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Slow cooling during crystallisation of barred olivine chondrules

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ABSTRACT

Barred olivine (BO) chondrules are small ferromagnesian silicate igneous droplets with unique dendritic textures that are considered to have formed in the early solar system during one or more brief high-temperature episodes, followed by rapid cooling in a gas. Rapid cooling rates of 100–7200 °C/h during chondrule formation have been proposed based on experiments attempting to reproduce BO crystal textures. However, the BO texture has never truly been reproduced under such rapid cooling conditions. Here, we experimentally show that true BO textures can be produced either after rapid cooling (>50 °C/h) following by reheating step or by cooling rates slower than 10 °C/h. Regardless of the thermal history considered, the chemical compositions of glass inclusions trapped within olivines of BO chondrules imply a final slow cooling rate one to two orders of magnitude below previous estimates. Such slow cooling rates are consistent with those estimated for plagioclase-bearing porphyritic chondrules and magmatic type-B Ca-Al-rich inclusions, suggesting that slow cooling rates are common to all similar chondritic objects.

Keywords: chondrule, olivine, dendrite, crystal growth, glass inclusion.

27 **1. Introduction**

28 Chondrules are the principal constituents of the least altered chondritic meteorites;
29 they are small ferromagnesian silicate igneous droplets considered to have formed in the early
30 solar system during one or more brief high-temperature episodes followed by rapid cooling in
31 a gas (Jones et al., 2000; Rubin, 2000 and references therein). A key parameter in chondrule
32 formation models is the cooling rate, which is generally constrained by experimental results
33 (Connolly and Desch, 2004; Desch et al., 2012; Jones et al., 2018) and varies greatly among
34 chondrule types. Porphyritic chondrules were not initially completely molten and their
35 resultant textures were essentially controlled by the presence of relict crystals or crystal nuclei
36 in the melt (Lofgren, 1989; Lofgren and Russell, 1986). Therefore, cooling rates spanning
37 0.5–1000 °C/h are generally proposed to replicate porphyritic textures (see Jones et al., 2018
38 for a recent compilation). Only plagioclase-bearing porphyritic chondrules seem to impose
39 very slow cooling rates (1 °C/h) at the end of crystallisation (Wick and Jones, 2012). Among
40 non-porphyritic chondrules, it is well established that barred olivine (BO) chondrules were
41 initially fully molten (Hewins and Radomsky, 1990); BO crystallisation during cooling did
42 not require triggering by collisions between molten chondrules and mineral dust, as it was
43 generally proposed to explain radial non-porphyritic chondrules (Connolly and Hewins,
44 1995), even if radial pyroxene textures can also be obtained by rapid cooling after an initial
45 step of total melting (Hewins et al., 1981). Thus, only BO chondrules can be used without
46 ambiguity to reliably constrain non-porphyritic chondrule cooling rates.

47 BO chondrules are droplet shaped, contain parallel bars of olivine set in glass, and are
48 typically rimmed by an olivine shell (Fig. 1; Weisberg, 1987). Olivine bars and rim are
49 optically continuous and therefore correspond to a single crystal. In three dimensions, the bars
50 correspond to platy crystals that are attached to the olivine shell in a comb-like texture
51 (Gooding and Keil, 1981; Noguchi, 2002; Tsuchiyama et al., 2000). This definition

52 corresponds to ‘classic’ BO chondrules; ‘multiple’ BO chondrules comprise several grouplets
53 of parallel bars/plates, with each grouplet corresponding to an individual crystal (Weisberg,
54 1987). Although these parallel bars/plates display smooth surfaces, this peculiar texture has
55 generally been termed a ‘dendritic’ bar or plate texture (Lofgren and Lanier, 1990;
56 Tsuchiyama et al., 2004); only recently have high-resolution cathodoluminescence images
57 confirmed the presence of true dendritic textures in the cores of these olivine bars (Libourel
58 and Portail, 2018). Nonetheless, previous dynamic crystallisation experiments attempting to
59 reproduce BO textures at 1 atm have explored a vast range of rapid cooling rates spanning
60 100–7200 °C/h (Lofgren, 1989; Lofgren and Lanier, 1990; Radomsky and Hewins, 1990;
61 Connolly and Hewins, 1991; Kennedy et al., 1993; Tsuchiyama et al., 2000). These
62 experiments reproduced well the sets of parallel olivine dendrites, but, with rare exceptions,
63 failed to reproduce the characteristic external rims of BO chondrules (Lofgren and Lanier,
64 1990; Radomsky and Hewins, 1990).

65 Experiments employing levitation systems to avoid heterogeneous nucleation on the
66 surface of the sample holder have produced bars and rims at even faster cooling rates of $36 \times$
67 10^4 – 10^5 °C/h (Tsukamoto et al., 2001). However, these experiments used pure forsterite
68 composition, and the crystal growth rates obtained are almost one order of magnitude faster
69 than those measured in more complex compositional systems (Jambon et al., 1992). In
70 contrast, Nagahara (1996) reproduced the BO texture isothermally (i.e., without cooling)
71 under vacuum to determine evaporation kinetics in the simple MgO-SiO₂ system. Tsuchiyama
72 et al. (2004) also reproduced the BO texture (rim and bars) under vacuum from a complex
73 analogue chondrule composition, but at relatively rapid cooling rates (500–1000 °C/h).
74 Therefore, excluding the isothermal experiments of Nagahara (1996) because the composition
75 was probably too simple to allow growth controlled by chemical diffusion, all previous
76 experiments (under vacuum, at 1 atm, or using levitation) suggest that the BO texture results

77 from rapid cooling rates (10^2 – 10^6 °C/h). However, Tsuchiyama et al. (2004) noted that *true*
78 BO textures have never been reproduced because experimental olivines always display a
79 marked dendritic morphology whereas bars in natural BO chondrules are generally smooth.
80 Moreover, glass inclusions in natural olivine bars display round or ovoid shapes (Varela et al.,
81 2006), not the ‘negative’ dendritic crystal shapes produced in experiments. Therefore, it was
82 suggested that natural BO textures may result from rapid cooling following by annealing at
83 high temperature (Tsuchiyama et al., 2004). However, it has never been considered that BO
84 textures were simply produced at slow cooling rates. Therefore, we here experimentally tested
85 both a large range of cooling rates (5–1000 °C/h) and the annealing hypothesis, and our
86 results show that BO chondrules formed under slow cooling rates.

87

88 **2. Methods**

89 The chemical compositions of natural BO chondrules vary greatly, suggesting that
90 composition is not the principal parameter controlling this texture. Therefore, we used a
91 simplified chondritic composition and added Al, Ca, and Fe^{3+} to diminish the MgO content
92 and thus the liquidus temperature, as proposed by Dehart and Lofgren (1996). The $\text{Al}_2\text{O}_3/\text{CaO}$
93 ratio in our composition (1.42) is between that used to simulate CI-like materials (1.55) by
94 Cohen et al. (2004) and that proposed by Anders and Grevesse (1989) for CI chondrites
95 (1.26).

96 The starting glass material was prepared from a mixture of reagent-grade oxides (38
97 wt.% SiO_2 , 10 wt.% Al_2O_3 , 7 wt.% CaO , 18 wt.% MgO , 27 wt.% Fe_2O_3), melted in a
98 platinum crucible at 1650 °C (about 200 °C above the liquidus temperature in oxidising
99 conditions, $T_{\text{liq}} = 1440$ °C, as determined by isothermal experiments) for 1 h in air, and
100 quenched in water. The glass obtained was then ground to a powder in an agate mortar and
101 pestle, loaded into a carbon crucible within an alumina crucible, and hung near the end of a

102 ceramic rod in the hot spot of a Nabertherm vertical furnace. The samples were introduced
103 directly into the preheated furnace, and the air volume inside the alumina tube of the furnace
104 was then evacuated by a primary pump at the bottom of the furnace. Pressure was monitored
105 using a gauge positioned in the upper part of the alumina tube. Experiments were conducted
106 under vacuum ($P < 10$ Pa) to allow evaporation of the moderately volatile species Fe, Mg,
107 and Si. The carbon crucible was used to form nearly spherical samples by exploiting the poor
108 wetting between silicate liquids and graphite (Tsuchiyama et al., 2004; Faure et al., 2006).

109 We used three thermal protocols in this study.

110 The first corresponded to isothermal experiments to ensure that all dynamic
111 crystallisation experiments (second protocol, below) began well above the liquidus
112 temperature. Three sets of isothermal experiments were performed at 1450 °C (i.e., 10 °C
113 above the oxidising liquidus temperature previously determined by isothermal experiments in
114 air), 1500 °C, and 1600 °C for various heating durations. However, it is difficult to precisely
115 determine the liquidus temperature in our experiments for two reasons. First, under vacuum,
116 the chemical composition of the starting liquid changed via evaporation during the
117 experiments. Second, the oxidation state of iron in the charge also changed during the
118 experiments: initially in its oxidised state (Fe^{3+}), heating the liquid in a carbon crucible
119 reduced iron to Fe^0 .

120 The second protocol corresponded to dynamic crystallisation experiments. These
121 experiments began with isothermal heating (2 h) at 1600 °C (at least 100 °C above the
122 liquidus temperature) followed by cooling to 1200–1210 °C at rates of 5–1000 °C/h before
123 quenching in air (Table 1). Four experiments (25-N267 and 26-N268, cooled at 500 °C/h, and
124 32-N274 and 33-N273, cooled at 50 °C/h) were quenched at higher temperatures of 1400 and
125 1300 °C, respectively. Moreover, experiment 27-N260 was held isothermally at 1200 °C for 2
126 h before quenching, and experiment 28-N263 was held at 1200 °C for 4 h before a second

127 stage of cooling at 300 °C/h down to 900 °C, at which temperature the charge was held
128 isothermally for 62 h before the air quench.

129 The third protocol was similar to the second, but at the end of the cooling step, the
130 charges were reheated to 1400 or 1500 °C for various durations before quenching in air
131 (Table 2).

132 At the end of all experiments, the charges were quenched in air by rapidly removing
133 the ceramic rod holding the sample crucible. Therefore, regardless of the thermal protocol, the
134 quench rate was not very rapid and allowed the formation of quench crystals.

135 After quenching, the charges were mounted in epoxy and prepared as polished
136 sections. Samples were examined using a scanning electron microscope (JEOL 6510)
137 equipped with a Bruker AXS Xflash detector "Quantax" operating in energy dispersive mode
138 (EDS) at the CRPG. Chemical analyses were performed with an accelerating voltage and
139 beam current of 15 kV and 0.25 nA, respectively, in analytical mode (EDS).

140

141 **3. Results**

142 Experimental conditions and results are detailed in Tables 1 and 2. Chemical composition of
143 olivines formed during dynamic crystallization experiments are given in supplementary Table
144 S1.

145

146 *3.1. Isothermal evaporation experiments*

147 Three temperatures were investigated to estimate the liquidus temperature of the
148 starting composition as a function of the evaporation duration and the changing iron oxidation
149 state. It is important to note that, although experiments were performed isothermally,
150 equilibrium was never achieved because the system was open.

151

152 *3.1.1. Experiments at 1450 °C*

153 Experiments at this temperature had durations of 5 min to 16 h. All experiments
154 displayed polyhedral olivines with skeletal or dendritic overgrowths, but dendritic olivine
155 rods appeared in experiments longer than 15 min (Supplementary Fig. S1a) and became
156 increasingly numerous at longer durations. These rods comprised units displaying H or dove
157 shapes according to the dendritic olivine nomenclature of Donaldson (1976) and Faure et al.
158 (2003a, 2003b). Rods occurred as either single rods randomly distributed throughout the
159 charge or grouplets of parallel bars resembling the BO texture (Fig. S1b). However, the
160 persistence of polyhedral and skeletal crystals, particularly along the borders of the charges,
161 implies that the liquidus temperature was never attained in these experiments, even at the
162 longest duration.

163
164 *3.1.2. Experiments at 1500 °C*

165 Isothermal experiments at 1500 °C had durations of 5 min to 7 h. These experiments
166 can be subdivided into three groups as a function of experimental duration.

167 The first group includes only the shortest duration experiment (5 min). This charge
168 was texturally similar to charges heated at 1450 °C; polyhedral and skeletal olivines were
169 distributed around the border, and the centre of the charge was occupied by dendritic olivine
170 rods.

171 The second group includes charges heated between 15 min and 3 h. These charges
172 (except that heated for 1 h) displayed only dendritic olivine crystals oriented randomly. The
173 charge heated for 1 h contained spinel crystals instead of dendritic olivines. It is unclear what
174 caused this difference in mineralogy, but our best explanation is that it resulted from a slight
175 variation in the evaporation rate, which increased the Al content in the residual liquid, making
176 spinel the stable phase instead of olivine. This seems consistent with the fact that the third

177 group of experiments at this temperature, charges heated for long durations of 5 and 7 h,
178 contained aggregates of Al-Ca-rich crystals within an Al-Ca-rich mesostasis; in these
179 experiments Mg and Fe had totally disappeared, and only trace amounts of Si were analysed
180 by EDS.

181

182 *3.1.3. Experiments at 1600 °C*

183 All samples obtained after isothermal evaporation at 1600 °C (Table 1) displayed only
184 rod-shaped dendritic olivine crystals embedded in a glassy mesostasis. Rods were either
185 randomly distributed in the charge or comprised sets of perfectly parallel rods. Olivine
186 crystals displayed the same dendritic morphology and size range (rod widths of 10–50 µm,
187 depending on sectioning) regardless of heating duration (5 min to 5 h). This result suggests
188 that these dendritic crystals were produced during the quench, in turn implying that the
189 charges were totally melted during the isothermal step. However, it is important to note that
190 olivine rims never formed in charges that experienced only an isothermal heating step.

191

192 *3.2. Cooling experiments*

193 After isothermally heating charges at 1600 °C for 2 h to ensure that they were initially
194 totally molten, we tested a large range of cooling rates from 5 to 1000 °C/h. To a first
195 approximation, all charges showed textures resembling the BO texture (Fig. 2). All
196 experiments quenched at ≤ 1300 °C showed one to five sets of parallel olivine bars, regardless
197 of the cooling rate (Table 1); charges quenched at 1400 °C contained more numerous
198 crystallographically distinct crystals (48–62 sets of bars), as observed in samples isothermally
199 heated at 1600 °C. The thickness of bars in a given crystal (i.e., set of parallel bars) was
200 usually variable (Fig. 2c–f) and mostly depended on sectioning effects rather than the cooling
201 rate. Rods either spanned the entire charge or were developed only on one side. When two

202 rods grew on opposite sides of the charge, but not rigorously face-to-face, the junction
203 between them was distorted and misoriented. Then, rods displayed waves and were
204 commonly slightly misoriented with respect to the main direction of elongation of the set. In
205 this case, we refer to the shape of rods as "corrugated". Rods were continuous or variably
206 segmented regardless of the cooling rate (Fig. 2). In all dynamic crystallisation experiments
207 (i.e., regardless of cooling rate), we observed discontinuous areas of olivine rimming the
208 borders of the charges, but none had rims around the entire circumference of the charge.
209 There is no clear relation between rim thickness and cooling rate; we thus attribute variations
210 in rim thickness to sectioning effects.

211 Although all dynamic crystallisation experiments broadly resembled the BO texture,
212 two groups can be defined in detail: rapid (50–1000 °C/h) and slow cooling experiments (5
213 and 10 °C/h).

214 In rapid cooling experiments (>50 °C/h), olivine rods showed the same dendritic
215 shapes as those observed in isothermal experiments. H- or dove-shaped units were very well
216 formed in the charges that were cooled the fastest (500 and 1000 °C/h). The dove shape was
217 more difficult to recognize in charges cooled at 50–250 °C/h; only the sides of the doves
218 (wings) were consistently visible (Fig. 3a, b). In contrast, H- or dove-shaped units were not
219 present in slowly cooled charges (5 and 10 °C/h); in those cases, rods or corrugated
220 segmented rods had smooth, flat surfaces. Similarly, glass inclusions within rapidly cooled
221 rods (500 or 1000 °C/h) showed characteristic 'negative' crystal (dove) shapes, whereas, with
222 decreasing cooling rate (≤ 250 °C/h), the limiting faces of inclusions became more rounded.
223 At cooling rates ≤ 10 °C/h, glass inclusions systematically had round or ovoid shapes.

224 The external rims of the charges also showed morphological variations as a function of
225 cooling rate (Fig. 4). Rims formed during rapid cooling experiments displayed dendritic
226 shapes, whereas rim became more rounded and undulous at slower cooling rates. This

227 transition seems to have occurred around 50 °C/h; at that cooling rate, rods attached to the rim
228 had smooth, wavy shapes, whereas rods well within the charge were always dendritic. At ≤ 10
229 °C/h, both rims and rods had smooth, wavy shapes and contained rounded glass inclusions
230 (Fig. 4d, e). We note that pure euhedral spinel crystals (MgAl_2O_4) were present inside the
231 charge that cooled at the slowest rate, i.e., the charge that spent the most time at high
232 temperature and thus endured the most protracted evaporation (Fig. 4f).

233

234 *3.3. Charges cooled, then isothermally held before quenching*

235 We performed two experiments to estimate the effect of an isothermal step before
236 quenching (Table 1). After cooling by 500 °C/h, these charges were held isothermally at 1200
237 °C for 2 h and then quenched (27-N260) or held at 1200 °C for 4 h, cooled to 900 °C by 300
238 °C/h and held isothermally for 62 h, and finally quenched (28-N263). No significant
239 differences were apparent between charges held isothermally at high temperature and those
240 that only experienced cooling at 500 °C/h (Figs. 2b, 5). However, in detail, the charge held
241 isothermally for 2 h showed incipient textural ripening, although the wings of the dove's units
242 were still present (Fig. 5b). In contrast, the charge held isothermally for 4 h before a second
243 cooling step displayed relatively smooth bars, although glass inclusions still had 'negative'
244 dove shapes (Fig. 5d).

245

246 *3.4. Cooling and reheating experiments*

247 We performed five experiments initially cooled to 1200 °C then reheated to 1400 or
248 1500 °C. Of these, four were initially cooled by 500 °C/h before reheating (three to 1400 °C
249 and one to 1500 °C); the fifth was cooled by 50 °C/h before reheating to 1400 °C (Table 2).

250

251 *3.4.1. Experiments reheated to 1400 °C*

252 The three experiments cooled at 500 °C/h then reheated to 1400 °C no longer showed
253 rods comprising dove units, but instead contained rods with smooth surfaces (Fig. 6a–f). Rods
254 were either continuous or formed from smaller segments. Rod segmentation increased with
255 increasing time spent at the reheated temperature, consistent with textural ripening (although
256 sectioning effects cannot be ruled out).

257 The first experiment was directly quenched after reheating to 1400 °C. That charge
258 displayed, to a first approximation, a texture that best matches the "classic" BO chondrule
259 texture because it contained both mostly parallel bars and a prominent rim. However, some
260 bars showed slight misorientations; these may represent several distinct olivine crystals.
261 Moreover, the rim is discontinuous and slightly offset from the border of the charge. These
262 two observations could represent an experimental artifact. Indeed, on the one hand,
263 Tsuchiyama et al. (2004) showed that contact with the carbon capsule precludes the formation
264 of a continuous rim. On the other hand, the offset of the border of the charge is probably due
265 to the air quench when the sample was rapidly removed from the vertical furnace, which
266 would be consistent with the small dendrites that grew in the free space between the olivine
267 rim and the border of the charge. Similarly, both experiments reheated and held isothermally
268 for 3 and 12.5 h showed numerous small dendritic olivine bars and dendritic overgrowths on
269 segments, suggesting that the dendrites resulted from the quench. Moreover, this quench
270 texture is consistent with the high MgO content of the liquid, which is due to reheating to
271 1400 °C. After ≥ 3 h of reheating, inclusions within olivine bars were ovoid and resemble
272 natural glass inclusions (Fig. 6d).

273 The experiment initially cooled by 50 °C/h before reheating to 1400 °C and held
274 isothermally for 11 h before quenching showed bars that were more or less segmented
275 depending on the section viewed. The larger segments were euhedral, with well-developed
276 external faces, even if containing a large central hole recalling their former skeletal shape, i.e.,

277 hopper crystals (Fig. 6g). Most glass inclusions were ovoid in shape. Moreover, numerous
278 overgrowths and dendritic olivines (quench crystals) were superimposed on the initial BO
279 texture.

280

281 *3.4.2. Experiment reheated to 1500 °C*

282 The experiment reheated to 1500 °C showed numerous dendritic olivine crystals
283 resembling those produced during the quench of 2h isothermal experiments at 1500 or 1600
284 °C (Fig. S2). This observation suggests that these dendritic crystals resulted from the quench
285 and do not correspond to the ripening of crystals formed during the initial cooling step.
286 Therefore, reheating to 1500 °C must have melted all crystalline phases formed during the
287 initial cooling step, and the charge was totally liquid before the quench.

288

289 **4. Discussion**

290 Numerous experiments over the past few decades have apparently reproduced barred
291 olivines as observed in chondrules. However, no clear consensus exists on the thermal
292 conditions necessary to produce barred olivines. This results from the fact that multiple
293 thermal parameters must be considered (degree of superheating, degree of undercooling,
294 cooling rate), and because even the definition of a barred olivine chondrule varies among
295 researchers. Therefore, we here first discuss the definition a barred olivine chondrule before
296 exploring the thermal parameters required to truly reproduce of this peculiar texture.

297

298 *4.1. Definition of barred olivine chondrules*

299 As indicated by their name, barred olivines constitute bars that are parallel when
300 belonging to the same crystal. Therefore, bars oriented in several directions suggest the
301 presence of several crystals, unless a twinning law can explain the misorientation. However,

302 only a few crystals are observed in natural BO chondrules, varying from one in "classic" BO
303 chondrules to eight in "multiple grouplet" BO chondrules. Another criterion defining barred
304 olivines is the presence of an external olivine rim connected to the bars. Furthermore, the
305 shape of the bars must be considered. In natural BO chondrules, bars have smooth or slightly
306 curved faces, and never complex faceted arrangements that would correspond to a true
307 dendritic morphology. Similarly, glass inclusions within olivine bars display rounded or ovoid
308 shapes, not 'negative' dendritic crystal shapes.

309 Based on these five criteria (few crystals, sets of parallel bars, the presence of an
310 olivine rim, smooth bar faces, round glass inclusions), we now discuss which thermal
311 protocol best reproduces the BO texture.

312

313 *4.1.1. Thermal conditions producing few crystals*

314 In contrast to porphyritic chondrules, BO chondrules characteristically contain only a
315 few crystals. This major difference in chondrule texture has been explained by the extent of
316 melting of chondrule precursors (Lofgren, 1989; Connolly et al., 1998; Tsuchiyama et al.,
317 2004). Partial melting promotes heterogeneous nucleation on relict crystals or nuclei that
318 survived the melting event; in this case, crystal growth begins immediately upon cooling,
319 forming porphyritic chondrules comprising numerous polyhedral crystals. In contrast,
320 crystallisation following complete initial melting requires nucleation, implying that an
321 energetic barrier must be overcome (Kirkpatrick, 1983). A recent experimental study has
322 shown that the number of crystals produced experimentally varies by one to two orders of
323 magnitude depending on whether the charge was initially completely or only partially melted
324 (Auxerre et al., in press). Our results here confirm that charges heated above their liquidus
325 temperature (superliquidus experiments) form few (1–5) crystals, regardless of the cooling
326 rate considered (5–1000 °C/h). Moreover, even if the liquidus temperature was not well

327 constrained in our open-system experiments (due to evaporation and variation of the
328 oxidation state of iron), our isothermal experiments longer than 15 minutes at 1500 °C and
329 dynamic crystallisation experiments reheated to 1500 °C demonstrate that olivine crystals
330 cannot survive at this temperature (Fig. S2). Indeed, these different experimental charges
331 showed similar dendritic quench textures comprising numerous crystals (40–80), i.e., at least
332 an order of magnitude more crystals than in superliquidus cooling experiments. Therefore, the
333 liquidus temperature in our experiments was below 1500 °C, but must have been above 1450
334 °C according to isothermal experiments. We therefore assume that the liquidus temperature
335 was near 1500 °C and that the degree of superheating ($+\Delta T$) at the beginning of dynamic
336 crystallisation experiments was around of 100 °C. Such a degree of superheating is sufficient
337 to ensure initial total melting but low enough that nucleation should not be suppressed.
338 Indeed, nucleation is totally suppressed at degrees of superheating exceeding 400 °C
339 (Connolly et al., 1998), although the duration of heating also effects nucleation (First et al.,
340 2020). Therefore, our experiments confirm that the BO texture requires that chondrules were
341 initially completely molten (Lofgren, 1989; Connolly et al., 1998; Tsuchiyama et al., 2004).

342

343 *4.1.2. Thermal conditions promoting the crystallisation of dendritic olivines*

344 It is well known that dendritic morphologies result from crystallisation at a high
345 degree of undercooling. Such degrees of undercooling can be induced by delayed nucleation,
346 which is promoted by initial superheating, as suffered by natural BO chondrules (see section
347 4.1.1). In our experiments, because the solidification process was not observed in situ, we
348 cannot directly measure the timing and temperature of nucleation. However, by quenching
349 two series of experiments (cooling rates of 500 and 50 °C/h) at three different temperatures,
350 we showed that charges were always completely liquid at 1400 °C. In contrast, at 1300 °C,
351 olivine crystals corresponded to the BO texture, not a dendritic quench texture, suggesting

352 that the degree of undercooling due to delayed nucleation was around 100 °C. However, this
353 value is not well constrained because we did not quench any experiments at temperatures
354 between 1300 and 1400 °C, and because the liquidus temperature evolved in our open-system
355 experiments. Therefore, determining the degree of undercooling in our experiments precisely
356 is beyond the scope of this study. Nevertheless, we estimate the degree of undercooling was
357 around 100 °C, regardless of the cooling rate tested, which is consistent with the occurrence
358 of dendritic crystallisation in the charges.

359

360 *4.1.3. Thermal conditions promoting the formation of parallel olivine bars*

361 Numerous previous experiments have reproduced olivines displaying parallel dendritic
362 bars over a large range of cooling rates (Donaldson, 1976; Tsuchiyama et al., 1980; Lofgren,
363 1989; Lofgren and Lanier, 1990; Radomsky and Hewins, 1990; Connolly and Hewins, 1991;
364 Kennedy et al., 1993; Connolly et al., 1998; Faure et al., 2003a, 2006). This observation is
365 consistent with our results that parallel olivine bars are observed at any cooling rate between 5
366 and 1000 °C/h. Even charges that were only isothermally melted well above their liquidus
367 temperature produced parallel bars during the quench, although this result is clearly an
368 experimental artifact because the air quench is not fast enough to chill MgO-rich liquid into
369 glass. Even if it is not possible to constrain the cooling rate during quenching precisely, the
370 quench rate is necessarily faster than all other cooling rates explored in our controlled cooling
371 experiments. Therefore, the presence of parallel bars does not seem to be a reliable criterion
372 for estimating the cooling rate of BO chondrules.

373

374 *4.1.4. Thermal conditions producing an olivine rim around the chondrule*

375 Reproducing the external rims around BO chondrules has long been an experimental
376 difficulty (Miura et al. 2011). As noted by Tsuchiyama et al. (2004), only two prior

377 experiments reproduced this peculiar texture with conventional experimental techniques (i.e.,
378 in 1-atm furnaces), although the experimental conditions that produced the rims were not
379 clear. In contrast, experiments performed under vacuum produced olivine rims (Nagahara,
380 1996; Tsuchiyama et al., 2004). Tsuchiyama et al. (2004) succeeded in reproducing both
381 olivine rims and parallel bars over a large range of cooling rates between 500 and 1200 °C/h
382 under vacuum. However, the olivine rims they produced displayed dendritic shapes not
383 observed in natural BO chondrules. This result is consistent with our experiments that
384 produced highly dendritic olivine rims under rapid cooling (1000 °C/h). Here, however,
385 olivine rims became increasingly rounded and smooth (ripening texture) with decreasing
386 cooling rate. Notably, this change in shape seems to occur around 500 °C/h because both
387 dendritic and rounded morphologies were present in that sample. Nonetheless, it was only at
388 cooling rates of ≤ 50 °C/h that olivine rims began to resemble natural BO rims.

389

390 *4.1.5. Thermal conditions forming smooth olivine bars*

391 Olivine bars in natural BO chondrules are flat, sometimes segmented, and variably
392 corrugated, whereas bars obtained experimentally are always dendritic (Tsuchiyama et al.,
393 2004). Although Tsuchiyama et al. (2004) suggested that decreasing the cooling rate might
394 produce smoother bars, they considered that a reheating step was more likely to texturally
395 ripen the dendritic shape. Our results demonstrate that the cooling rate must indeed be
396 relatively slow (< 10 °C/h) because experiments cooled faster (≥ 50 °C/h) always showed
397 dendritic crystal units, whereas those cooled at ≤ 10 °C/h showed more or less segmented bars
398 limited by smooth faces. Corrugation increased with decreasing cooling rate, and was
399 particularly obvious at 5 °C/h. Our reheating experiments showed that the same corrugated
400 texture can be obtained by holding the charge for several hours at 1400 °C, producing
401 segmented bars after 3 h and corrugated bars after 11–12 h. In contrast, the duration that the

402 charges were held at increased temperature was not long enough to produce textural ripening
403 because pieces of dendrites were always noticeable. Therefore, our experimental results
404 demonstrate that bars truly similar to natural BO chondrules require slow cooling ($<10\text{ }^{\circ}\text{C/h}$)
405 or a relatively long reheating episode ($>10\text{ h}$). However, reheating enriched the liquid in the
406 olivine component, causing a second dendritic crystallisation step that is not observed within
407 natural BO chondrules.

408

409 *4.1.6. Thermal conditions forming round glass inclusions*

410 Glass inclusions in both olivine bars and rims of natural BO chondrules are rounded or
411 ovoid (Varela et al., 2006). In contrast, glass inclusions in olivines crystallised in rapidly
412 cooled charges ($>10\text{ }^{\circ}\text{C/h}$) are limited by faces that correspond to the ‘negative’ crystal shape
413 that is characteristic of melt inclusions formed during rapid crystal growth (Colin et al.,
414 2012). Tsuchiyama et al. (2004) described glass inclusions with the same shape in their
415 rapidly cooled experiments ($>500\text{ }^{\circ}\text{C/h}$). Therefore, our results suggest that slow cooling ($<$
416 $10\text{ }^{\circ}\text{C/h}$) is necessary to form rounded glass inclusions. However glass inclusions obtained in
417 reheating experiments are similarly shaped. .

418

419 *4.2. Cooling conditions required to crystallise BO chondrules*

420 Our experimental results show reproducing all the characteristics of BO chondrules
421 (few crystals, parallel bars, rims, smooth and sometimes corrugated bars, and ovoid glass
422 inclusions), requires slow cooling ($<10\text{ }^{\circ}\text{C/h}$). Although reheating after fast cooling could be
423 an alternative to slow cooling because it allows textural ripening and reproduces most of the
424 textural characteristics of BO chondrules, reheating also results in olivine dissolution.
425 Therefore, the chemical composition of the liquid mesostasis becomes enriched in the
426 forsterite component, particularly MgO. The first consequence of this change in liquid

427 composition translates to difficulty in quenching the samples and the presence of numerous
428 dendritic olivine crystals. The second consequence is that melt inclusion MgO contents
429 should also increase accordingly. However, our results (Supplementary Table S2) and scarce
430 literature data (Varela et al., 2006) show that natural BO glass inclusions always have low
431 MgO contents (2.65 ± 1.87 wt.%). Such low-MgO glass inclusions are undersaturated in the
432 olivine component and are compositionally very similar to glass inclusions hosted in
433 magnesian olivines in porphyritic chondrules (Fig. 7), which are only produced through slow
434 cooling (Faure et al., 2012; Faure, 2020). Indeed, such low MgO contents result in the
435 equilibrium metastable crystallisation of the olivine rim around the inclusion (Faure and
436 Tissandier, 2014). In natural BO chondrules, glassy mesostases are also olivine-
437 undersaturated (Varela et al., 2006; Berlin, 2010), inconsistent with rapid cooling. Moreover,
438 slow cooling can explain the lack of Fe-Mg growth zoning in bars of natural BO chondrules,
439 in contrast to synthetic olivines crystallised under rapid cooling rates (Lofgren and Lanier,
440 1990; Tsuchiyama et al., 2004). Therefore, although BO chondrules might have formed
441 during a singular cooling event or experienced an oscillatory thermal history (reheating), slow
442 terminal cooling before quenching is necessary to obtain the true BO texture.

443

444 *4.3. Implications for chondrule crystallisation*

445 Our results on BO chondrule crystallisation have broad implications because there
446 remains no further textural evidence for the rapid cooling of chondrules, porphyritic or not.
447 Indeed, this result is consistent with plagioclase-bearing porphyritic chondrules that seem to
448 require very slow cooling rates (1 °C/h) at the end of crystallisation (Wick and Jones, 2012).
449 Moreover, the slow cooling rates obtained here for BO chondrule crystallisation are consistent
450 with those (0.5 – 50 °C/h) determined for magmatic type-B Ca-Al-rich inclusions, which are
451 considered to have experienced a similar thermal history (Jones et al., 2000). Therefore, slow

452 cooling rates may be common to all similar chondritic objects (Fig. 8), with important
453 implications for the formation of the solar system.

454 No consensus exists on the process(es) of chondrules formation, and numerous models
455 ranging from nebular to planetary processes have been proposed to explain why chondrules
456 display such a wide variety of textures and chemical compositions (Desch et al., 2012;
457 Connolly and Jones, 2016; Hewins et al., 2018). However, in all cases, it is largely accepted
458 that chondrules resulted from the crystallisation of small beads of liquid that had already more
459 or less crystallised within a gas. The density of chondrules in the chondrule-forming region of
460 the gas is generally constrained based on the occurrence of compound chondrules, peculiar
461 chondrules that resulted from chondrule-chondrule collisions while at least one of them was
462 partially molten. Initially thought to have formed exclusively at above 1400 K (Ciesla et al.,
463 2004), compound chondrules may have formed at lower temperatures during collisions
464 between undercooled melt droplets (Arakawa and Nakamoto, 2016). Whatever the
465 temperature range considered, it is generally proposed that the BO texture forms during a
466 rapid phenomena occurring over 100–1,000 s in the gas cloud (Miura et al. 2010; Bischoff et
467 al., 2017). However, the slow cooling rates determined herein for chondrule crystallisation
468 suggest a longer time scale of several days, not minutes to hours, implying that the density of
469 chondrules in the chondrule-forming region was two to four orders of magnitude lower than
470 previously considered (Table S3). Similarly, solid:gas ratios calculated for this new time scale
471 are larger than the canonical value (0.005), but smaller than oft-proposed values that result in
472 too rapid a gravitational instability (Bischoff et al., 2017).

473

474 **5. Conclusions**

475 We proposed a definition of the natural BO texture that considers (i) the presence of
476 parallel bars and rims, (ii) the fact that bars correspond to ripened dendrites, and (iii) that melt

477 inclusions have ovoid shapes and are olivine undersaturated. Our experimental results show
478 that these characteristics can only be reproduced under relatively slow cooling rates (<10
479 °C/h); reheating scenarios cannot form true BO textures because they cause the melt to
480 become enriched in the olivine component, producing olivine-enriched melt inclusions.
481 Therefore, chondrule crystallisation must have occurred over days, not minutes to hours as
482 generally suggested. These slow rates are consistent with rates determined for other chondritic
483 objects, including plagioclase-bearing porphyritic chondrules and magmatic type-B Ca-Al-
484 rich inclusions, suggesting that slow cooling could be common to all chondritic objects.

485

486

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631 **Author contributions**

632 F.F. and V.C. designed the study and experiments. F.F. and M.A. conducted the analytical
633 work. All authors participated in the interpretation of the data. F.F. wrote the manuscript with
634 input from M.A. and V.C.

635

636 **Competing interests**

637 The authors declare no competing interests.

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641 **Figure captions**

642 **Fig. 1.** A classic BO chondrule from the Felix (CO3) carbonaceous chondrite. (a) Optical
643 image under transmitted light, displaying that the BO chondrule is rimmed by a shell of
644 olivine and contains parallel bars of olivine set in glass. (b) Enlarged view of the square in (a),
645 highlighting ovoid glass inclusions (Gi) in olivine (ol).

646

647 **Fig. 2.** Backscattered electron (BSE) images of dynamic crystallisation experiments cooled to
648 (a–e) 1200 °C or (f) 1210 °C at decreasing cooling rates (Table 1). (a) Experiment 23-N258;
649 (b) experiment 24-N259; (c) experiment 29-N262; (d) experiment 31-N261; (e) experiment
650 34-N270; (f) experiment 35-N272.

651

652 **Fig. 3.** BSE images of experimental charges showing that the dendritic shapes of rods
653 decrease with decreasing cooling rate. (a) Dove-shaped units ('wings' indicated by arrows)
654 constituting dendritic rods are obviously visible in rapidly cooled charges (here, experiment
655 30-N299). (b) Only pieces of the 'wings' of dove units are observable in charges cooled more
656 slowly (experiment 31-N261).

657

658 **Fig. 4.** BSE images of olivine rims as a function of cooling rate. (a) Experiment 26-N268; (b)
659 experiment 29-N262; (c) experiment 31-N261 (d) experiment 34-N270; (e) enlarged view of
660 the square in (d) showing ovoid glass inclusions (Gi) hosted in the olivine rim. (f) Experiment
661 35-N272; in addition to olivine crystals, this charge contained euhedral spinel crystals.

662

663 **Fig. 5.** BSE images of experimental charges showing minimal textural ripening during
664 periods of isothermal heating during dynamic crystallisation experiments. (a) Experiment 27-
665 N260 was held isothermally at 1200 °C for 2 h after rapid cooling. (b) Enlarged view of the
666 rectangle in (a), showing that rods are always dendritic. (c) After rapid cooling at 500 °C/h,
667 experiment 28-N263 was held isothermally at 1200 °C for 4 h before a second rapid constant
668 cooling step (300 °C/h) down to 900 °C, at which temperature the charge was held
669 isothermally for 62 h. This long duration at low temperature can explain the spherulitic
670 texture in the mesostasis. (d) Enlarged view of the rectangle in (c), showing that glass
671 inclusions (Gi) hosted in olivine bars have 'negative' skeletal crystal shapes.

672

673 **Fig. 6.** BSE images of experimental charges showing textural ripening due to reheating to
674 1400 °C after rapid cooling by (a–f) 500 °C/h or (g–h) 50 °C/h. (a) Experiment 36-N264 was
675 reheated to 1400 °C and immediately quenched. (b) Enlarged view of the rectangle in (a),
676 showing that bars are still dendritic and quench dendrites developed on the rim. (c)

677 Experiment 37-N265 was reheated to 1400 °C and held for 3 h; this charge displays the true
678 BO texture with flat olivine bars. (d) Enlarged view of the rectangle in (c), showing that
679 quench dendritic rods developed between the smooth surfaces of the well-developed rods. (e)
680 Experiment 38-N266 was reheated to 1400 °C and held for 12.5 h. (f) Enlarged view of the
681 rectangle in (e), showing dendritic overgrowths developed on segmented rods. (g) Experiment
682 39-N271 was cooled at 50 °C/h then reheated to 1400 °C for 11 h. (h) Enlarged view of the
683 rectangle in (g), showing that, even with a slower initial cooling rate, quench overgrowths are
684 always present in reheating experiments.

685

686 **Fig. 7.** Normative compositions of olivine-hosted glass inclusions in BO chondrules projected
687 onto the forsterite-anorthite-silica plane. Analysed glass inclusions in natural BO chondrules
688 (open red squares, this study; filled red circles, Varela et al., 2006) show the same
689 compositional variability as olivine-hosted glass inclusions in porphyritic chondrules (Al-rich,
690 Al-poor, Na-rich, and Si-rich glass inclusions, represented by their respective coloured fields).
691 Regardless of chondrule texture, the compositions of glass inclusions plot outside the stability
692 field of their host forsterite.

693

694 **Fig. 8.** Cooling rates used to experimentally reproduce chondrule textures. Various chondrule
695 textures (BO, barred olivine; PO, porphyritic olivine and porphyritic olivine-pyroxene; RP,
696 radial pyroxene) can be reproduced over large ranges of cooling rates, except BO chondrules,
697 which are traditionally interpreted to result from rapid cooling (red rectangle; data
698 compilation after Desch et al., 2012; Jones et al., 2018). However, those experiments never
699 reproduced the true BO texture, which our slow cooling results (red circles) reproduce well,
700 thus challenging the traditional assumption that chondrules crystallised under rapid cooling.
701 Consequently, all chondrule textures can be explained by slow cooling rates (<10 °C/h),

702 consistent with those envisioned for magmatic type-B Ca-Al-rich inclusions (Jones et al.,
703 2000).

704

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707

708 **Table 1.** Summary of run conditions and products in isothermal and dynamic crystallisation
709 experiments.

710

711 **Table 2.** Summary of run conditions and products in reheating experiments.

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715

716 **Supplementary Material**

717 **Fig. S1.** BSE images of isothermal experimental charges showing dendritic crystal textures
718 produced during air quenching. (a) Experiment 8-N180 was held isothermally at 1450 °C for
719 16 h before quenching in air and shows both dendritic rods and polyhedral-skeletal olivine
720 crystals. (b) Experiment 7-N173 was held isothermally at 1450 °C for 7 h before quenching in
721 air and shows dendritic parallel rods of olivine.

722

723 **Fig. S2.** BSE images of experimental charges showing dendritic crystal textures produced
724 during air quenching. (a) Dynamic crystallisation experiment 40-N269 was cooled to 1200 °C
725 and reheated to 1500 °C; it displays numerous thin dendrites of olivine in the glass
726 mesostasis. (b) Isothermal experiment 12-N194 was held at 1500 °C for 2 h before air

727 quenching and shows a dendritic texture similar to that in (a). (c) Isothermal experiment 16-
728 N234 was held at 1600 °C for 5 minutes before air quenching, and shows a dendritic texture
729 similar to those in (a) and (b).

730

731 **Table S1.** Chemical compositions (EDS analyses, in wt.%) of olivines crystallized during
732 dynamic crystallization experiments.

733

734 **Table S2.** Chemical compositions (EDS analyses, in wt.%) and normative mineralogy of
735 glass inclusions in barred olivine chondrules.

736

737

738 **Table S3.** Chondrule number density and solid:gas ratio as a function of cooling time scale.

739 T_{in} , initial chondrule temperature; T_{end} , the lowest temperature at which melt could have been
740 present in the chondrule.

741 n : the local number density of chondrules can be estimated by $n = \frac{0.8}{t_{cool} r_p^2 v}$, where $r_p = 0.5$

742 mm is the chondrule radius; v is the collision velocity, which typically varies between 0.5 and

743 5 m/s; and t_{cool} is the cooling time, which corresponds to the time elapsed before chondrules

744 were too cold to stick together (Bischoff et al., 2017).

745 ρ_s : the initial local mass density of all chondrule precursor materials can be calculated as

746 $\rho_s = 3.3 \rho_p \frac{r_p}{t_{cool} v}$, where the individual chondrule mass density $\rho_s = 3,500 \text{ kg/m}^3$ (Bischoff et

747 al., 2017). The ratio between precursor density and gas density is calculated assuming a mass

748 density of $1.4 \times 10^{-6} \text{ kg/m}^3$ at 1 AU in a minimum-mass solar nebula (Hayashi et al., 1985).

749

750 **Supplemental reference list**

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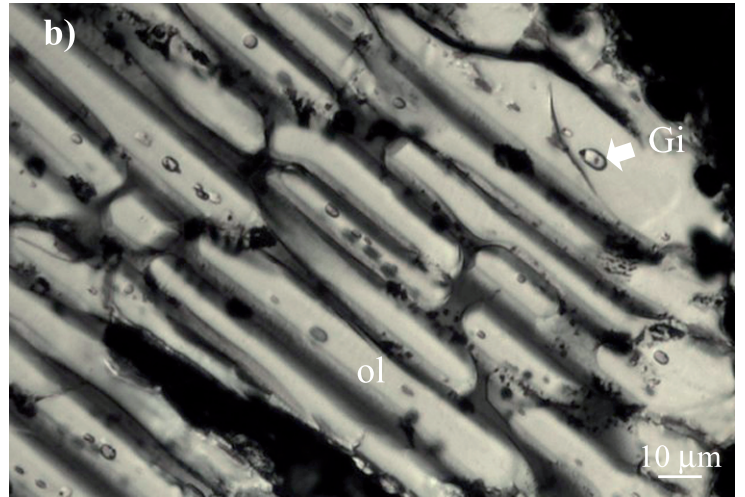
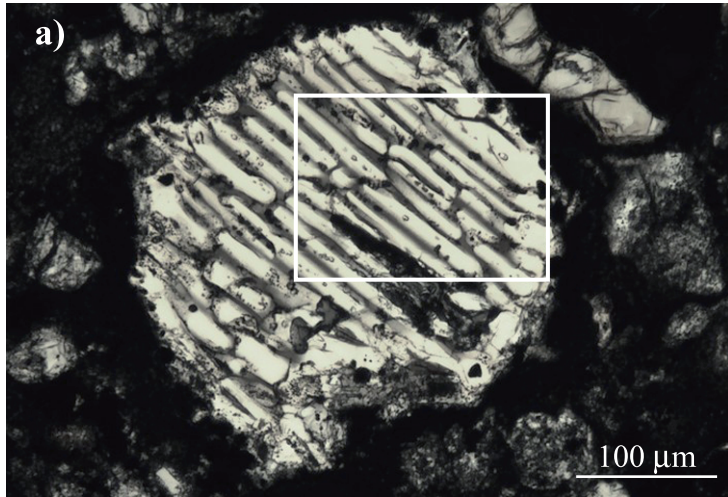


Fig. 1. A classic BO chondrule from the Felix (CO3) carbonaceous chondrite. (a) Optical image under transmitted light, displaying that the BO chondrule is rimmed by a shell of olivine and contains parallel bars of olivine set in glass. (b) Enlarged view of the square in (a), highlighting ovoid glass inclusions (Gi) in olivine (ol).

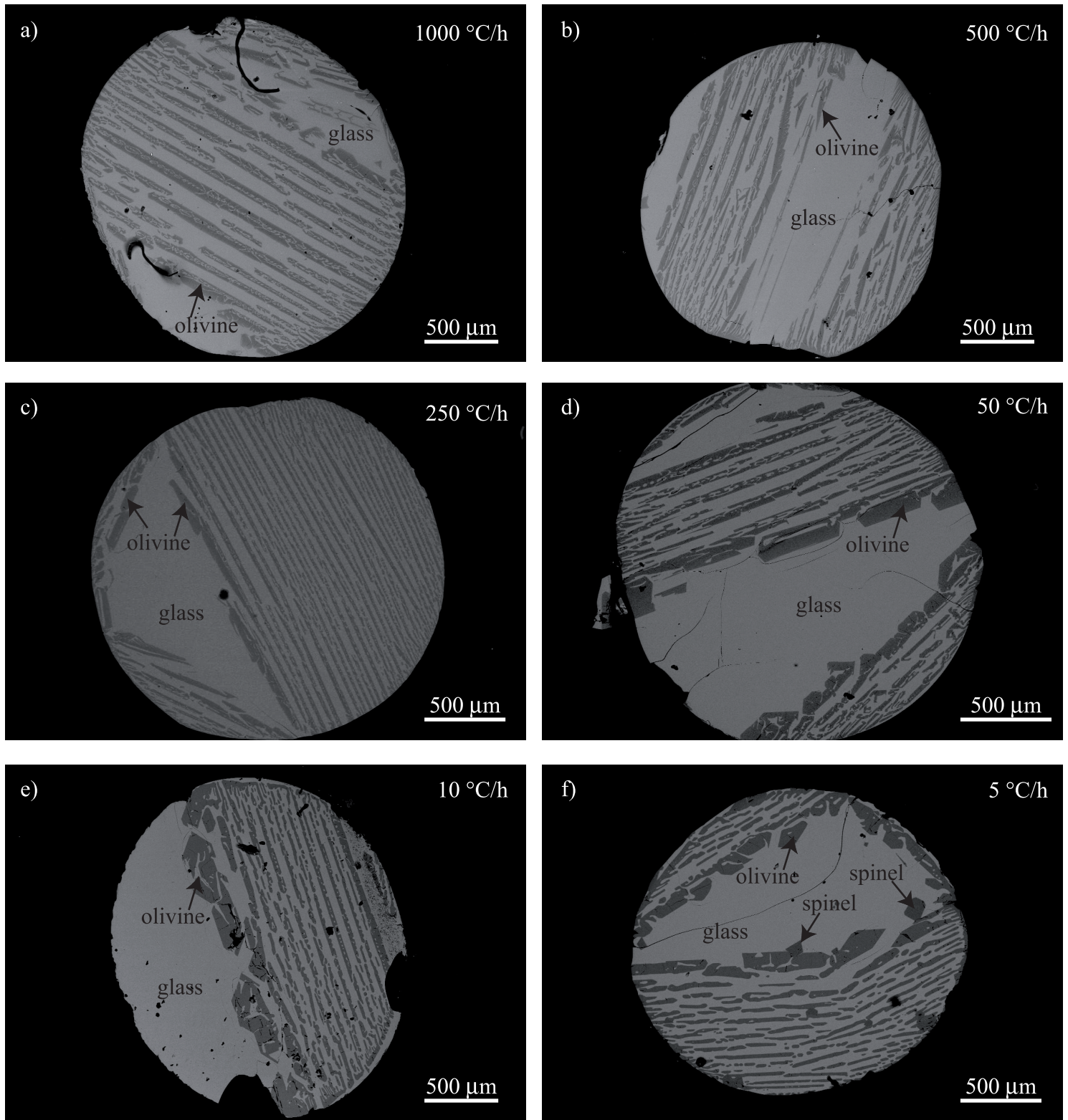


Fig. 2. Backscattered electron (BSE) images of dynamic crystallisation experiments cooled to (a–e) 1200 °C or (f) 1210 °C at decreasing cooling rates (Table 1). (a) Experiment 23-N258; (b) experiment 24-N259; (c) experiment 29-N262; (d) experiment 31-N261; (e) experiment 34-N270; (f) experiment 35-N272.

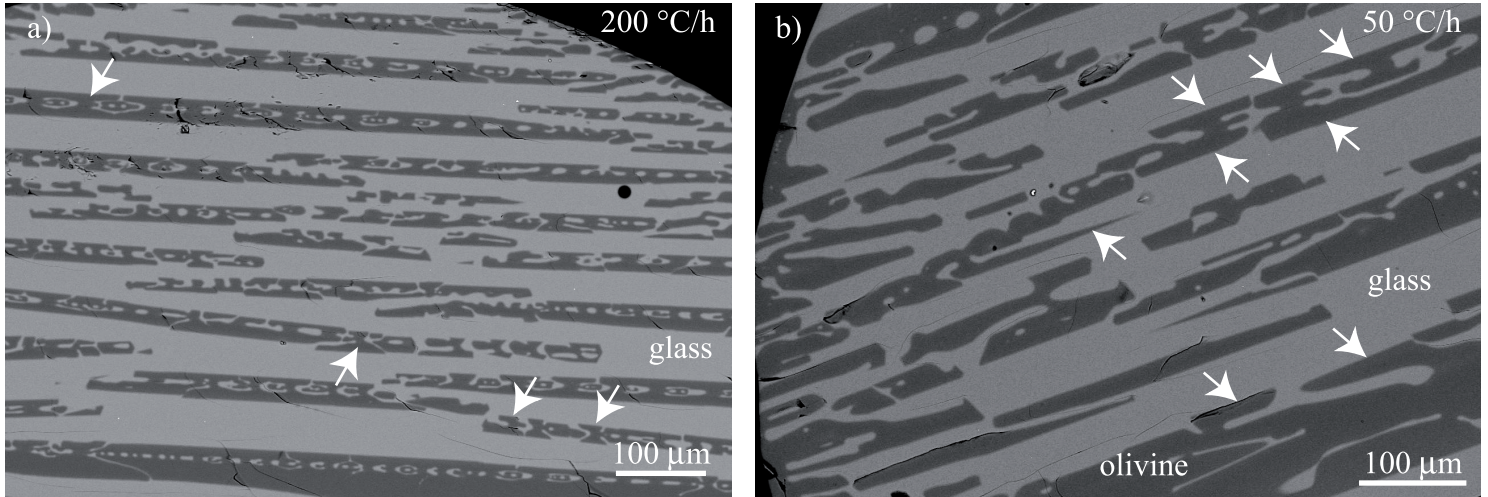


Fig. 3. BSE images of experimental charges showing that the dendritic shapes of rods decrease with decreasing cooling rate. (a) Dove-shaped units ('wings' indicated by arrows) constituting dendritic rods are obviously visible in rapidly cooled charges (here, experiment 30-N299). (b) Only pieces of the 'wings' of dove units are observable in charges cooled more slowly (experiment 31-N261).

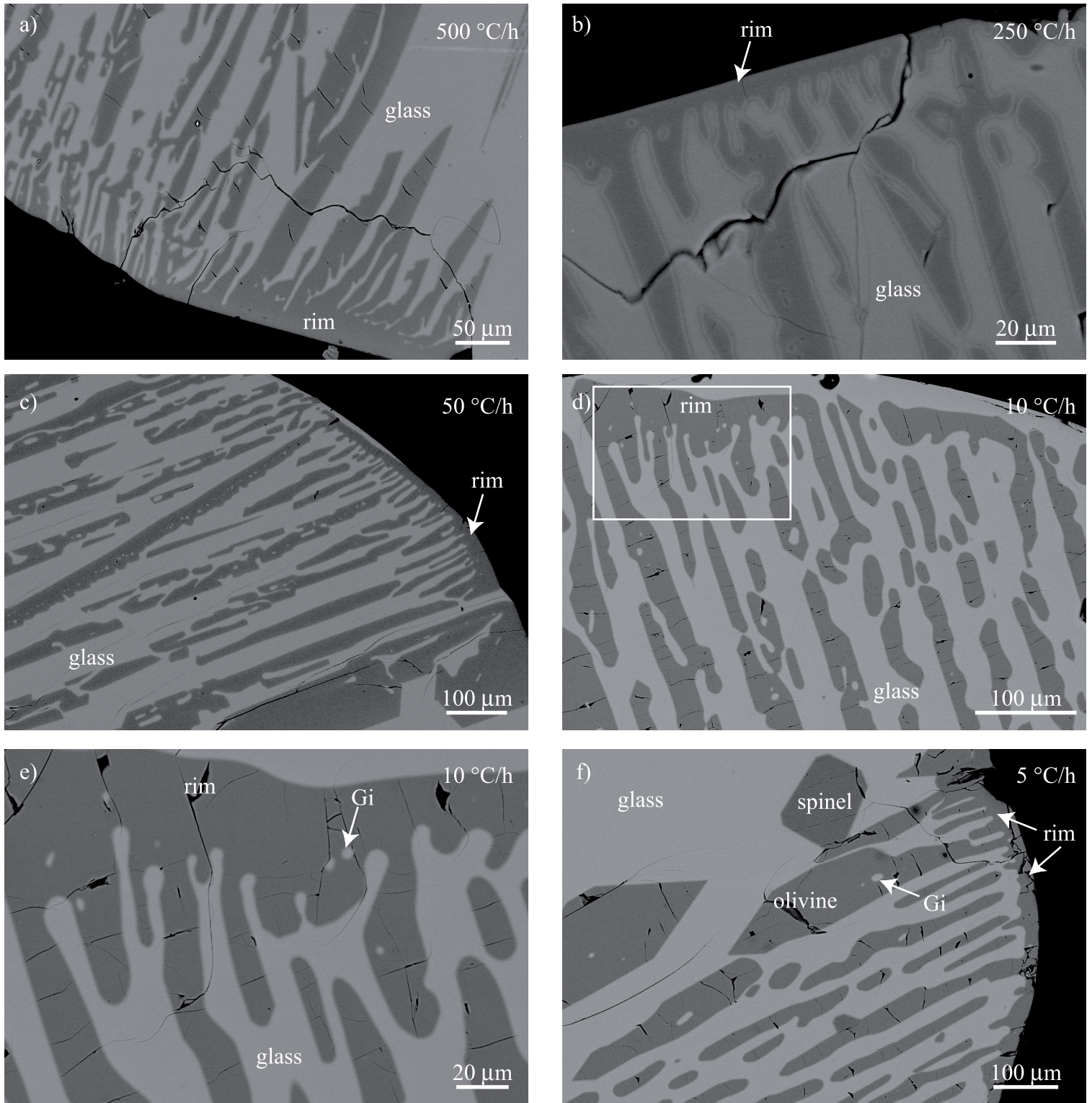


Fig. 4. BSE images of olivine rims as a function of cooling rate. (a) Experiment 26-N268; (b) experiment 29-N262; (c) experiment 31-N261 (d) experiment 34-N270; (e) enlarged view of the square in (d) showing ovoid glass inclusions (Gi) hosted in the olivine rim. (f) Experiment 35-N272; in addition to olivine crystals, this charge contained euhedral spinel crystals.

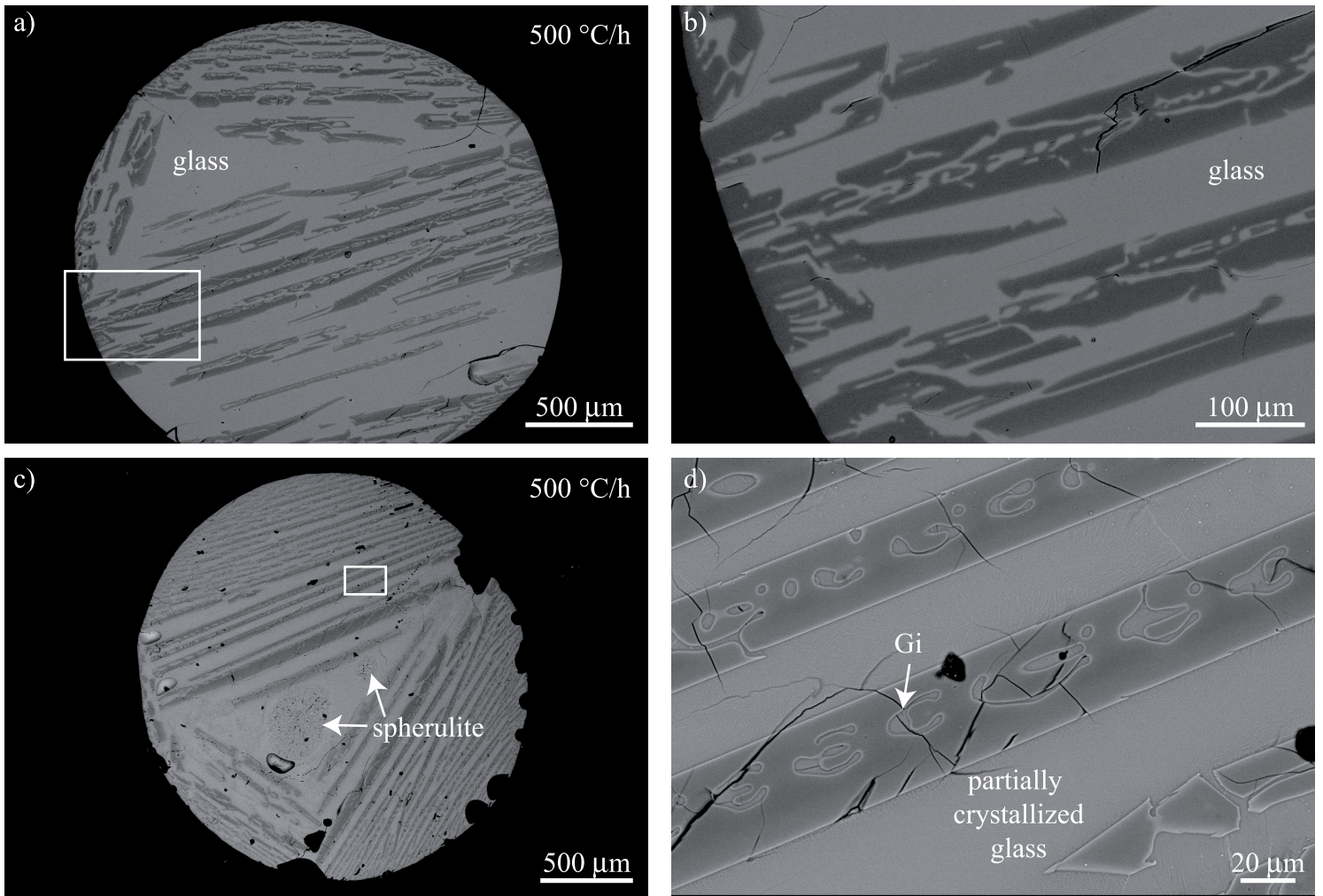


Fig. 5. BSE images of experimental charges showing minimal textural ripening during periods of isothermal heating during dynamic crystallisation experiments. (a) Experiment 27-N260 was held isothermally at 1200 °C for 2 h after rapid cooling. (b) Enlarged view of the rectangle in (a), showing that rods are always dendritic. (c) After rapid cooling at 500 °C/h, experiment 28-N263 was held isothermally at 1200 °C for 4 h before a second rapid constant cooling step (300 °C/h) down to 900 °C, at which temperature the charge was held isothermally for 62 h. This long duration at low temperature can explain the spherulitic texture in the mesostasis. (d) Enlarged view of the rectangle in (c), showing that glass inclusions (Gi) hosted in olivine bars have ‘negative’ skeletal crystal shapes.

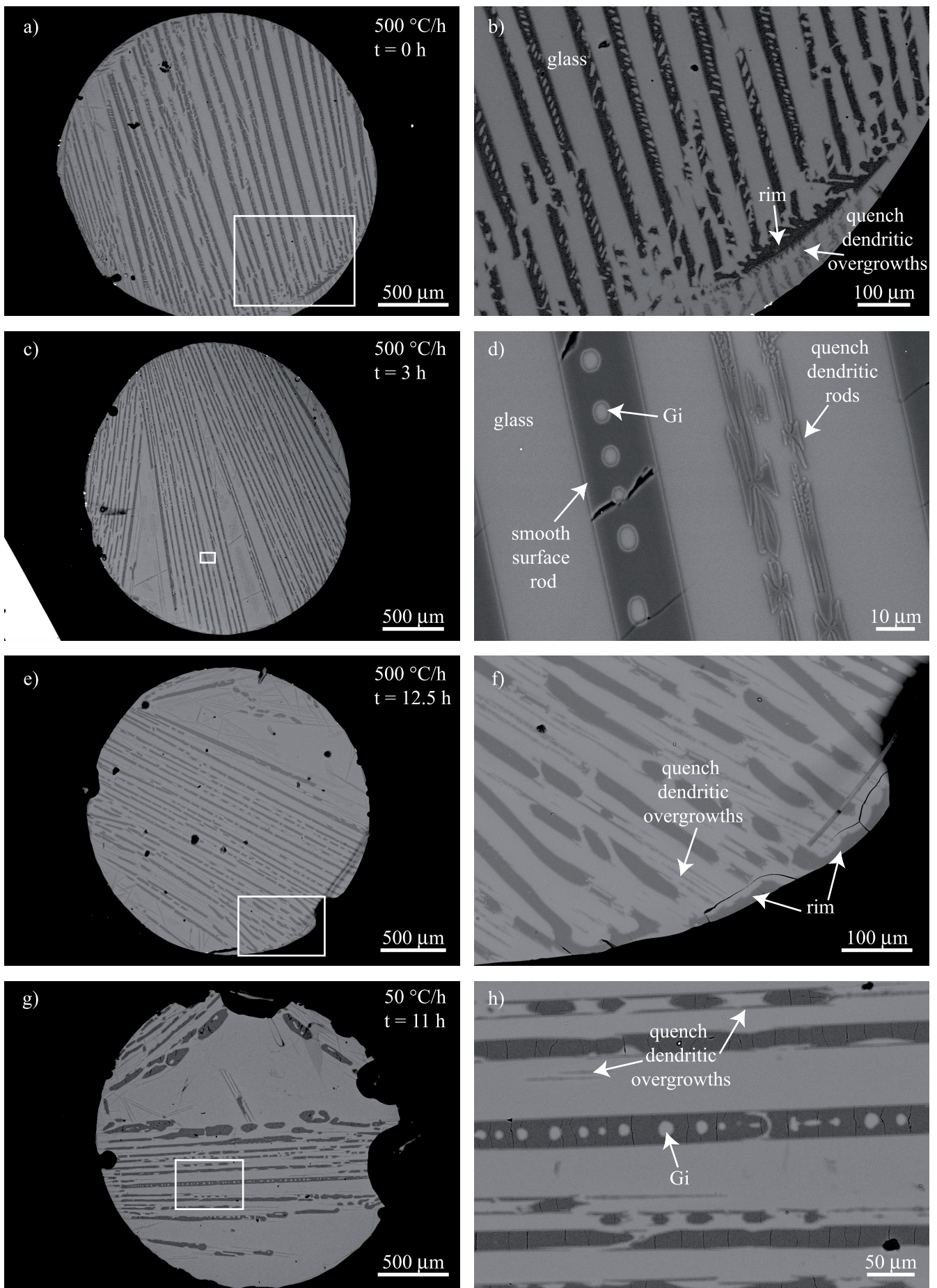


Fig. 6. BSE images of experimental charges showing textural ripening due to reheating to 1400 °C after rapid cooling by (a–f) 500 °C/h or (g–h) 50 °C/h. (a) Experiment 36-N264 was reheated to 1400 °C and immediately quenched. (b) Enlarged view of the rectangle in (a), showing that bars are still dendritic and quench dendrites developed on the rim. (c) Experiment 37-N265 was reheated to 1400 °C and held for 3 h; this charge displays the true BO texture with flat olivine bars. (d) Enlarged view of the rectangle in (c), showing that quench dendritic rods developed between the smooth surfaces of the well-developed rods. (e) Experiment 38-N266 was reheated to 1400 °C and held for 12.5 h. (f) Enlarged view of the rectangle in (e), showing dendritic overgrowths developed on segmented rods. (g) Experiment 39-N271 was cooled at 50 °C/h then reheated to 1400 °C for 11 h. (h) Enlarged view of the rectangle in (g), showing that, even with a slower initial cooling rate, quench overgrowths are always present in reheating experiments.

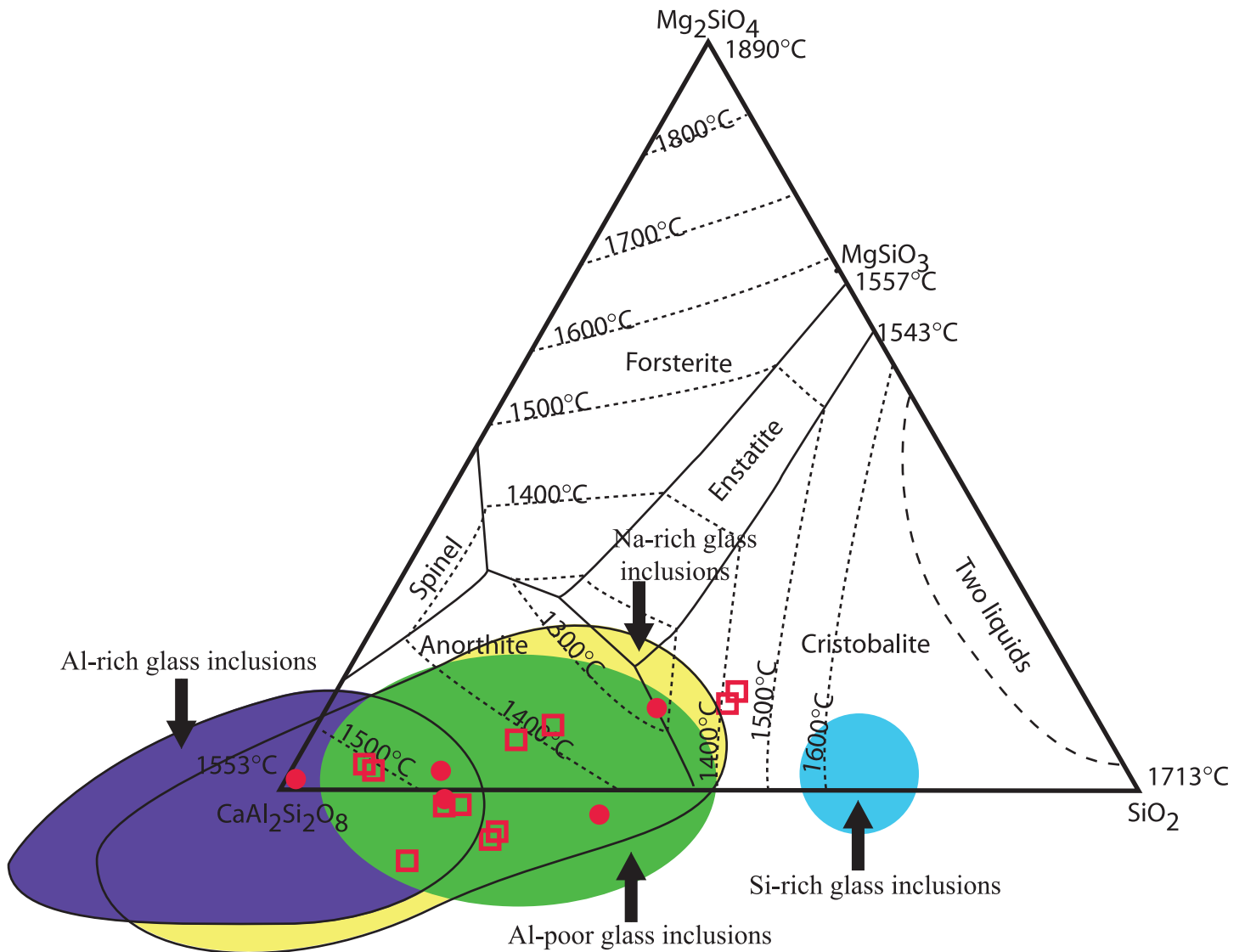


Fig. 7. Normative compositions of olivine-hosted glass inclusions in BO chondrules projected onto the forsterite-anorthite-silica plane. Analysed glass inclusions in natural BO chondrules (open red squares, this study; filled red circles, Varela et al., 2006) show the same compositional variability as olivine-hosted glass inclusions in porphyritic chondrules (Al-rich, Al-poor, Na-rich, and Si-rich glass inclusions, represented by their respective coloured fields). Regardless of chondrule texture, the compositions of glass inclusions plot outside the stability field of their host forsterite.

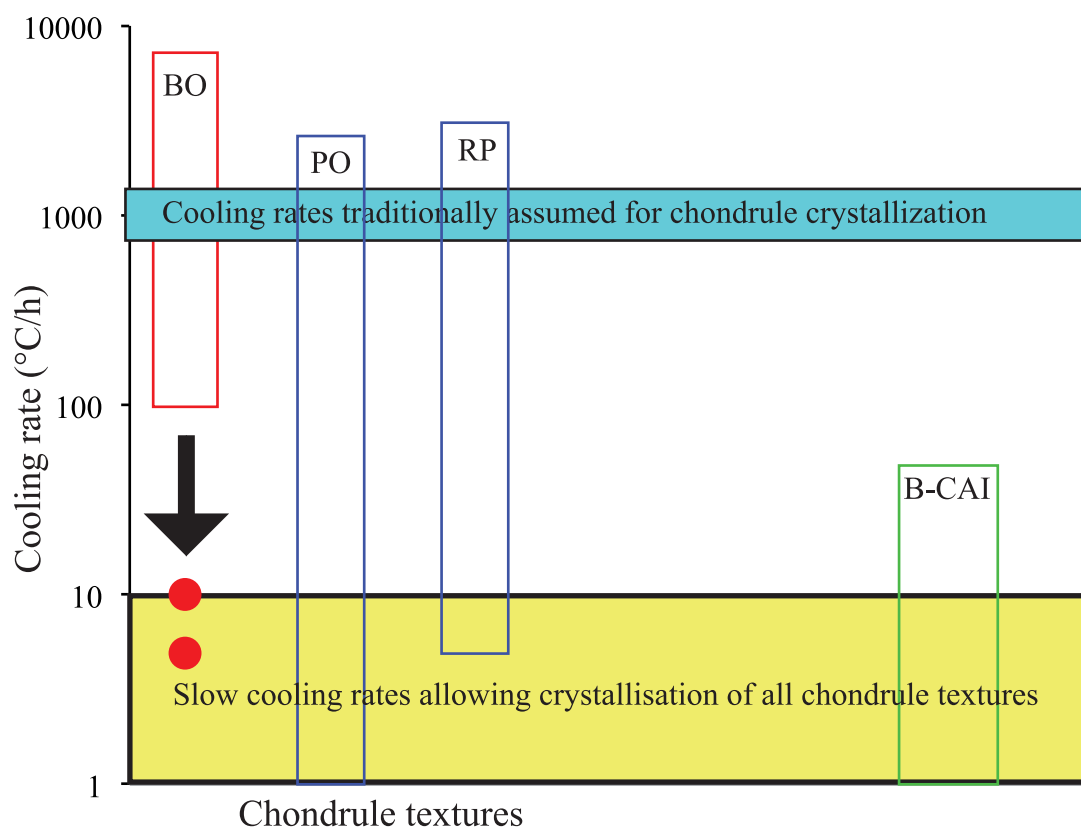


Fig. 8. Cooling rates used to experimentally reproduce chondrule textures. Various chondrule textures (BO, barred olivine; PO, porphyritic olivine and porphyritic olivine- pyroxene; RP, radial pyroxene) can be reproduced over large ranges of cooling rates, except BO chondrules, which are traditionally interpreted to result from rapid cooling (red rectangle; data compilation after Desch et al., 2012; Jones et al., 2018). However, those experiments never reproduced the true BO texture, which our slow cooling results (red circles) reproduce well, thus challenging the traditional assumption that chondrules crystallised under rapid cooling. Consequently, all chondrule textures can be explained by slow cooling rates (<10 °C/h), consistent with those envisioned for magmatic type-B Ca-Al-rich inclusions (Jones et al., 2000).

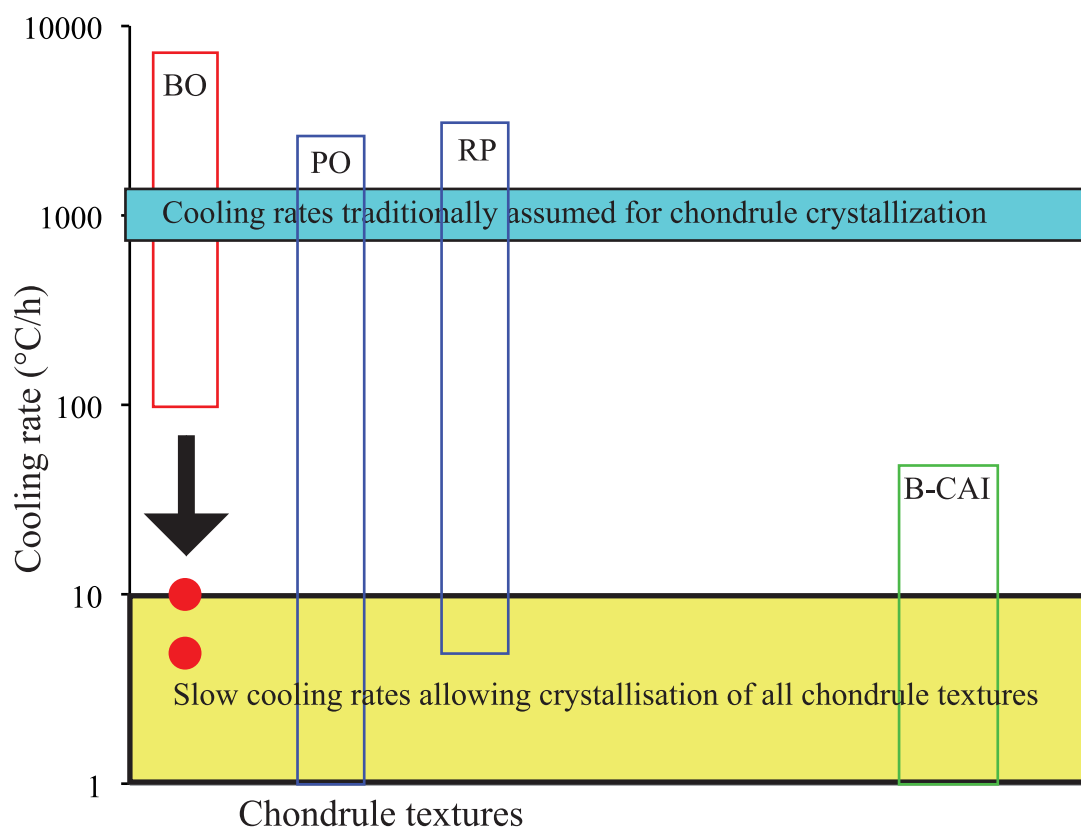


Fig. 8. Cooling rates used to experimentally reproduce chondrule textures. Various chondrule textures (BO, barred olivine; PO, porphyritic olivine and porphyritic olivine- pyroxene; RP, radial pyroxene) can be reproduced over large ranges of cooling rates, except BO chondrules, which are traditionally interpreted to result from rapid cooling (red rectangle; data compilation after Desch et al., 2012; Jones et al., 2018). However, those experiments never reproduced the true BO texture, which our slow cooling results (red circles) reproduce well, thus challenging the traditional assumption that chondrules crystallised under rapid cooling. Consequently, all chondrule textures can be explained by slow cooling rates (<10 °C/h), consistent with those envisioned for magmatic type-B Ca-Al-rich inclusions (Jones et al., 2000).

Table 1. Summary of run conditions and products in isothermal and dynamic crystallisation experiments.

Run n°	T_{starting} (°C)	dT/dt (°C/h)	Dwell time before quench (min)	T_{quench} (°C)	Nb cx	Run products (textures)
Isothermal crystallisation experiments						
1-N171	1450	0	5	1450	nd	gl, Fe-cx, fo (p, s)
2-N170	1450	0	15	1450	nd	gl, Fe-cx, fo (p, s, d)
3-N165	1450	0	30	1450	nd	gl, fo (p, s)
4-N168	1450	0	60	1450	nd	gl, fo (p, s, d)
5-N169	1450	0	120	1450	nd	gl, fo (p, s, d)
6-N174	1450	0	300	1450	nd	gl, fo (p, s, d)
7-N173	1450	0	420	1450	nd	gl, fo (p, s, d)
8-N180	1450	0	960	1450	nd	gl, fo (p, s, d)
9-N193	1500	0	5	1500	nd	gl, Fe-cx, fo (p, s, d)
10-N191	1500	0	15	1500	nd	gl, fo (d)
11-N192	1500	0	30	1500	nd	gl, fo (d)
12-N194	1500	0	120	1500	nd	gl, fo (d)
13-N221	1500	0	180	1500	nd	gl, fo (d)
14-N195	1500	0	300	1500	nd	Ca-Al cx
15-N196	1500	0	420	1500	nd	Ca-Al cx
16-N234	1600	0	5	1600	nd	gl, fo (d)
17-N235	1600	0	15	1600	nd	gl, fo (d)
18-N236	1600	0	30	1600	nd	gl, fo (d)
19-N237	1600	0	60	1600	nd	gl, fo (d)
20-N238	1600	0	120	1600	82	gl, fo (d)
21-N241	1600	0	180	1600	nd	gl, fo (d)
22-N239	1600	0	300	1600	nd	gl, fo (d)
Dynamic crystallisation experiments						
23-N258	1600	1000	0	1200	4	gl, fo (FBO)
24-N259	1600	500	0	1200	1	gl, fo (FBO)
25-N267	1600	500	0	1400	62	gl, fo (d)
26-N268	1600	500	0	1300	5	gl, fo (FBO)
27-N260	1600	500	120	1200	3	gl, fo (FBO)
28-N263*	(i) 1600	500	240	1200	3	gl, fo (FBO)
	(ii) 1200	300	3720	900		
29-N262	1600	250	0	1200	4	gl, fo (FBO)
30-N299	1600	200	0	1200	4	gl, fo (FBO)
31-N261	1600	50	0	1200	3	gl, fo (FBO)
32-N274	1600	50	0	1400	48	gl, fo (d)
33-N273	1600	50	0	1300	3	gl, fo (FBO)
34-N270	1600	10	0	1200	1	gl, fo (TBO)
35-N272	1600	5	0	1210	3	gl, sp, fo (TBO)

Nb cx, number of crystals; nd, not determined.

Phase abbreviations: gl, glass; sp, spinel; fo, forsterite; Fe-cx, iron-rich oxide crystal; Ca-Al cx, Ca-Al-rich crystal.

Textural abbreviations: p, polyhedral crystal; s, skeletal crystal; d, dendritic crystal; FBO, false barred olivine (dendritic olivine bars, olivine rim, non-ovoid glass inclusions); TBO, true barred olivine (flat olivine bars, olivine rim, ovoid glass inclusions).

*Experiment 28-N263 was (i) rapidly cooled to 1200 °C at 500 °C/h and held for 4 h, then (ii) rapidly cooled to 900 °C at 300 °C/h and held for 62 h before the air quench.

Table 2. Summary of run conditions and products in reheating experiments.

Run n°	T_{starting} (°C)	dT/dt (°C/h)	Dwell temperature (°C)	Reheating temperature (°C)	Dwell time before quench (h)	Number of crystals	Run products (textures)
36-N264	1600	500	1200	1400	0	1	gl, fo (FBO)
37-N265	1600	500	1200	1400	3	4	gl, fo (TBO)
38-N266	1600	500	1200	1400	12.5	3	gl, fo (TBO)
39-N271	1600	50	1200	1400	11	4	gl, fo (TBO)
40-N269	1600	500	1200	1500	0	46	gl, fo (d)

Phase abbreviations: gl, glass; fo, forsterite.

Textural abbreviations: d, dendritic crystal; FBO, false barred olivine (dendritic olivine bars, olivine rim, non-ovoid glass inclusions); TBO, true barred olivine (flat olivine bars, olivine rim, ovoid glass inclusions).

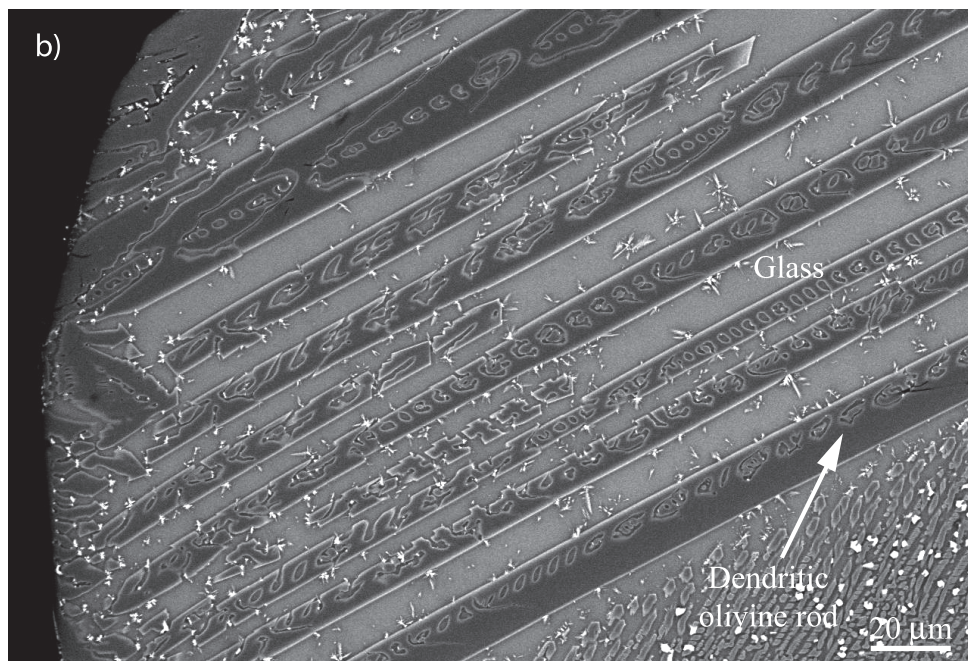
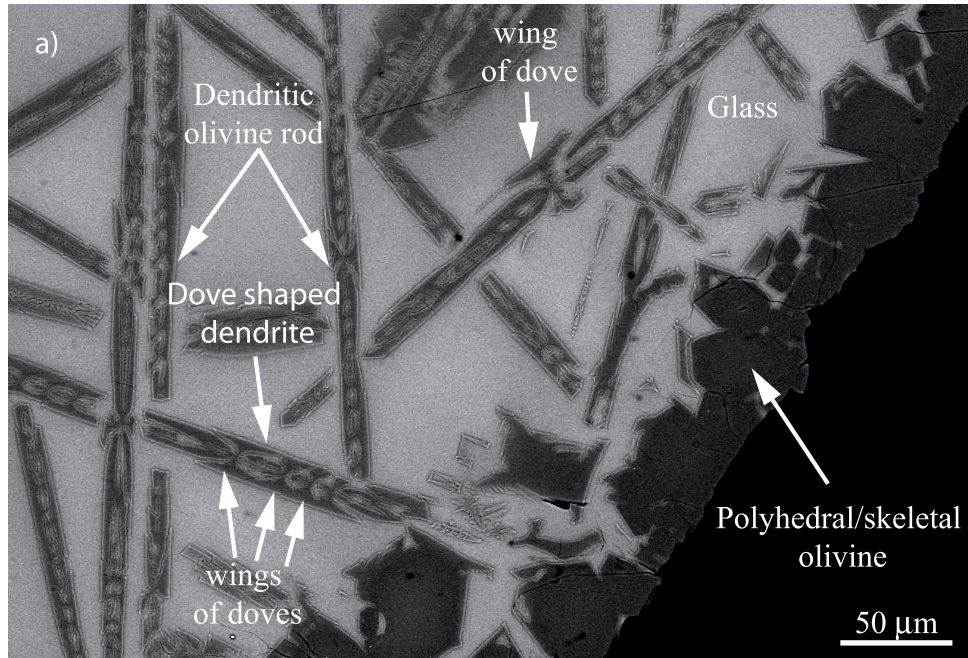


Fig. S1. BSE images of isothermal experimental charges showing dendritic crystal textures produced during air quenching. (a) Experiment 8-N180 was held isothermally at 1450 °C for 16 h before quenching in air and shows both dendritic rods and polyhedral-skeletal olivine crystals. (b) Experiment 7-N173 was held isothermally at 1450 °C for 7 h before quenching in air and shows dendritic parallel rods of olivine..

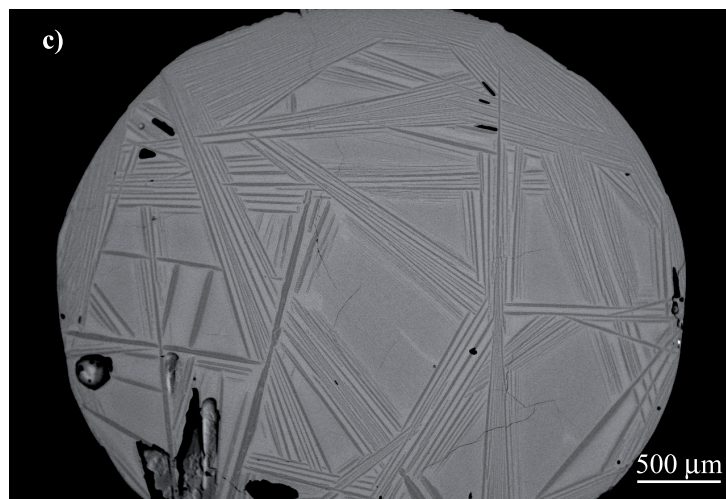
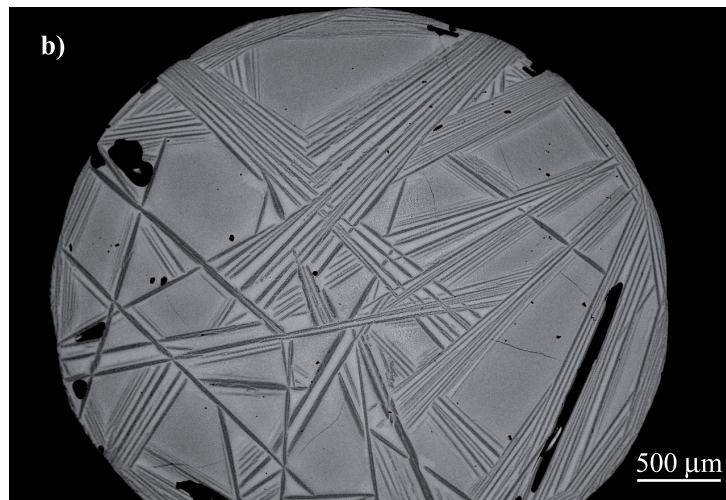
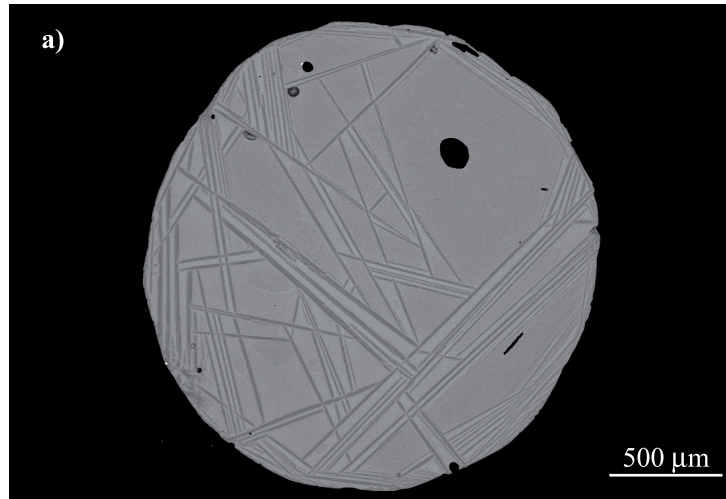


Fig. S2. BSE images of experimental charges showing dendritic crystal textures produced during air quenching. (a) Dynamic crystallisation experiment 40-N269 was cooled to 1200 °C and reheated to 1500 °C; it displays numerous thin dendrites of olivine in the glass mesostasis. (b) Isothermal experiment 12-N194 was held at 1500 °C for 2 h before air quenching and shows a dendritic texture similar to that in (a). (c) Isothermal experiment 16-N234 was held at 1600 °C for 5 minutes before air quenching, and shows a dendritic texture similar to those in (a) and (b).

Table S1. Chemical compositions (EDS analyses, in wt.%) of olivines crystallized during dynamic crystallization experiments.

Run n°	n	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Fa, mol %
23-N258	4	41.01 (0.12)	0.44 (0.08)	7.75 (0.30)	50.59 (0.28)	0.19 (0.01)	7.85 (0.32)
24-N259	5	40.94 (0.21)	0.51 (0.20)	7.24 (0.36)	51.04 (0.42)	0.24 (0.02)	7.29 (0.38)
25-N267	5	41.08 (0.20)	0.53 (0.03)	10.55 (0.30)	47.47 (0.26)	0.34 (0.04)	10.94 (0.31)
26-N268	4	40.81 (0.13)	0.14 (0.09)	8.09 (0.23)	50.70 (0.21)	0.24 (0.04)	9.94 (0.29)
27-N260	5	41.46 (0.30)	0.37 (0.03)	9.54 (0.44)	48.31 (0.26)	0.30 (0.07)	9.86 (0.46)
28-N263	4	41.37 (0.49)	0.27 (0.03)	11.12 (0.22)	46.95 (0.38)	0.26 (0.06)	11.62 (0.17)
29-N262	4	40.96 (0.14)	0.15 (0.12)	8.65 (0.59)	49.95 (0.47)	0.27 (0.07)	8.78 (0.61)
30-N299	5	42.71 (0.55)	0.37 (0.06)	5.29 (0.26)	51.37 (0.39)	0.24 (0.05)	5.41 (0.25)
31-N261	5	42.54 (0.32)	0.21 (0.04)	6.59 (0.19)	50.41 (0.31)	0.23 (0.04)	6.77 (0.19)
32-N274	4	41.96 (0.34)	0.66 (0.02)	6.63 (0.20)	50.39 (0.29)	0.33 (0.05)	6.78 (0.19)
33-N273	5	42.41 (0.20)	0.38 (0.03)	6.08 (0.21)	50.86 (0.30)	0.24 (0.04)	6.23 (0.23)
34-N270	4	42.49 (0.15)	0.07 (0.04)	0.26 (0.09)	56.93 (0.22)	0.22 (0.03)	0.26 (0.09)
35-N272	6	44.07 (0.47)	0.42 (0.10)	0.03 (0.04)	55.07 (0.41)	0.40 (0.04)	0.03 (0.04)

Abbreviations: n, number of analyses; Fa, fayalite content

Table S2. Chemical compositions (EDS analyses, in wt.%) and normative mineralogy of glass inclusions in barred olivine chondrules.

sample	A-211	A-212	A-225	A-226	A-228	A-230	A-231	A-232	F-340	S-273	V-1 ^a
SiO ₂	46.78	51.58	51.02	49.30	48.25	49.16	48.74	51.97	63.90	65.34	47.51
TiO ₂	nd	2.46	2.00	2.05	2.74	3.00	3.78	2.43	nd	nd	0.05
Al ₂ O ₃	32.36	19.98	24.77	25.49	21.72	21.18	18.19	20.23	16.13	16.57	32.79
Cr ₂ O ₃	nd	0.93	0.97	1.02	0.82	nd	1.19	1.28	2.15	nd	0.01
FeO	nd	nd	nd	nd	nd	nd	nd	nd	1.16	1.08	0.59
MnO	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.00
MgO	1.45	0.87	1.28	1.04	1.86	1.15	3.85	0.82	3.93	3.98	0.69
CaO	17.38	16.00	8.43	10.34	16.03	18.23	16.59	15.71	4.93	3.20	17.11
Na ₂ O	2.03	8.17	11.52	10.75	8.57	7.28	7.66	7.56	6.52	8.34	2.07
K ₂ O	nd	nd	nd	nd	nd	nd	nd	nd	1.29	1.49	0.04
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.85
An	90.14	61.64	79.06	80.72	67.46	64.40	56.82	62.22	49.51	50.75	91.22
Di	-1.67	21.90	-23.48	-16.50	17.95	28.34	29.08	19.94	-17.11	-25.65	-3.66
Fo	3.12	-5.39	10.25	7.47	-2.14	-6.97	-1.76	-4.87	13.27	16.13	2.41
Qtz	8.41	21.85	34.17	28.31	16.72	14.22	15.86	22.71	54.33	58.76	10.03

Abbreviations: sample A, Allende chondrite; sample F, Felix chondrite; sample S, Sahara chondrite; sample V, Vigarano chondrite; nd, not determined; An, anorthite; Di, diopside; Fo, forsterite; Qtz, quartz.

^aAnalysed by WDS.

Table S3. Chondrule number density and solid:gas ratio as a function of cooling time scale.

T_{in} (K)	T_{end} (K)	Cooling rate (K/h)	Cooling time scale (s)	Collision velocity v (m/s)	Chondrule number density n (m^{-3})	Mass density of precursors ρ_s (Kg/m^3)	Solid:gas density ratio
1900	1400	10	180,000	5	3.55	6.4×10^{-6}	4.5
1900	1200	10	252,000	5	2.53	4.5×10^{-6}	3.2
1800	1400	10	144,000	5	4.44	8.0×10^{-6}	5.7
1800	1200	10	216,000	5	2.96	5.3×10^{-6}	3.8
1900	1400	5	360,000	5	1.77	3.2×10^{-6}	2.2
1900	1200	5	504,000	5	1.26	2.2×10^{-6}	1.6
1800	1400	5	288,000	5	2.22	4.0×10^{-6}	2.8
1800	1200	5	432,000	5	1.48	2.6×10^{-6}	1.9
1900	1400	10	180,000	0.5	35.5	6.4×10^{-5}	45.8
1900	1200	10	252,000	0.5	25.3	4.5×10^{-5}	32.7
1800	1400	10	144,000	0.5	44.4	8.0×10^{-5}	57.2
1800	1200	10	216,000	0.5	29.6	5.3×10^{-5}	38.19
1900	1400	5	360,000	0.5	17.7	3.2×10^{-5}	22.9
1900	1200	5	504,000	0.5	12.6	2.2×10^{-5}	16.3
1800	1400	5	288,000	0.5	22.2	4.0×10^{-5}	28.6
1800	1200	5	432,000	0.5	14.8	2.6×10^{-5}	19.0
Results of Bischoff et al. (2017) calculations							
1900	1400	1,800	1,000	5	640	1.1×10^{-3}	825
1900	1400	18,000	100	5	6,400	1.2×10^{-2}	8,250
1900	1400	1,800	1,000	0.5	6,400	1.2×10^{-2}	8,250
1900	1400	18,000	100	0.5	64,000	1.2×10^{-1}	82,500

T_{in} , initial chondrule temperature; T_{end} , the lowest temperature at which melt could have been present in the chondrule.

n : the local number density of chondrules can be estimated by $n = \frac{0.8}{t_{\text{cool}} r_p^2 v}$, where $r_p = 0.5$

mm is the chondrule radius; v is the collision velocity, which typically varies between 0.5 and 5 m/s; and t_{cool} is the cooling time, which corresponds to the time elapsed before chondrules were too cold to stick together (Bischoff et al., 2017).

ρ_s : the initial local mass density of all chondrule precursor materials can be calculated as $\rho_s = 3.3 \rho_p \frac{r_p}{t_{\text{cool}} v}$, where the individual chondrule mass density $\rho_p = 3,500 \text{ kg}/\text{m}^3$ (Bischoff et al., 2017). The ratio between precursor density and gas density is calculated assuming a mass density of $1.4 \times 10^{-6} \text{ kg}/\text{m}^3$ at 1 AU in a minimum-mass solar nebula (Hayashi et al., 1985).