large proportion of ores in magmatic sulfide deposits consist of mixtures of cumulus
16 silicate minerals, sulfide liquid and silicate melt, with characteristic textural relationships that
17 provide essential clues to their origin. Within silicate-sulfide cumulates, there is a range of
18 sulfide abundance in magmatic-textured silicate-sulfide ores between ores with up to about
19 five modal percent sulfides, called “disseminated ores”, and “net-textured” (or “matrix”) ores
20 containing about 30 to 70 modal percent sulfide forming continuous networks enclosing
21 cumulus silicates. Disseminated ores in cumulates have a variety of textural types relating to
22 the presence or absence of trapped interstitial silicate melt and (rarely) vapour bubbles.

23 Spherical or oblate spherical globules with smooth menisci, as in the Black Swan
24 disseminated ores, are associated with silicate-filled cavities interpreted as amygdales or
25 segregation vesicles. More irregular globules lacking internal differentiation and having
26 partially faceted margins are interpreted as entrainment of previously segregated, partially
27 solidified sulfide. There is a textural continuum between various types of disseminated and
28 net-textured ores, intermediate types commonly taking the form of “patchy net-textured ores”
29 containing sulfide-rich and sulfide-poor domains at cm to dm scale. These textures are
30 ascribed primarily to the process of sulfide percolation, itself triggered by the process of

31 competitive wetting whereby the silicate melt preferentially wets silicate crystal surfaces. The
32 process is self-reinforcing as sulfide migration causes sulfide networks to grow by
33 coalescence, with a larger rise height and hence a greater gravitational driving force for
34 percolation and silicate melt displacement. Many of the textural variants catalogued here,
35 including poikilitic or leopard-textured ores, can be explained in these terms. Additional
36 complexity is added by factors such as the presence of oikocrysts and segregation of sulfide
37 liquid during strain-rate dependent thixotropic behaviour of partially consolidated cumulates.
38 Integrated textural and geochemical studies are critical to full understanding of ore-forming
39 systems.

40 *Keywords: nickel deposits, magmatic sulfides, komatiites, layered intrusions*

41 **1 Introduction**

42 Magmatic sulfide ore deposits account for some of the world's most valuable metal
43 accumulations, currently accounting for ~56% of the world's nickel production and over 96%
44 of supply of platinum, palladium and the other platinum group elements (Mudd and Jowitt,
45 2014; Zientek et al., 2014; Peck and Huminicki, 2016). They form by the accumulation of
46 immiscible sulfide liquid that has scavenged chalcophile elements from a coexisting silicate
47 magma, in a variety of settings:

- 48 1. Stratiform accumulations of disseminated sulfide in cumulates within layered mafic-
49 ultramafic intrusions, including PGE-enriched "Reefs" (Mungall and Naldrett, 2008;
50 Naldrett, 2011);
- 51 2. Accumulations of widely varying proportions of sulfide in small mafic or mafic-
52 ultramafic intrusions, usually identifiable as magma conduits (Barnes et al., 2016a;
53 Lightfoot and Evans-Lamswood, 2015);
- 54 3. Accumulations of widely varying proportions of sulfide in komatiite (Leshner, 1989;
55 Leshner and Keays, 2002; Barnes, 2006) or ferropicrite (Hanski, 1992; Keays, 1995;
56 Hanski et al., 2001) lava flows or associated shallow subvolcanic intrusions,
57 commonly identifiable as magma conduits or feeder tubes;
- 58 4. Sulfide disseminations, commonly PGE-rich, in the marginal facies of large layered
59 intrusions; the Platreef of the Bushveld Complex is the type example (Holwell and
60 McDonald, 2006)
- 61 5. Sulfide accumulation from an impact-generated crustal melt sheet: the unique
62 example of Sudbury (Keays and Lightfoot, 2004; Naldrett, 2004).

63 Within all these settings, sulfides occur as composite aggregates or “blebs” of the typical
64 mineral assemblage formed by solidification of the original sulfide liquid, which in most
65 cases has Fe as the dominant metal component, and subsequent subsolidus unmixing of that
66 assemblage (Craig and Kullerud, 1969). The predominant minerals under most circumstances
67 are pyrrhotite, pentlandite and chalcopyrite, forming aggregates that in many cases preserve
68 the original physical form of the sulfide component as it existed in the liquid state. The nature
69 and diversity of the physical form of the sulfide liquid, as droplets, pools, veins and networks,
70 provide essential clues to understanding the physical processes of ore formation. In this
71 contribution, we focus on “sulfide-silicate textures”, that is, the range in morphologies of
72 intergrowths between sulfide and associated gangue silicate and oxide minerals. Textures and
73 intergrowths in massive ores, semi-massive breccia ores and other variants of sulfide-
74 dominated ores will be described in a forthcoming companion paper.

75 Our main purpose in the study of textures is to make deductions about ore-forming processes
76 (using the term “ore” in a loose sense to denote sulfide-bearing rocks, rather than in the strict
77 sense of being economically exploitable). Ore textures are commonly the end product of
78 multiple stages, and magmatic sulfides are no exception. For this reason, we restrict this
79 study to the spectrum of textures ranging from those in disseminated ores, with a few percent
80 sulfide in a predominantly silicate matrix, through to matrix or net-textured ores containing
81 up to around 70% sulfide forming a continuous network enclosing cumulus silicate grains. In
82 many deposits, disseminated sulfides form large discontinuous haloes around higher grade,
83 more economically attractive bodies of sulfide-rich ores; hence a second major purpose of
84 this study is to assess whether spatial variations in ore textures, coupled with geochemical
85 observations, can be used as exploration proxies and vectors towards high-grade ore.

86 We interpret disseminated and net-textures to be the end result of a relatively restricted
87 sequence of processes:

- 88 1. Generation of a dilute sulfide-silicate liquid emulsion, i.e. a small proportion of
89 sulfide liquid droplets within a transporting silicate magma;
- 90 2. Physical separation of a mixture of sulfide liquid droplets and cumulus silicate
91 minerals, containing varying proportions of trapped silicate melt, from this emulsion;
- 92 3. Migration of sulfide liquid droplets and networks through a porous crystal mush,
93 driven by the balance between capillary and gravitational forces.

94 The first two processes are clearly indispensable components of any magmatic sulfide ore
95 forming system, although there is plenty of scope to debate how they occur in individual
96 deposits. The extent of the third process may be minimal in some cases and pervasive in
97 others, but understanding it is essential in order to be able to make any useful deductions
98 about the first two. For this reason, consideration of the empirical evidence and underlying
99 physics of sulfide liquid migration in intercumulus pore space forms a central theme of this
100 study. Further implications extend to understanding the behaviour of sulfide droplets during
101 mantle melting, segregation of S-bearing metal melts in meteorites and hence the formation
102 of planetary cores (Gaetani and Grove, 1999; Mare et al., 2014).

103 The results presented here are the culmination of an extended body of work using a variety of
104 characterization techniques to investigate sulfide-silicate ore textures, with the core
105 technology being x-ray computed tomography for investigating microtextures in 3D.

106 Combining this methodology with other newly-available techniques, such as high-resolution
107 microbeam XRF mapping, opens a range of observations impossible to obtain using
108 conventional petrographic techniques, particularly on the size, morphology and connectivity
109 of phases and grain aggregates. We have made extensive use of supplementary online
110 materials and the CSIRO online data repository to display animations and interactive
111 visualizations of the 3D images. We strongly encourage the reader to make use of these
112 resources in order to get the full value from the observations we present here.

113 **1.1 Terminology**

114 There is a spectrum of sulfide abundances in many magmatic sulfide ore deposits. In many
115 cases, particularly in komatiite-hosted ores and also at Voisey's Bay (Fig. 1) there is a
116 broadly trimodal distribution between massive ores typically containing 80-100% sulfide,
117 ores with up to about five modal percent sulfides, called "disseminated ores", and ores
118 containing about 30 to 70 modal percent sulfide forming continuous networks enclosing
119 cumulus silicates (usually but not always olivine). The 30-70% sulfide type has gone by two
120 completely synonymous terms: "matrix ore", commonly used in Australia, and "net-textured
121 ore", used in Canada and elsewhere. Here we stick to the more descriptive term "net-
122 textured". Ores with intermediate abundance between disseminated and net-textured do exist,
123 and in some deposits are the predominant ore type, as in the giant Jinchuan deposit in China
124 (Tonnelier, 2009). As we will see, these ores commonly have the characteristic of being
125 mixtures of cm-scale domains of net-textured and disseminated ores.

126 Discrete sulfide mineral aggregates in magmatic sulfide ores (or sulfide-bearing igneous
127 rocks in general) have commonly been referred to as “blebs”. This was originally a medical
128 term referring to spheroidal fluid-filled skin blisters, but it has become widespread in the
129 petrology literature referring to bodies of originally immiscible liquids at mm to cm scale.
130 The term “ocelli”, meaning eye-like spots, has also been used to refer to immiscible liquids,
131 usually silica-rich melt in a more mafic Fe-rich matrix (Frost and Groves, 1989), but has
132 generally not been used for sulfide liquids. Given the diversity of size and morphology, we
133 need to establish a consistent terminology to describe “sulfide aggregates”, which we define
134 as any contiguous body of minerals derived entirely from original immiscible sulfide or
135 sulfide-oxide melt regardless of size or morphology. We retain the word “bleb” in recognition
136 of its common usage, but attempt to define it specifically as a composite aggregate, at a scale
137 from tens of microns to a few cm, regardless of its textural relationship to associated gangue
138 silicate phases. Where blebs have sub-spherical morphologies, as in cases that have tended to
139 be referred to in the literature as “blebby ores”, we refer to them as “globules” and the ore
140 type as “globular ore”. Cuspate to round blebs that are developed within the interstitial space
141 of silicate mineral cumulates are referred to as “interstitial blebs”; as we will see, there is a
142 continuous spectrum between interstitial blebs and globules.

143 **1.2 Silicate-sulfide wetting and dihedral angles**

144 A fundamental control on the development of sulfide-silicate textures is the extent to which
145 sulfide liquid wets silicate and oxide phases. Where three phases come together along a
146 contact line, the angles between the phases perpendicular to the contact line can be described
147 in several ways, illustrated in Fig.2. The angle between the faces of two solids (S) in contact
148 with a liquid (L) is an interfacial angle (Fig. 2a). At equilibrium the interplay between the
149 interfacial energies of the three contacts (e.g., S-S, S-L, S-L) leads to the establishment of an
150 equilibrium dihedral angle θ (Fig. 2b) which generally is not equivalent to the interfacial
151 angle outside the immediate vicinity of the contact line. At the contact line where two fluid
152 phases meet a planar solid surface, an equilibrium wetting angle can be defined as in Figure
153 2c. In the example the wetting angle is 160° , as measured by Mungall and Su for sulfide melt
154 and silicate melt against an alumina crucible (2005). Similar wetting angles have been
155 observed in many other experiments e.g. (Brenan, 2003; Mungall and Brenan, 2014). Figure
156 2d shows cross sections of channels occupied by silicate melt along contact lines where three
157 crystals meet. If the equilibrium dihedral angle is $< 60^\circ$ as in the two upper sketches, the
158 walls of the channel are convex into the channel. If the dihedral angle θ is $> 60^\circ$ then the

159 walls of the pore are concave into the channel, as in the lower example. In Figure 2e the same
160 channels are shown with an immiscible sulfide liquid occupying the centre of each channel,
161 making a contact angle of 160° with the channel walls. If $\theta < 60^\circ$, the melt is defined as
162 “wetting” and occupies prismatic grain edge channels, giving rise to an interconnected melt
163 phase in three dimensions (Fig. 3), even at melt fractions below 1% by volume (Von Bargen
164 and Waff, 1986; Jung and Waff, 1998; Wark et al., 2003). Conversely, in cases where $\theta >$
165 60° , the melt is defined as “non-wetting” and grain edges become dry as a result of the liquid
166 phase “beading-up” at grain-edge intersections. For $\theta > 60^\circ$, melt connectivity is achieved
167 only above a finite fraction that is a strong function of θ . In the descriptions that follow, we
168 use the terms wetting and non-wetting in this specific sense. However, in sulfide-bearing
169 cumulates the situation is complicated by the presence of not one but two potentially wetting
170 liquids: silicate and sulfide. We will show that the wetting behaviour of sulfide liquid against
171 solid silicates is strongly influenced by the presence and absence of coexisting silicate melt.
172 If both liquid phases are present then the sulfide melt does not wet the crystals because of the
173 very large wetting angle as shown in Figures 2e and 3c. If only sulfide melt is present then it
174 is not prevented from making contact with the solids. Depending on the solid-solid-liquid
175 dihedral angle the sulfide melt will either bead up in isolated pores (Fig. 3a) or spread into a
176 well-connected network of channels as shown in Figure 3b. Whereas basaltic liquids have
177 low dihedral angles against olivine and form networks resembling Figure 3b, measured
178 dihedral angles for sulfide against olivine and chromite are sensitive functions of temperature
179 and melt composition (Ballhaus and Ellis, 1996; Gaetani and Grove, 1999; Rose and Brenan,
180 2001). At typical moderately reducing conditions, sulfide liquids with appreciable Ni and Cu
181 contents have dihedral angles > 60 and will not form interconnected networks. One therefore
182 anticipates that in texturally equilibrated olivine cumulates entirely lacking silicate melt, the
183 sulfide melt should form isolated blebs at four-grain contact points, but that small amounts of
184 silicate melt will force the generation of an extended network of open channels along which
185 the sulfide melt is able to propagate as shown in Figure 2c. These principles guide the physics
186 behind sulfide-silicate textures.

187

188 **2 Methods and samples**

189 In this contribution, we focus on the diversity of intergrowths between original sulfide liquid
190 and associated gangue silicate minerals, using the term “sulfide-silicate textures” to cover

191 these intergrowths. The underlying assumption is the textures described are essentially
192 magmatic and have not been substantially modified by deformation and alteration. To this
193 end, we take examples as far as possible from undeformed deposits that have undergone little
194 or no post-magmatic alteration or metamorphic modification. This criterion is very hard to
195 satisfy in deposits hosted within ultramafic rocks, particularly komatiites which are almost
196 universally hydrated or carbonated to some degree. However, it has been well established that
197 under most circumstances the process of serpentinization faithfully pseudomorphs original
198 igneous textures, even where primary silicate and sulfide mineralogy is completely
199 transformed. Consequently, most of the komatiite-associated examples are from serpentinized
200 rocks. This is necessary because komatiite-hosted ores are some of the simplest and best
201 understood ore systems, forming under conditions of rapid cooling where primary
202 depositional textures have the best chance of being frozen in. Hence they give some of the
203 least ambiguous and most useful textural information. Localities discussed and illustrated
204 here are summarized in Table 1.

205 *Table 1.*

206 A variety of imaging techniques has been used to illustrate sulfide-silicate textures, the most
207 revealing being 3D X-ray computed tomography (XCT). Data are represented from low
208 resolution (~mm scale) imaging using medical XCT scanning technology, on decimetre scale
209 samples with coarse sulfide aggregates (Robertson et al., 2016), and also from high resolution
210 HRXCT techniques (Godel, 2013) that can achieve resolutions of 0.7-10 μm on mm to cm
211 scale samples (or volumes of interest within larger samples) at very much greater cost in
212 instrument time.

213 The Medical X-Ray Computed Tomography system used for this study is a SOMATON
214 Definition AS Medical CT Scanner. This instrument is composed of a rotating X-Ray source
215 producing a fan-shaped X-ray beam, along with a rotating set of X-Ray detectors (Multislice
216 UFC™ detectors), and a 100 kW generator. The X-Ray source is fitted with an STRATON
217 MX P High Performance CT-X-Ray tube, with intensity and voltage ranging from 20 to 800
218 mA and from 70 to 140 kV, allowing the X-Ray to be transmitted through dense and complex
219 material such as disseminated to blebby magmatic Fe-Ni-Cu sulphides. Reconstruction to
220 produce the tomographic dataset was done on the Syngo® Acquisition Workspace, and
221 involves correction for anisotropic voxel sizes.

222 High resolution micro-scale computed tomography was collected on two different
223 instruments: a Skyscan (now Bruker) 1172 desktop scanner at CSIRO's Waterford
224 Laboratory, and an XRadia (now Zeiss) Versa-XRM 500 3D x-ray microscope at CSIRO-
225 Australian Resource Research Centre (both in Perth, Australia). Details for the Skyscan
226 instrumental conditions are given by Godel (2013) and Godel et al. (2013), and for the
227 XRadia instrument by Godel et al. (2014), Godel (2013) and Prichard et al. (2015). The
228 resulting dataset after reconstruction using each of these instruments represents a regular
229 volumetric grid, where each voxel has a unique grey-scale value. This grid is then processed
230 and analysed with AvizoFire® (FEI). Digital image filters are applied to enhance and remove
231 instrumental noise from the image (generally a non-local mean filter was applied), and a 3D
232 gradient watershed segmentation process is carried out, attributing a range of grey-scale
233 values to a given phase, with phase boundaries being located at the point of maximum
234 gradient in grey-scale (Godel, 2013).

235 Conventional 2-D petrographic images are combined with X-ray fluorescence element maps
236 using two different techniques: desktop microbeam XRF using the Bruker Tornado
237 instrument at spatial resolutions around 40 μm (Barnes et al., 2016b), and 2-4 μm resolution
238 images collected using the Maia multi-detector array on the XFM beamline of the Australian
239 Synchrotron (Ryan et al., 2010; Paterson et al., 2011; Ryan et al., 2014; Fisher et al., 2015),
240 the latter being referred to hereafter as MAIA-XFM images. Visualization of textures using
241 combinations of 2D and 3D images by these various techniques has given us new insights
242 into the diversity and origin of sulfide-silicate textures.

243 Textures are described from a number of deposits exemplifying all of the four main settings
244 described above. Brief descriptions and sources of data and previously published images are
245 given in Supplementary Material.

246 **3 Disseminated sulfide textures**

247 This section is concerned with sulfide-silicate textures in ores containing less than 10 modal
248 percent sulfide, most typically in the range 0.5-2.5%. We begin with the simplest examples:
249 disseminated sulfides in komatiitic olivine cumulates (Figs. 4 - 6).

250 **3.1 Disseminated sulfides in komatiitic dunites and peridotites**

251 Barnes et al. (2008b) used high resolution X-ray tomography to obtain 3D images of sulfide
252 textures in komatiitic disseminated ores, comparing the two typical host rock cumulate types,

253 olivine adcumulates and olivine orthocumulates from several mineralized localities within the
254 Norseman-Wiluna Greenstone Belt of the Yilgarn Craton in Western Australia. Images are
255 shown from the adcumulate-dominated Mt. Keith MKD5 (Barnes et al., 2011a) and Dumont
256 (Sciortino et al., 2015) deposits (Figs. 4-6) and the orthocumulate-dominant Black Swan
257 deposit (Dowling et al., 2004; Barnes et al., 2009) (Fig. 7). The Mt Keith samples comprise
258 nearly pure olivine-sulfide adcumulates, with less than 5% trapped intercumulus silicate melt
259 component and a sulfide mode of less than 5%; whereas the Black Swan olivine-sulfide
260 orthocumulates contain an original interstitial silicate liquid abundance of around 30% and 1-
261 5% modal percent sulfide. The samples have all undergone secondary serpentinization which
262 produces complete pseudomorphic replacement of the original olivine grains, but extensive
263 observation of large numbers of samples with varying degrees of serpentinization convinces
264 us that the degree of modification of the original igneous morphology of the sulfide blebs is
265 minor. This conclusion is backed up by a synchrotron XFM image of disseminated sulfides in
266 almost completely fresh olivine adcumulate from Dumont (Fig. 6 c,d) (and see also
267 previously published images of sulfides in fresh dunite from the Betheno locality – Barnes et
268 al., 2011b). Sulfide aggregates in the Black Swan olivine orthocumulates tend to form
269 rounded globules within the interstitial space, in comparison with the more lobate
270 morphologies of sulfides in the adcumulate rocks from Mt Keith. Olivine grain size in the
271 dunite hosted deposits at Mt Keith and Yakabindie is systematically finer within sulfide-
272 bearing domains relative to sulfide-free domains, at a scale of decimetres or about ten times
273 the characteristic olivine grain size (Godel et al., 2013), but this relationship is not evident at
274 Black Swan.

275 The CT-scan images of Barnes et al. (2008b) and Godel et al. (2013) indicate that a
276 proportion of sulfides in the Mount Keith adcumulate-textured samples appear to wet the
277 former olivine grains with highly variable dihedral angles (Fig. 3) ranging down to less than
278 30 degrees (as estimated in the 3D image), but some samples also contain a population of
279 typically coarser more globular sulfides with high dihedral angles. (See supplementary
280 materials for animated rotating 3D images, which give a much clearer impression of the true
281 geometry of the sulfide blebs). Sulfides in the more “wetting” samples form well-connected
282 “channels” along the triple-grain boundaries even at low sulfide abundance of less than 3%,
283 with sulfide channels extending on a scale of about 2-4 times the characteristic olivine grain
284 size. In the Dumont sample, the wetting angle is evidently much higher, such that sulfide
285 liquid forms completely isolated triple-point blebs with high dihedral angles (Figure 6). With

286 decreasing abundance in the Mt Keith samples, sulfides tend to occupy triple-point
287 “channels” to a limited degree, but the degree of interconnectivity between blebs is low, and
288 there is a high proportion of small isolated blebs. In marked contrast, sulfides from the
289 orthocumulate-textured samples from Black Swan (Fig. 7) exclusively form isolated sub-
290 spherical blebs with poor connectivity despite having a sulfide content similar to that of the
291 Mt. Keith samples. Larger blebs in the Black Swan samples show irregular “coalesced”
292 morphologies occupying interstitial space, in some cases occupying olivine grain faces but
293 for the most part forming rounded non-wetting boundaries with no measurable dihedral
294 angle.

295 We conclude that sulfides either form isolated patches in the complete absence of silicate
296 melt, or interconnected frameworks along olivine triple grain boundaries that were lined by
297 small quantities of silicate melt (Fig. 3a,c).

298 **3.2 Disseminated sulfides in layered intrusion cumulates**

299 Disseminated sulfides in peridotitic and pyroxenitic cumulates have been studied in a number
300 of deposits, with examples being given here from four: Kevitsa in arctic Finland (Yang et al.,
301 2013; Santaguida et al., 2015; Le Vaillant et al., 2016), the Mirabela Intrusion (Santa Rita
302 deposit) in north-eastern Brazil (Barnes et al., 2011c), the Merensky Reef of the Bushveld
303 Complex in South Africa (Godel et al., 2010), and the JM Reef of the Stillwater Complex in
304 the USA (Godel et al., 2006).

305 In the Kevitsa and Mirabela intrusions, sulfides form typical interstitial disseminated blebs
306 within wehrlite and poikilitic clinopyroxenite (Kevitsa), and poikilitic harzburgites and
307 orthopyroxenites (Mirabela). Blebs are characteristically less than 1 mm in size and poorly
308 interconnected, and are characteristically isolated at olivine/pyroxene triple and quadruple
309 point grain boundaries (Figs. 8, 9). They show some interesting textural variants as the result
310 of some additional factors: presence of pyroxene oikocrysts (Figure 8), presence of chromite,
311 and in the case of Mirabela, differentiation of the sulfide blebs producing Cu-rich residual
312 liquids coexisting with fractionated trapped liquid (Figure 9).

313 The Kevitsa sulfides are dominated by small interstitial blebs, with more than 95% of the
314 number of blebs having sizes expressed as equivalent sphere diameters of less than 500
315 microns (see discussion of bleb sizes below). Dihedral angles are generally high and
316 interconnectivity low. However, in the sample illustrated in Figure 8, containing 6.3 volume
317 percent sulfide, the three largest blebs, representing 52% of the total volume of sulfide in the

318 sample, occur as much larger networks forming interconnected triple-boundary channels
319 extending at scales tens to hundreds of times the characteristic cumulus silicate grain size
320 (Fig. 8a – this is best seen in the animated image in the supplementary material). A similar
321 observation was made by Godel et al. (2013) on some of the sulfide-rich (>3 modal %)
322 samples from Mt Keith; there appears to be a threshold value of around 3-5% sulfide at which
323 sulfide networks begin to form and coexist with much finer isolated blebs. This texture
324 appears to represent a transition between typical interstitial disseminated and patchy net-
325 texture, an important point to which we will return.

326 The Kevitsa disseminated sulfides also display a characteristic feature evident in a wide
327 variety of other deposits displaying a range of sulfide abundances. Where poikilitic phases
328 are present, in this case clinopyroxenes enclosing chadacrysts of orthopyroxene or olivine,
329 the oikocrysts are characteristically free of sulfide inclusions. A striking example of this
330 texture is seen in 3D in Fig. 8e,f: the “holes” in the sulfide “cloud” are subhedral equant
331 clinopyroxene oikocrysts.

332 Disseminated sulfides in the mesocumulate orthopyroxenite and harzburgites of the Mirabela
333 intrusion show broadly similar textures to those at Kevitsa (Fig. 9), but also have a tendency
334 to be associated with patches of late-crystallising postcumulus silicate and oxide phases
335 representing the “dregs” of the trapped liquid solidification process. An additional complexity
336 at Mirabela is that chalcopyrite, formed from the liquid residual to solidification of mss from
337 the sulfide melt fraction, commonly forms complex, almost symplectic intergrowths in these
338 late postcumulus patches (Fig. 9b). This texture is attributed to migration of both silicate and
339 sulfide residual liquids during the late stages of compaction and solidification of the crystal
340 pile, such that both accumulate in the same remnant pore space. These late stage Cu-rich
341 liquids are evidently strongly wetting against silicates. A similar feature was noted in the
342 Mordor intrusion in central Australia (Barnes et al., 2008a) where residual Cu-rich sulfides
343 form complex intergrowths with late-forming mica and oxide grains.

344 The chromite content of the disseminated sulfide zone at Mirabela ranges up to about 5%,
345 and in the more chromite-rich samples sulfide blebs show a strong tendency to associate with
346 and interconnect between chromite grains (Fig. 9d,e). This is attributable to a tendency for
347 sulfide liquids to wet oxide minerals in preference to silicate minerals (Rose and Brenan,
348 2001; Brenan and Rose, 2002). A similar preference for sulfide blebs (and platinum group
349 element minerals) to be attached to chromite grains is apparent in the Merensky Reef (Godel
350 et al., 2010), although measured dihedral angles in the Merensky chromitite seams appear to

351 indicate non-wetting behaviour (Godel et al., 2006). Similar discrepancies between grain
352 scale textures and dihedral angles, and wide-short range variability in wetting angles, are a
353 common theme in these investigations.

354 In the olivine gabbronorite from the J-M Reef (Fig. 10a and b) and the gabbronorite from the
355 Merensky Reef (Fig. 10c), the sulfide forms 3D-interconnected networks that extend over
356 variable length based on the sample considered. These networks tend to be elongated parallel
357 to the paleo-vertical and occur at both pyroxene/pyroxene and pyroxene/plagioclase
358 boundaries. This particular sulfide topology is inferred to be due to downward percolation of
359 sulfide liquid during the early stage of compaction, resulting in the formation of vertical
360 dilatancy triggered by local extension in the plane of the layering (Godel, 2006). Similar
361 features are seen in sulfides from the JM Reef of the Stillwater Complex (Godel, 2015).

362 **3.3 Globular sulfides**

363 Globular ores are defined by the presence of convex, typically sub-spherical or ellipsoidal
364 sulfide aggregates with diameters ranging from hundreds of microns to several cm. These
365 occur in two major varieties, with and without associated polymineralic silicate caps
366 ("capped" and "uncapped"), and in several settings:

- 367 1. in the chilled margins and interiors of mafic dikes as both capped and uncapped
368 varieties
- 369 2. in komatiitic olivine orthocumulates, as capped and uncapped varieties
- 370 3. in xenolith-bearing cumulate rocks from subvolcanic sills and chonoliths, most
371 notably in the Noril'sk - Talnakh camp but also in a number of other intrusion-hosted
372 deposits worldwide. The Noril'sk-Talnakh examples include both capped and
373 uncapped varieties, but examples in mineralized olivine cumulate layers in the lower
374 portions of the chonoliths are mostly capped.
- 375 4. in Offset Dikes of the Sudbury Igneous Complex, where they are closely associated
376 with xenolith-bearing sulfide breccias; these are exclusively uncapped.

377

378 *3.3.1 Globular sulfides in dikes.*

379 Capped globules trapped within chilled dike margins have been described in detail from two
380 localities: one of a suite of mafic "macro-dikes" associated with the Tertiary basaltic volcanic
381 province in the Kangerlussuaq area of East Greenland (Holwell et al., 2012), and from a
382 mafic dike occurrence in Uruguay (Prichard et al., 2004). Fig. 11 illustrates the textures from

383 the gabbroic Togeda Macrodiike, where spherical globules are present up to a maximum
384 diameter of around 10 mm (Fig. 11A-F). Larger globules are present, up to several
385 centimetres, but they do not preserve the spherical shape, and become transitional with
386 interstitial disseminated textures. In most cases, the spherical globules display a coarse-
387 grained silicate cap (Fig. 11A-D) made up of plagioclase and clinopyroxene, above and
388 partially intergrown with the top of the sulfide globule, which has a spherical bowl shape at
389 its base. Identical textures were also observed by Prichard et al. (2004) in sulfide globules in
390 a mafic dyke from Uruguay. Prichard et al. (2004) interpreted the textures to have formed
391 from sinking of the sulfide during crystallization, leaving a void into which the coarse
392 silicates grew. However, there are a number of explanations to explain these caps, including
393 the association with vapour bubbles, which are discussed below. Notwithstanding this, such
394 textures are reliable geopetal indicators in such intrusions.

395 Interestingly, the S isotope signatures of the globules in the Togeda Macrodiike indicate a
396 sulfur source from sediments present stratigraphically hundreds of metres higher than the
397 present position of the dike-hosted globules (Holwell et al., 2012). This provides compelling
398 evidence for downward transport of these sulfide globules; similar isotopic evidence for
399 downward transport of sulfides on a scale of tens of metres has been found in ultramafic-
400 mafic plugs on the Isle of Rum, Scotland (Hughes et al., 2016).

401 3.3.2 *Globular sulfides in komatiitic cumulates*

402 These are relatively widespread, although usually not a large proportion of the total volume
403 of sulfide in individual deposits, exceptions being some of the Kambalda deposits and
404 particularly the Marriott's deposit in Western Australia where almost the entire deposit is
405 comprised of flattened ellipsoidal sulfide globules. As shown above, there is a complete
406 transition, sometimes within the same few cubic centimetres of rock, between interstitial
407 disseminated and globular blebs, with globules becoming more predominant in more
408 orthocumulate rocks.

409 The Black Swan disseminated deposit is dominated by transitional sulfide morphologies (Fig.
410 7) but is marked by one of the best-developed known examples of capped globules (Fig. 12).
411 Here, sulfide globules are associated with rounded segregations of chlorite-rich material
412 containing weakly pseudomorphed microspinfex texture (Fig. 12e), occupying convex
413 spaces between cumulus olivine grains). These are interpreted by Barnes et al. (2009) as
414 segregation vesicles, analogous to those seen in basalts (Anderson et al., 1984; Caroff et al.,
415 2000) and described in unmineralized komatiite by Siegel et al. (2015) and Beresford et al.

416 (2000). The caps are originally gas filled vesicles that subsequently become filled with
417 evolving interstitial silicate melt due to vapour pressure gradients generated during the late
418 stages of solidification, a process referred to as gas filter-pressing (Anderson et al., 1984).
419 Sulfide globules occupy the bottom contacts of these vesicles, and have characteristic
420 concave-up menisci against the silicate infill material. In rare cases (Fig. 12b,c,d) the sulfide
421 globules have rinds of skeletal chromite that is unlikely to have crystallized from the
422 segregated melt within the vesicle on mass balance grounds; these provide evidence that the
423 vesicles formed after the sulfide droplet, which itself must have reacted with a large volume
424 of silicate melt before becoming embedded in the olivine orthocumulate crystal pile.

425 The experimental observations of Mungall et al. (2015) provide the essential clue to the
426 processes in action here. Where sulfide melt, silicate melt and vapour bubbles coexist, vapour
427 bubbles have a strong tendency to nucleate against and then to remain attached to sulfide
428 droplets owing to surface tension effects. Depending on the proportion of the phases, this
429 may enable sulfide droplets to float within a much less dense mafic magma like a basket
430 beneath a hot-air balloon. This process may explain the retention of coarse silicate-capped
431 sulfide globules in mafic dykes in the examples cited above. Sulfide flotation may have
432 played a role in the formation of the Black Swan globular ores, but these only form a small
433 proportion of the orebody, and much of the sulfide at Black Swan occurs as sub-rounded
434 blebby aggregates (Fig. 7) with no evidence of an attached vapour phase. The Black Swan
435 komatiites are highly contaminated and probably contained high proportions of assimilated
436 water, such that vapour saturation would have been achieved during solidification of the
437 trapped interstitial melt (Barnes et al., 2004). We therefore prefer the interpretation that the
438 droplet-bubble association at Black Swan arose from in-situ nucleation of a hydrous vapour
439 phase from the fractionated intercumulus silicate melt fraction, with the vapour bubbles
440 nucleating preferentially on the already-accumulated sulfide droplets due to surface energy
441 effects. Interestingly, capped globules associated with probable amygdales, similar to those at
442 Black Swan, have also been reported from komatiitic flow tops (Keele and Nickel, 1974;
443 Stone et al., 1996), implying that the sulfides may have floated in free melt by the “balloon
444 basket” mechanism in these cases.

445 3.3.3 Globular sulfides at Insizwa and Noril'sk-Talnakh

446 Globular sulfides in intrusions associated with flood basalt volcanism are known from two
447 localities: the Insizwa Complex (Waterfall Gorge locality) in the Karoo Province in South
448 Africa (Lightfoot et al., 1984), and in the mineralized chonolith intrusions of the Noril'sk-

449 Talnakh camp (Dodin, 1971; Genkin et al., 1982; Distler et al., 1988) (Fig. 13). The Noril'sk-
450 Talnakh bodies form part of the intrusive component of the super-giant Siberian Traps flood
451 basalt province, formed at the Permian-Triassic boundary during a mantle plume arrival event
452 (Fedorenko, 1994; Naldrett, 1999; Naldrett and Lightfoot, 1999; Campbell, 2007; Arndt,
453 2011). Globular sulfides are abundant within the olivine cumulates that form the lower layers
454 of the ore-bearing intrusions, typically immediately above the large basal pools of sulfide
455 liquid now preserved as massive sulfide. These include the heterogeneous, highly
456 contaminated olivine cumulates called "taxitic picrodolerites", whose characteristic texture is
457 a continuous framework of olivine crystals that in some case develop skeletal textures, with
458 interstitial space filled primarily by clinopyroxene and plagioclase. Globules are also
459 abundant in the more homogeneous, conventionally orthocumulate textured olivine gabbros
460 (locally called "picrodolerites") that form continuous layers above the lower taxites within
461 the lower third of the mineralized intrusions (Torgashin, 1994; Czamanske et al., 1995;
462 Sluzhenikin et al., 2014). The globules in these rocks have a number of very distinctive
463 features (Fig. 13), notably a pronounced flattening in the plane of the layering, preferentially
464 developed (within the same sample) by the larger globules (Fig. 13a). In some samples
465 globules show complex external morphologies reminiscent of squeezed balloons (Figure
466 13e), implying that they have retained their surface integrity while being deformed. They
467 show an almost universal differentiation into MSS (now pyrrhotite plus exsolved pentlandite)
468 in the lower half and chalcopyrite in the upper half, this being attributed to fractional
469 crystallization of the sulfide liquid as described in a number of previous publications (e.g.
470 Barnes et al., 2006). The individual droplets form microcosms of the large-scale process of
471 differentiation into Cu-rich and Cu-poor components evident within the massive sulfide
472 orebodies of the Kharealakh intrusion (Sukhanova, 1968; Torgashin, 1994; Naldrett et al.,
473 1997; Distler et al., 1999). On close inspection, a large proportion of Noril'sk globules from
474 the picrodolerites are "capped" (Fig. 13) in a similar way to the Black Swan, as is the globule
475 from the Insizwa locality shown in Fig. 13e. The silicate caps are developed above the sulfide
476 globules, the caps being occupied by variable proportions of plagioclase, clinopyroxene,
477 orthopyroxene, Ti-rich magnetite, ilmenite, hornblende, phlogopite, titanite, apatite and rarely
478 anhydrite. Details are discussed by Le Vaillant et al. (in review).

479 3.3.4 *Globular sulfides at Sudbury*

480 Globular sulfide ores are well-known in the Sudbury ore deposits and were discussed by
481 Naldrett (1969), under the term "buckshot ore", in one of the first papers to address the

482 mechanisms of sulfide ore texture formation. They are found in two main settings: within the
483 quartz diorite-hosted sulfide ores and ore breccias within the Offset Dikes (Lightfoot et al.,
484 1997b), and much less commonly within the Mafic Norite unit that forms the lowermost layer
485 of silicate cumulates within the Sudbury Intrusive Complex and also within the Sublayer
486 (Souch and Podolsky, 1969; Mungall, 2002). The Offset Dikes are extensive composite dikes
487 that extend to depths of up to several thousand metres below the base of the Sudbury
488 Intrusive Complex (SIC), typically comprising an outer chilled margin of fine-grained
489 sulfide-poor quartz diorite, an inner zone of inclusion-rich quartz diorite and a central
490 mineralized zone that ranges from sulfide-matrix breccias to complex mixtures of quartz
491 diorite matrix, inclusions of quartz diorite, SIC cumulates and wall rocks, and sulfide blebs
492 ranging from sub-spherical globules to irregular elongate cm-sized blebs (Lightfoot et al.,
493 1997a; Lightfoot et al., 1997b; Lightfoot and Farrow, 2002). Medical CT images and
494 Tornado XRF maps of typical offset dike globular ores from the Copper Cliff mine are shown
495 in Fig. 14.

496 A number of features of the Copper Cliff globular sulfides are distinct from those described
497 above. Internal differentiation into Cu-rich and Fe+Ni-rich components is common, but they
498 lack the consistent geopetal relationship of Cu-rich sulfide at the top that is so characteristic
499 of the globules at Noril'sk. The globules are only rarely smooth and subspherical, and there
500 are no silicate caps. Size distributions measured in 3D show a similar characteristic to most
501 other disseminated sulfides in that particle sizes define a log-linear negative slope on the
502 equivalent of crystal-size distribution (CSD) plots, as discussed below. Margins of the
503 globules are in many cases angular and faceted, and there is fine scale intergrowth with
504 matrix silicates. Grain boundary ("loop-texture") exsolution of pentlandite defines the
505 margins of original MSS grains, now pyrrhotite, and in some cases idiomorphic hexagonal
506 facets define the margins of the globules (Fig. 14c). These relationships are consistent with
507 the proposal by Naldrett (1969) that the textures are the result of an almost complete
508 temperature overlap in the melting ranges of the sulfide melt and the host quartz diorite
509 liquid; the morphology of the sulfide globules was frozen in at an early stage due to a
510 framework of growing MSS crystals that formed while the transporting silicate melt was still
511 largely liquid and flowing. It is possible that these textures arise from the disruption and
512 mechanical remobilization of a cumulus MSS-enriched component of a previously segregated
513 and partially crystalline sulfide melt (Leshner et al., 2008). This explanation would resolve an
514 old argument about the apparent heterogeneity of composition of individual sulfide blebs, an

515 observation which led Fleet (1977) to question the magmatic origin of very similar ores in the
516 Frood offset deposit.

517 Very similar textures are found in the small Piaohechuan prospect in northern China, a Ni
518 sulfide occurrence hosted within a small differentiated mafic intrusion with hydrous mafic
519 parent magma (Wei et al., 2015). The deposit incorporates globular, network and breccia
520 textures, the latter types to be discussed in a companion paper. The globular textures show
521 irregular and locally faceted morphologies of similar size and morphology to those at
522 Sudbury (Fig. 15), as well as very similar sulfide mineral relationships. They are distinctly
523 depleted in Cu relative to the deposit as a whole. Wei et al. (2015) show 2D images
524 indicating the presence of rounded silicate inclusions within the globules, but 3D scanning of
525 the same sample (Fig. 15c) reveals that these are 2D artefacts of complex indented 3D
526 morphologies similar to those at Copper Cliff. The margins of the globules locally truncate
527 grain boundaries between plagioclase and hornblende in the silicate matrix (altered olivine
528 orthocumulate), leading to the initial suggestions of post-solidification replacement; however,
529 Wei et al. (2015) interpret them as the result of growth impingement of late-crystallising
530 silicates from hydrous magma against already partially solidified sulfide globules. We regard
531 these textures, like those at Sudbury, as the result of entrainment and redeposition of a
532 partially solidified and differentiated sulfide liquid pool from elsewhere in the mineralized
533 system.

534 **4 Net-Textured Ores**

535 Net-textured ores, also called matrix ores, are defined by the presence of a continuous matrix
536 of sulfide containing a connected framework of cumulus silicate crystals, usually olivine.
537 They are most commonly found in komatiitic or komatiitic basaltic settings, where they
538 typically form a component of a regular vertical sequence, from bottom to top: massive
539 sulfide from tens of centimetres to several metres in thickness with a sharp upper contact;
540 net-textured ore, up to tens of metres thick in some of the larger deposits; a gradational upper
541 contact over tens of centimetres to a metre, into olivine cumulates containing less than 5 %
542 disseminated sulfides. This sequence, first described from komatiite settings at Kambalda,
543 Western Australia (Ewers and Hudson, 1972; Marston, 1984) and Alexo, Ontario (Naldrett,
544 1973; Houle and Lesher, 2011; Houle et al., 2012), became the basis for the “billiard-ball
545 model” of Naldrett (1973), in which the succession of textures was interpreted in terms of
546 Archimedes Law buoyancy equilibrium, as discussed below.

547 Some of the best developed net-textured ores are found in the komatiitic basalt-hosted
548 deposits of the Raglan Belt in the Ungava Peninsula of north-eastern Canada (Barnes et al.,
549 1982; Lesher, 2007) (Fig. 16). In the sample shown here from the Katinniq deposit, olivine is
550 the only enclosed silicate phase, forming a relatively open framework of interconnected
551 grains ranging in abundance from about 30-50 volume percent. As a general rule the
552 abundance of olivine in net-textured ores is considerably less than the theoretical proportion
553 of around 60% from close-packed individual particles, implying that the olivines accumulated
554 not as isolated crystals but as chains and clusters formed either by heterogeneous self-
555 nucleation (Campbell, 1978) or by the process of random agglomeration of crystals referred
556 to as synneusis (Schwindinger, 1999). Net-textured ores thereby constitute one the best lines
557 of evidence for crystal clustering in cumulates (Jerram et al., 2003). These textures often
558 cause terminological confusion in that the olivine framework is typical of that seen in sulfide-
559 free olivine orthocumulates (Hill et al., 1995), but the rocks are commonly free of a trapped
560 intercumulus silicate liquid component and are actually adcumulates (strictly,
561 heteradcumulates), the cumulus phases being olivine and sulfide liquid.

562 Simple olivine-sulfide (give or take minor chromite or magnetite) net-textures are an end-
563 member of a family of variants, two of the most widespread and genetically significant being
564 poikilitic net-textures (often informally called “leopard textures”) (Fig.16b,c,d) and patchy
565 net-textures (Fig. 17).

566 **4.1 Poikilitic net-textures (“Leopard ore”)**

567 Poikilitic net-texture is particularly well developed at Katinniq in the Raglan belt. The large
568 “leopard spots” in this case (Fig. 16b,c,d) are 1-2 cm subhedral oikocrysts of orthopyroxene
569 (now altered to antigorite in the illustrated example) with Cr-rich cores (Fig. 16d),
570 corresponding to the presence of chromite as well as olivine chadacrysts. Similar examples
571 with clinopyroxene instead of orthopyroxene are also known in the same deposit. These
572 oikocrysts are almost completely devoid of sulfide inclusions. We have already encountered
573 this relationship in the case of disseminated ores in pyroxene rich cumulates at Kevitsa (Fig.
574 8). Similar examples exist in other deposits including Ntaka Hill, Tanzania (Barnes et al.,
575 2016b). The absence of sulfide inclusions from poikilitic phases is evidently a widespread
576 feature that imparts useful clues as to the origins of net-textures, percolation and migration of
577 sulfides in crystal mushes, and the origin of poikilitic textures themselves.

578 **4.2 Patchy net-textures**

579 Patchy net-textures are a widespread variant where the sulfide content of the rock is less than
580 the typical 50-60%, in some cases grading down to less than 10%, but the texture of the rock
581 is heterogeneous at a scale of ten to a hundred times the characteristic silicate grain size. The
582 rock is divided into irregular three-dimensional domains of sulfide-poor orthocumulate,
583 where crystallization products of trapped parent silicate melt form the matrix to the cumulus
584 silicates (usually olivine), and sharply-bounded domains of true net texture, free of visible
585 interstitial silicate melt components. An example of patchy net-textured ore from the
586 komatiite-hosted deposit at Alexo, Ontario (the original type locality for the “billiard ball
587 model”) is shown in Fig. 17. Within the net-textured domains, dihedral angles between
588 olivine and sulfide are typically low implying wetting of olivine silicate melt channels which
589 in turn have served to permit infiltration by sulfide. In the silicate orthocumulate domains,
590 what little sulfide there is forms non-wetting globular blebs in the intercumulus pore space,
591 now occupied by relict acicular clinopyroxene and chlorite as an alteration product of trapped
592 liquid and possible plagioclase. The Alexo sample shown here is also of interest in that it
593 contains a component of spherical sulfide globules. The significance of this particular
594 combination of features is discussed below in the framework of the physics of sulfide melt
595 migration in crystal mushes. It is important to note that the paucity of perfectly fresh and
596 unaltered examples of these textures makes it nearly impossible to determine with confidence
597 whether or not small volumes of silicate melt persisted at the cusped terminations of the
598 sulfide-filled channels as illustrated in Figures 1e and 2c

599 Exactly the same relationship has been reported in the giant Jinchuan deposit in China
600 (Lehmann et al., 2007; Tonnelier, 2009; Tonnelier et al., 2009), which is important in this
601 context in two respects: firstly, almost the entire orebody, probably the largest single
602 contiguous accumulation of magmatic sulfides in the world, is composed of patchy net
603 textured ores, with domains of true net texture and only very minor massive ores (Tonnelier,
604 2009). Secondly, it is by far the largest accumulation of net-textured ores in an intrusive non-
605 komatiitic setting.

606 **4.3 “Leopard” net-textures at Voisey’s Bay**

607 “Leopard-textured” ores are widespread in the Eastern Deeps, Ovoid, and Reid Brook
608 orebodies that comprise the Voisey’s Bay system. They are mainly associated with
609 mineralization hosted in the dike system that connects the major orebodies. They form the
610 lower-grade haloes around the massive sulfide orebodies such as the Ovoid and the Eastern

611 Deeps that occur at or close to the entry point of the dyke into the chamber (Evans-
612 Lamswood et al., 2000). Unlike the "leopard ore" example from the Katinniq deposit, at
613 Voisey's Bay the term applies to net-textured sulphides including sulfide-free pyroxene and
614 olivine oikocrysts surrounding primary plagioclase. In the example illustrated in Fig. 18,
615 plagioclase is clearly a liquidus phase forming a 3D framework (confirmed by x-ray
616 tomography), whereas olivine and lesser orthopyroxene form oikocrysts enclosing multiple
617 plagioclase laths. Again, the oikocrysts are almost entirely free of sulfide inclusions,
618 imparting the "leopard spot" appearance to the rock in hand sample. The textural relationship
619 is the same as that observed in the Katinniq example, but the phases are different. We
620 therefore recommend caution in the use of the term "leopard texture", it being applicable to a
621 variety of textures involving the presence of sulfide-free oikocrysts within net-textured
622 domains. Poikilitic net texture is a preferable term.

623 **4.4 Combined globular and patchy net-textured ores**

624 A distinctive feature of the Alexo patchy net-textured ore in Fig. 17 is the presence of
625 globular sulfides, forming very regular flattened ellipsoids with almost perfectly circular
626 morphologies in plan view, flattened parallel to the mineral lamination defined by platy
627 olivines in the rock. Unfortunately the original orientation of the sample is not known, but by
628 analogy with other occurrences we take the flatter side of the globules to be the base, with an
629 upwardly convex meniscus at the top. These globules occur primarily within the relatively
630 sulfide-poor domains in between the net-textured patches. In some samples these globules are
631 seen to be associated with silicate caps (Fig. 17g,h) that show strong similarities to those at
632 Black Swan; here the caps are occupied by very fine grained serpentine, probably derived by
633 Mg-metasomatism of an original amygdale filling, rather than being original segregated melt.
634 The deposits of the South Raglan trend in the Cape Smith Belt (Mungall, 2007a) are
635 primarily hosted within the lower margins of blade-shaped dykes, and consist of a mixture of
636 massive, net-textured and composite globular and patchy net textures (Fig. 20). These
637 textures are different from those described above from Alexo in that they are developed
638 within altered "pyroxenitic" marginal rocks of the dykes: felted intergrowths of acicular
639 pyroxene grains (now amphibole) with interstitial silicate melt (now amphibole plus chlorite)
640 and sulfide blebs. Sulfides form patchy net textures interstitial to the pyroxenes, which are
641 thought to grow in situ as a form of microspinfex texture. These deposits also contain
642 poikilitic olivine-bearing patchy net-textures, and patchy net-textures where clinopyroxene is

643 the cumulus phase. Sulfides also form spheroidal or ellipsoidal globules, in some cases within
644 the net-textured domains but also in between them (Fig. 19).

645 **4.5 Interspinifex ore**

646 Interspinifex ore is a very rare but distinctive textural type, unique to komatiite-settings. It
647 forms a category of its own but can be regarded as a special case of net-textured ore in that
648 sulfide forms an interconnected framework interstitial to olivine (Fig. 20). In this case, the
649 olivine takes the form of skeletal spinifex plates characteristic of the upper, liquid-rich
650 portions of komatiite flows (Arndt et al., 2008). Interspinifex ore has been described from
651 Kambalda localities by Groves et al. (1986), Beresford et al. (2005) and Barnes et al. (2016a),
652 in the Langmuir deposit in Ontario by Green and Naldrett (Green and Naldrett, 1981) and
653 mentioned at the Alexo deposit, Ontario by Houle et al. (2012) (Fig. 21 B,C). In the Lunnon
654 Shoot locality described by Groves et al. (1986) a massive sulfide pool overlies the basal
655 komatiite flow, the top of which has been eroded such that the A1 and A2 quenched flow top
656 and random spinifex zone have been removed, leaving the coarse parallel-plate A2 spinifex
657 zone in direct contact with the base of the sulfide pool (Fig. 20A). The original silicate melt
658 component of this A2 zone is missing, and the space is now occupied by a typical magmatic
659 Fe-Ni sulfide assemblage that has either replaced or displaced that silicate melt component.
660 The spinifex plates are curved, bent and slightly crumpled, indicative of high temperature
661 deformation. At the top of this zone, at the interface with the massive sulfide, small plumes of
662 quenched silicate melt about 10-20 mm in size are partially enclosed within the lower few cm
663 of the sulfide pool. Each plume has a narrow rim of fine, wiry skeletal spinel, a hallmark of
664 primary contacts between massive sulfide ores and komatiite melt and a feature also seen in
665 the Langmuir interspinifex ores. Groves et al. (1986) concluded that heat from the sulfide had
666 caused interstitial komatiitic melt between the olivine plates to be physically displaced
667 upward by dense, downward percolating sulfide liquid. Several tens of centimetre at least of
668 originally quenched komatiite flow top must have been removed altogether. As well as
669 providing an outstanding piece of evidence for thermal erosion beneath komatiite flows, this
670 ore type also provides clear evidence for the process of downward migration of sulfide liquid
671 through interstitial pore space on a scale of decimetres; this is an important observation for
672 the interpretation of net-textured ores as a whole.

673 **4.6 Lobate-symplectic sulfide-silicate intergrowths at Duke Island.**

674 An unusual variant on net-textured ores is described from the Duke Island intrusion in the
675 Alaskan Panhandle by Stifter et al. (2014). These textures are developed within olivine-

676 clinopyroxene-sulfide accumulates where, instead of entirely occupying the interstitial space
677 between the cumulus silicates, the sulfides also develop complex symplectic intergrowths
678 with clinopyroxene and form subspherical inclusions (in two dimensions) in olivine. There
679 are no 3D images available for these samples, but it is likely that these sulfide inclusions and
680 intergrowths actually represent interconnected networks that are intimately intergrown with
681 the silicate phases. Stifter et al. (2014) propose that these intriguing textures reflect
682 downward percolation of sulfide melt and displacement of original silicate melt, along the
683 lines of the mechanism proposed above for spinifex ore. We further suggest that the complex
684 textures here may reflect an origin of the cumulus silicates as crescumulate dendritic
685 (harrisitic) phases, which underwent partial textural equilibration before displacement of the
686 interstitial silicate melt by percolating sulfide. It is noteworthy that the sulfide included in the
687 symplectic intergrowths appears to be exclusively pyrrhotite, perhaps indicating that
688 represents a true solid-solid symplectite produced by simultaneous growth of mss and
689 pyroxene under water-rich conditions where both sulfide and silicate melts were between
690 their liquidus and solidus over the same range of temperatures. Further 3D investigation of
691 these textures is warranted, as they may provide critical evidence for or against the
692 mechanisms discussed here.

693

5 Discussion

694 5.1 The Billiard-Ball Model reconsidered – origins of net-textured ores

695 The billiard-ball model was originally proposed by Naldrett (1973) to account for the
696 characteristic vertical progression of massive to net-textured to disseminated ores in any
697 komatiite-hosted deposits. In the analogy, the sulfide liquid is represented by mercury,
698 olivine by billiard balls and komatiite magma by water (Fig. 21). The mercury (sulfide liquid)
699 sinks to the bottom, while a column of billiard balls (olivine) sinks in the water and floats in
700 the mercury to the point where the upward and downward buoyancy forces balance. The
701 model was criticized by Groves et al. (1979) on the grounds that the thickness of the olivine
702 cumulate pile in most Kambalda komatiite flows was too great to allow the retention of any
703 olivine-free sulfide liquid to make the basal massive ore. This issue was addressed in a
704 quantitative thermal model by Usselman et al. (1979), who showed that the massive sulfide
705 could be explained by upward solidification of the sulfide liquid pool simultaneously with
706 sinking of olivine crystals. The olivine column sinks to meet the ascending sulfide
707 solidification front (Fig. 21B).

708 Subsequently a number of other challenges have arisen to the model, the main one being the
709 recognition that this deposit type forms by sequential accumulation in dynamic flow channels
710 rather than by static accumulation from stagnant magma. In detail, ore profiles are commonly
711 more complex than the stereotype (Leshner, 2007; Houle et al., 2012). In a number of cases the
712 composition of the sulfide fraction is not homogeneous, but shows a systematic variation
713 from Cu- and Pt-Pd poor, Ir-Ru-Os-Rh enriched massive ore, indicative of an origin as MSS
714 cumulate, to net textured ores with the opposite characteristics (Keays et al., 1981; Barnes
715 and Naldrett, 1986; Barnes et al., 1988; Heggie et al., 2012). These complexities could still be
716 accommodated within the basic theory, but the presence of leopard-textured poikilitic matrix
717 ores as well as patchy net-textured ores, especially patchy net-texture with sulfide globules as
718 described above from Alexo and the South Raglan deposits, become very hard to explain.
719 Poikilitic ores arise as a result of the early and probably liquidus heteradcumulate origin of
720 the oikocrysts (Barnes et al., 2016b); clearly, olivine or pyroxene oikocrysts could not have
721 grown from the sulfide liquid, so their presence attests to early growth from now-displaced
722 silicate melt.

723 As an alternative, or in some cases complementary, mechanism to the billiard-ball model, we
724 propose that much net-textured ore, and particularly the globular-net texture combination, is
725 the result of downward percolation of sulfide through originally silicate melt-filled porosity
726 in unconsolidated olivine-sulfide orthocumulate mush, with concomitant upward
727 displacement of the silicate melt. We have seen clear evidence for the operation of this
728 process in the example of interspinifex ores (Fig. 20).

729 We propose that patchy net textures arise from self-organized gravity-driven migration of
730 both sulfide and silicate melt through the intercumulus pore space of original sulfide-olivine
731 (or sulfide-pyroxene) orthocumulates, mediated by the presence of thin films of silicate melt
732 lining inter-crystalline channels and pores as illustrated in Figure 3c. The critical extra factor
733 is the linking up of sulfide blebs into chains or aggregates with sufficient rise height to
734 overcome the capillary barrier to migration of sulfide blebs through the silicate pore throats
735 (Mungall and Su, 2005; Chung and Mungall, 2009) Fig. 3c).

736 Chung and Mungall's theoretical analysis considered the sulfide bleb dimensions relative to
737 the characteristic silicate grain size. Where sulfide blebs are significantly smaller than the
738 pore throats between the cumulus grains, sulfide microdroplets are capable of migrating
739 distances of hundreds to thousands of meters vertically through crystal mushes as long as
740 silicate melt remains between the crystals. However, larger droplets, comparable in size to the

741 cumulus minerals, become stranded as a result of capillary forces preventing droplet
742 deformation as they attempt to pass into pore throats narrower than themselves (Fig. 3). Only
743 in very coarse-grained mushes with grain sizes greater than about 2 cm can droplets the size
744 of intergranular pores migrate downwards.

745 Extensive drainage and coupled melt migration occurs when coalescence of many
746 microdroplets generates connected net-textured domains (networks) of the dense liquid that
747 are many times larger than the grain size of the mush. An example of this is observed in the
748 Kevitsa sample imaged in Fig. 8. When the vertical height of the connected network is great
749 enough, the pressure gradient inside the dense phase exceeds the capillary force impeding
750 downward motion through narrow pore throats and the immiscible phase is able to move
751 down along vertically-oriented networks, displacing silicate melt upward as it migrates. The
752 process is closely similar to that which forms interspinifex ores. As the sulfide networks
753 migrate they grow by coalescing with previously stranded droplets; this progressive
754 coalescence increases the rise height of the interconnected sulfide droplets, hence increasing
755 their tendency to drain downward and further displacing silicate melt. Patchy net-textures are
756 the result of this feedback-driven self-organization within the sulfide-bearing mush, whereas
757 leopard textures are the result of the sulfide flowing around early formed, essentially cumulus
758 oikocrysts (Fig. 22).

759 The common persistence of globular textures in net-textured sulfide ores is a key textural
760 observation in support of the notion that net-textures form by infiltration of sulfide melt into
761 formerly disseminated or sulfide-free orthocumulates (Figures 15-17). A globule is a textural
762 record of a large drop of sulfide melt that maintained its form to minimize surface energy in a
763 deformable mushy silicate magma (Figure 22a). After consolidation of the mush into a rigid
764 framework, subsequent infiltration of the now-rigid mush by sulfide melt (Figure 22b,c)
765 caused the globular shape of the original bleb to be retained even after it no longer marked
766 the boundary of an isolated drop. Globular blebs of this nature cannot have formed from a
767 crystal mush that was already filled with intercumulus sulfide melt, because in that situation
768 there would be no sulfide-silicate melt interface whose surface tension could generate the
769 globular shape.

770 It has been noted above (e.g. Figs. 4-5 and associated discussion) that sulfide-silicate wetting
771 relationships are often inconsistent at very fine scales. The apparent local wetting of silicate
772 minerals by sulfide may in some cases be a result of the efficient displacement of the former
773 interstitial silicate melt. Dihedral angles in cumulate rocks adjust themselves towards

774 equilibrium by diffusive migration of the “wetted” component through the wetting liquid
775 (Holness et al., 2013). Where the cumulus silicates are insoluble in the liquid, as in the case
776 of olivine and sulfide, this adjustment is not possible, and the original silicate-silicate
777 dihedral angle is inherited by the sulfide-olivine interface. Where small amounts of silicate
778 liquid remain as a film between sulfide and olivine along the solid-solid-melt contact lines,
779 this may give rise to the complex bleb morphologies and highly inconsistent wetting
780 relationships observed in some disseminated interstitial ores.

781 We suggest that under ideal circumstances, runaway sulfide percolation within original
782 olivine-sulfide-silicate liquid mushes forms true net-textured ores, and even potentially
783 allows sulfides to drain all the way to the bottom of the cumulate pile to form massive ores. It
784 is unlikely that this is the mechanism for forming all of the typical Kambalda-style “billiard
785 ball” intersections, where the original Naldrett mechanism may also operate in ideal
786 circumstances, but the presence of patchy and globular net-textured ores suggests strongly
787 that feedback-driven, self-organized sulfide drainage plays an important role in the generation
788 of high-sulfide magmatic ores.

789 **5.2 Implications for sulfide migration and ore genesis**

790 *5.2.1 Origins of massive ore veins*

791 The typical mode of occurrence for massive sulfide ores in all the settings mentioned in the
792 introduction is as basal accumulations in flows or intrusions. However, in many cases the
793 situation is more complex; massive sulfides commonly occur as cross-cutting veins in floor
794 rocks and in host intrusions. Such veins range in scale from a few mm (Fig. 23) to tens of
795 metres at Noril’sk and Sudbury (Lightfoot and Zotov, 2005; Lightfoot and Zotov, 2014).

796 Figure 23 a and b show examples of small-scale vein-type segregations of massive sulfide
797 within dominantly disseminated ore, which we attribute to a combination of two factors:
798 downward migration of an interconnected sulfide liquid network, coupled with transient
799 fracturing of the crystal mush during sudden stress events such as earthquakes. We propose
800 that partially solidified cumulates have thixotropic rheology like water-saturated sand; they
801 flow under low strain rates, but fracture during rapid shocks. Where sulfide melt is migrating
802 through a mush, such events could cause transient fractures to be occupied by dense
803 migrating sulfide melt. This process may operate at a range of scales, giving rise to sulfide
804 veins ranging from mm to metres wide. An incipient stage may be recorded in the sheet-like
805 sulfide aggregates identified by Godel et al. (2006) in the Merensky Reef (Fig. 10). This

806 process is a small-scale analogue to the migration of sulfide liquid into fractures in floor
807 rocks, often accompanied by melting of those rocks and incorporation of silicate rock
808 fragments into massive sulfide, as documented in a komatiite setting by Dowling et al. (2004)
809 and illustrated in a variety of settings by Barnes et al. (2016a). The various manifestations of
810 this process are discussed in a companion paper (Barnes et al., in prep).

811 Figure 23c shows a complex intermingling of textures observed along auto-intrusive contacts
812 at the base of the Tootoo deposit in the Cape Smith Belt of northern Quebec. In this view
813 there are lobate margins between domains of net-textured ore and other domains of fine-
814 grained "pyroxenitic" chilled margin containing isolated sulfide globules. Also present are
815 patches of massive sulfide with ragged margins against net-textured ore. This complex
816 texture is interpreted to have resulted from rupture of the lower boundary of a net-textured
817 crystal mush and intrusion of mingled sulfide-free to globular-textured magma with net-
818 textured and massive sulfide together into a keel-shaped extension of the intrusion below its
819 original floor (Liu et al., 2016).

820 *5.2.2 Tenor variability within deposits*

821 The compositions of magmatic sulfide ores are often characterized by variability at a range of
822 scales: between different textural zones of the same mineral system (Naldrett et al., 1996;
823 Naldrett et al., 2000; Lightfoot et al., 2012) and short-range variability on decimetre scale
824 within orebodies (Tonnelier, 2009). This variability is caused primarily by a combination of
825 magmatic controls during deposition (parent magma composition, silicate sulfide mass
826 balance) and subsequent differentiation of the sulfide liquid itself during solidification. This
827 variability is a complex topic beyond the scope of this paper, but some of the textural
828 evidence presented here throws light on the origin of short-range variability.

829 An example of short range variability is seen in Figure 19, where domains of Cu-rich and Ni-
830 rich sulfides are observed at cm scale in patchy net-textured ore. This variability is
831 interpreted as the result of simultaneous migration and fractional crystallization of MSS from
832 the migrating sulfide liquid. Crystallization of MSS (monosulfide solid solution, the liquidus
833 phase for almost all natural sulfide magmas) results in Cu-depleted zones of partially
834 solidified sulfide, while the relatively Cu-enriched residual sulfide liquid continues to
835 migrate, solidifying deeper in the system. This process leads to differentiation at a range of
836 scales: mm-scale, in the case of the Cu-rich interstitial intergrowths described at Mirabela
837 (Figure 9) and up to several metres in the case of Jinchuan (Tonnelier, 2009). Striking
838 evidence of this phenomenon is offered by the common observation that pyrrhotite forms

839 giant oikocrysts in net-textured ores at the Mequillon deposit in the Cape Smith Belt of
840 northern Quebec (Fig. 19e); these oikocrysts are thought to have formed originally as
841 oikocrysts of monosulfide solid solution (now inverted to pyrrhotite plus pentlandite) during
842 solidification of the intercumulus sulfide melt, and occur together with nearby domains that
843 are greatly enriched in chalcopyrite that crystallized from the sulfide melt residual to early
844 mss crystallization. Similar poikilitic pyrrhotite is also commonly observed in net-textured
845 sulfides at the Eagle's Nest deposit (Mungall et al., 2010) in northwestern Ontario.

846 It is widely believed that the formation of Cu-rich veins and patches is enhanced by a higher
847 tendency of Cu-rich sulfide liquids to wet silicates. Ebel and Naldrett (1996) reported
848 experimental evidence suggesting that wetting of glass tubes by sulfide liquid in the presence
849 of a vapour phase was more extensive in more Cu-rich liquids, although the surface tension
850 measurements of Mungall and Su (2005) did not find this effect. Textural evidence from
851 globular ores at Noril'sk tends to argue against it; differentiated sulfide globules such as those
852 shown in Figure 12 show no tendency for the Cu-rich residual component to leak
853 preferentially into the intercumulus pore space. It is important to bear in mind that the wetting
854 angle between sulfide melt, silica glass, and vapour should not be expected to bear any
855 resemblance to the wetting angle in the completely different physical environment of silicate
856 melt, sulfide melt, and solids that obtains in ore deposits. However, there may be an indirect
857 surface-wetting effect. Residual copper-rich liquids tend to form at lower temperatures where
858 the associated silicate melt is more likely to have crystallized; hence there may be a tendency
859 for Cu-rich liquids to migrate preferentially under certain circumstances owing to the absence
860 of the competitive wetting effect discussed above.

861 At conditions below the solidus of an enclosing silicate assemblage, sulfide may remain
862 partially molten. Under these circumstances, MSS may remain stranded in formerly isolated
863 blebs while residual sulfide liquid rich in Cu and PGE may be free to migrate along
864 microfractures (Mungall, 2002; Mungall and Su, 2005; Mungall, 2007b). At Sudbury there
865 are domains of disseminated sulfide mineralization hosted by norite extending tens to
866 hundreds of meters above the net-textured to massive contact ores. These disseminated haloes
867 have compositions clearly representative of MSS rather than of the sulfide melt that was
868 originally trapped in the intercumulus space. Whereas Mungall (2002) argued that the
869 missing fractionated sulfide liquid might have risen to form a halo above the disseminated
870 mineralization, this idea was modified by Mungall (2007b) to suggest that the missing
871 fractionated sulfide melt descended along microfractures after solidification of the norite.

872 According to this interpretation, this mobile sulfide joined the residual sulfide melt streaming
873 off the contact ores below, eventually moving into the footwall of the Sudbury Igneous
874 Complex to form the Ni-, Cu-, and PGE-rich sharp-walled vein systems.

875 **5.3 Bleb sizes and implications for transport and deposition mechanisms**

876 Clues to the transport and deposition mechanisms of sulfide liquids in magma can be
877 obtained from the study of sulfide bleb sizes, which can only be measured meaningfully from
878 3D images. Published data on disseminated sulfides from komatiites and mafic intrusions
879 (Godel et al., 2013; Robertson et al., 2016) are combined with new data from Sudbury and
880 Kevitsa (this study) in a series of particle size distribution plots (PSDs) (Fig. 24). These plots
881 take the same form as crystal size distribution (CSD) plots widely used in petrology and
882 materials science (Marsh, 1998), being frequency distributions of the number of particles
883 within a size range (size being defined as the diameter of a sphere of the same volume as the
884 particle) per cubic cm of sample volume, normalized to the width of the size bin on the x
885 axis. Populations of growing crystals from a cooling magma generate linear trends of negative
886 slope on such plots, which can then be modified by processes such as textural maturation,
887 mechanical sorting and accumulation of phenocrysts (Marsh, 1998).

888 Almost all measured bleb size distributions show broadly linear and variably convex-up
889 patterns on PSD plots, and most show similar slopes at the fine-grained end of the
890 distribution. Godel et al. (2013) suggested that the concave-up distributions in sulfide blebs in
891 komatiitic dunites were the result of a mixture of two linear components: a mechanically
892 sedimented population of transported droplets, and a finer (and steeper) population of cotectic
893 sulfide droplets that had nucleated and grown in situ. Robertson et al. (2016) pointed out that
894 linear negative slopes on PSD plots could also be generated by dynamic breakup of
895 transported liquid droplets. They showed that this process is likely to be dominant over
896 coalescence during flow of magmatic emulsions, consistent with previous experimental and
897 theoretical work (de Bremond d'Ars et al., 2001). They interpreted sulfide bleb and droplet
898 PSDs as the result of multiple superimposed processes which are active on different portions
899 of the droplet size distribution: growth of sulfide droplets from sulfide-saturated silicate
900 magma, and mechanical accumulations of transported assimilated droplets that have
901 undergone break-up by a variety of mechanisms during transport.

902 The observations presented here suggest that coalescence is also an important factor in
903 generating the strongly convex-up PSD observed at Kevitsa. In the Kevitsa case, this

904 coalescence is post-accumulation, and takes place during self-organized percolation of sulfide
905 liquid networks through the crystal pile. The geometry of some of the larger more irregular
906 blebs at Copper Cliff and Kharelakh is also strongly suggestive of post-deposition
907 coalescence of larger droplets. However, the predominance of broadly linear negative slopes
908 on PSDs for all globular ores strongly suggests a control by dynamic droplet breakup during
909 flow, with a relatively minor degree of mechanical sorting during deposition. This implies
910 that sulfide droplet accumulation to form orebodies occurs by a type of “avalanche” process,
911 whereby a sulfide liquid rich slurry accumulates in a cascade of strongly interacting particles,
912 rather than by simple Stokes-Law settling of non-interacting individual particles (Robertson
913 et al., 2014). The presence of large uncapped sulfide globules of the Copper Cliff type
914 described above, in excess of 1 cm, is a strong indicator of proximity either to a massive
915 sulfide accumulation, or to a site of assimilation of sulfide-rich country rock. Where such
916 globules are Cu and/or Ni enriched, requiring enough time for effective equilibration with the
917 host magma, they are an indicator of proximity to sulfide-rich ore.

918 **6 Conclusions**

919 The diversity of the major textural types of disseminated and net-textured sulfides arises from
920 the interplay of a relatively small number of factors: the modal abundance of sulfide; the
921 modal abundance of co-existing silicate melt; the relative liquidus and solidus temperatures
922 of the co-existing melts; the presence or absence of a co-existing vapour phase; the
923 proportion of silicate melt to solid cumulus (or phenocryst) silicates and oxides; and the
924 cooling history. These relationships are summarized in the classification scheme in Table 2.

925 Disseminated sulfides fall into two major categories:

- 926 1. Interstitial blebs, which may be more or less concave and globule-like depending on
927 the abundance of silicate melt in the local micro-environment.
- 928 2. Globules. These in turn can be subdivided into (a) typically rounded and sub-spherical
929 globules associated with amygdalae and/or segregation vesicles; and (b) equant but
930 non-spherical, locally faceted globules without any associated amygdalae or vesicles.
931 The latter (b) type, as at Sudbury, are associated with silicate magmas with relatively
932 low solidus temperatures. The morphology of these blebs may be the result of
933 disruption and re-deposition of partially solidified pre-existing sulfide concentrations.
934 The former (a) type may form either as a result of flotation of sulfide droplets on
935 vapour bubbles in high-level emplacement settings, or by nucleation of bubbles on

936 sulfide droplets due to post-cumulus vapour saturation of intercumulus silicate liquid.

937 Vapour saturation of the solidifying sulfide melt itself may also be a factor.

938 A continuum exists between relatively sulfide-rich disseminated ores and net-textured ores,
939 but the intermediate ore types are typically patchy net-textured ores consisting of domains of
940 sulfide-rich net-texture with low wetting angles, separated by sulfide-poor domains where
941 silicate melt occupies the pore space. This texture is driven by self-organized sulfide
942 percolation, itself triggered by the process of competitive wetting whereby the silicate melt
943 preferentially wets silicate crystal surfaces. The process is self-reinforcing as sulfide
944 migration causes sulfide networks to become larger, with a larger rise height and hence a
945 greater gravitational driving force for percolation and silicate melt displacement.

946 The sulfide percolation process is coupled with upward displacement of silicate melt, and in
947 ideal circumstances gives rise to fully net-textured ores. Interspinifex ores are a special case,
948 providing convincing evidence of this migration-displacement process. The poikilitic
949 “leopard-textured” ores at Voisey’s Bay (Fig. 19) are likely to be another manifestation of
950 this process, where the cumulus framework is made up of plagioclase and olivine rather than
951 olivine alone. The presence of globular sulfides within patchy net-textured ores is attributed
952 to a two stage process: formation of low-sulfide globular disseminated ore, followed by
953 infiltration by downward percolating sulfide from above. Poikilitic ores probably reflect a
954 similar two-stage process: deposition of a poikilitic orthocumulate, followed by displacement
955 of silicate melt by percolating sulfide. The leopard-textured troctolite-hosted ores at Voisey’s
956 Bay are from a process point of view simply another variety of net-textured ore, but with
957 plagioclase as the predominant cumulus phase. They could be seen as the plagioclase-bearing
958 equivalent of interspinifex ore.

959 Where sulfide abundances are too low, less than about 3 modal percent, sulfide blebs remain
960 unconnected, and gravitational forces are too small to drive percolation. Sulfides then become
961 trapped in pore space to form disseminated ores. This accounts for the broadly bimodal
962 distribution of sulfide abundances between disseminated and net-textured ores as seen at
963 Voisey’s Bay.

964 Strain-rate dependent thixotropic behaviour of sulfide bearing-crystal mushes gives rise to
965 localized opening of fractures during sudden shock events such as earthquakes. This results in
966 the formation of sulfide veins and veinlets at a variety of scales within net-textured and

967 disseminated ore profiles, as percolating sulfide liquid flows into transient high-permeability
968 pathways.

969 The Naldrett (1973) “billiard ball model” for net-textured ores may have operated under
970 some circumstances, but is likely to be coupled with the various other processes outlined
971 here. The initial step may be transport and co-deposition of a slurry of silicate and sulfide
972 melt with olivine or pyroxene crystals, followed by gravitationally-driven percolation and
973 textural re-organization.

974 **7 Implications**

975 The panoply of sulfide textures described here provides important genetic clues to the origin
976 of some of the world’s most valuable ore deposits. Furthermore, from an exploration point of
977 view, the textures and size distributions of disseminated sulfide populations may be
978 incorporated with standard geochemical data sets to infer vectors towards sulfide-rich Ni-Cu-
979 PGE ores and potential for high-grade ore in the system. The presence of large uncapped
980 sulfide globules, in excess of 1 cm, is a strong indicator that the transporting magma was
981 capable of generating a massive sulfide accumulation. This is particularly true for the large,
982 irregular Ni- and Cu-enriched globules of the type observed at Sudbury. Restriction of sulfide
983 populations to low modal abundance and steep log-normal particle size distributions is
984 indicative of a dominant origin by in-situ nucleation of newly-formed sulfide droplets
985 growing from the host magma (Godel et al., 2013; Robertson et al., 2016), which represents a
986 more distal environment to sulfide-rich ore deposition, and may not be associated with
987 sulfide-rich ores at all. A transition from the latter case to ores with coarse blebs of any form
988 can be taken as a potential vector towards high-grade sulfide-rich mineralization. Systematic
989 and consistent mapping out of textural types within individual orebodies has potential to be
990 just as important and instructive as standard geochemical and petrographic investigations,.
991 Complementary textural and geochemical investigations are necessary for the full
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1425

10 Figure Captions

1426 Figure 1. Frequency distribution of S abundance in ores from the Ovoid and Eastern Deeps at
1427 Voisey's Bay, after Lightfoot et al. (Lightfoot et al., 2012), illustrating the typical pattern of
1428 distribution, with peaks corresponding to disseminated and massive ores and a long tail on
1429 the disseminated mode leading into a broad peak corresponding to net-textured ores.

1430 Figure 2 Sketches of contact angles in partially molten rocks, drawn in the plane
1431 perpendicular to the tangent of the contact line or lines where three phases come together. S =
1432 solid, L = liquid, L1, L2 = two immiscible liquids. a. Interfacial angle of 28° between two
1433 planar crystal faces. b. An example of a contact where the interfacial angle is 28° but the
1434 equilibrium dihedral angle is 50° ; the interfaces are deflected close to the contact line to
1435 achieve local textural equilibrium. c. Axial cross section of a sulfide liquid drop sessile on a
1436 planar olivine crystal face, both in contact with silicate melt. The wetting angle is 160°
1437 (Mungall and Su, 2005) and the drop is small enough not to be deformed under its own
1438 negative buoyancy; i.e., the system is small enough that surface tension predominates over
1439 body forces. d. Axial view down three linear channel separating three crystals (S) and
1440 occupied by liquid (L). e. Melt-filled channels as in d are now occupied by two liquids with a
1441 wetting angle of 160° ; L2 in this case could correspond to sulfide liquid in a basalt-filled
1442 channel (L1) between olivine crystals (S).

1443 Figure 3. Sketches of the distribution of melts and solids in idealized partially molten systems
1444 with very low melt fraction, corresponding closely to olivine adcumulate textures in dunites
1445 (after van Barga and Waff, 1986; Mungall, 2015). a. Dihedral angle $> 60^\circ$, as would occur
1446 in oxygen-rich sulfide melts hosted by olivine in the absence of silicate melt (Rose and
1447 Brenan, 2001). b. Dihedral angle $< 60^\circ$, as would occur where basaltic liquid was hosted by
1448 olivine (Van Barga and Waff, 1986). c. One wetting liquid has dihedral angle $< 60^\circ$ (e.g.,
1449 basaltic liquid against olivine) but a second non-wetting liquid has a wetting angle of 160°
1450 (e.g., sulfide liquid). The presence of the network of channels of wetting basaltic liquid opens
1451 up a pathway for extended drops of sulfide liquid spanning several pores and channels;
1452 however sulfide melt cannot spontaneously migrate downwards as isolated drops unless they
1453 are small enough to fit through the smallest dimensions of the grain-edge channels
1454 (microdrop at top right). Larger isolated drops are stranded in pores at the junction of four

1455 crystals, unable to move because capillary forces impede the deformation require to force
1456 them through grain-edge channels (stranded drop, deformed drop at right). Large, extended
1457 drops of sulfide melt within the basaltic melt channel network can only migrate downwards if
1458 the hydraulic head expressed over the vertical distance ζ exceeds the capillary force resisting
1459 downward motion at the bottom of the sulfide mass (Chung and Mungall, 2009).

1460 Figure 4. Disseminated sulfides in komatiitic olivine adcumulates from Mt Keith (a to e),
1461 traced from polished sections. Note the wide variability of dihedral angle within the same
1462 sample and in some cases within the same bleb. Modified from Godel et al. (2013).

1463 Figure 5 (a) Microbeam X-ray fluorescence (XFM) element map collected using the Maia
1464 detector array on the XFM beamline of the Australian Synchrotron. False colour image
1465 showing relative normalized abundances of Ni (red), Fe (green) and Cu (blue) in a polished
1466 section of interstitial disseminated ore from Mt Keith. (b): MAIA-XFM false colour image of
1467 disseminated sulfides in 95% fresh dunite from Dumont, same colour scheme as (f).

1468 Figure 6. 3D textures in interstitial disseminated ores, perspective views of HRXCT images.
1469 (a) Disseminated sulfide blebs in olivine-sulfide adcumulate from Mt. Keith, showing triple-
1470 point “tubules” or micro-channels of sulfide along olivine triple grain boundaries – compare
1471 Fig.1a. (b) olivine-sulfide meso-accumulate from Mt Keith, individual sulfide blebs colour-
1472 coded by size (after Godel et al., 2013). (Animations of 3D scans at
1473 <https://www.youtube.com/watch?v=uJXfKNQx3nY>). Blebs in this sample are primarily
1474 convex/globular. (c) perspective views of single 3D image of disseminated sulfides from
1475 Dumont (same sample as Fig. 5b) showing isolated, poorly interconnected non-wetting
1476 sulfides. Yellow = sulfide, red = awaruite (Ni-Fe alloy) – note presence of an awaruite grain
1477 in each sulfide bleb (See supplementary material for 3D animations of these images).

1478 Figure 7. 2D and 3D images of globular sulfides from olivine-sulfide orthocumulates at Black
1479 Swan, Western Australia. A phase map traced from polished slab showing distribution of
1480 (alteration products of) olivine, interstitial silicate melt and sulfide blebs, after Barnes et al.
1481 (2009). B,c– 3D HRXCT image of sulfide globules in a similar olivine-sulfide orthocumulate
1482 rock, drill core approximately 4 cm across. Animation of 3D image at
1483 https://www.youtube.com/watch?v=U-wj_kx4ns0

1484 Figure 8. Sulfide textures in pyroxenites from the Kevitsa intrusion, Finland. (a), (b),
1485 perspective views of 3D microCT image of disseminated sulfides in orthopyroxenite. Colours

1486 indicate separate sulfide networks. (c), (d), same image, same view, showing only the largest
1487 interconnected network in the sample. See

1488 <https://www.youtube.com/watch?v=OXC7ICRP1Iw> for 3D animation. E, Tornado

1489 MicroXRF image of sample KV148-337, disseminated sulfide in poikilitic websterite.

1490 Relative normalized proportions of Ni (red), Cu (green) and Ca (blue). Oikocrysts of
1491 clinopyroxene (blue) enclosing orthopyroxene (black). Sulfides indicated by Ni and Cu –

1492 note exclusion of sulfides from interior of oikocrysts. F, perspective view of 3D image of

1493 same sample, sulfides in yellow. Sulfides primarily form poorly interconnected blebs; vacant

1494 volumes are occupied by oikocrysts.

1495 Figure 9 Sulfide textures in the Mirabela Intrusion (a-e), after Barnes et al. (2011b) A, b:

1496 reflected light photomicrographs of interstitial blebs, pn=pentlandite, po = pyrrhotite, cp =
1497 chalcopyrite, py = pyrite. Note symplectic intergrowth of cp with pyroxene in (b). c,

1498 transmitted crossed polar light photomicrograph of sulfide (black) intergrown with

1499 intercumulus patch of plagioclase, amphibole, mica and apatite. (d,e), perspective view of 3D

1500 microCT image of non-connected interstitial disseminated sulfide in chromite-bearing

1501 harzburgite.

1502 Figure 10. 3D rendering showing the 3D distribution and morphology of sulfides in samples

1503 from the JM-Reef of the Stillwater Complex (U.S.A) and the Merensky Reef of the Bushveld

1504 Complex (South-Africa). a) 3D distribution of sulfides in olivine-gabbro from the JM-

1505 Reef in red and yellow (modified from Godel, et al., 2006). The red colour represent the

1506 largest interconnected network in the specimen scanned. b) 3D morphology of sulfides-

1507 silicate boundaries in similar JM Reef sample obtained using HRXCT, modified after Godel

1508 (2015); c) 3D distribution of sulfides in gabbro from the Merensky Reef (modified from

1509 Godel, et al. (2006)) with three largest sulfide network coloured in red, blue and green.

1510 Figure 11. Globules with silicate caps from Togeda macrodyke, after Holwell et al. (2012).

1511 A,b,c;; oblique view of horizontal slices and cylindrical edges of core sample located in d,

1512 microCT images. Note silicate cap occupied by plagioclase (pl), and clinopyroxene (cpx)

1513 intergrown with the top of the sulfide globule. D, 3D microCT image of drill core showing

1514 location of detailed slices a,b,c. E, outcrop photograph. F, medical CT image of multiple

1515 sulfide globules in outcrop sample (different sample from a,b,c,d). See

1516 <https://data.csiro.au/dap/SupportingAttachment?collectionId=17878&fileId=1234>

1517 for a fully interactive 3D visualization and <https://www.youtube.com/watch?v=lUm3sope5y0>
1518 for animation.

1519 Figure 12. Capped sulfide globules associated with segregation vesicles in olivine
1520 orthocumulate, Black Swan komatiite-hosted deposit. A –C, drill core samples showing
1521 globules occupying lower portion of segregation vesicles (Seg-black), after Dowling et al.
1522 (2004). Sulf= sulfide, ol-Srp, SM = interstitial silicate melt. D, Tornado false colour
1523 microbeam XFM image, normalized relative abundances of Cr (red), Ni (green) and Fe
1524 (blue). Sulfide (blue, green – pyrite plus millerite) rimmed by skeletal chromite (Chr, pink)
1525 within skeletal textured olivine orthocumulate – olivine now pseudomorphed by serpentine
1526 (Ol-Srp) plus magnetite, interstitial space occupied by fine chlorite-serpentine intergrowth
1527 after original trapped silicate liquid. E, detail of D, synchrotron XFM image, Cr (red), log Ni
1528 (green), Fe (blue) – note fine-grained microspinfex texture (psp) within segregated silicate
1529 component (upper right). F, 3D perspective view of microCT image of same sample – note
1530 chromite rimming sulfide (yellow) interconnects with a larger octahedral chromite grain
1531 outside the vesicle – after Godel et al. 2014).

1532 Figure 13. Polished slab photos of capped globules in samples of globular disseminated ore
1533 from the Noril'sk 1 and Kharelakh intrusions, Noril'sk-Talnakh, Siberia. A, B, olivine gabbro
1534 containing two sulfide populations: flattened globules with upper silicate caps, and interstitial
1535 blebs. Globules show characteristic differentiation into po-pn at the base, chalcopyrite-
1536 dominant at top, with a smooth meniscus between. Note variable degree of flattening of
1537 globules. C, Enlargement of capped bleb in (B), showing upper boundary of Cu-rich sulfide
1538 with silicate cap, and percolation of Fe-rich sulfide at bottom into interstitial space within the
1539 cumulus olivine framework of the rock. D, capped differentiated sulfide globule from
1540 Waterfall Gorge, Insizwa Intrusion, Karoo province. F, 3D medical CT image of globular
1541 disseminated sulfides from the Kharelakh intrusion. Colours have no compositional
1542 significance, but indicate individual non-interconnected globules. Note irregular multi-lobate
1543 morphologies of many globules. See
1544 <https://data.csiro.au/dap/SupportingAttachment?collectionId=17878&fileId=1233> and
1545 <https://data.csiro.au/dap/SupportingAttachment?collectionId=17878&fileId=1231> for
1546 interactive 3D visualizations.

1547 Figure 14. Globular disseminated sulfides from Copper Cliff offset, Sudbury. A) photo
1548 mosaic of polished slab. B, c, Tornado XFM 3-element false colour maps of same slab. See

1549 <https://www.youtube.com/watch?v=-kVK3kNygic> for animation of moving slices through
1550 3D image.

1551 Figure 15. XRF and CT images of globular disseminated sulfides, Piaohechuan deposit,
1552 China. A) photo mosaic of polished slab. B, Tornado XFM 3-element false colour map of
1553 same slab. Pyrrhotite in blue, pentlandite pink, chalcopyrite green. c) representative slices
1554 through medical CT 3D image with sulfide globule intersections picked out in yellow. Note
1555 embayed morphologies of some of the larger globules. d) perspective view of 3D medical-CT
1556 image showing arbitrary colours for individual interconnected globules. Note that the large
1557 globules tend to be less spherical and more coalesced (see

1558 <https://data.csiro.au/dap/SupportingAttachment?collectionId=17878&fileId=1230>

1559 for interactive 3D visualization and <https://www.youtube.com/watch?v=pxnQeBjTwNA> for
1560 animation.

1561 Figure 16. Net-textured and poikilitic “leopard” net-textured ores from the Katinniq deposit,
1562 Raglan belt, Canada. A, typical oikocryst-free net-textured ore, B, poikilitic net-textured ore;
1563 inset enlargement showing chromite grains in orthopyroxene core. A-B reflected light
1564 photomicrographs. Note olivine, opx are completely replaced by serpentine. C, Tornado
1565 XFM map, normalized relative concentrations of Cr (red), Fe (green) and S (blue). Not Cr-
1566 enriched zones in cores of opx, Cr-poor outer opx zones, greatly reduced proportion of
1567 sulfide (blue/turquoise) inside oikocrysts. D, same, Ni (red), Cu (green) and S (blue).

1568 Figure 17. Net-textured ore textures – combined patchy net-textured and globular sulfides,
1569 with and without silicate caps, Alexo, Ontario. A,b: photomosaics of polished slabs showing
1570 sulfide as interstitial network and ellipsoidal globules. Olivine pseudomorphs as equant and
1571 aligned platy grains (black). c, d: Tornado XFM images – ol=olivine, sul=sulfide, TL =
1572 trapped liquid alteration product, cpx=clinopyroxene. Note trapped-liquid rich orthocumulate
1573 micro-domains are relatively poor in sulfide and vice versa. E, transmitted light
1574 photomicrograph showing relic acicular cpx and chlorite interstitial to olivine pseudomorphs
1575 in orthocumulate domain. F, orthoslices through medical CT image showing oblate spheroid
1576 geometry of coarse sulfide globules (see supplementary material for animated version). g:
1577 photomosaic of polished slabs showing sulfide (sul) as interstitial network and ellipsoidal
1578 globules capped by amygdales (amg) filled with very fine-grained serpentine. Olivine
1579 pseudomorphs as equant and aligned platy grains (black). h: Tornado XFM image (S red, Ca
1580 green and Al blue) highlighting orthocumulate (ooc) micro-domains with low sulfide content

1581 separated by sulfide-rich, trapped-liquid poor net-textured micro-domains. Interactive 3DE
1582 visualization at
1583 <https://data.csiro.au/dap/SupportingAttachment?collectionId=17878&fileId=1235>

1584 Figure 18. Voisey's Bay "Leopard textured" ore. Net-textured ore with plagioclase as the
1585 main enclosed silicate, with oikocrysts of olivine and minor orthopyroxene that are free of
1586 sulfide inclusions.

1587 Figure 19. Patchy net-textures combining matrix and globular sulfides, Mesamax (Raglan)
1588 developed within altered "pyroxenitic" marginal rocks of the dykes: felted intergrowths of
1589 acicular pyroxene grains (now amphibole) with interstitial silicate melt (now amphibole plus
1590 chlorite) and sulfide blebs. A,b, Sulfides form patchy net-textures interstitial to the
1591 pyroxenes, which are thought to grow in situ as a form of microspinfex texture. Sulfides also
1592 form spheroidal or ellipsoidal globules, in some cases within the matrix domains but also in
1593 between them. C, heavily disseminated sulfides with distinct globules– note Cu-rich
1594 composition reflecting decimetre scale variability in Ni/Cu ratio of sulfide component, d)
1595 same sample as C, perspective view of 3D medical CT scan with disseminated interstitial
1596 sulfides in yellow, largest globular sulfides in blue. Interactive 3D image at
1597 <https://data.csiro.au/dap/SupportingAttachment?collectionId=17878&fileId=1232>, animation
1598 at <https://www.youtube.com/watch?v=BksdEnjBpec>

1599 E), net-textured ore from Mequillon deposit – dashes outline single crystal oikocrysts of
1600 pyrrhotite (formerly MSS).

1601 Figure 20. Interspinifex ores. A) underground face photo from M.J. Donaldson, hanging wall
1602 ore at Lunnon Shoot. Massive ore overlying interspinifex ore – note mushroom-shaped
1603 plumes (arrowed) of displaced silicate melt at interface between interspinifex ore (ISO) and
1604 overlying massive sulfide (MS). Kom = host komatiite flows. B,c,d – Tornado images of
1605 interspinifex ore from Langmuir, Ontario. Optical photo-mosaic (b), Phase map showing
1606 olivine (green), sulfide (po + pn) in yellow, chromite in red. D) three-element false colour
1607 image with Ni red, Cu green and S blue. For moving slice animation through 3D medical CT
1608 scan see <https://www.youtube.com/watch?v=szBQa0LCZOW>

1609 Figure 21. Cartoon illustrating the "billiard ball model" for the origin of net textured sulfide,
1610 after Naldrett (1973) and Usselman et al. (1979)

1611 Figure 22. Cartoon illustrating evolution of patchy net-texture from coalescence and inter-
1612 pore drainage of originally disseminated sulfides.

1613 Figure 23. Features related to sulfide liquid percolation. A,b: “soft-wall” sulfide-rich vein-
1614 like segregations (SV) developed within intervals of predominantly in disseminated ores. a)
1615 Kevitsa deposit, Finland; b) Ntaka Hill deposit, Tanzania – disseminated ores in coarse-
1616 grained orthopyroxenite. C, complex mixed sulfide textures in the Tootoo deposit, Cape
1617 Smith Belt, northern Quebec: lobate margins between domains of net-textured ore and other
1618 domains of fine-grained "pyroxenitic" chilled margin containing isolated globular blebs of
1619 sulfide. Also present are patches of massive sulfide with ragged margins against net-textured
1620 ore. C, complex mixed sulfide textures in the Tootoo deposit, Cape Smith Belt, northern
1621 Quebec: lobate margins between domains of net-textured ore and other domains of fine-
1622 grained "pyroxenitic" chilled margin containing isolated globular blebs of sulfide. Also
1623 present are patches of massive sulfide with ragged margins against net-textured ore.

1624

1625 Figure 24. Sulfide bleb sizes, modified from Robertson et al. (2015). (a) Particle size
1626 distribution plots (equivalent to CSD plots of Marsh (1988)) showing equivalent sphere
1627 diameter measurements for sulphide blebs from a number of disseminated ore deposits
1628 consisting of 2-5% disseminated sulphides in komatiitic olivine adcumulates. All
1629 measurements were made in 3D using x-ray microtomography on 2-5 cm³ samples following
1630 the procedure of Godel (2013). The Mount Keith population is composite of five samples. (b)
1631 data from three Noril'sk globular ore samples. (c) droplet size distributions for samples from
1632 Mesamax (Expo), Black Swan and Marriots. D) disseminated sulfide blebs from Kevitsa,
1633 same samples as shown in Fig. 8.

1634

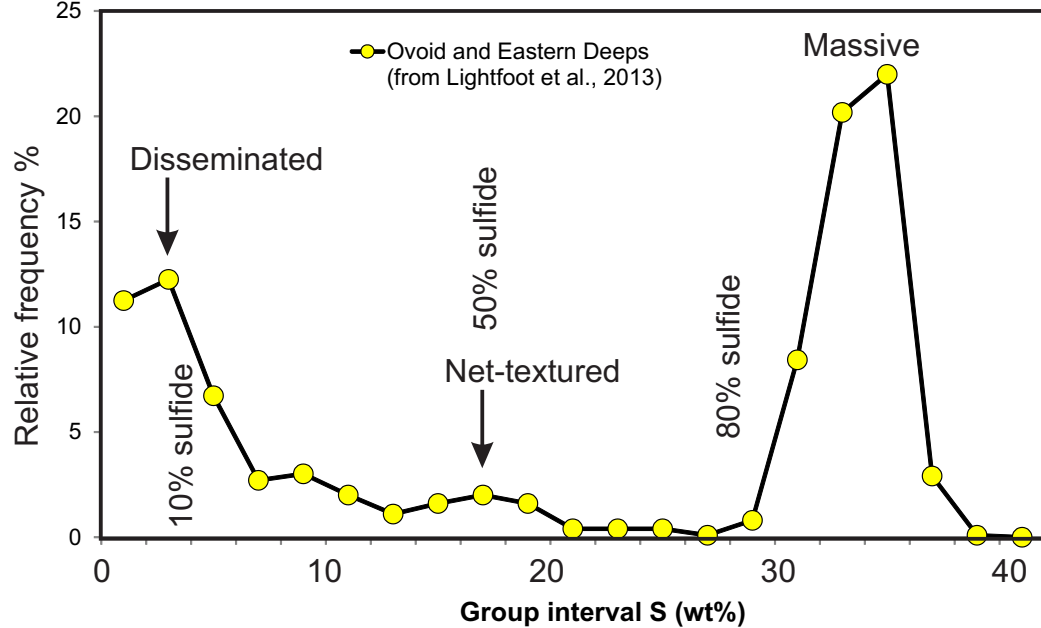
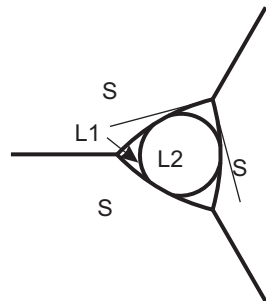
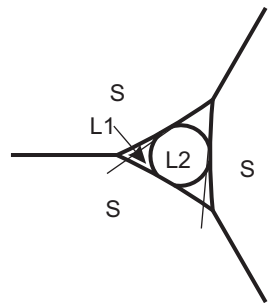
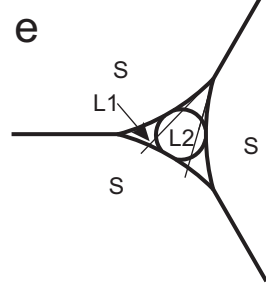
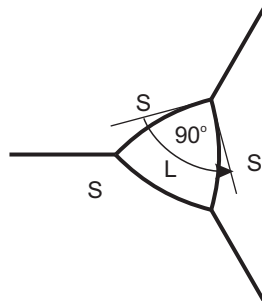
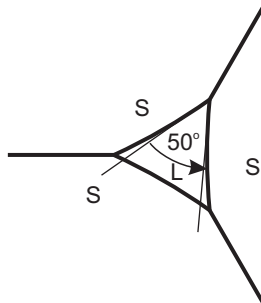
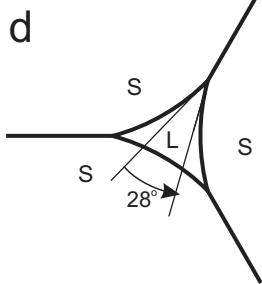
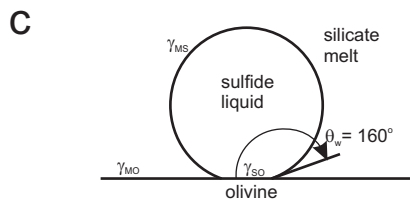
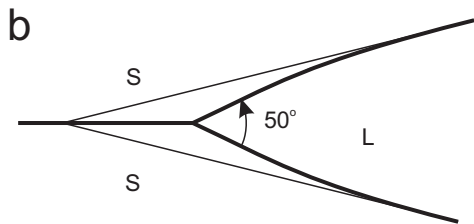
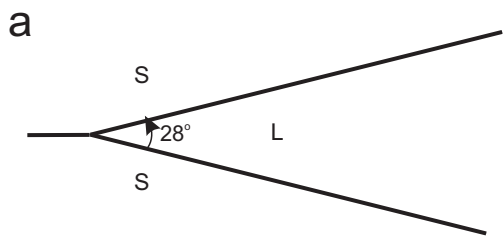
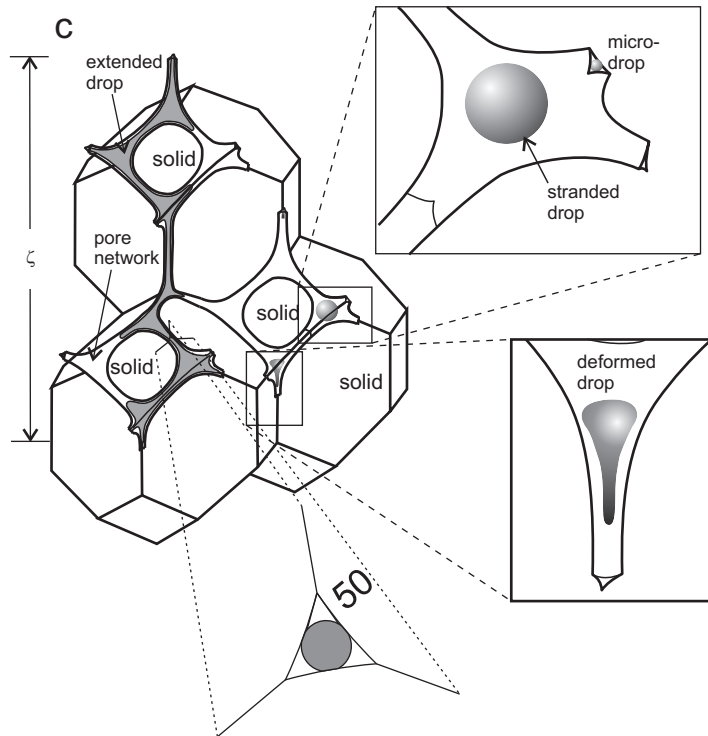
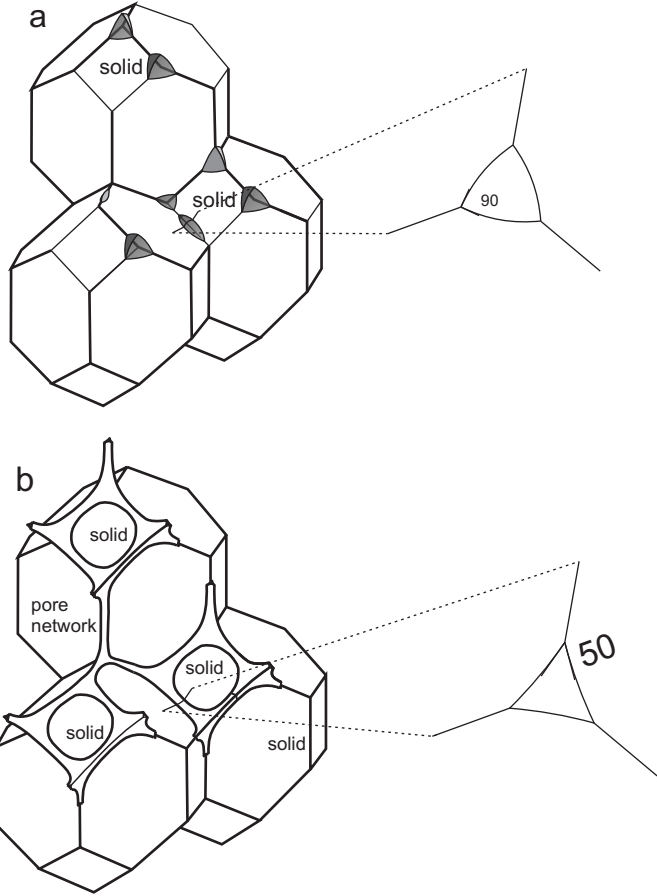
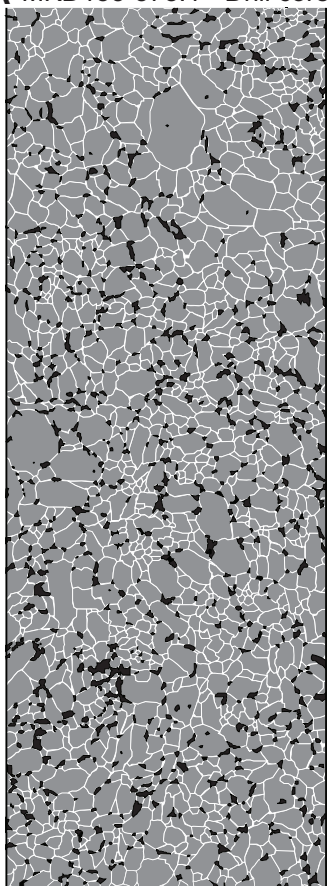


Figure 1

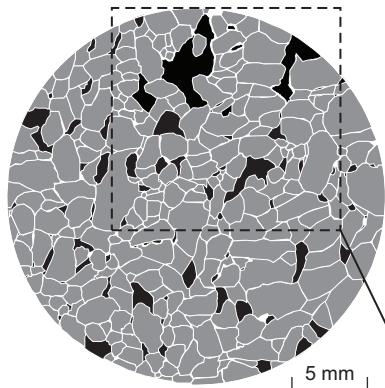




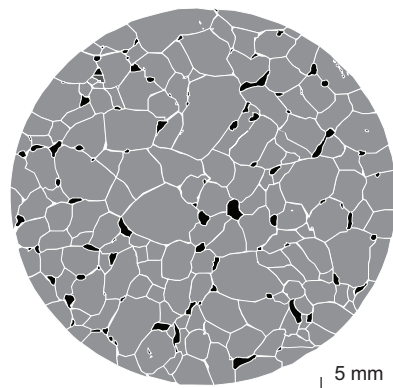
A MKD153-578.1 - Drill core



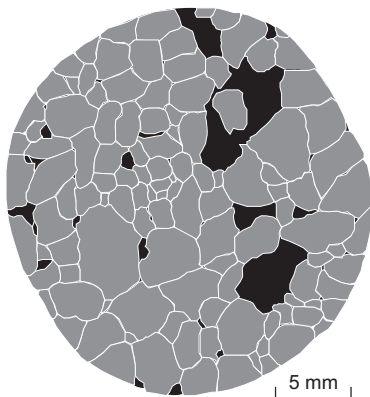
B MKD153-578-2 Part A



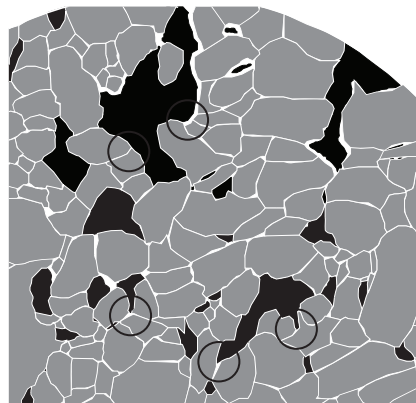
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D MKD153-649-5



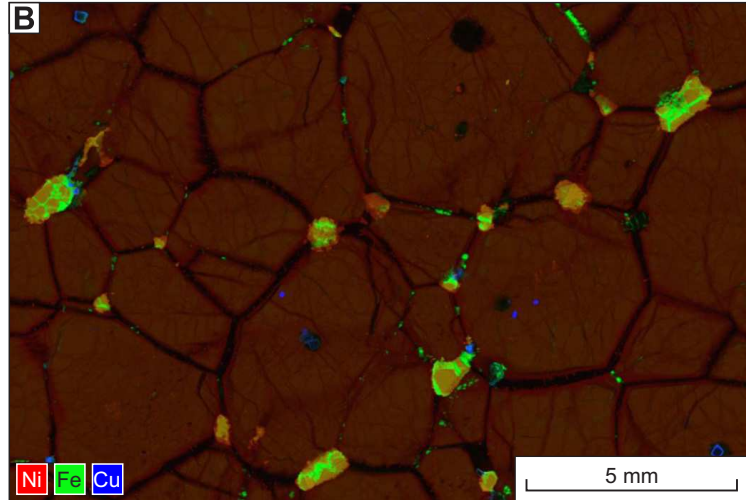
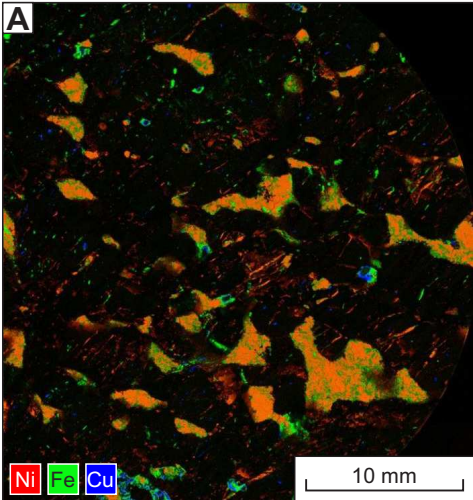
E MKD153-578-2 Part A enlargement



20 mm

■ Sulfide

■ Olivine



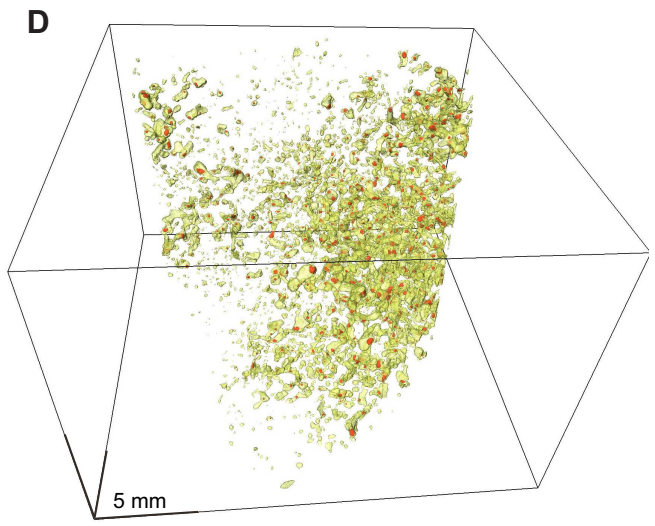
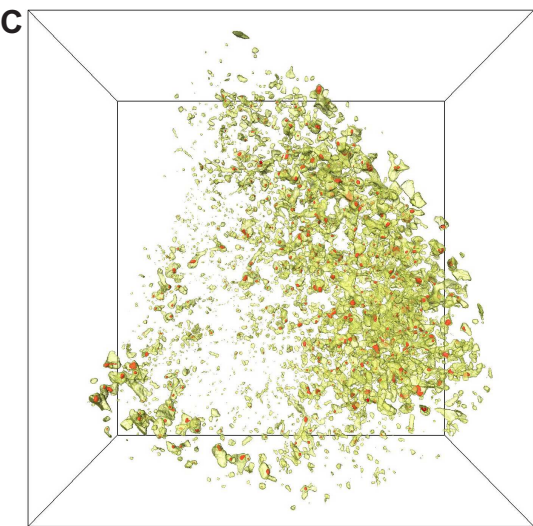
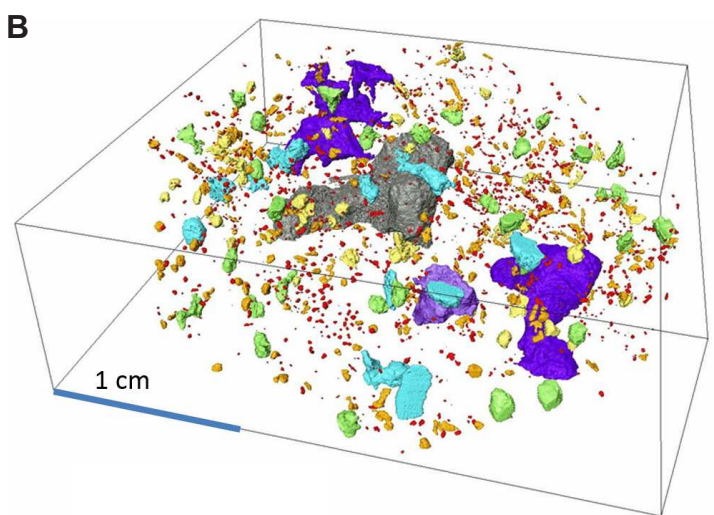
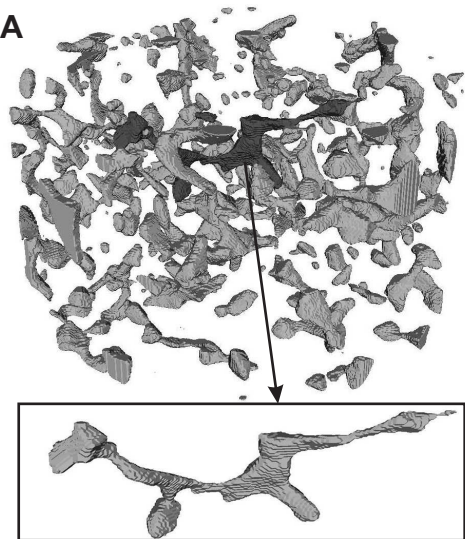


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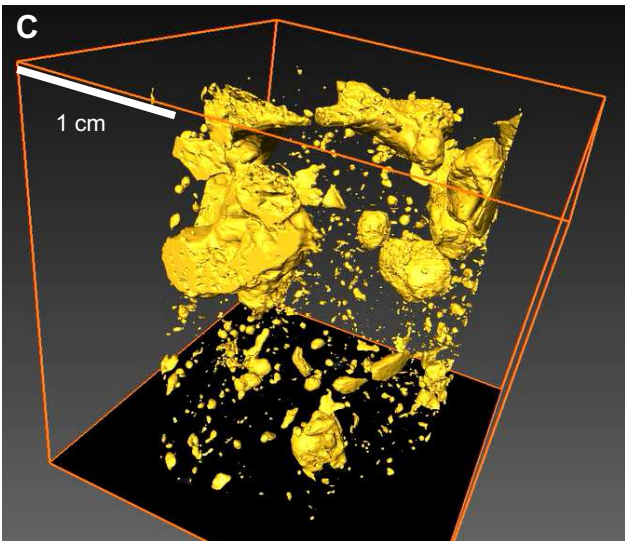
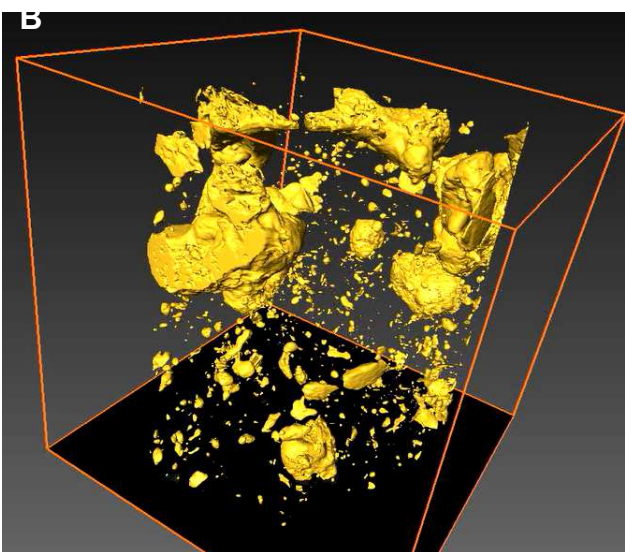


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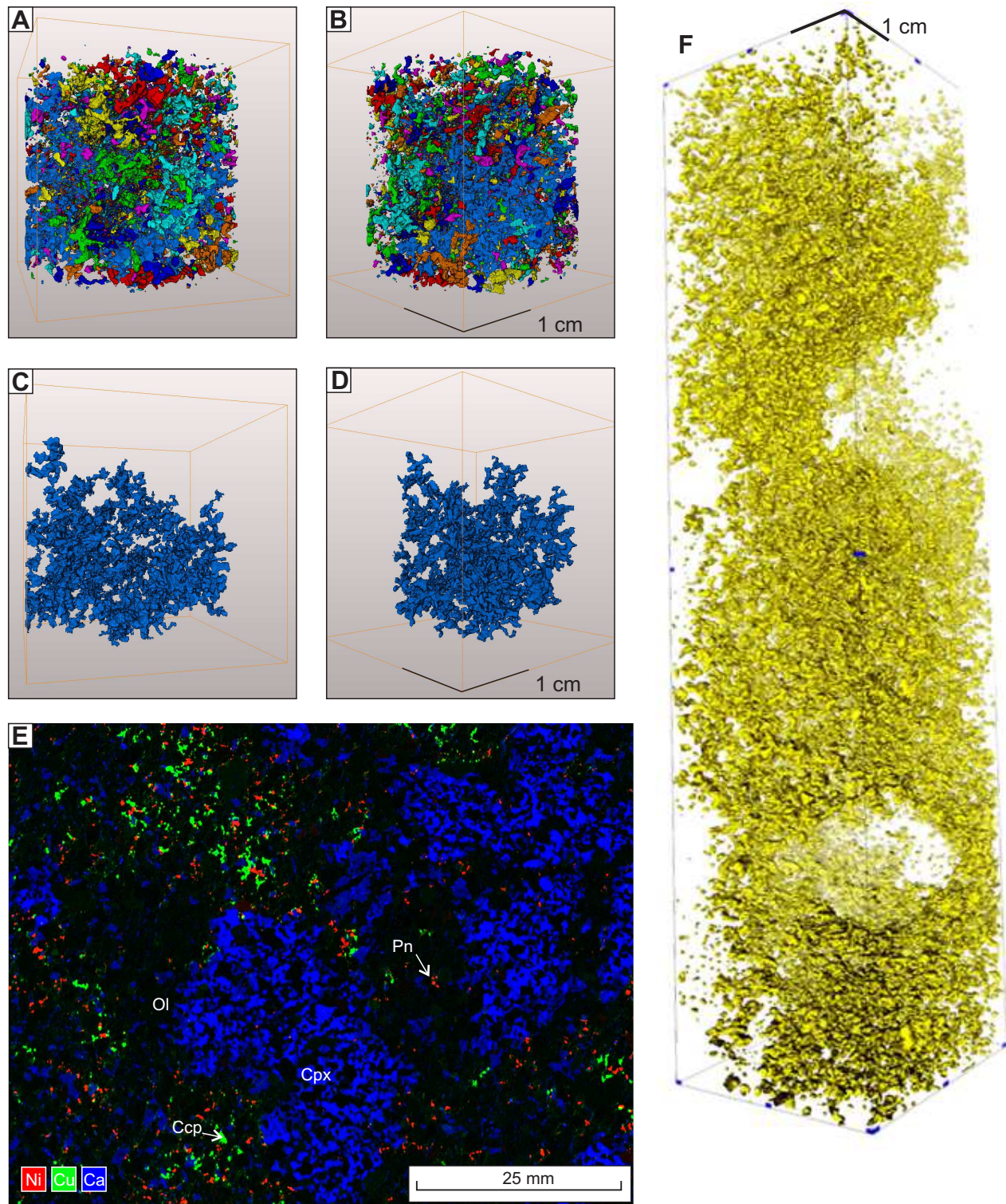


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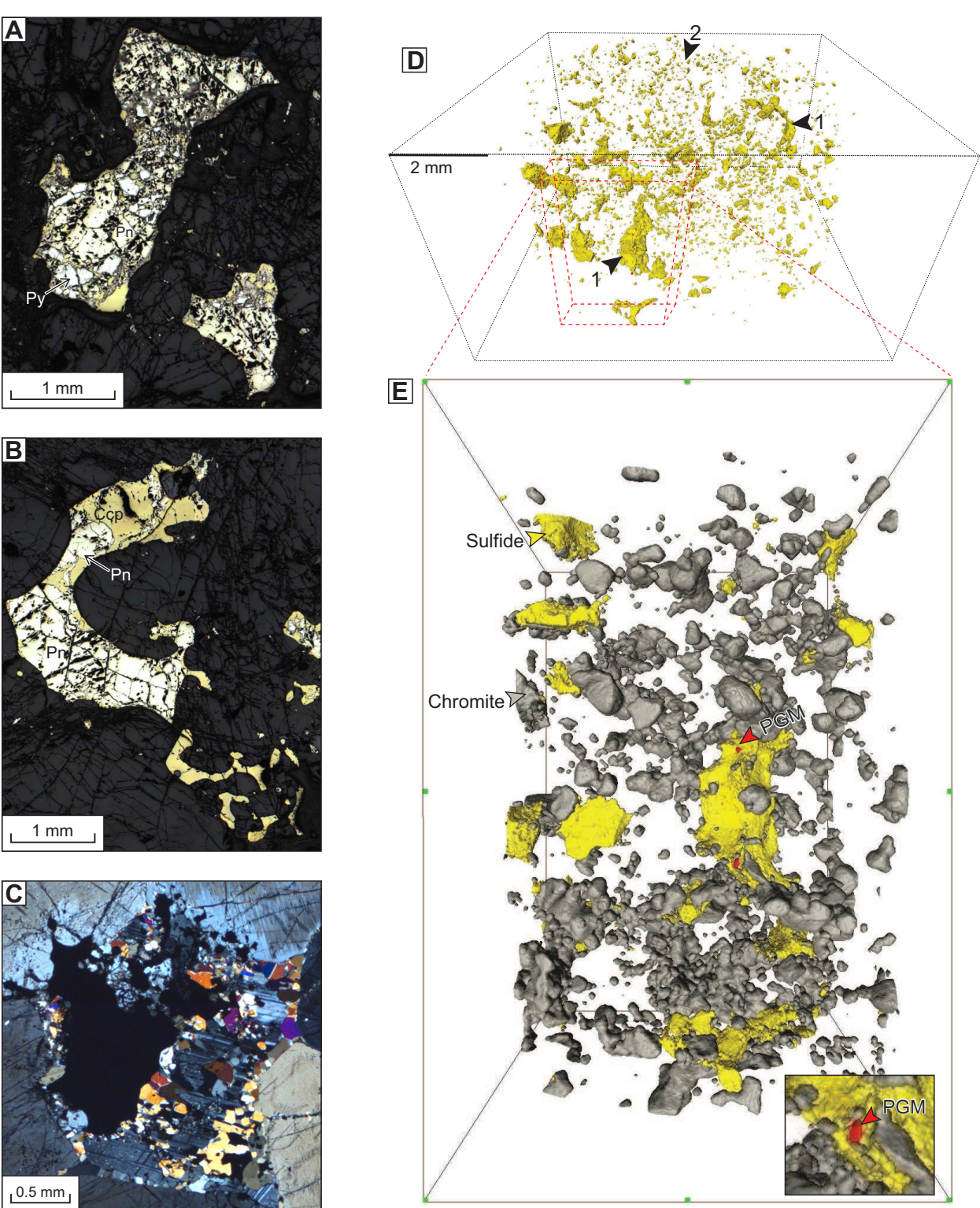


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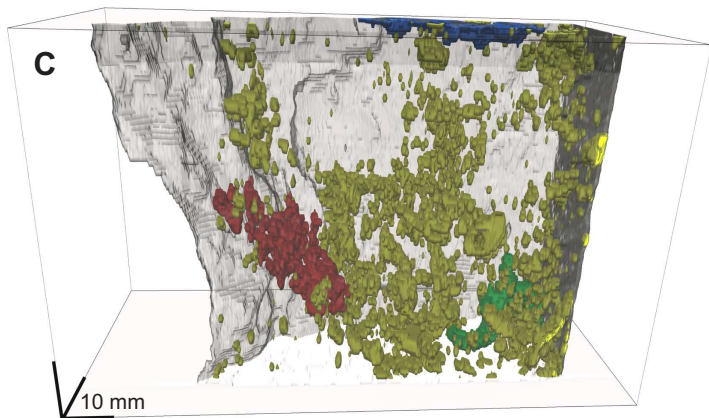
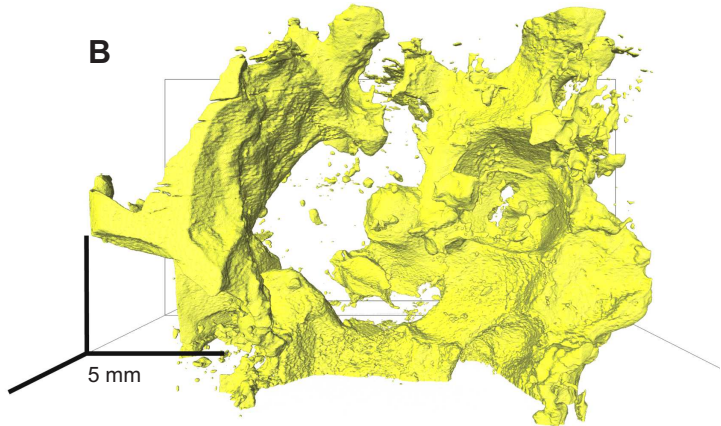
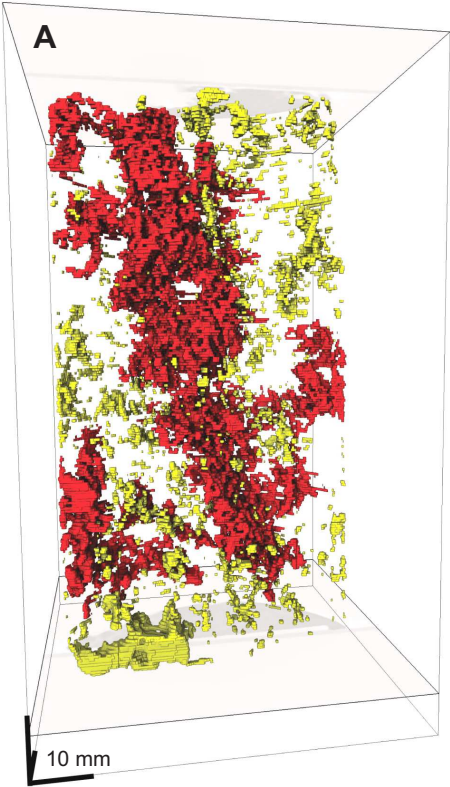
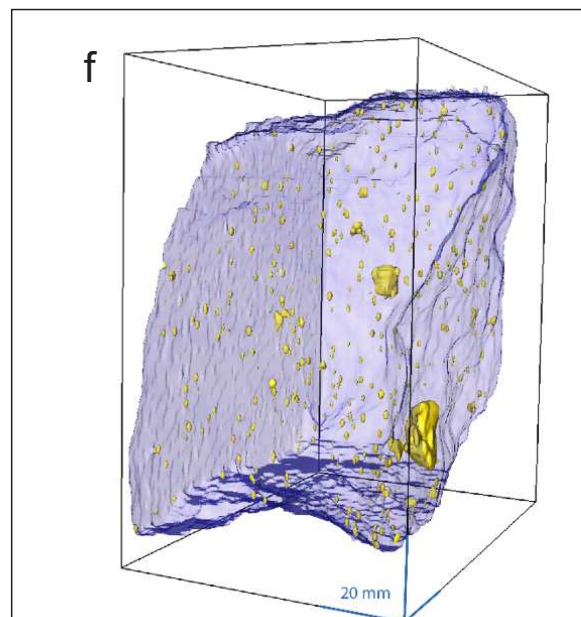
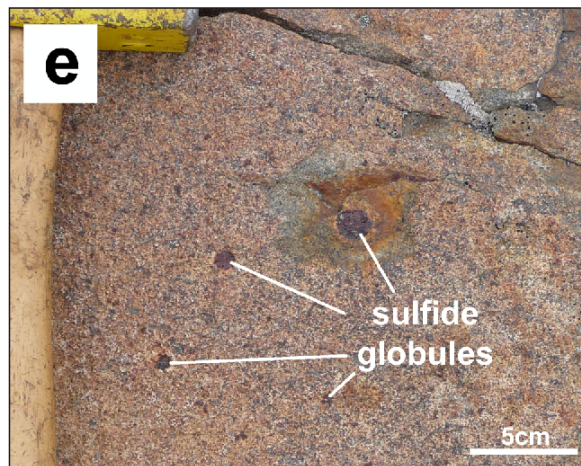
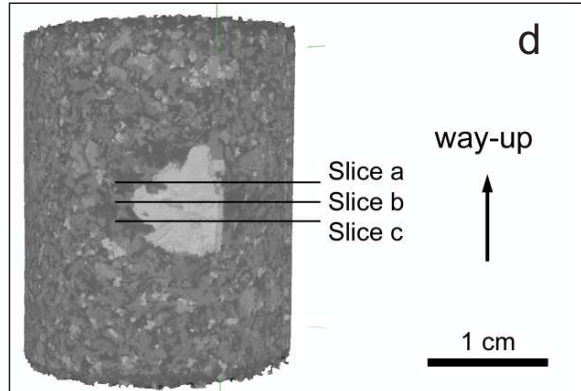
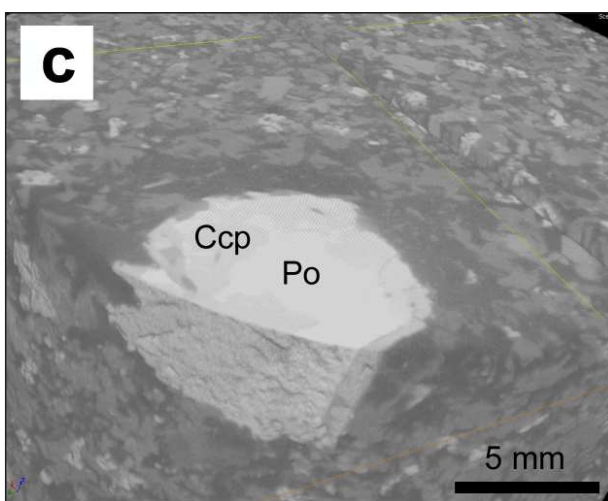
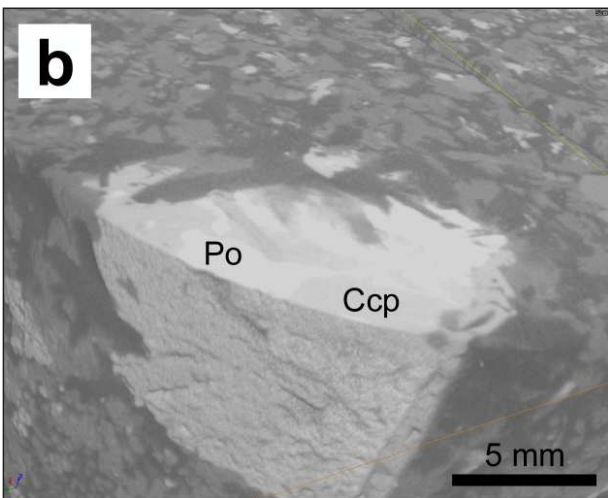
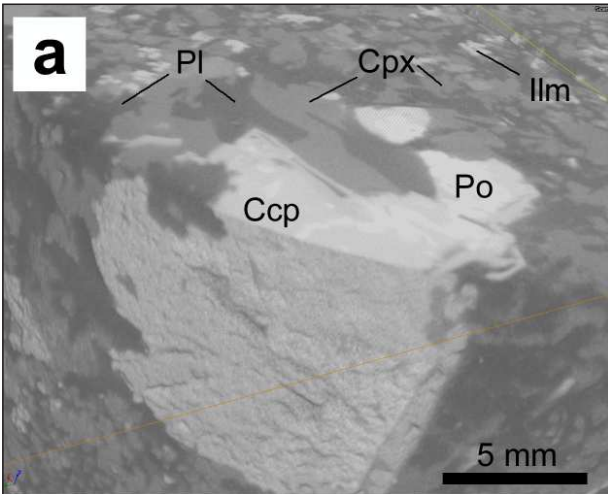
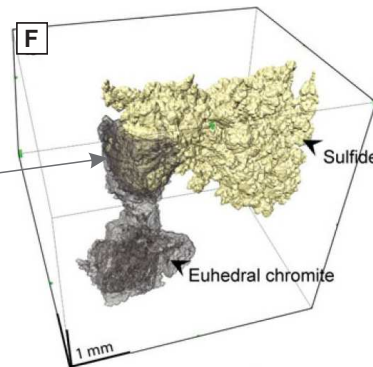
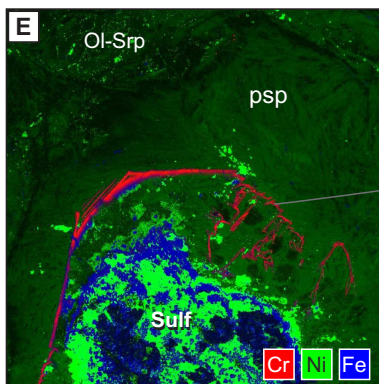
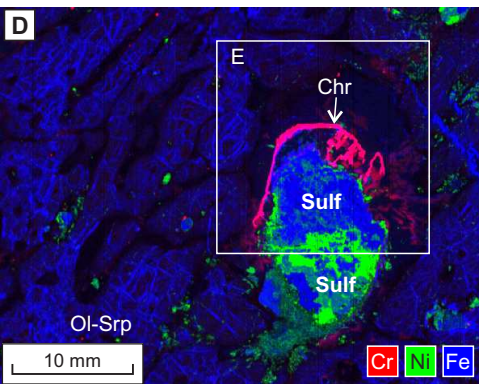
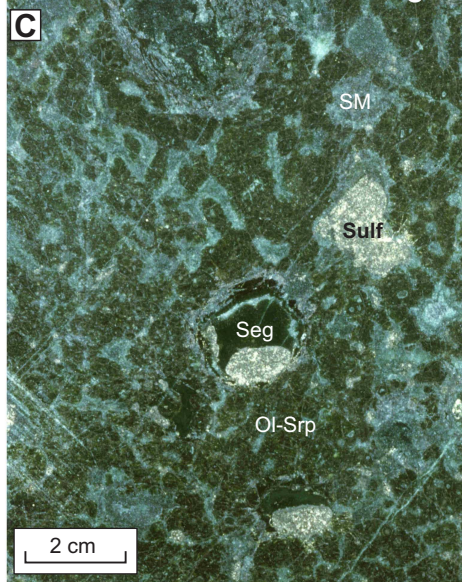
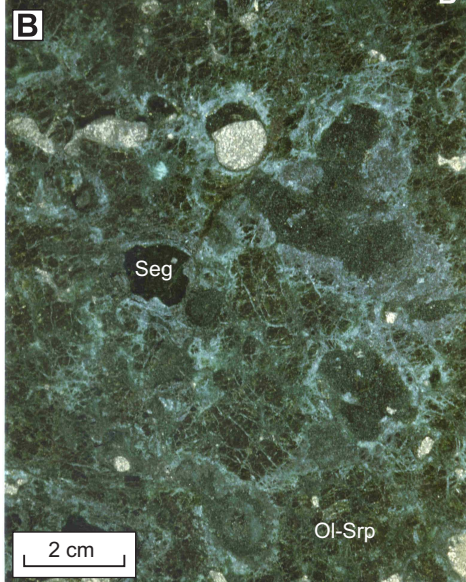
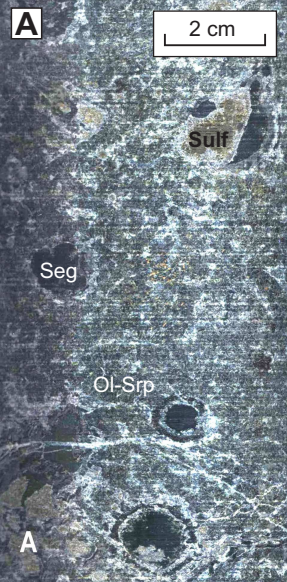
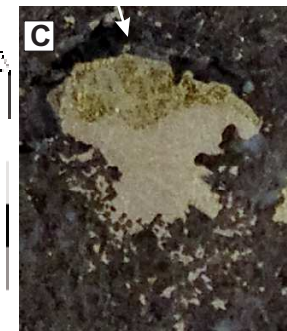
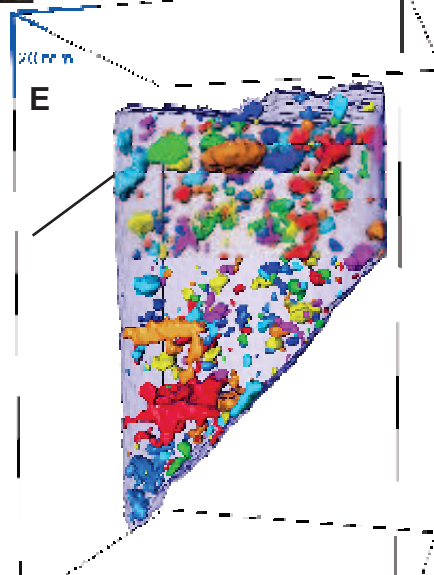
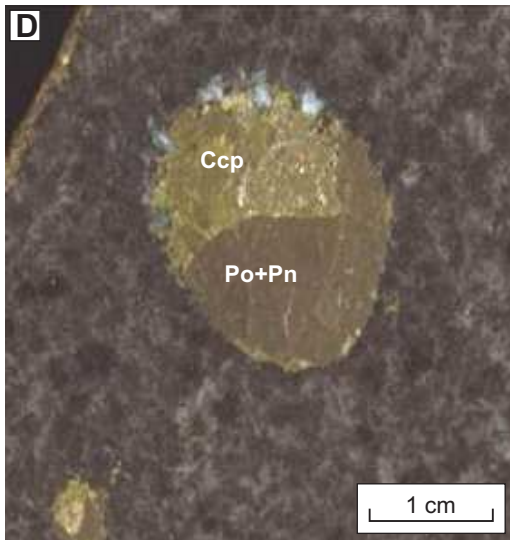
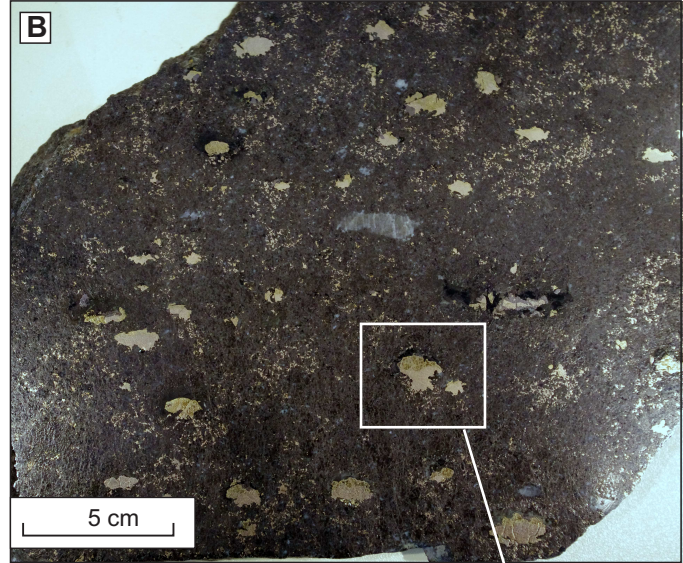
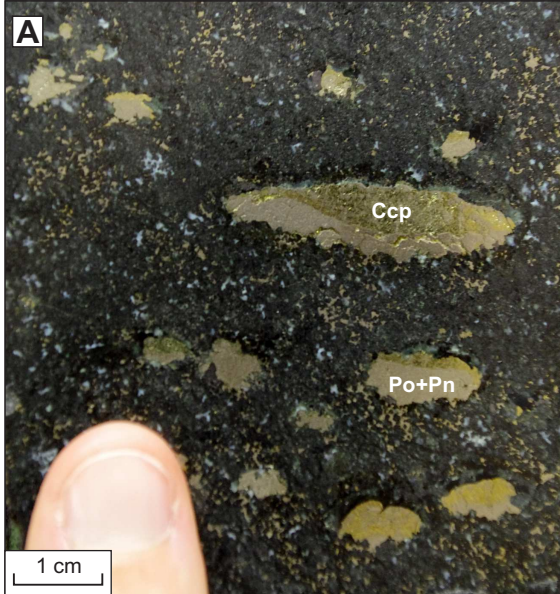
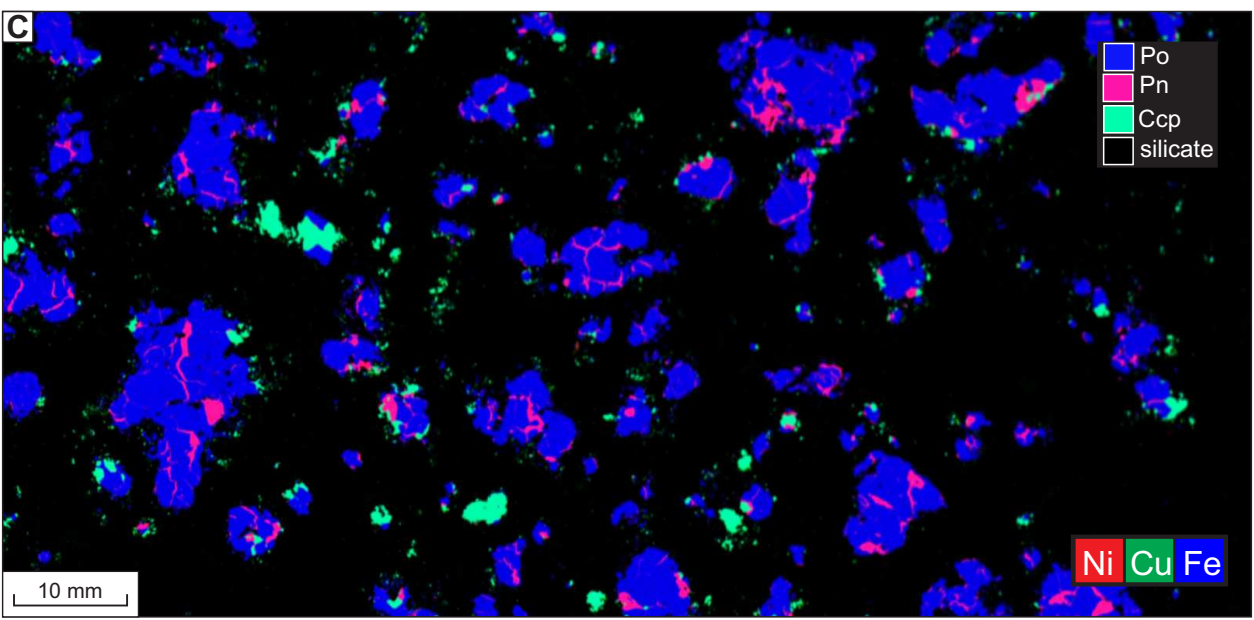
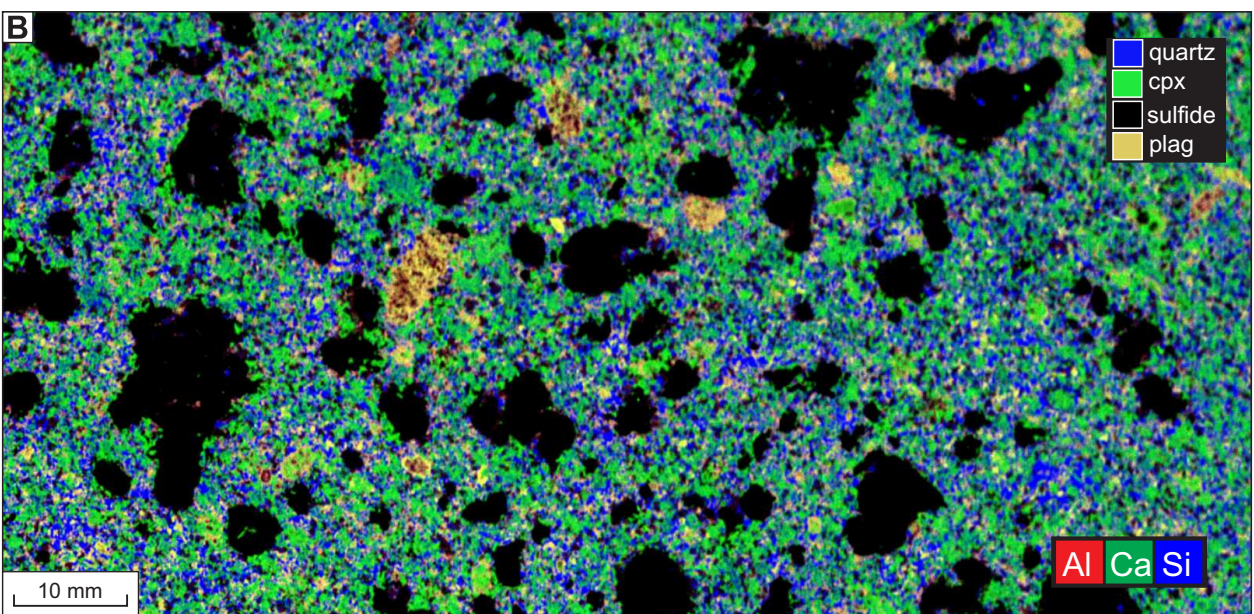
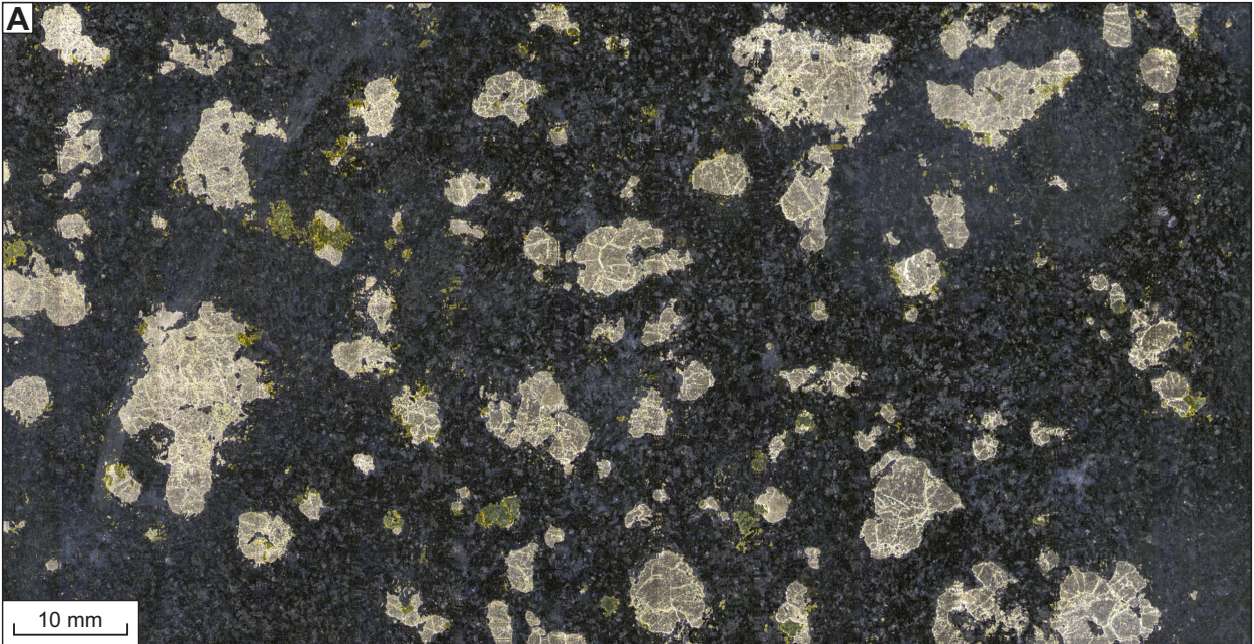


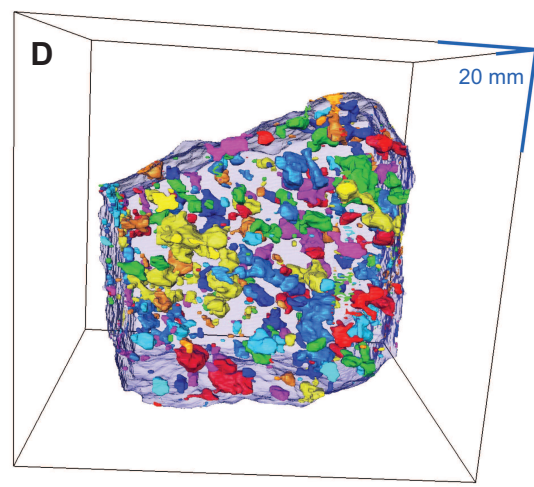
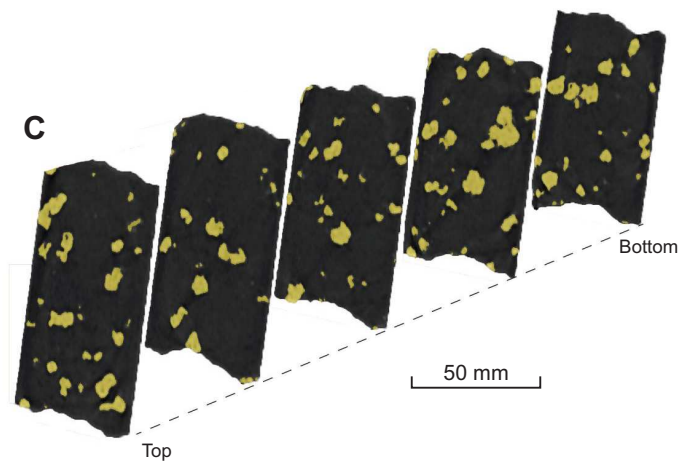
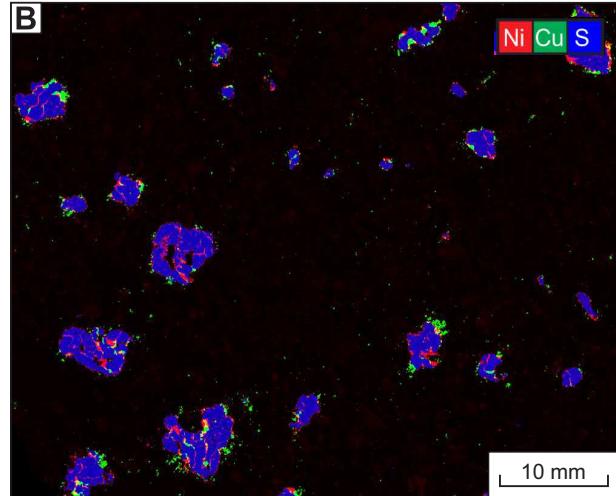
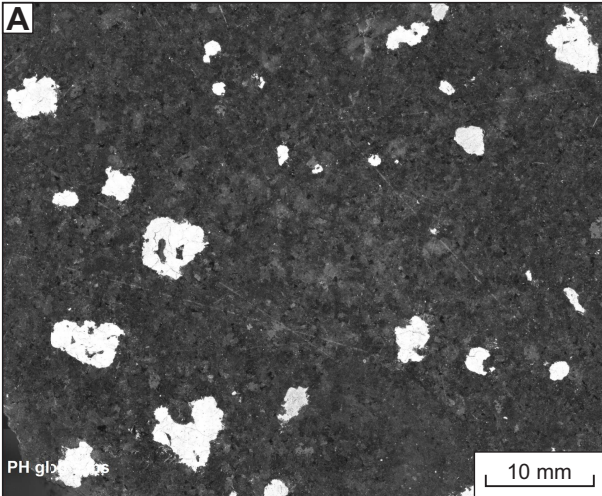
Figure 10

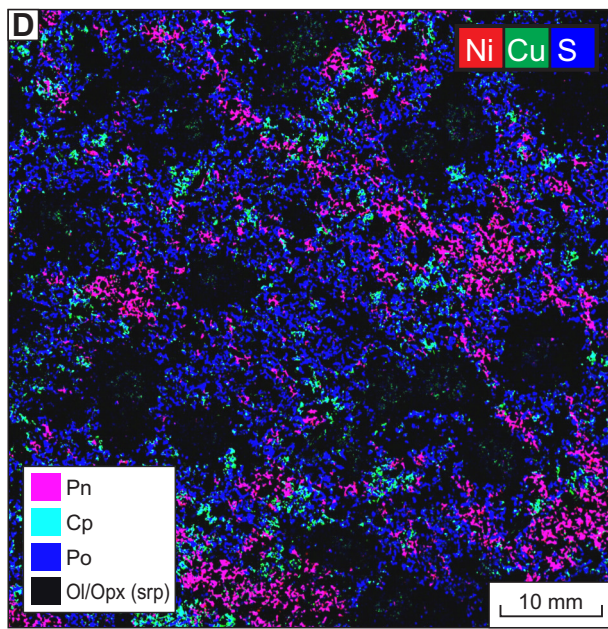
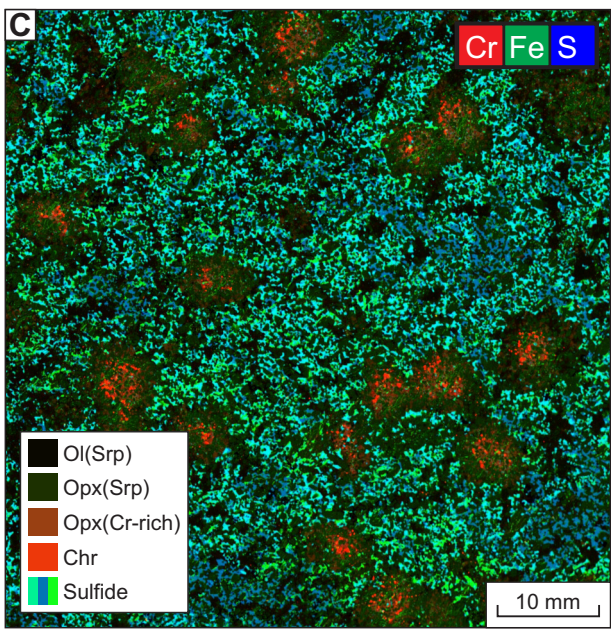
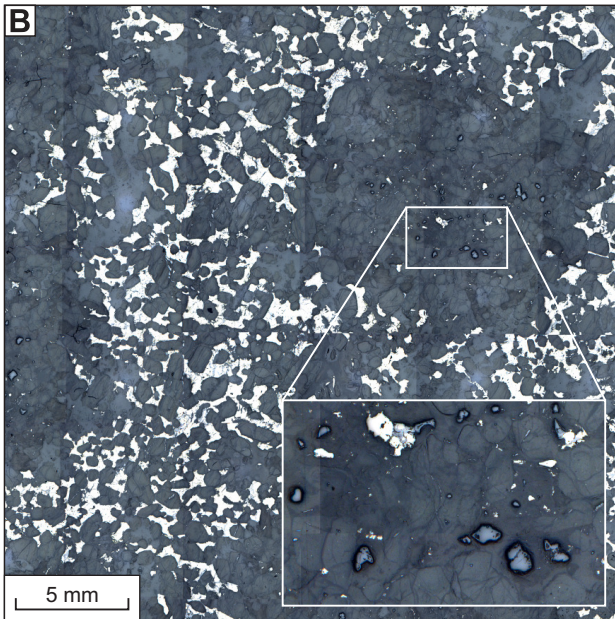
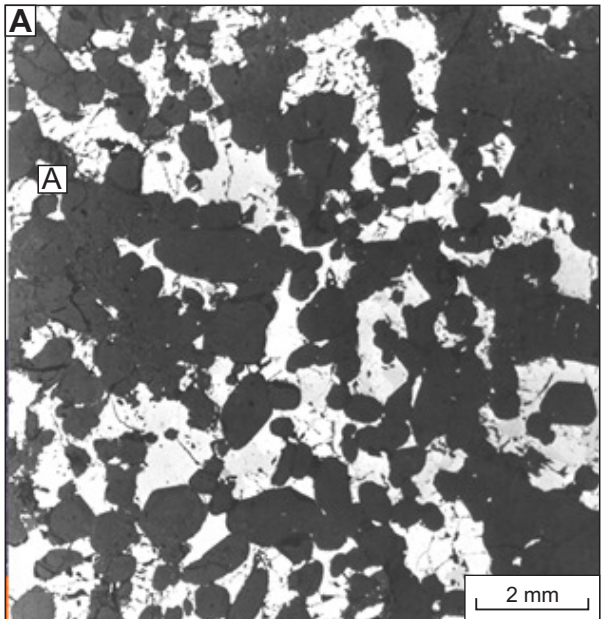


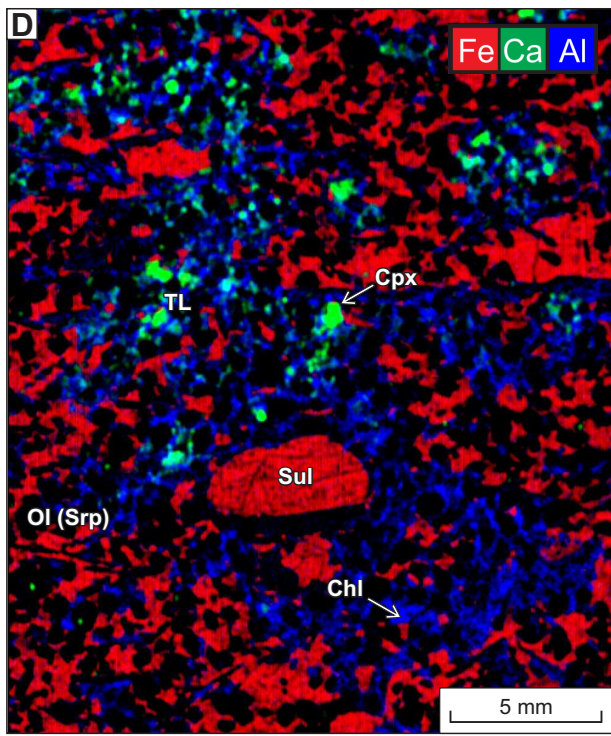
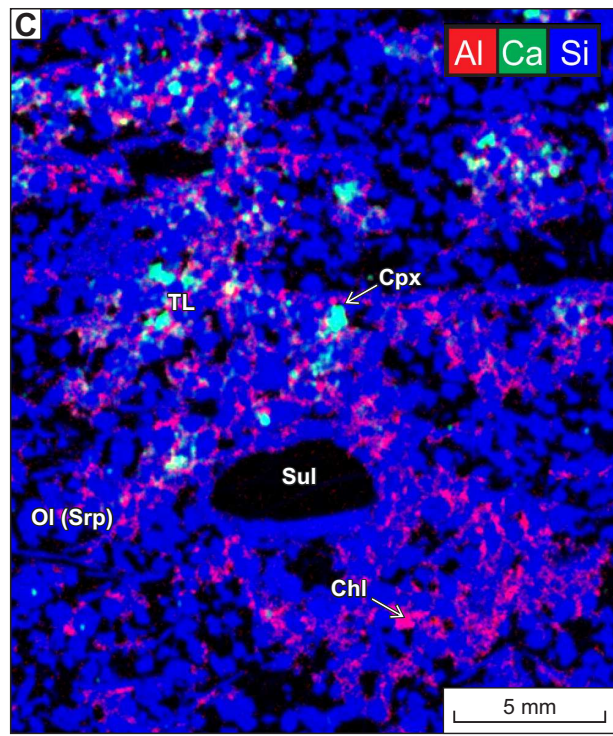
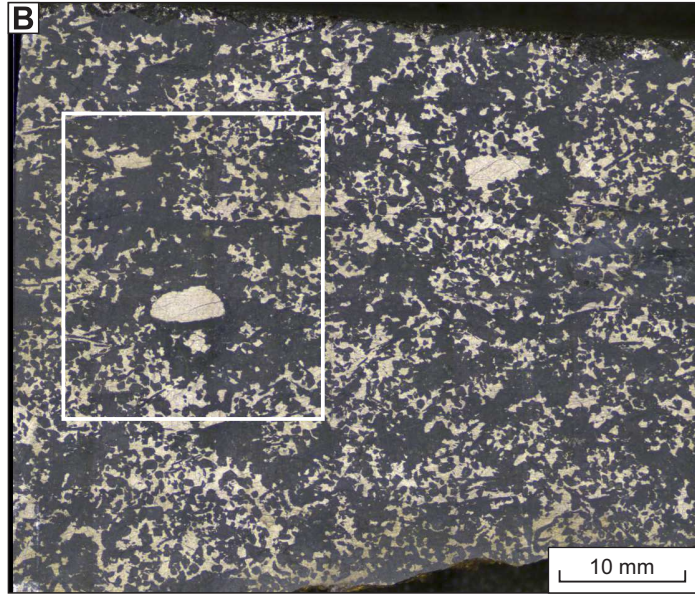
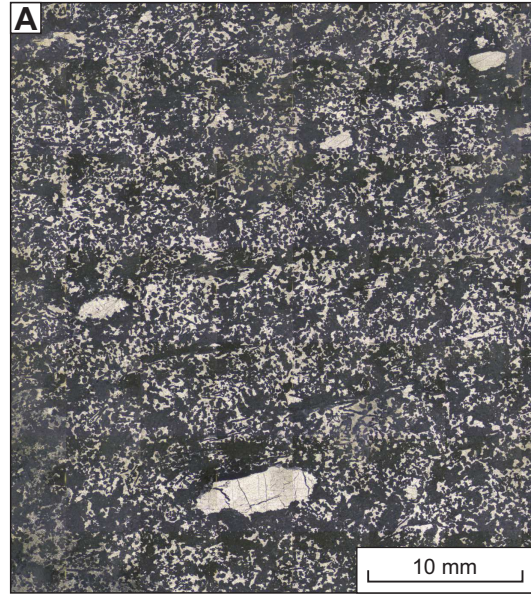


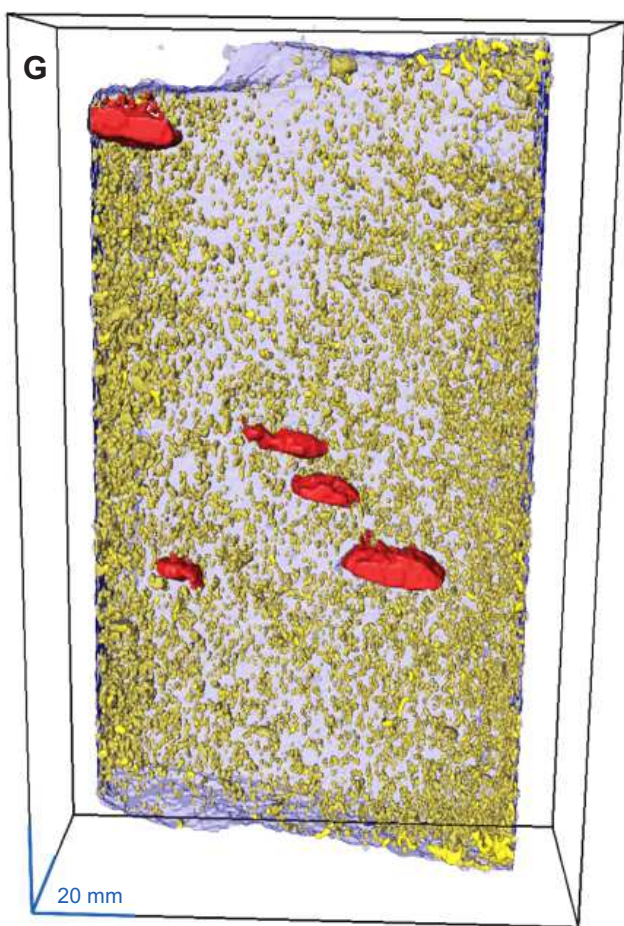
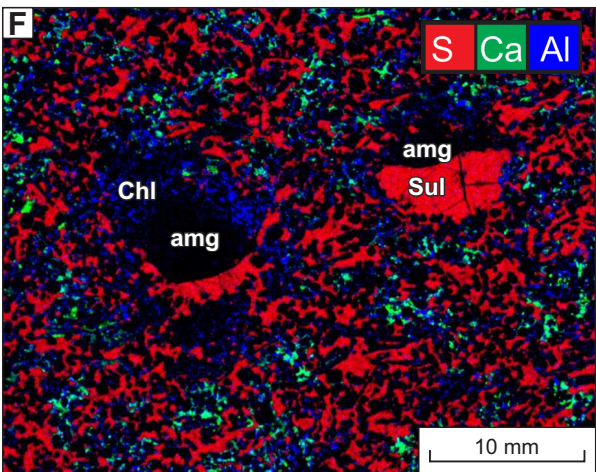
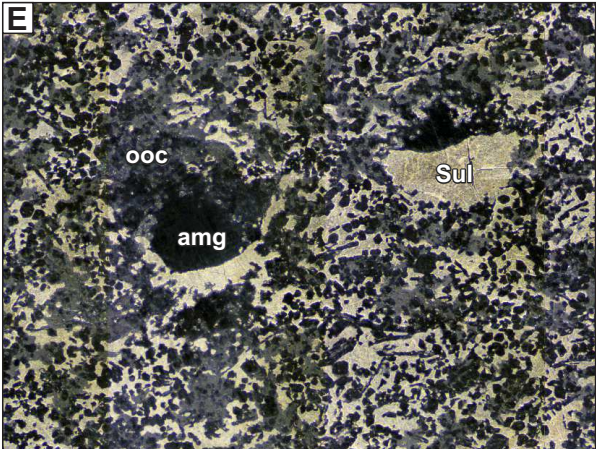


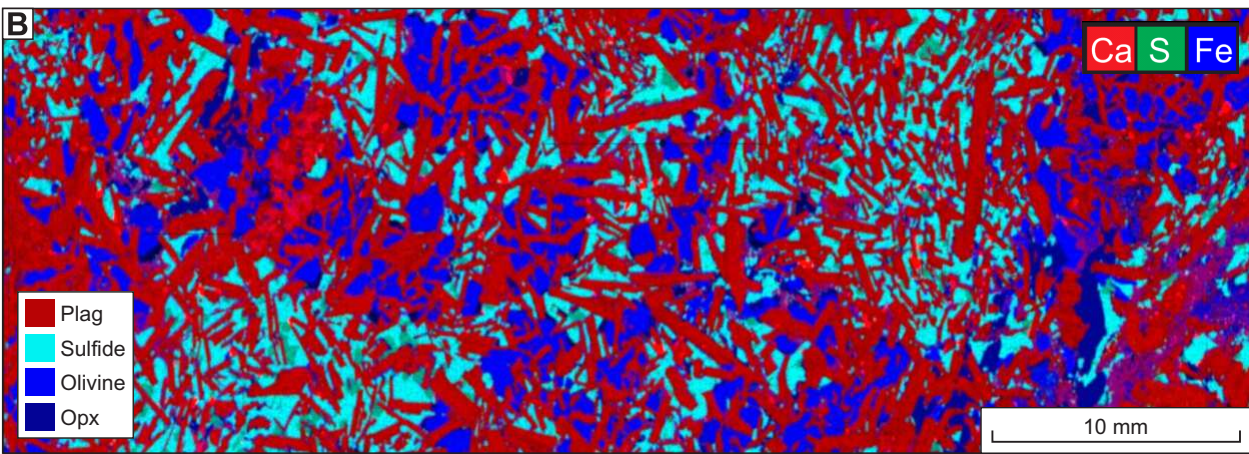
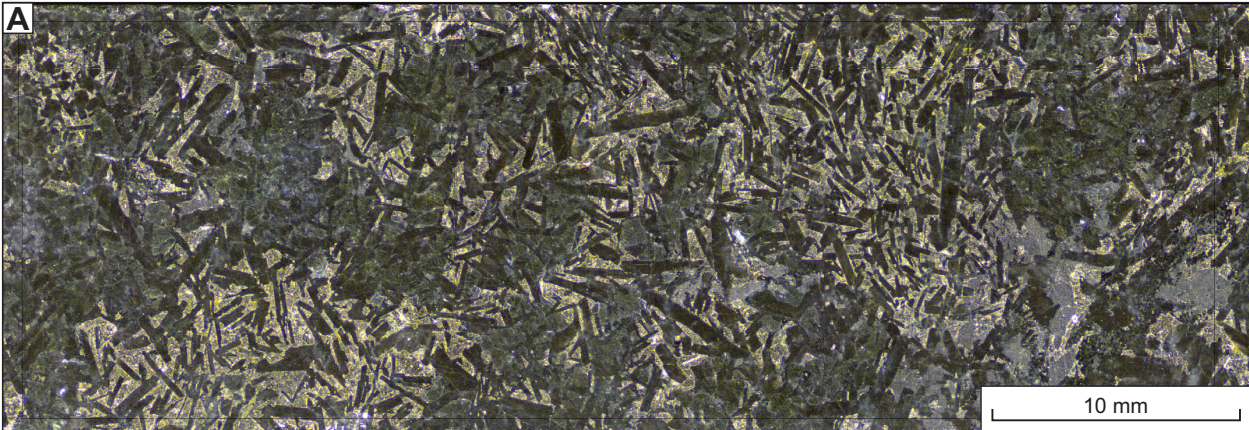


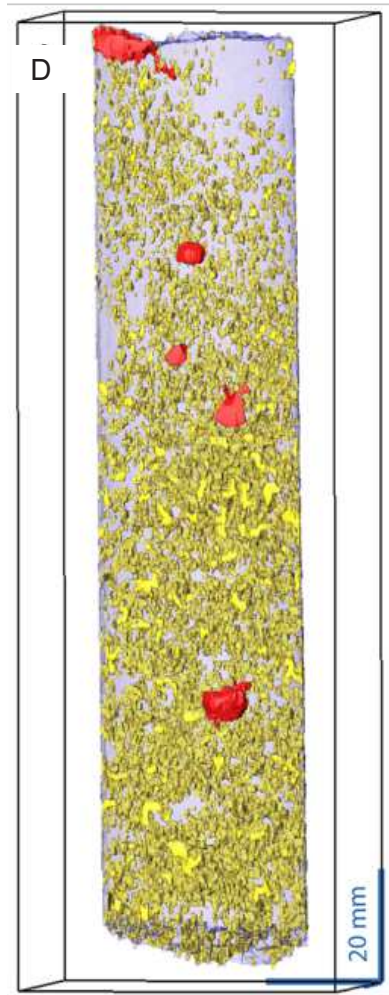
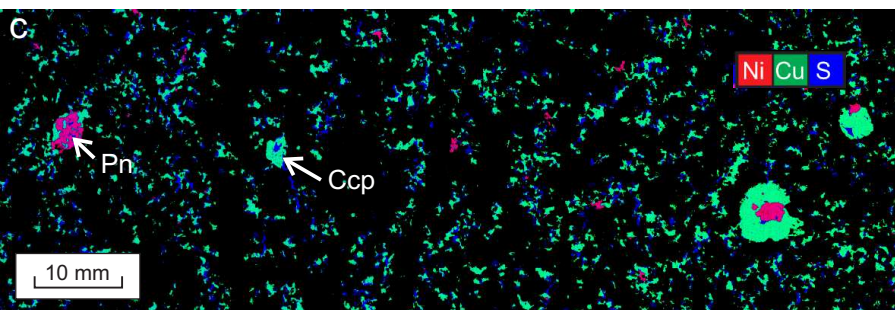
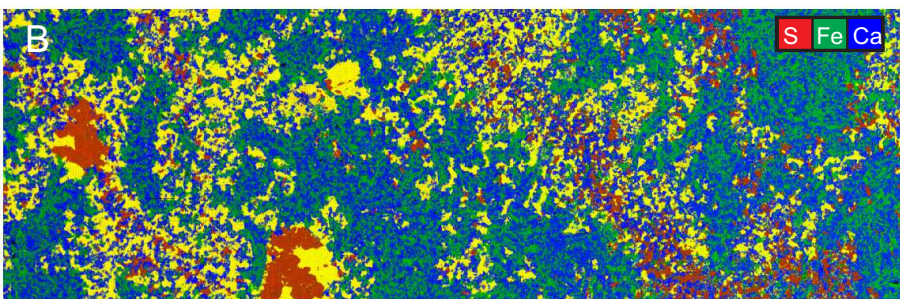
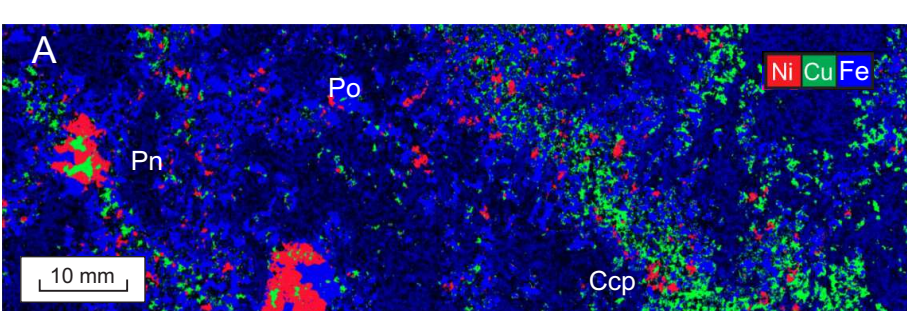


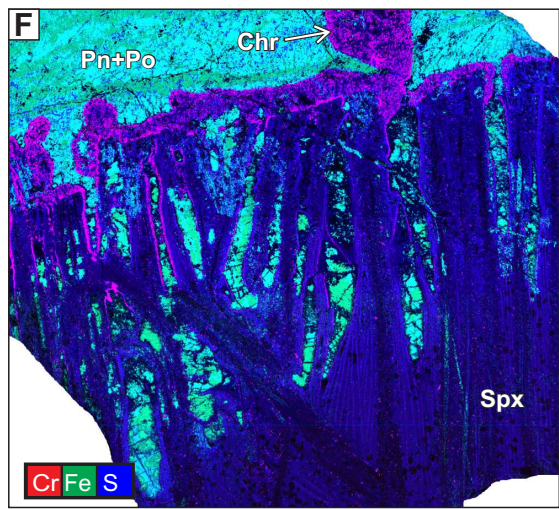
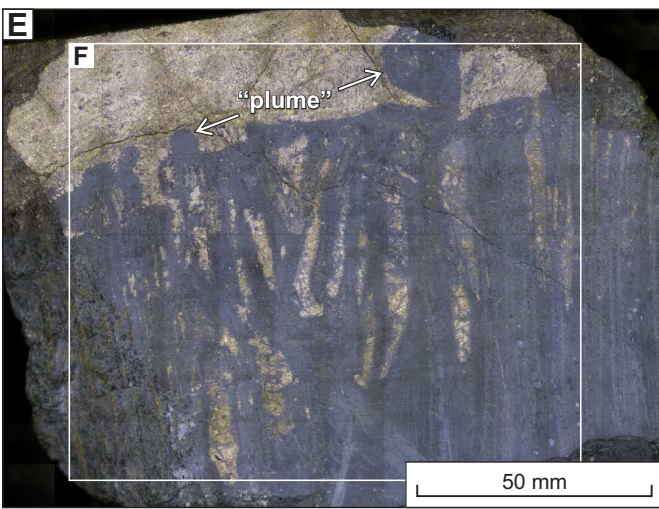
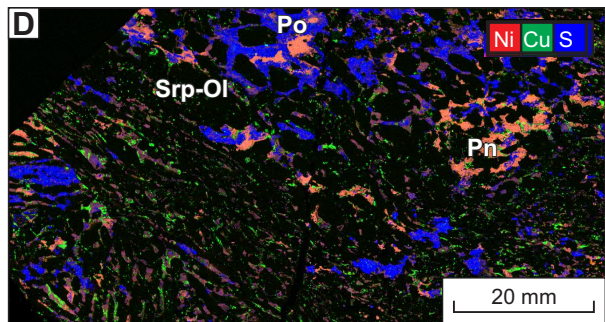
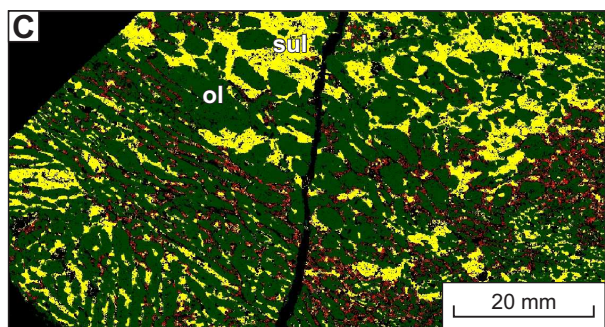
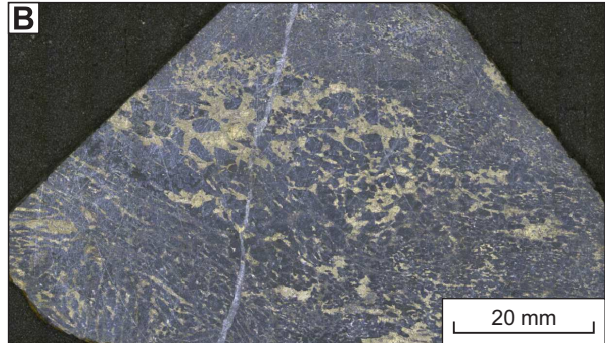
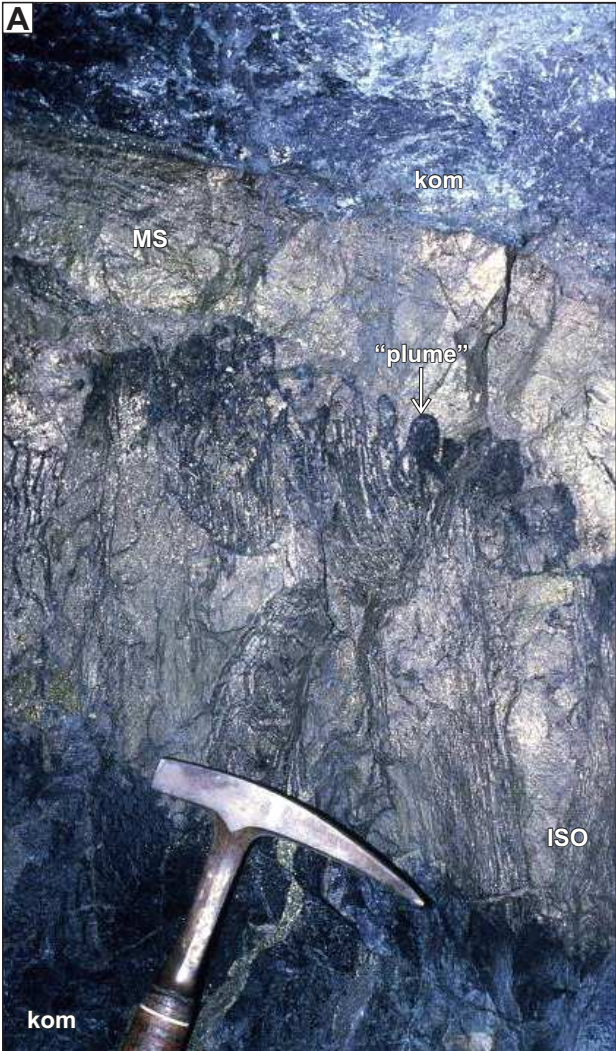


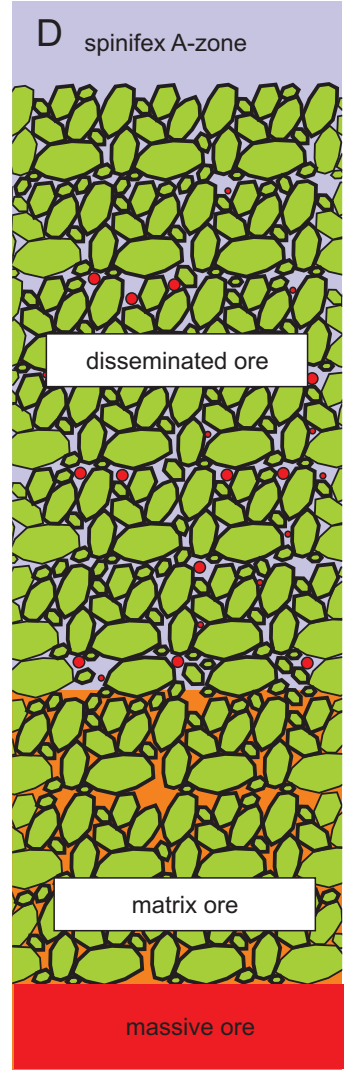
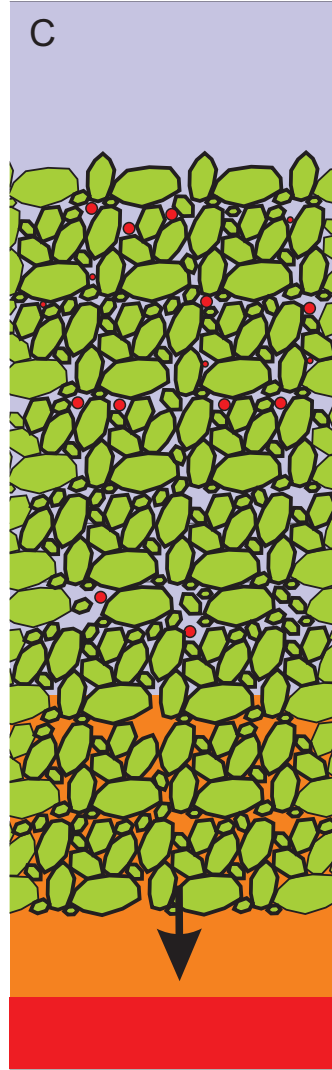
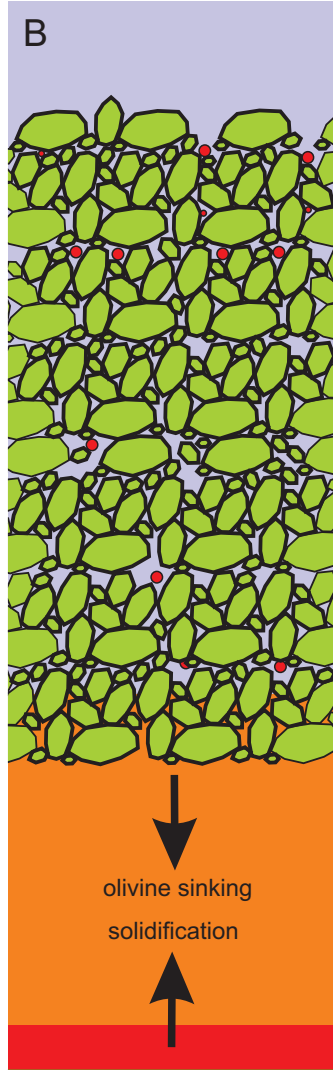
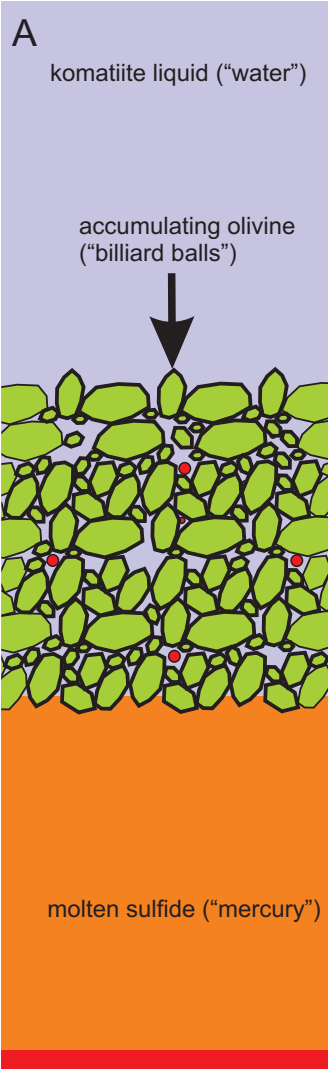


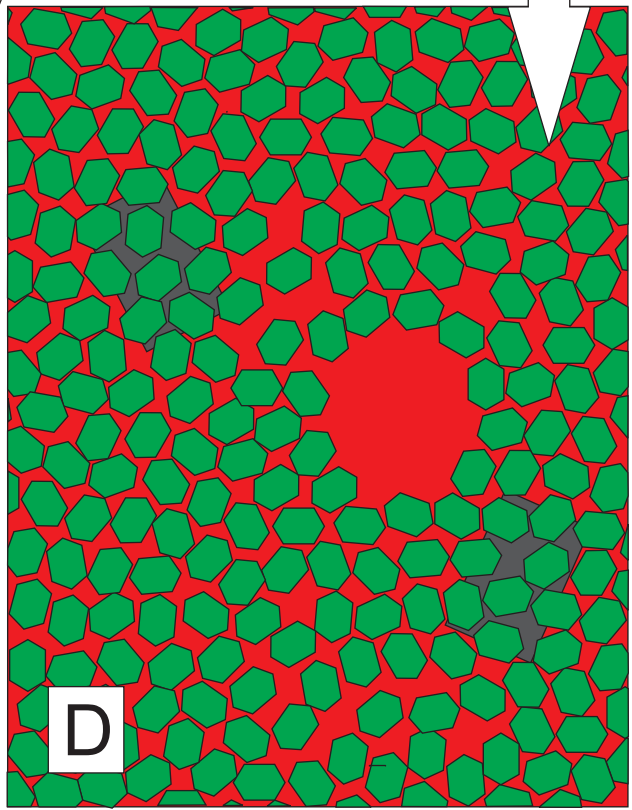
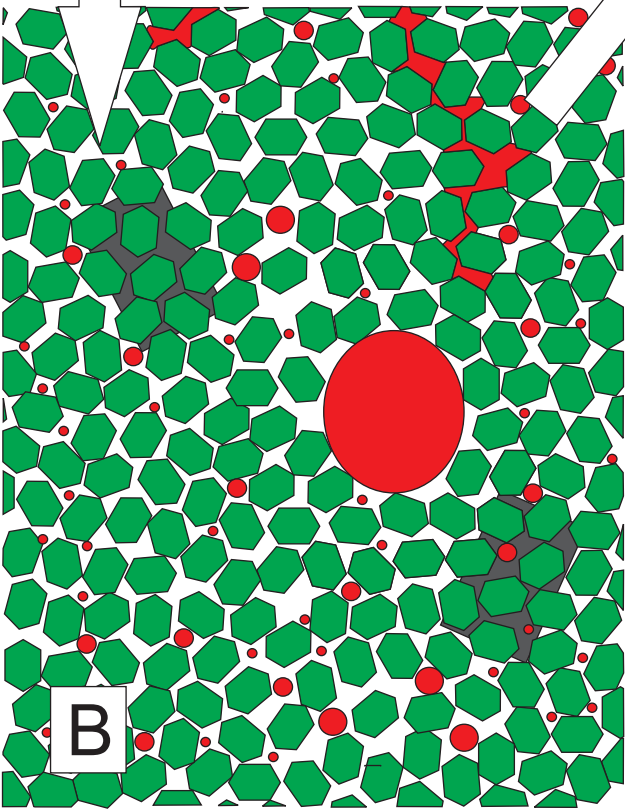
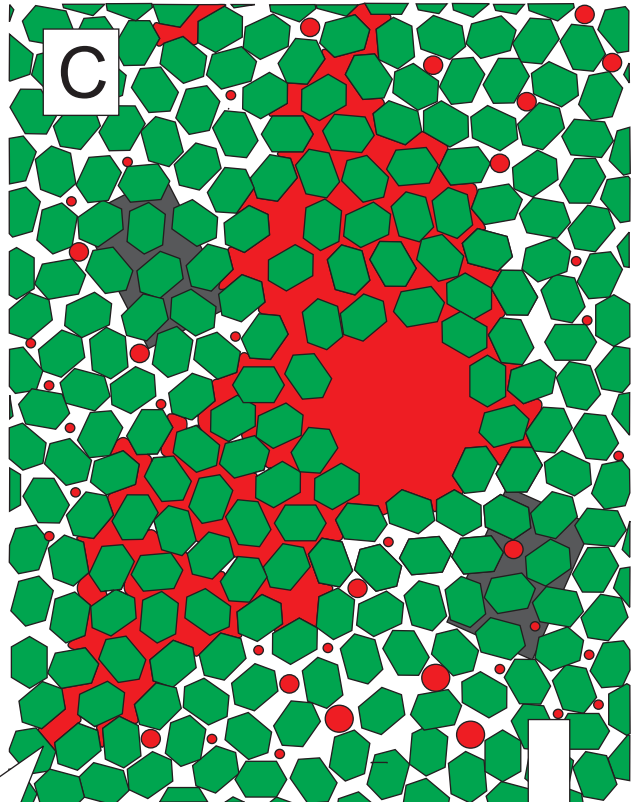
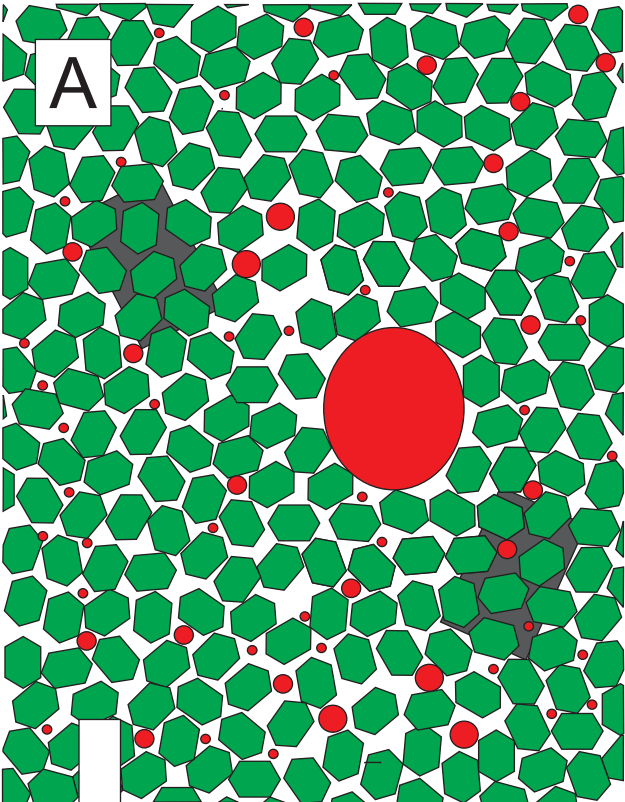


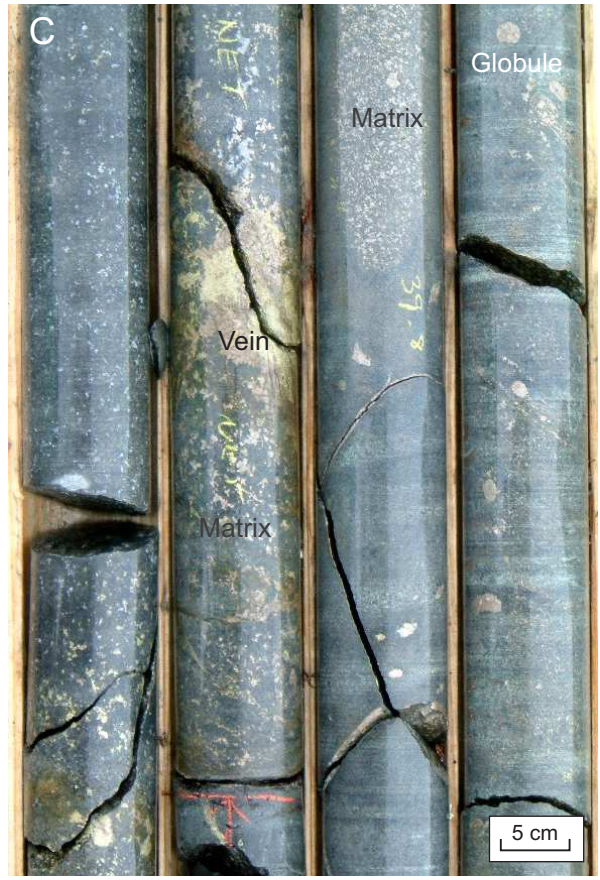












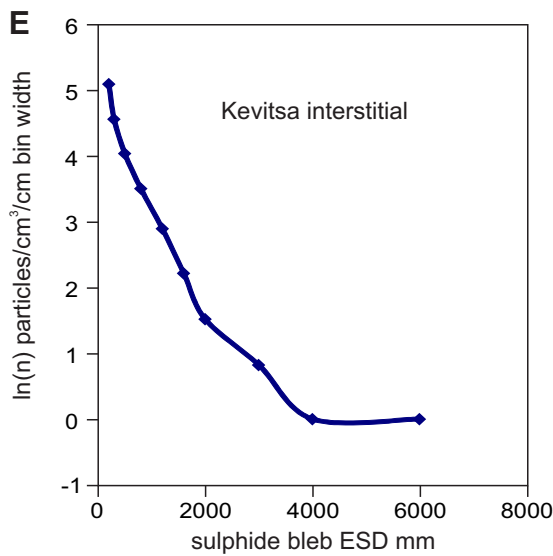
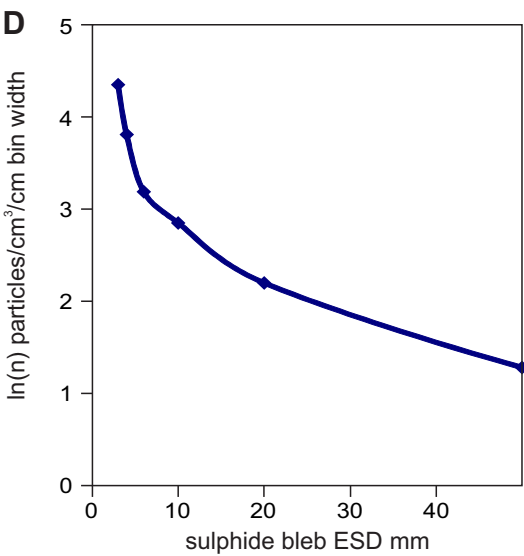
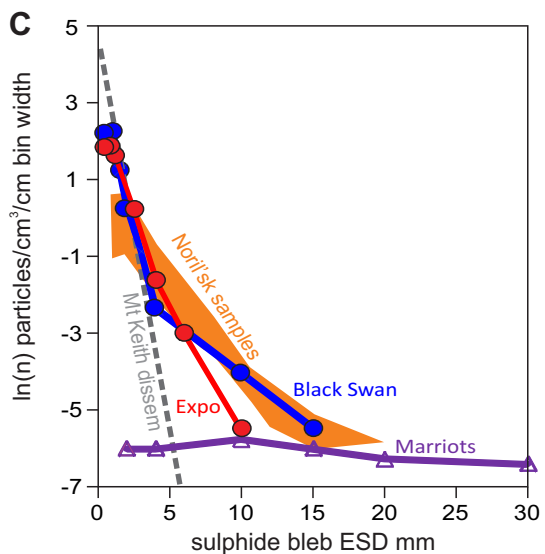
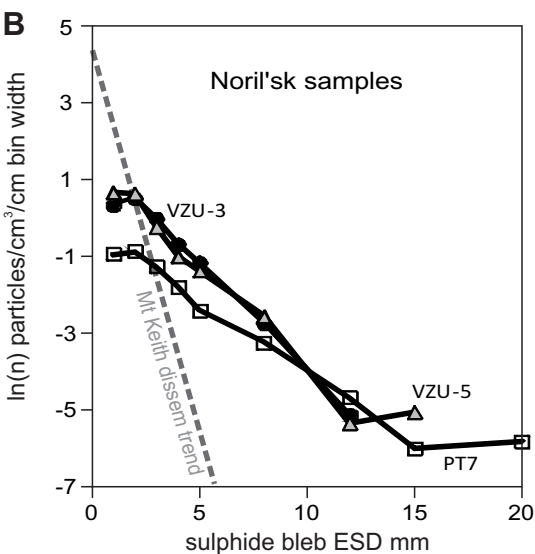
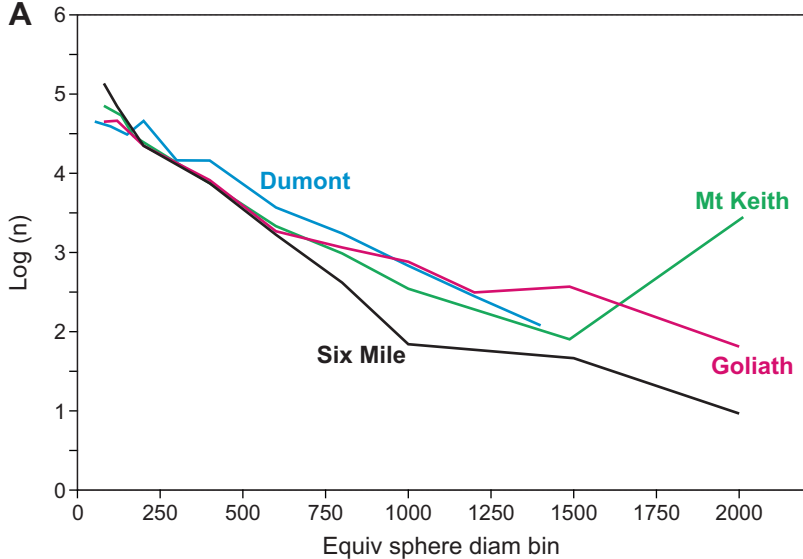


Table 1. Summary of localities and sulfide textures discussed in the text.

Locality/deposit	Type of occurrence	Sulfide textural types dominant	Reference
Alexo, Ontario	Komatiite Ni	Net-textured, patchy and globular net-textured, massive	(Naldrett, 1973; Houle and Leshner, 2011; Houle et al., 2012)
Black Swan, WA	Komatiitic Ni	Disseminated interstitial and globular, some capped globules	(Barnes et al., 2009) (Dowling et al., 2004; Barnes, 2006)
Copper Cliff, Sudbury	Astrobleme-associated Ni-Cu-PGE	Disseminated interstitial and globular, massive	(Lightfoot et al., 1997a; Lightfoot et al., 1997b; Lightfoot and Farrow, 2002) (Naldrett, 1969; Mungall, 2002)
Dumont, Quebec	Komatiitic dunite Ni	Disseminated interstitial	(Sciortino et al., 2015)
Togeda macrodyke, Kangerlussuaq, East Greenland	Disseminated sulfides in dike margin	Disseminated globular (capped)	(Holwell et al., 2012)
Katinniq, Quebec	Komatiite Ni	Net-texture, “leopard” net-texture	(Barnes et al., 1982; Leshner, 2007)
Kevitsa, Finland	Mafic-ultramafic intrusion, disseminated Ni	Disseminated interstitial	(Yang et al., 2013; Santaguida et al., 2015)
Kharelakh and Noril’sk 1	Mafic intrusion, chonolith-style, Ni-	Wide variety from disseminated and	(Czamanske et al., 1992; Czamanske et

intrusions, Noril'sk-Talnakh, Siberia	Cu-PGE	disseminated interstitial to net-textured and massive ores,	al., 1995; Naldrett, 2004; Barnes et al., 2006; Lightfoot and Zotov, 2014; Sluzhenikin et al., 2014)
Langmuir, Ontario	Komatiite Ni	Interspinifex ore	(Green and Naldrett, 1981)
Lunnon, Kambalda, WA	Komatiite Ni	Interspinifex ore	(Groves et al., 1986)
Merensky Reef, Bushveld Complex	Reef-style disseminated PGE	Disseminated interstitial	(Godel et al., 2006; Godel et al., 2010)
Mesamax, Quebec	Komatiite Ni (intrusive)	Patchy and globular net-textured, massive	(Mungall, 2007a)
Mirabela (Santa Rita), Brazil	Mafic-ultramafic intrusion, disseminated Ni	Disseminated interstitial	(Barnes et al., 2011c)
Mount Keith, Western Australia	Komatiitic dunite Ni	Disseminated interstitial	(Barnes et al., 2011a; Godel et al., 2013)
Piaohechuan, China	Mafic-ultramafic intrusion, disseminated Ni	Disseminated globular	(Wei et al., 2015)
Voisey's Bay	Mafic intrusion, Ni-Cu	Net-texture, "leopard" net-texture, massive	(Evans-Lamswood et al., 2000)
Yakabindie (including Goliath), Western Australia	Komatiitic dunite Ni	Disseminated interstitial	(Barnes et al., 2011a; Barnes et al., 2011b; Godel et al.,

			2013)
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Table 1. Summary of characteristics of disseminated and net-textured ore types

<i>Host rock characteristic</i>	Sulfide abundance		
	0-5 % - Disseminated ores	5-40% Patchy Net Textured	40-70% Net-Textured ores
Sulfide-olivine adcumulate - no silicate melt	Disseminated interstitial - low wetting angles, sulfides form weakly connected triple-point channels - e.g. Mt Keith-type komatiitic dunite setting.		Net-textured ores - standard variety, e.g. Kambalda, Katinniq Error! Reference source not found.
Sulfide-olivine orthocumulate - 30-50% silicate melt	Disseminated globular - high wetting angles, sulfides form unconnected or weakly coalesced convex globules - e.g. Black Swan-type komatiitic peridotite setting.	Patchy net-textured ores - standard variety, e.g. Jinchuan	
Sulfide-olivine orthocumulate - 20-50% silicate melt plus amygdales/vesicles	Interstitial capped globular - high wetting angles, sulfides form unconnected spherical globules inside segregation vesicles - e.g. Black Swan-type komatiitic peridotite setting.	Patchy net-texture with capped globules - sulfides form unconnected spherical globules inside segregation vesicles within low-sulfide domains in otherwise net-textured ores - e.g. Alexo	
Poikilitic sulfide-olivine or sulfide-pyroxene orthocumulate with pyroxene oikocrysts	Interstitial disseminated "leopard" variety - e.g. Kevitsa	Patchy net-textured ores - "Leopard" variety, e.g. Jinchuan	"Leopard" net-texture - e.g. Katinniq
Poikilitic sulfide-plagioclase or sulfide-olivine-plagioclase orthocumulate with pyroxene and/or olivine oikocrysts		"Leopard Troctolite" ores - e.g. Voisey's Bay	"Leopard Troctolite" ores - e.g. Voisey's Bay
Non-cumulate, porphyritic or aphyric chilled silicate melt, non-vesicular	Disseminated globular - subspherical sulfide globules in marginal phase rocks, narrow dikes or sulfide-poor flows e.g. Raglan South	Patchy net-texture in pyroxene-rich marginal facies rocks, with or without minor globules - e.g. Raglan South	

<p>Non-cumulate, porphyritic or aphyric chilled silicate melt, vesicular</p>	<p>Disseminated capped globular -spherical sulfide globules with silicate caps in marginal phase rocks - e.g. East Greenland macrodiikes, Uruguay mafic dikes</p>		
<p>Non-cumulate, porphyritic or aphyric chilled silicate melt, overlapping melting range between silicate and sulfide</p>		<p>Disseminated globular - non-spherical blebs with MSS facets e.g. Sudbury Copper Cliff</p>	