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PARTIAL MELTING AND P-T EVOLUTION OF ECLOGITE-FACIES METAPELITIC MIGMATITES FROM THE EGERE TERRANE (CENTRAL HOGGAR, SOUTH ALGERIA)

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ABSTRACT

The Egéré terrane (Central Hoggar, South Algeria) includes mafic eclogite lenses boudinaged in metapelitic rocks with high-pressure relicts. These metapelites show textural records of partial melting, mainly primary melt inclusions enclosed in garnet crystals and later crystallized as "nanogranitoids". Garnet porphyroblasts also contain inclusions of quartz, kyanite, phengite, biotite, staurolite and rutile, and show a smoothed prograde zoning with a Mn bell-shaped profile. The peak high-pressure metamorphic assemblage consists of garnet, kyanite, phengite (Si up to 6.36), quartz, rutile, ±ilmenite, ±feldspars and melt. Phengite has partially transformed into fine-grained aggregates of biotite, plagioclase and K-feldspar, a microstructure interpreted as resulting from a dehydration melting during exhumation. Phengite breakdown, along with other retrograde reactions, produced a late paragenesis with biotite, plagioclase, K-feldspar, quartz, almandine-rich garnet, ±sillimanite, ±staurolite, ±muscovite and ilmenite. The thermodynamic modeling of P-T pseudosections allows to constrain various steps of the metamorphic history: beginning of the garnet growth at 4.0 kbar and ~600ºC during prograde metamorphism; pressure peak at 14–20 kbar; temperature peak at 800–820ºC; formation of the last assemblage at 6.0–5.5 kbar and 725–685°C. Partial melting likely started during the prograde path when crossing the H_2O-saturated solidus, at $T \geq 650$–670°C and $P \geq 10$ kbar, continued upon heating, up to the peak conditions, as well as during decompression. This evolution is interpreted in terms of subduction of the continental crust to mantle depths, followed by an exhumation through a clockwise P-T path, during the Pan-African orogeny. The Egéré metapelites are relatively well-preserved eclogite-facies rocks, contain inclusions of "nanogranitoids" hitherto very little

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38 known in eclogite-facies metamorphic rocks, and represent an unusual trace of
39 subduction within a Neoproterozoic orogen.

40 **Keywords:** Hoggar, Egéré, high-pressure metapelites, phengite, partial melting,
41 nanogranitoids, pseudosections.

42 **1. INTRODUCTION**

43 The study of anatexis and *P-T* conditions of high-grade rocks is fundamental for
44 understanding the geodynamic evolution and rheological behavior of the continental
45 crust, particularly in convergent plate boundaries (*e.g.*, Rosenberg and Handy 2005).
46 Understanding the significance of anatexis requires the coupling of detailed petrological,
47 (micro)structural, geochemical and geochronological studies on migmatites.

48 This work combines two modern techniques to retrieve information on the
49 petrogenesis of Neoproterozoic anatectic continental crust exposed in the Hoggar orogen,
50 a Pan-African collisional belt extending from southern Algeria to northwestern Niger
51 (Black et al. 1994; Caby 2003; Liégeois et al. 2003): (a) thermodynamic modeling of *P-T*
52 pseudosections and (b) microstructural study of melt-bearing inclusions, including
53 nanogranitoids (*i.e.*, crystallized melt inclusions) and providing information on the
54 relative timing and nature of anatexis.

55 While melt inclusions are well-known to igneous petrologists and have been
56 extensively studied in subvolcanic and extrusive rocks, their occurrence in high-grade
57 metamorphic rocks of anatectic terranes is a novel and powerful research tool (Cesare et
58 al. 2009, 2015). Melt inclusions in migmatites and granulites are generally trapped by
59 peritectic minerals produced by incongruent melting reactions and, hence, represent
60 snapshots of primary anatectic melts (Cesare et al. 2009, 2015; Ferrero et al. 2012, 2018;
61 Bartoli et al. 2014, 2016). Although the study of melt inclusions in metamorphic rocks is
62 still in its infancy, those investigated so far indicate that the retrieved melt compositions
63 can be representative of the matrix melt present in the rock during entrapment (Acosta-
64 Vigil et al. 2010, 2012; Cesare et al. 2015; Bartoli et al. 2016).

65 An increasing number of high-grade metamorphic rocks have been recently
66 discovered and investigated from different localities in the Hoggar. Among them, rocks
67 that reached eclogite-facies conditions and preserved high-pressure (HP) parageneses are
68 particularly interesting because their study is essential to unravel the nature and evolution
69 of orogenic processes (*e.g.*, Berger et al. 2009, 2014; Doukkari et al. 2014, 2015; Adjerid
70 et al. 2015; Fettous 2016). To date, however, most of the reported and investigated HP
71 rocks are represented by metric to hectometric mafic eclogitic lenses. This study, in
72 contrast, investigates HP migmatitic metapelites of the Egéré-Aleksod terrane, Central
73 Hoggar, which are the first reported in the Hoggar with melt inclusions, now crystallized

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74   into nanogranitoids. The principal goal of this contribution is elucidating the
75   metamorphic and anatectic history of these migmatites, and their implications for the
76   history of the Egéré terrane. This new data is combined with data from the surrounding
77   domains, to add new constraints on the eclogite-facies metamorphism in the Central
78   Hoggar and understand the geodynamic evolution of this orogenic belt.

79   **2. GEOLOGICAL BACKGROUND AND FIELD RELATIONSHIPS**

80   The Tuareg shield (S Algeria, W Mali and NW Niger) represents a Pan-African belt
81   located in between the West African Craton (WAC) to the west and the Saharan
82   metacraton to the east (Fig. 1). Formed by amalgamation of up to twenty-five terranes, it
83   is composed of Archean, Paleoproterozoic and juvenile Neoproterozoic rocks variably
84   reworked during the Pan-African orogeny (750–550 Ma; Black et al. 1994; Caby 2003;
85   Liégeois et al. 2003; Peucat et al. 2003; Liégeois et al. 2013; Liégeois 2019). According
86   to Liégeois et al. (1998), the long orogenic process includes a first major collision
87   between the Saharan metacraton and Eastern Hoggar terranes at ~750 Ma, marked by
88   major thrusts and the exhumation of HP metamorphic rocks. At around 650 Ma,
89   subduction and the maximum of tonalite-trondhjemite-granodiorite (TTG) magmatism
90   took place (Bechiri-Benmerzoug 2009). This episode produced HP metamorphism in the
91   Central Hoggar, the oblique collision of the Western Hoggar terranes with the WAC, and
92   northward migration of the Hoggar terranes along north-south shear zones, hundreds of
93   kilometers long (Bertrand and Caby 1978; Bertrand et al. 1986; Black et al. 1979; Caby
94   et al. 1989; Peucat et al. 2003). Later events, between 630 and 580 Ma, included high-
95   temperature (HT) regional metamorphism and the generation of high-K calc-alkaline
96   batholiths (Liégeois et al. 2003; Acef et al. 2003; Abdallah et al. 2007).

97   The polymetamorphic Central Hoggar is well-exposed at the core of the Tuareg
98   shield (Fig. 1a). It is made of eight terranes, delimited by shear zones: Laouni, Aouilène,
99   Tefedest, Egéré-Aleksod, Azrou n'Fad, Assode-Issalane, Serouenout and Tazat (Black et
100   al. 1994). The first five are grouped under the "LATEA metacraton" acronym (Fig. 1b;
101   Liégeois et al. 2003, Liégeois 2019).

102   Lelubre (1952) and Duplan (1967, 1972) were the first to study the Egéré-Aleksod
103   terrane, where Latouche (1985) described ortho- and para-derived rocks constituting
104   domes and basins, respectively. However, Doukkari et al. (2014, 2015), Doukkari (2016),
105   Arab et al. (2015) and Arab (2016) have considered the Egéré terrane as composed of two
106   juxtaposed tectonic units separated by a mylonitic thrust, considered as a major tectonic
107   contact: (i) The Arechchoum basement made of migmatitic ortho- and para-gneisses
108   derived from Paleoproterozoic protoliths; (ii) the Egéré meta-sedimentary cover, an
109   eclogite-facies unit made up mainly of kyanite-bearing metapelites (Fig. 2c-d) associated
110   with subordinate marbles, quartzites, several-meter-long lenses of mafic eclogite,

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111 amphibolite and rare ultramafic rocks (Fig. 2a-b; Sautter 1985; Doukkari et al. 2014,
112 2015; Arab et al. 2015). In the investigated Izzilatène area, migmatites appear as
113 metatexites (Fig. 2d), and mafic eclogites constitute lenses within both migmatites and
114 marbles (Fig. 2a-b). Field observations, metamorphic constraints and U-Pb ages, as well
115 as geochemical data, suggest that the Egéré represents a former passive continental
116 margin intruded by mafic rocks, which afterwards was deeply subducted and then
117 exhumed (Arab 2016; Doukkari 2016; Ouzegane et al. in preparation).

3. PETROGRAPHY AND MINERAL CHEMISTRY

119 Representative metapelitic samples were collected from the Egéré meta-sedimentary
120 unit in the Izzilatène area, at the north of the Egéré terrane and ca. 50 km south of similar
121 rocks first reported by Arab et al. (2015) in the Tighsi area (Fig. 1b). In the field, these
122 metapelites appear as stromatic migmatites, with cm-to-mm-thick leucocratic bands
123 (leucosomes) alternating with darker bands rich in garnet and biotite, and parallel to the
124 main foliation. In hand specimen and under the microscope, they are banded rocks,
125 consisting of two petrographically different domains, leucosomes and melanosomes. The
126 leucosomes consist of quartz, feldspars and minor garnet. They are interspersed with
127 quartz-poor mafic melanosomes, which contain large garnet crystals, up to several
128 centimeters in diameter, together with kyanite, biotite, white micas, staurolite, sillimanite,
129 rutile and ilmenite (Fig. 2c-d).

130 Eight specimens of migmatitic metapelites (Table A in supplementary materials
131 [SM]) have been studied under the SEM and analyzed at the electron microprobe (see
132 methods in SM). They consist of variable proportions of garnet, kyanite, white micas
133 (phengite and muscovite), biotite, K-feldspar, plagioclase, quartz, staurolite and
134 sillimanite. Under the polarizing microscope, these rocks show a fine- to medium-grained
135 matrix made of quartz, feldspars, phengite, biotite, kyanite, sillimanite and staurolite,
136 which encloses cm-sized porphyroblasts of garnet and, less commonly, of kyanite (Fig. A
137 in SM). Accessory minerals are apatite, rutile, allanite, tourmaline, ilmenite and zircon.
138 These rocks often show an *augen*-like microstructure produced by large monocrystalline
139 quartz crystals or polycrystalline quartz aggregates (Fig. 3e), and/or large polymineralic
140 pseudomorphs after phengite (Figs. 3f, 4d-f; see below).

141 All the rocks sampled show comparable features; on the basis of microstructural
142 observations, the minerals have been grouped into the following three main metamorphic
143 parageneses.

144 (i) The earliest preserved assemblage (M_1) is represented by abundant mineral relicts
145 armored within garnet porphyroblasts (Grt_1), including quartz (Qz_1), biotite
146 (Bt_1), phengite (Ph_1), staurolite (St_1), kyanite (Ky_1), plagioclase (Pl_1), rutile
147 (Rt_1) and ilmenite (Ilm_1) (Figs. 3a-d, 4c).

148   (ii) The high-grade peak paragenesis (M_2) consists of the rims of the garnet
149   porphyroblasts (Grt_2) at contact with their matrix, made of kyanite (Ky_2),
150   phengite flakes (Ph_2), quartz (Qz_2), plagioclase (Pl_2), K-feldspar (Kfs_2),
151   apatite, rutile (Rt_2) and ilmenite (Ilm_2) (Fig. 4a). The minerals in the matrix,
152   mainly Qz_2, Ph_2 and Ky_2, define the main foliation in the rock. The
153   coexistence of melt with this paragenesis is discussed later.
154   (iii)   A late assemblage (M_3) occurs either as a recrystallized matrix with biotite
155   (Bt_3), plagioclase (Pl_3), K-feldspar (Kfs_3), quartz (Qz_3), muscovite (Ms_3),
156   garnet (Gt_3), sillimanite (Sil_3), ilmenite (Ilm_3) and/or staurolite (St_3) (Figs.
157   3g-h, 4d), or as fine-grained symplectites made up of Bt_3, Pl_3 and Kfs_3 (Fig.
158   4e-f), which formed mostly after Grt_{1-2} and Ph_2.

159   In the following subsections, we describe the microstructure and composition of the
160   main minerals, whose analyzes are summarized in Tables B-F (SM).

161   *3.1. Garnet*

162   Three generations of garnet have been distinguished on the basis of microstructures
163   and compositions. The first two generations (Grt_{1-2}) correspond to the core and rims,
164   respectively, of euhedral to subhedral porphyroblasts, ~0.4 to 7 cm in diameter. These
165   porphyroblasts are well preserved, except some rims that appear partially replaced by
166   fine-grained Bt_3+Pl_3 aggregates (Figs. 3a, 4b). These Grt_{1-2} crystals are crowded with
167   mono- and poly-crystalline inclusions, which often define an either straight (Fig. Ac, e, g
168   in SM), sigmoid or spiral (Fig. Ab) internal foliation, at variable angles with respect to
169   the foliation in the matrix but occasionally in continuity with it, indicating that the garnet
170   porphyroblasts grew before or during the main deformation event. Some inclusions are
171   large (0.5–1.5 mm), anhedral, and consist of either individual or polycrystalline
172   inclusions of Qz_1, Ph_1, Bt_1, St_1, Rt_1, Ilm_1 and/or zircon (Fig. 3b-d). Others, from 0.1 to 0.5
173   mm in size, are characterized by the presence of a thin optically-continuous moat of
174   plagioclase surrounding quartz (Pl in Figs. 3c, 4c). There are also small (~5–30 μm)
175   polymineral inclusions with the negative shapes of the host garnet (Fig. 5), which have all
176   the characteristics of nanogranitoids (Cesare et al. 2015). The largest polymineral
177   inclusions are visible mainly in the mantle and rim of the garnet porphyroblasts, while the
178   nanogranitoids are apparently distributed throughout the entire crystals. Sometimes,
179   garnet is also skeletal and appears intergrown with quartz (Fig. 3e).

180   Garnet porphyroblasts are rich in almandine ($Alm_{83-65}Prp_{4-13}Grs_{26-8}Sps_{6-0}$: Fig. 6a-d;
181   Table B in SM). In most of the samples, they show profiles characterized, from core to
182   rims, by decreases in X_{Grs}, X_{Sps} and X_{Fe} and an increase in X_{Prp} (Fig. 6a-d). A late
183   compositional zoning, with increases in X_{Fe}, X_{Sps} and X_{Grs}, and a decrease in X_{Prp} (Fig.
184   6c), is observed in the outer rims that are corroded by a late Bt_3+Pl_3 symplectite.

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185   Grt_3 is observed as small crystals either scattered in the matrix, in association with

186   Bt_3, Pl_3, St_3 and sometimes Sil_3, or close to the large Grt_{1-2} porphyroblasts, of which they

187   can represent modified relics of their resorbed rims. Compared with Grt_1, Grt_3 is richer in

188   Fe and poorer in Ca (Table B), having a very low grossular content (X_{Grs} = 0.06–0.12)

189   and a fairly high X_{Fe} (0.88–0.94), similarly to the retrograde outer rims of some corroded

190   garnet porphyroblasts (Fig. 6c-d).

191   *3.2. White micas*

192   Three generations of white mica have been observed. Phengite Ph_1 appears as rare

193   inclusions in the garnet porphyroblasts. Phengite Ph_2, by far the most abundant, occurs in

194   the matrix as large flakes, ~0.5–3.0 mm long, defining the main foliation; it therefore

195   developed before and/or during the main deformation event. These large crystals

196   frequently show Bt_3 and Ilm_3 lamellae, exsolved preferentially parallel to the (001)

197   cleavage (Figs. 3f, 4e-f). Ilm_3 exsolution lamellae are particularly abundant in the vicinity

198   of pre-existing Ilm_2 crystals (1 *in* Fig. 4f), suggesting that the initial Ph_2 was more

199   titaniferous here. Ph_2 flakes are partially or totally replaced by fine-grained symplectitic

200   aggregates of Bt_3+Pl_3, bounded by a continuous Kfs_3 corona at contact with Qz_2 (Fig. 4f)

201   and by a Pl_3+Ilm_3 symplectite around Ilm_2 (2 *in* Fig. 4f). Similar pseudomorphs after

202   phengite, observed elsewhere, are generally interpreted as formed during exhumation

203   (*e.g.*, Indares and Dunning 2001; Korhonen and Stout 2005; Lang and Gilotti 2007;

204   Dokukina et al. 2017). The third generation of white mica consists of small grains (0.1–

205   0.3 mm) of muscovite Ms_3, some of which are by-products of the Ph_2 breakdown, being

206   isolated in the Bt_3+Pl_3 symplectites (Figs. 3f, 4f).

207   White micas in most microstructural settings have a phengitic composition, though

208   with various Si contents (Fig. 4e; Table C in SM). Ph_1 is poorly substituted (Si ≈ 6.25

209   a.p.f.u.). The Ph_2 flakes are zoned, showing a decrease in phengite substitution from core

210   to rims: Si = 6.44 a.p.f.u. at core *vs.* 6.05 at rim; Al^t = 4.96 *vs.* 5.76; Ti = 0.17 *vs.* 0.08;

211   (Mg + Fe) = 0.51 *vs.* 0.22. The initial composition of a Ph_2 zone rich in Ilm_3 exsolution

212   lamellae (1 *in* Fig. 4f) was reconstructed at the electron microprobe by scanning ~100-

213   μm^2 adjacent areas with the electron beam during acquisition; the average composition

214   (Ti-Ph *in* Table C) suggests that Ph_2 before exsolution was here strongly substituted by

215   the theoretical end-member Ti-Fe-phengite (~1/3 of $K_2Fe_2Ti_2[Si_6Al_2]O_{20}(OH)_4$:

216   Auzanneau et al. 2010). Ms_3 in the Bt_3-Pl_3 pseudomorphs after phengite Ph_2 is similar in

217   chemistry to individual Ms_3 grains present in the rock matrix (Table C; Fig. 4e; Si =

218   5.96–6.05 a.p.f.u.; Ti = 0.03–0.12; [Mg + Fe] = 0.16–0.20) and to the rims of Ph_2 flakes,

219   suggesting that the zoning of the latter is linked to the formation of the Bt_3-Pl_3

220   symplectite and thus to retrogression.

221   *3.3. Biotite*

222   Biotite occurs in four main microstructural varieties: (i) As inclusions in garnet (Bt_1:
223   Fig. 3b). (ii) In the rock matrix, associated with Pl_3, Kfs_3 or St_3. Commonly, these biotite-
224   rich aggregates are fairly coarse-grained and oriented according to the main foliation
225   (Figs. Ac in SM, 3g bottom), but they sometimes show a gradual transition with fine-
226   grained unoriented $Bt_3+Kfs_3+Pl_3$ aggregates after Ph_2 (Fig. 3g upwards). Therefore,
227   biotite in the matrix is a post-peak Bt_3, the size and orientation of which depend on when
228   it formed relative to the main deformation event. (iii) Bt_3 is also intergrown Sil_3 (Fig. 3h).
229   (iv) Finally, minute Bt_3 lamellae parallel to the (001) plane of Ph_2 resulted from late
230   exsolution (Fig. 4e-f).

231   The large oriented biotite flakes in the matrix are unzoned, more magnesian (X_{Fe} =
232   0.40–0.54) and lower in Ti (≤0.34 a.p.f.u.) with respect to biotite from the fine-grained
233   aggregates in the matrix (Bt_3: X_{Fe} = 0.67–0.87; Ti = 0.36–0.48 a.p.f.u.) (Fig. 6g; Table D
234   in SM). Biotite exsolution lamellas in phengite are similar to biotite in the pseudomorphs
235   after Ph_2 (Bt_3; X_{Fe} = 0.66–0.69; Ti = 0.32–0.34 a.p.f.u.) (Fig. 4f; Table D).

236   *3.4. Feldspars*

237   K-feldspar ($Or_{99–84}Ab_{1–15}An_{0–2}$: Fig. 6h; Table E in SM) is widespread and, in most
238   cases, present in the leucosome. Late K-feldspar (Kfs_3) occurs in the late Bt_3-rich
239   aggregates and as coronae enveloping quartz at the former Qz_2-Ph_2 boundaries (Fig. 4e-
240   f).

241   The rare plagioclase crystals (0.1 mm) present in the leucosomes are relatively
242   homogeneous, with X_{An} ranging from 0.29 to 0.33 (Fig. 6h; Table E). The thin plagioclase
243   coronae surrounding Qz_1 inclusions in garnet are oligoclase ($An_{14–15}$; Fig. 3c; Table E).
244   The plagioclase Pl_3 associated with Bt_3, St_3 and/or Sil_3 in the matrix, and produced
245   essentially from Ph_2 (Fig. 4e-f), is $An_{14–26}$ (Table E), whereas Pl_3 in the Bt_3-rich
246   aggregates that replaced garnet porphyroblasts (Figs. 3a, 4b) is slightly richer in anorthite
247   ($An_{25–41}$), due to the Ca content of garnet from which it grew.

248   *3.5. Other minerals*

249   Kyanite is observed as inclusions in garnet (Ky_1) and as large laths in the matrix
250   (Ky_2), ranging in size from ~0.1 mm to 2 cm, which, together with micas and quartz,
251   defines the main foliation (Fig. Ag in SM). Ky_2 may appear partially or completely
252   transformed to mm-sized bundles of fibrolitic sillimanite (Sil_3). Sil_3 appears also
253   intimately intergrown with Bt_3 as sheaf-like clusters (Fig. 3h).

254   Staurolite occurs both as inclusions in Grt_1 porphyroblasts (St_1 in Fig. 3c-d; X_{Mg} =
255   0.13–0.15; Si = 7.4–7.6 a.p.f.u.; TiO_2 = 0.64–0.87 wt%) and in the matrix associated with
256   Bt_3, Kfs_3, Pl_3, Gt_3 and Sil_3, as small scattered subhedral crystals (St_3 in Fig. 3g-h; X_{Mg} =
257   0.06–0.10; Si = 6.65–7.37 a.p.f.u.; TiO_2 = 0.49–0.74 wt%), with a more intense yellow

258 pleochroism. Clear $Si_{-1}Al^{IV}_{+1}Al^{VI}_{+1}Fe_{-1}$ (*i.e.*, Tschermak) and $Mg_{+1}Fe_{-1}$ substitutions are
259 observed in the analyzed staurolites (Fig. 6f; Table F in SM).

260 Rutile largely replaced by ilmenite, fluorapatite, allanite, zircon and tourmaline are
261 accessory minerals.

4. MICROSTRUCTURAL EVIDENCE OF PARTIAL MELTING

263 There are typical microstructures indicating the former presence of melt during high-
264 grade metamorphism, provided that crystallized and/or solidified melt has not been
265 affected by subsequent subsolidus deformation and recrystallization phenomena. The
266 most obvious are those present in shallow contact metamorphic aureoles, where melt has
267 either solidified into glass or crystallized into a granophyric intergrowth. Former melt
268 commonly constitutes thin films in between most crystals, and may include anhedral
269 reactant and/or euhedral peritectic minerals (Holness and Sawyer 2008).

270 The presence of melt is not so obvious in slowly cooled contact and regional
271 anatectic rocks (Sawyer 2001). There is a consensus however that several microstructures
272 are diagnostic: (i) subhedral to euhedral shapes, particularly for minerals that do not
273 typically produce crystal faces in metamorphic rocks (Vernon and Collins 1988); (ii) melt
274 pseudomorphs, identified by quartz or K-feldspar or sodic plagioclase, forming either
275 strongly cuspate grains or thin films between other crystals (Harte et al. 1991; Clemens
276 and Holness 2000; Sawyer 2001; Marchildon and Brown 2002; Holness and Sawyer
277 2008); (iii) structures indicative of melt-producing reactions, like euhedral peritectic
278 minerals, anhedral relicts of reactant minerals surrounded by melt pseudomorphs,
279 oscillatory zoning, symplectitic coronae of Bt + Pl or Bt + Qz around ferromagnesian
280 crystals (Sawyer 1999; Vernon and Collins 2011); (iv) magmatic flow orientation
281 underlined by undeformed euhedral elongated crystals (Paterson et al. 1989; Sawyer
282 2001; Vernon and Collins 2011).

283 In the case of the studied Egéré metapelites, the first indications of the presence of
284 melt are based on field observations of leucosomes parallel to the main foliation. Under
285 the microscope, the leucosomes appear made of quartz with subhedral to euhedral
286 crystals of sodic plagioclase and K-feldspar. The presence of several types of mineral
287 intergrowths also points to the presence of melt: (i) Bt_3+Pl_3 aggregates around garnet
288 (Figs. 3a, 4b), interpreted by some authors as resulting from the breakdown of garnet
289 during cooling and melt crystallization (Janák et al. 1999); (ii) skeletal garnet intergrown
290 with quartz (Fig. 3e), interpreted as related either to prograde dehydration during melting
291 reactions or to a back-reaction with melt (Waters and Whales 1984; Waters 1988, 2001;
292 Vernon and Collins 1988; Powell and Downes 1990); (iii) Sil_3+Bt_3 sheaf-like
293 intergrowths (Fig. 3h), interpreted as products of a melt-residuum back-reaction (Dusel
294 and Foster 1983).

295   Strong microstructural evidence of the former presence of melt in high-grade
296   metamorphic rocks is also provided by some polycrystalline inclusions in garnet (*e.g.*,
297   Hartel et al. 1990; Perchuk et al. 2005; Lang and Gilotti 2007; Cesare et al. 2009, 2015).
298   Cesare et al. (2009, 2015) described what they termed "nanogranitoids", referring to tiny
299   polycrystalline inclusions, up to a few tens of micrometers in size, representing
300   crystallized droplets of primary anatectic melt, trapped by the host peritectic mineral
301   growing during an incongruent melting reaction. Lang and Gilotti (2007) described
302   relatively large and mostly anhedral inclusions in garnet, consisting of mono- or poly-
303   crystalline quartz rimmed by a discontinuous moat of plagioclase and K-feldspar. They
304   interpreted this microstructure as representing a crystallized melt from the matrix, which
305   infiltrated or invaded the garnet crystals along cracks or grain boundaries, probably
306   during the expansion due to the transformation into quartz of former coesite inclusions
307   (see also the crown-like wavy microstructure of Korsakov and Hermann, 2006). On the
308   basis of experiments on inclusion-bearing garnet crystals from mafic eclogites, Perchuk
309   et al. (2005) showed that some large polycrystalline inclusions with melt-bearing
310   microstructures could be produced by the post-entrapment melting of former solid
311   polycrystalline inclusions involving hydrous minerals.

312   In the specific case of the Egéré migmatites, all three types of polycrystalline
313   inclusions are present in garnet and demonstrate anatexis of the host rock:

314   (i)   *Nanogranitoids*: These inclusions are very small (~5–30 μm), equant, and
315   show the negative crystal forms of the host garnet (Fig. 5). They are rare and
316   scattered throughout the garnet porphyroblasts. These inclusions are
317   composed of quartz, biotite, plagioclase, K-feldspar, chlorite and accessory
318   minerals such as zircon and allanite. Given their distribution, size, shape and
319   mineralogy, they are interpreted as nanogranitoids. While zircon and allanite
320   would constitute solid inclusions entrapped with the melt, quartz, feldspars
321   and biotite probably represent daughter minerals crystallized from the trapped
322   melt; chlorite may be a low-*T* mineral formed during the retrograde *P-T* path.

323   (ii)   *Inclusions of quartz surrounded by a thin feldspar moat*: Very similar to
324   those described by Lang and Gilotti (2007), these inclusions are subhedral to
325   euhedral, ~0.1–0.5 mm in size (Figs. 3c, 4c), and made up of mono- or poly-
326   crystalline quartz (Qz_1) in the center, rimmed by a thin moat of plagioclase,
327   either optically continuous or sometimes polycrystalline (Fig. 4c), which
328   suggest the former presence of melt (Sawyer 2001; Lang and Gilotti 2007).
329   Although these inclusions have been observed mainly at the rims of garnet
330   porphyroblasts, the secondary infiltration of matrix melt might not be the only
331   explanation for this particular microstructure; a primary mixture of reactants
332   and melt-crystallization products could be an alternative interpretation.

333   (iii)   *Large polyphase inclusions*: About 0.5 to 1.5 mm in size, they consist of
334   quartz, feldspars, phengite, biotite, kyanite, staurolite, rutile and ilmenite, and
335   are found in the intermediate and rim regions of garnet porphyroblasts. They
336   could be interpreted as phengite-bearing polycrystalline inclusions that
337   partially melted after their entrapment in garnet (Perchuk et al. 2005). A more
338   detailed and specific study would however be necessary to confirm such an
339   origin.

5. PHASE EQUILIBRIA MODELING

341   In order to specify the metamorphic evolution of the metapelites, *P-T* pseudosections
342   (Fig. 7) were calculated using the software THERMOCALC (Powell and Holland 1988)
343   and an updated release of the thermodynamic dataset of Holland and Powell (2011) (see
344   method in SM for the details). To model the early prograde *P-T* evolution, we have
345   constructed a pseudosection for sample T78 (Fig. 7a). Results should however be
346   considered with caution, for two main reasons: (i) The early prograde evolution of a
347   pelitic metasediment takes place reasonably under conditions of H_2O saturation. As soon
348   as partial melting occurs, H_2O is strongly partitioned into the melt and the aqueous fluid
349   rapidly becomes absent in the system. The quantity of H_2O that has been considered for
350   modeling this early stage, higher than the loss-on-ignition value of the final rock, takes
351   these considerations into account, but is nevertheless arbitrary which causes large
352   uncertainties on the high-*T* part of Figure 7a. (ii) Some melt may have been lost from the
353   analyzed volume of the rock, and in part segregated to form the leucosomes (*e.g.*, White
354   et al. 2004; Lasalle and Indares 2014). It would be wise to reintegrate a certain (arbitrary)
355   amount of melt into the modeled composition. We actually preferred considering a
356   sample large enough to include a representative amount of leucosome.

357   During partial melting, any water initially present dissolves into the melt (see above).
358   This is why it is better to calculate H_2O-undersaturated pseudosections to model the peak
359   and retrograde *P-T* evolution of these rocks, which we did using the bulk composition of
360   samples T52 and T78, of which the H_2O content was deduced from their loss-on-ignition
361   value (Fig. 7b-c; see Table A in SM for the compositions). A melanocratic part of sample
362   T52 was also separated and analyzed, in order to model a rock microdomain (Fig. 7d)
363   that mainly consists of Bt_3, St_3, Sil_3, Pl_3, Grt_3, quartz and ilmenite, which is considered to
364   be the most retrograde paragenesis.

6. DISCUSSION

366   On the basis of microstructural and mineralogical evidence, at least three distinct
367   stages of metamorphism have been recognized in the Egéré metapelites: (i) the earliest
368   metamorphic stage (M_1) is prograde and documented by mineral inclusions enclosed in

369   garnet porphyroblasts; (ii) the peak eclogite-facies stage (M_2) developed a paragenesis
370   made of garnet, kyanite, phengite, quartz, rutile and melt; (iii) finally, the retrograde post-
371   peak stage (M_3) is highlighted by post-foliation minerals that developed in the matrix,
372   mainly as fine-grained pseudomorphs resulting from the breakdown of peak minerals like
373   phengite and garnet.

374   *6.1 Prograde evolution*

375   The prograde metamorphic evolution is documented by mineral inclusions preserved
376   in the core of garnet porphyroblasts (Grt_1), including Qz_1, Ky_1, Bt_1, St_1, Ph_1, Rt_1 and Ilm_1
377   (Figs. 3a-d, 4c). Some of these inclusions exist alongside polycrystalline inclusions with
378   negative crystal shapes that are interpreted as nanogranitoids (Fig. 5), and thus testify to
379   the presence of a melt trapped in the host garnet during its growth (Section 4).

380   It is reasonable to assume that any initial prograde zoning in garnet would have been
381   smoothed or erased by diffusion at peak high-grade conditions (Spear and Florence 1992;
382   Caddick et al. 2010), which is corroborated here by the generally flat zoning pattern
383   observed in the core of the studied garnets (Fig. 6a, c). However, it is also well known
384   that bell-shaped X_{Sps} zoning profiles in garnet (*e.g.*, samples T78, T138; Fig. 6a, c)
385   indicate prograde growth zoning (*e.g.*, Tracy 1982; Loomis 1983; Mahar et al. 1997).
386   Likewise, the grossular content, higher in the core of garnet crystals than in their rims, is
387   also typical of a prograde growth zoning of garnet from metapelites (*e.g.*, Woodsworth
388   1977; Chernoff and Carlson 1997; Keller et al. 2006). Overall, all these observations
389   suggest that Grt_1 grew at the expense of minerals now preserved as single mineral
390   inclusions, via reactions that occurred during the prograde evolution of the rock. At least
391   part of Grt_1 crystallized in the presence of melt, as shown by the presence of
392   nanogranitoids.

393   The prograde *P-T* trajectory was modeled by calculating a pseudosection for sample
394   T78 (Fig. 7), despite the uncertainties linked to such modeling (Section 5). Given the
395   high temperature reached by these rocks (800–820ºC, see below), the initial prograde
396   zoning of garnet has been likely smoothed by diffusion at peak conditions. Hence, we did
397   not use garnet isopleths for modeling the prograde *P-T* path, which thus remains poorly
398   constrained. However, we tried to define a *P-T* evolution (red dashed arrow in Fig. 7a)
399   that explains both the growth of the garnet porphyroblasts (by crossing the garnet
400   isomodes: red dotted lines) and the entrapment of the various inclusions. An anchor
401   point, at ~600–630°C and ~6.0–6.5 kbar (blue ellipse in Fig. 7a), is provided by the
402   assemblage $Qz_1 + Bt_1 + Ph_1 + St_1 \pm Ky_1 + Pl + Ilm_1 (+Grt_1)$, shielded as inclusions in Grt_1
403   porphyroblasts of sample T78; it is further constrained by the intersection of Bt_1 and St_1
404   isopleths (*x(Bt)* = 0.62–0.64; *x(St)* = 0.85–0.88). To account for the presence of
405   "nanogranitoids" in garnet porphyroblasts, this early *P-T* evolution must have reached
406   fields of the pseudosection where melt ("Liq") is present and where the isomodes of

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407 garnet are tightly spaced suggesting its peritectic growth (Fig. 7a). This could have

408 occurred during the crossing of the H_2O-saturated rock solidus at ca. $T \geq 650–670°C$ and

409 $P \geq 10$ kbar. A modeled melt formed along the postulated trajectory at 10 kbar and

410 670°C, has the following composition: $Si_{39.84}Al_{10.15}Fe_{0.12}Mg_{0.06}Ca_{0.38}Na_{7.38}K_{1.69}O_{100}$·

411 xH_2O, which, after crystallization, would give a mineral assemblage compatible with the

412 nanogranitoids observed (Fig. 5; Section 4): 62.8 Pl (Ab_{95}) + 22.0 Qz + 13.8 Or + 1.4 Bt

413 (in vol.%; molar volumes from the Thermocalc database).

414 *6.2 Peak P-T conditions*

415 The prograde evolution should have continued towards the peak of metamorphism.

416 The H_2O-undersaturated pseudosections (Section 5) are used to constrain the peak or

417 near-peak *P-T* conditions (Fig. 7b-c). The peak assemblage (M_2) observed in the matrix

418 (Grt_2 + Ph_2 + Ky_2 + Qz_2 + Rt_2 + Ilm_2 + Kfs_2 + Pl_2 ± Liq) and whose feldspars are

419 concentrated in leucosomes, is stable over a large *P* range between 12 and 20 kbar. It is

420 therefore necessary to better define the peak conditions by using the isopleths of garnet

421 and/or phengite. In doing so, several drawbacks arise:

422 (i) The temperatures reached during the peak of metamorphism have produced a

423 significant, but incomplete, chemical homogenization of garnet porphyroblasts, with

424 almost flat zonation profiles except at their rim, which reequilibrated during the

425 retrograde metamorphism (Fig. 6a-d). Hence, it is appropriate to use the composition of

426 the large central parts of the garnet porphyroblasts to refine the peak *P-T* conditions.

427 However, the calculated X_{Fe} and X_{Grs} isopleths in garnet (*x(Grt)* and *z(Grt)* in Fig. 7b-c)

428 vary only very little over the large *P* range in which the paragenesis M_2 is stable, and are

429 thus of limited interest.

430 (ii) The composition of phengite seems more reliable because the isopleths *Si(Ph)*,

431 related to the content in celadonite, are closely spaced (Fig. 7c-d), and can be applied to

432 the nearly homogeneous Ph_2 flakes. The measured values of Si in phengite suggest *P* >

433 14 kbar when compared with the calculated *Si(Ph)* isopleths (*Si(Ph)* ± 1σ: 6.278 ± 0.038

434 [T78]; 6.234 ± 0.022 [T52]). High-grade conditions are also indicated by the Ti richness

435 of parts of Ph_2 (Section 3.2; Ti-Ph in Table C; *e.g.*, Nahodilová et al. 2014; Auzanneau et

436 al. 2010).

437 (iii) The liquid produced by anatexis (Section 4) could have been partially extracted

438 from the rock, producing a change in composition of the system and a shift of the solidus

439 curve towards higher temperatures (dashed blue arrows in Fig. 7b-c). In the borderline

440 case where all melt is extracted, the solidus curve would shift and follow the *P-T*

441 conditions of the rock, since the solidus corresponds to those conditions where the melt

442 exists only in infinitesimal amount. It is unlikely, however, that all of the melt was

443 extracted because a critical threshold of liquid is required for melt interconnection and

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444 migration (<1 to a few vol.%; Laporte and Watson 1995; Laporte et al. 1997; Rosenberg
445 and Handy 2005). Consequently, the modeled pseudosections of Figure 8b-c give a
446 "snapshot" that probably approaches but does not reach this borderline case. They would
447 reflect the situation close to the *T* peak, and are thus poorly suited for determining the
448 conditions prior to it.

449   The *P* peak must have been reached at lower temperatures relative to the ultimate
450 solidus curve given by the pseudosections, in the stability field of the M_2 paragenesis (Grt
451 + Ph + Ky + Qz + Ilm ± Rt + Kfs + Pl), and in the wide range of *P* between 14 and 20
452 kbar given with great uncertainty by the garnet and phengite isopleths (Fig. 7b-c). Some
453 constraints, like Ph_2 still abundant in the rock, together with feldspars and melt, and the
454 location of the ultimate solidus curve, suggest a subsequent *T* peak at about 800–820°C.
455 The Ti-in-Zrn thermometry applied to similar neighboring metapelites yielded peak
456 temperatures of 811 ± 15°C (Bruguier et al. 2014). The *P-T* trajectories drawn in Figure
457 8b-c are an attempt to represent this imperfectly constrained evolution.

458 *6.3 Retrograde evolution*

459   The *P-T* trajectory of exhumation is documented by the M_3 paragenesis, made of
460 abundant Bt_3, Pl_3, Kfs_3 and quartz, scarce Sil_3, Ms_3, Grt_3, ±St_3 and Ilm_3. The M_3
461 assemblage often forms unoriented fine-grained polymineralic aggregates (almost
462 symplectites) and therefore postdates the main foliation. In some specimens, however,
463 Bt_3 shows a significant orientation (Section 3.3; Fig. 3g), indicating some deformation at
464 this stage. M_3 developed at the expense of previous M_2 minerals, mainly garnet and
465 phengite. Sillimanite and ilmenite also replaced kyanite and rutile, respectively.

466   The garnet porphyroblasts, largely homogenized at the peak of metamorphism (see
467 above), show a drop in X_{Fe} and X_{Grs} and an increase of X_{prp} at their rims ("rims" in Fig.
468 6a, c). Moreover, when they have been corroded by a fine-grained Bt_3+Pl_3 aggregate
469 (Fig. 4b), these porphyroblasts show slight increases of X_{Fe} and X_{Grs} at their very edges
470 ("outer rim" of Fig. 6c). Some small anhedral Grt_3 crystals, whose X_{Fe} is even greater
471 (Fig. 6d; Table B), may well be relics of these porphyroblast edges, isolated during the
472 development of the replacing minerals. Many authors have interpreted such an increase in
473 X_{Fe} as resulting from Fe-Mg exchange between garnet and surrounding biotite during
474 retrogression (*e.g.*, Tracy et al. 1976; Woodsworth 1977; Tuccillo et al. 1990; Konrad-
475 Schmolke et al. 2005).

476   The phengite flakes in the matrix (Ph_2) have been partly or totally replaced by a fine-
477 grained Bt_3+Pl_3 aggregate, which is further rimmed by a Kfs_3 corona at contacts with Qz_2
478 (Figs. 3f, 4e-f). They show a chemical evolution towards the muscovite end-member
479 (Fig. 6e), mainly at their rims transformed into Bt_3+Pl_3. A few specks of Ms_3 (Figs. 4f
480 and 6e) isolated among Bt_3 and Pl_3 seem to be re-equilibrated relics of Ph_2. Ilm_2 initially

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481   in contact with Ph_2 is also rimmed by concentric coronas of Pl_3 and Bt_3 (2 in Fig. 4f), and
482   would have operated as a minor reactant, supplying some Ti (and Fe) to the newly
483   formed biotite, whose high Ti-content is likely related to HT metamorphic conditions
484   (*e.g.*, Henry and Guidotti 2002).

485   The stoichiometric balance of the phengite breakdown reaction was made by the
486   least-squares method (sample T138; for 1 mol of Ph_2):

487    $1\ Ph_2 + 3.79\ Qz_2 + 0.20\ Ilm_2 \rightarrow 0.21\ Bt_3 + 1.25\ Pl_3 + 2.01\ Kfs_3 + 1.57\ H_2O + 1\ R$,

488   where R is the vector of the residuals (R: $Si_{0.00}Al_{-0.48}Cr_{+0.00}Ti_{-0.23}Fe_{+0.23}Mn_{-0.00}Mg_{+0.07}Ca_{+0.42}Na_{+0.80}K_{+0.47}O_{0.00}$). The conversion into volumes yields:
489

490    $1\ Ph_2 + 0.321\ Qz_2 + 0.022\ Ilm_2 \rightarrow 0.229\ Bt_3 + 0.446\ Pl_3 + 0.774\ Kfs_3$.
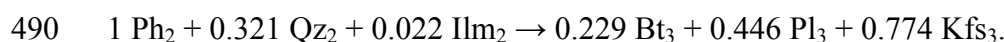
491   The minerals are correctly distributed between reactants and products, in volumetric
492   proportions comparable to what is observed (Fig. 4f). The increase in volume during the
493   reaction ($\Delta V_s/V_s = +0.079$) is also consistent with an evolution at decreasing pressure.
494   However, associated residuals are abnormally important, indicating that some additional
495   exchange took place during the reaction, which therefore occurred in an open system with
496   respect to the reaction domain considered.

497   Indeed, such an exchange could be linked to a mobile melt. Fluid-absent melting of
498   phengite typically occurs during the decompression of HP metapelitic and felsic rocks
499   (*e.g.*, Vielzeuf and Holloway 1988; Hermann and Green 2001; Schmidt et al. 2004;
500   Hermann et al. 2006; Massonne 2009; Dokukina et al. 2017). Phengite melting in the
501   studied rocks is consistent with the calculated *P-T* pseudosections, where the phengite-
502   out and solidus curves almost coincide (Fig. 7b-c). During the retrograde evolution, the
503   metapelites followed a *P-T* path sub-parallel to these two curves or, more likely, these
504   curves were shifted in the vicinity of the *P-T* path, by extraction of melt, as discussed
505   before (Section 6.2 iii). This evolution can explain the zonation observed at the rims of
506   both garnet porphyroblasts (decrease in X_{Fe} and X_{Grs}: Fig. 6a-d) and phengite flakes
507   (decrease in the celadonite end-member: Fig. 6e), which are consistent with the
508   decreasing values of *x(Grt)*, *z(Grt)* and *Si(Ph)* predicted by the pseudosections during a
509   drop of *P* (Fig. 7b-c).

510   The final step of decompression and cooling is manifested by the formation of M_3
511   fine-grained aggregates, indicating an evolution into the melt-free stability fields of
512   sillimanite and biotite (Fig. 7). Despite the tight spacing of isopleths in this region of the
513   pseudosections, the compositional heterogeneity of the M_3 domains and minerals, which
514   likely did not fully reach equilibrium, makes it difficult to specify the *P-T* conditions of
515   this late metamorphic stage. Garnets in contact with the matrix, either "outer rims" of
516   porphyroblasts or Grt_3, have the lowest grossular content [*z(Grt_3)*: 0.13–0.05 for sample

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517   T78; 0.10–0.08 for T52] and the highest X_{Fe} ratio [$x(Grt_3)$: 0.85–0.91 for T78; 0.87–0.93

518   for T52]. The X_{Fe} isopleth values for Bt_3 are: $x(Bt_3)$ = 0.58–0.62 for T78; 0.67–0.69 for

519   T52. The isopleths do not intersect at a point but in a P-T region that provides a

520   reasonable estimate for the conditions of this stage (blue ellipses in Fig. 7b-d): 725–

521   740°C at 7–8 kbar (T78); 720–730°C at 7.0–7.5 kbar (T52). Since equilibrium is

522   imperfectly achieved at the scale of the sample, we modeled a small homogeneous matrix

523   domain, similar to that of Figure 3g, for sample T52 (Fig. 7d). The compositions of the

524   minerals [$x(Grt_3)$: 0.87–0.88; $z(Grt_3)$: 0.05–0.06; $x(St_3)$: 0.89–0.94; $x(Bt_3)$: 0.62–0.71]

525   suggest P-T conditions of 5.5–6.0 kbar, 675–725°C (blue ellipse in Fig. 7d) on a regular

526   geothermal gradient of ~15°C.km^{-1}. Moreover, modeling this microdomain reveals

527   features not shown by the bulk-rock pseudosection, like the local stability of St_3 and the

528   late increase of X_{Fe} in the garnet "outer rim" (see $x(Grt)$ isopleths in Fig. 7d).

529   *6.4. Petrological and geological implications*

530   The metapelites studied here are distinctive regarding three particular circumstances

531   that, combined, make these rocks a kind of "geological miracle":

532   (i) *Eclogite-facies metapelites*. Eclogite-facies mafic metabasites, *i.e.*, true eclogites,

533   have been known for two centuries, but metapelites related to eclogites went unnoticed

534   for a long time, to the point that, in the 1980-90s, a controversy "foreign" vs. "in-situ"

535   raised the question of the relationships between eclogites and their metapelitic host, in

536   which traces of such metamorphism were not observed (see the historical summary *in*

537   Godard 2001). It has since been recognized that, among eclogite-facies rocks, metapelites

538   are not less rare than metabasites, but have rarely preserved their eclogite-facies imprint

539   due to the combined effects of retrograde metamorphism, rehydration and late

540   deformation. In this regard, the difficulty in specifying the P-T conditions prevailing at

541   the peak of metamorphism (Section 6.2) is usual for this type of rock. It remains that it is

542   amazing to observe in the Egéré terrane such rocks on a regional scale. Without wishing

543   to reignite the controversy, it should be noted that the mafic eclogites and eclogite-facies

544   metapelites from Egéré seem to have recorded slightly different P-T evolutions: In

545   Tighsi, 30–40 km N of the investigated Izzilatène area, the apparent P-T path of mafic

546   eclogites (19.6 kbar/695ºC → 15.5 kbar/775ºC → 9.3 kbar/695ºC) does not exactly

547   superimpose on that of the host metapelites (17–19 kbar/850ºC → 9 kbar/750 ºC)

548   (Doukkari et al. 2014; Arab et al. 2015). The same is observed in Izzilatène, between the

549   mafic eclogites (13–14 kbar/580ºC → 19 kbar/650–700 ºC → 8–9 kbar/700-750 ºC:

550   Doukkari et al. 2015) and the investigated eclogite-facies metapelites (6.0–6.5 kbar/600–

551   630ºC → 14–20 kbar/800–820ºC → 5.5–6.0 kbar/675–725ºC: this study). In both cases,

552   the apparent P peak is slightly lower, or at least less well defined, for the metapelites than

553   for the metabasites. On the other hand, the T peak seems higher by a hundred degrees for

554   metapelites compared with the mafic eclogite lenses that they contain. It is difficult to

555   imagine that these differences are linked to some major geological process. It makes

556 more sense to invoke a bias linked to thermodynamic modeling, or even more surely a
557 contrasting behavior of the two types of rock, since, relative to the metapelites, the
558 metabasites preserve more easily the imprint of the *P* peak but record less easily the *T*
559 peak because of their refractory properties.

560   (ii) *Nanogranitoids in eclogite-facies rocks*. Partial melting of eclogite-facies rocks is
561 still a matter of debate, not because melting under (ultra)high-pressure conditions is not
562 predicted by experiments and thermodynamics (*e.g.*, Hermann et al. 2006), but because
563 of the lack of irrefutable petrological evidence, especially for mafic eclogites. There is a
564 score of microstructures that suggest partial melting in some eclogite-facies rocks (see
565 review in Section 4), but a compelling evidence like melt inclusions sheltered in garnet
566 and crystallized as "nanogranitoids" is rare. Such inclusions are well known in HT
567 granulite-facies migmatites (*e.g.*, Cesare et al. 2009, 2015; Ferrero et al. 2012; Bartoli et
568 al. 2016), less frequently in HP granulite-facies rocks (Ferrero et al. 2018), and more
569 rarely in eclogite-facies quartzo-feldspathic rocks (Ferrero et al. 2015). This study
570 confirms that they exist under eclogite-facies conditions, despite less favorable
571 geotherms, although no evidence of melting has been found in the associated mafic
572 eclogites, likely because of their refractory composition.

573   (iii) *Eclogite-facies metamorphism in a Neoproterozoic orogen*. Recent studies (*e.g.*,
574 Doukkari et al. 2014, 2015; Arab et al. 2015; Arab 2016; and references therein) suggest
575 that the Egéré supracrustal sequence deposited in a continental rift/passive margin
576 environment, at an age of ≥745 Ma. It has been suggested that these sediments were
577 intruded by mafic rocks and subducted deeply during the Neoproterozoic evolution of the
578 Hoggar, likely during the Upper Cryogenian-Lower Ediacarian (Liégeois et al. 2003;
579 Arab 2016), thus recording eclogite-facies conditions, before being exhumed. The LA-
580 ICP-MS U-Pb analysis of a zircon megacryst from a neighboring eclogite-facies
581 metapelite, crystallized from the anatectic melt at conditions close to the *T* peak, gave an
582 Upper Cryogenian age of 654 ± 5 Ma (Bruguier et al. 2014). The Egéré terrane would
583 then represent an old passive margin that underwent a subduction-exhumation cycle
584 related to the Pan-African orogeny that led to the Western Gondwana assembly (Liégeois
585 et al. 2013; Berger et al. 2014; Liégeois 2019). The existence in the Hoggar of numerous
586 traces of an eclogite-facies metamorphism dating back to the Neoproterozoic is
587 remarkable, since the first true eclogites on Earth formed around 2.1 Ga ago (*e.g.*, Loose
588 and Shenk 2018), indicating the emergence of modern plate tectonics. This type of
589 metamorphism remained quite rare in the Neoproterozoic, before gradually increasing
590 from the Paleozoic to the Present. The Egéré terrane belongs to the West Gondwana
591 Orogen (WGO), which stretches from Hoggar to the northeast of Brazil and is
592 characterized by a Cryogenian-Ediacarian subduction, which Ganade de Araujo et al.
593 (2014) consider as the earliest evidence of large-scale deep continental subduction and
594 Himalayan-scale mountains in the geological record.

595 **7. IMPLICATIONS**

596   The studied migmatitic metapelites preserve mineral zoning and textures related to
597 various stages of their prograde and retrograde metamorphic evolution, and provide
598 constraints on partial melting reactions under HP conditions. The following conclusions
599 can be made:

600   1. The metasedimentary Egéré unit (LATEA terrane, Central Hoggar, Algeria)
601 mainly consists of kyanite-bearing metapelites, quartzites, marbles and mafic rocks that
602 have undergone eclogite-facies metamorphism.

603   2. The studied metapelites consist of quartz, garnet, phengite, kyanite, rutile, with
604 secondary biotite, staurolite, muscovite, K-feldspar, plagioclase, sillimanite and ilmenite.
605 Garnet porphyroblasts show smoothed bell-shaped zoning patterns, with spessartine and
606 grossular decreases from core to rim. They grew during prograde metamorphism,
607 enclosing quartz, biotite, phengite, staurolite, kyanite, rutile and ilmenite. Coarse-grained
608 minerals, namely phengite, quartz and kyanite, form a foliated matrix and, together with
609 the rims of euhedral garnet porphyroblasts, constitute the peak paragenesis. Fine-grained
610 matrix minerals, mostly unoriented, like biotite, plagioclase, K-feldspar, muscovite,
611 staurolite and sillimanite, developed during exhumation throughout retrograde reactions
612 that produced a variety of intergrowths, coronas and pseudomorphs.

613   3. Two types of melting phenomena have occurred in the studied rocks: (i) H_2O-
614 saturated melting during the prograde stage; and (ii) H_2O-unsaturated melting near the
615 peak and during decompression, likely associated with the dehydration melting of
616 phengite.

617   4. Polycrystalline micro-inclusions in garnet, with negative crystal shapes, formed
618 after entrapment of former melt and are therefore "nanogranitoids". Together with quartz
619 inclusions surrounded by feldspar, they provide evidence for anatexis during the prograde
620 evolution. Anatexis close to the metamorphic T peak gave a migmatitic structure to the
621 rocks. Biotite-plagioclase-bearing pseudomorphs are linked to dehydration melting of
622 phengite during exhumation.

623   5. A clockwise P-T path is suggested for the Egéré metapelites, based on micro-
624 textures and P-T pseudosections. The recorded starting conditions of the prograde
625 evolution, evidenced from the mineral inclusions preserved in garnet, are 600–630°C and
626 6.0–6.5 kbar. The inferred peak assemblage (quartz, garnet, kyanite, phengite, rutile,
627 melt, ±plagioclase, ±K-feldspar) indicates a P peak of metamorphism at 14–20 kbar and a
628 T peak at 800–820°C. The assemblage garnet–biotite–staurolite–sillimanite–plagioclase–
629 K-feldspar–ilmenite, which occurs as late intergrowths, coronas and pseudomorphs,
630 formed at the expense of the HP paragenesis and documents the completion of the
631 retrograde evolution at ~6 kbar and 600–620°C.

632   6. The clockwise *P-T* path recorded by the Egéré HP metapelites is related to
633 continental subduction followed by exhumation during the Pan-African orogeny that led
634 to the amalgamation of the Hoggar shield. Recent geochronological data indicate that the
635 HP event likely took place at ~650 Ma.

636   7. The rocks studied are remarkable because (i) they are relatively well-preserved
637 eclogite-facies metapelites, (ii) they contain "nanogranitoids", rarely described so far in
638 eclogite-facies metamorphic rocks, and (iii) they indicate a subduction-related
639 metamorphism during a Neoproterozoic orogeny.

640 **ACKNOWLEDGEMENTS**

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928 **FIGURE CAPTIONS**

929   **Figure 1.** Geological context. (**a**) Geological sketch map of the Tuareg Shield (Black
930 et al. 1994; Liégeois 2019). (**b**) Geological map of the LATEA metacraton (after Liégeois
931 et al. 2003), showing the area studied. Ao: Aouilène; As-Is: Assodé-Issalane; Az: Azrou
932 n'Fad; Eg-Al: Egéré-Aleksod; La: Laouni; Se: Serouenout; Te: Tefedest; Tz: Tazat;
933 HKCA: high-potassium calc-alkaline rocks.

934   **Figure 2.** Outcrop photographs. (**a**) Upper metasedimentary unit of Egéré showing
935 metapelites interbedded with marbles, quartzites and eclogite lenses (hills on the
936 horizon). (**b-d**) Close-up views of the migmatitic metapelites studied, showing the
937 alternation of various lithologies, in particular of leucosomes and melanosomes rich in
938 garnet porphyroblasts, kyanite and phengite (d).

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939   **Figure 3.** Mineral assemblages and microtextures of kyanite-bearing metapelites.
940   Plane-polarized (b-e, g, h) and cross-polarized (a, f) lights. (**a**) Garnet megacryst, rich in
941   inclusions defining a straight internal foliation and corroded by aggregates of biotite +
942   plagioclase (Bt_3+Pl_3)**.** (**b-d**) Close-up views of various inclusions (Bt_1, Ilm_1, Qz_1, St_1, Rt_1)
943   in garnet porphyroblasts (Grt_1), some of which are surrounded by a plagioclase moat (Pl
944   in c). (**e**) Garnet + quartz skeletal intergrowth. (**f**) Phengite flake (Ph_2), partially resorbed
945   by aggregates consisting of biotite (Bt_3), plagioclase (Pl_3) and K-feldspar (Kfs_3). (**g**)
946   Symplectite mainly consisting of Bt_3, Pl_3, Kfs_3, Sil_3 and St_3, developed at the expense of
947   the peak paragenesis, in particular Grt_2, Ph_2, Ky_2 and Qz_2. (**h**) Second generation of fine-
948   grained staurolite (St_3) associated with late Bt_3, Kfs_3 and Sil_3.

949   **Figure 4.** Reaction microstructures in kyanite metapelites. BSE images (a-e), and
950   RGB image (f), the red, green and blue channels of which are the first three main
951   components of the PCA of element maps. (**a**) The HP paragenesis (M_2), consisting of
952   garnet (Grt_{1-2}), phengite (Ph_2), kyanite (Ky_2) and quartz, is partially replaced by late M_3
953   assemblages (Bt_3+Pl_3). (**b**) Garnet megacryst (Grt_{1-2}) corroded by Bt_3+Pl_3 aggregates. (**c**)
954   Close-up view of quartz inclusions (Qz_1) in a garnet porphyroblast (Grt_1), which are
955   surrounded by thin films of plagioclase (Pl). (**d**) Aggregates of Bt_3, Pl_3, Sil_3, St_3 and Ms_3,
956   having replaced the M_2 paragenesis (Ph_2+Ky_2+Grt_2+Qz_2); K-feldspar Kfs_3 mainly
957   developed as coronas around large Qz_2 grains. (**e, f**) Phengite flake (Ph_2) partially
958   resorbed by aggregates consisting of Bt_3, Pl_3, Ms_3 and Kfs_3, which forms a continuous
959   corona at contacts with Qz_2; lamellae of Ilm_3 and Bt_3 are exsolved parallel to the (001)
960   plane of phengite Ph_2; 1: numerous micro-inclusions of ilmenite inside muscovite (*i.e.*,
961   Ms_3+Ilm_3) after Ph_2, which was probably richer in Ti near Ilm_2; 2: Pl_3+Ilm_3 symplectite
962   between Ilm_2 and Ph_2.

963   **Figure 5.** Nanogranitoids in garnet porphyroblasts. Plane-polarized light (a) and BSE
964   (b-f) images (sample T100). (**a**) Garnet megacrysts in a matrix with leucosomes and
965   micaceous segregations. (**b**) Very small melt inclusions hosted in a garnet porphyroblast
966   (Grt_1) and now crystallized as "nanogranitoids". (**c-f**) Close-up views of
967   "nanogranitoids", which generally display the negative euhedral forms of the host garnet
968   (d-f) and consist of quartz + biotite + plagioclase ± K-feldspar ± zircon.

969   **Figure 6.** Mineral compositions of the metapelites. (**a-d**) Composition of garnet in
970   samples T78 (a-b) and T138 (c-d). The profiles across garnet megacrysts (a, c) show a
971   smoothed compositional zoning at their cores, where a bell-shaped Mn profile is
972   observed; the zoning at the rims of profile (a) is similar to that of the inner rims of profile
973   (b), whose outer rims show a reverse zoning when at contact with Bt_3+Pl_3 symplectites.
974   (**e**) White mica compositions in the diagram (Si+Fe^{2+}+Mg) vs. (Al^{IV}+Al^{VI}), showing the
975   phengite substitution ($Si_{+1}[Fe^{2+},Mg]_{+1}$+$Al^{IV}_{-1}Al^{VI}_{-1}$). (**f**) Staurolite compositions in the
976   diagram X_{Mg}-Si. (**g**) Biotite compositions (diagram of Rieder et al. 1998). (**h**) Feldspar

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977   compositions. The symbols and colors in (g) and (h) represent microstructural sites and
978   samples, respectively (see the common legend).

979   **Figure 7.** *P-T* pseudosections for samples T78 and T52. Notations used for the
980   isopleths: $x(Grt/Bt/St) = (Fe/(Fe + Mg))$; $z(Grt) = (Ca/(Ca + Fe + Mg + Mn))$; $Si(Ph) = Si$.
981   The presumed prograde and retrograde *P-T* paths (red dashed curves) are constrained by
982   various isopleths and isomodes; the blue dashed arrows indicate the shift of the solidus
983   curve towards higher temperatures during melt extraction (see text).
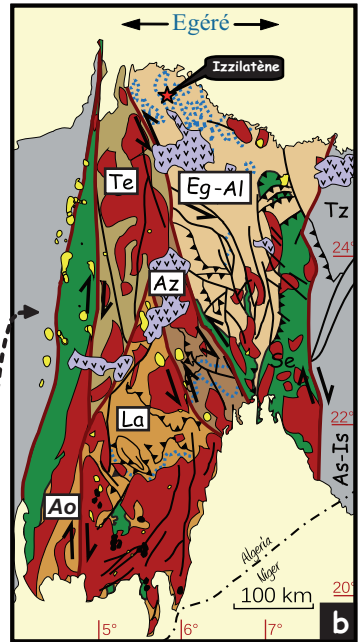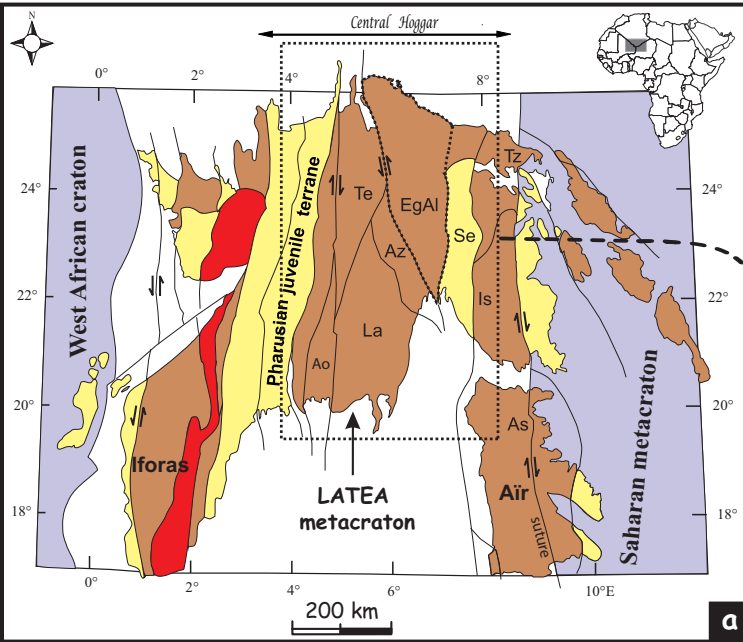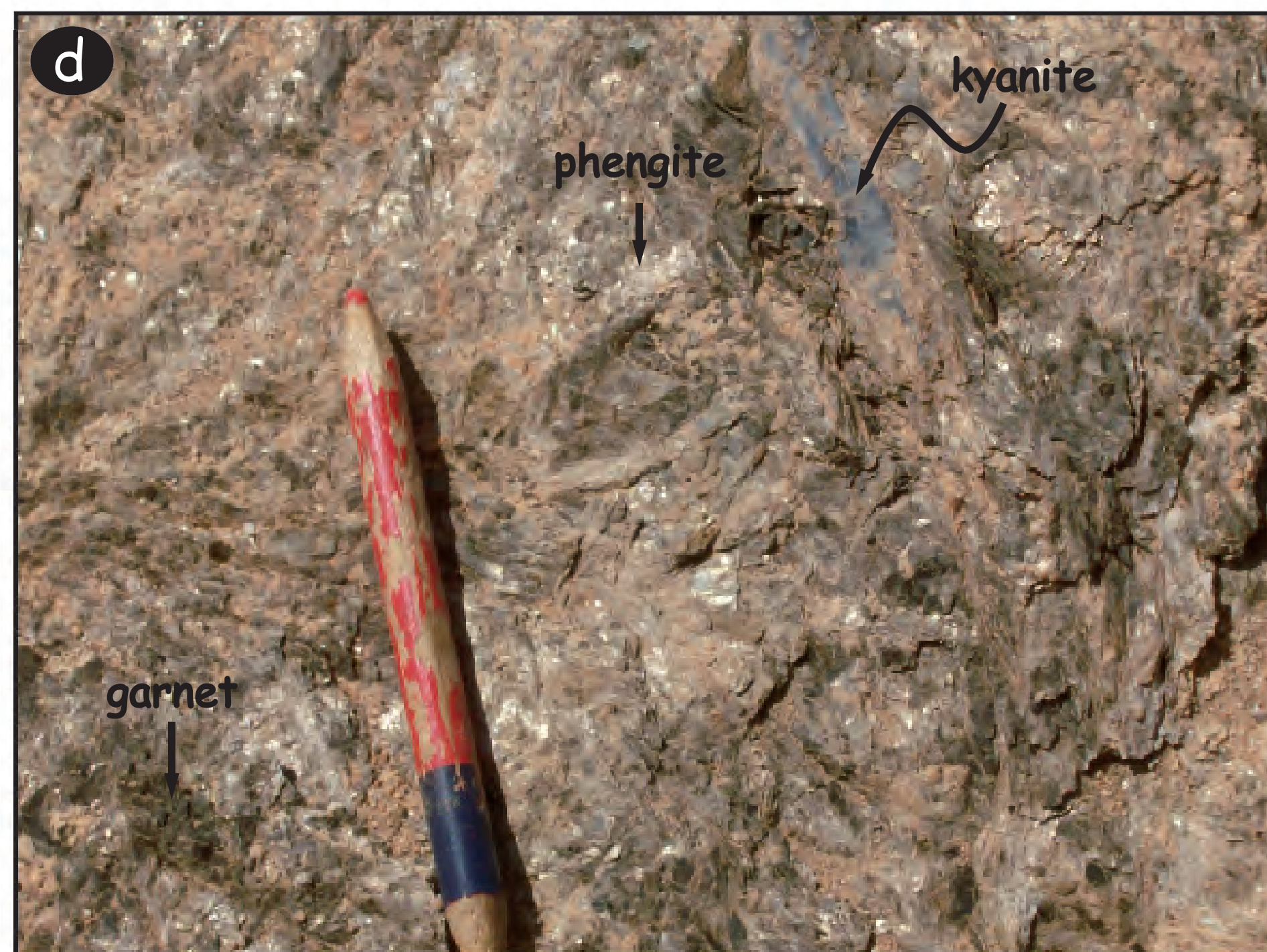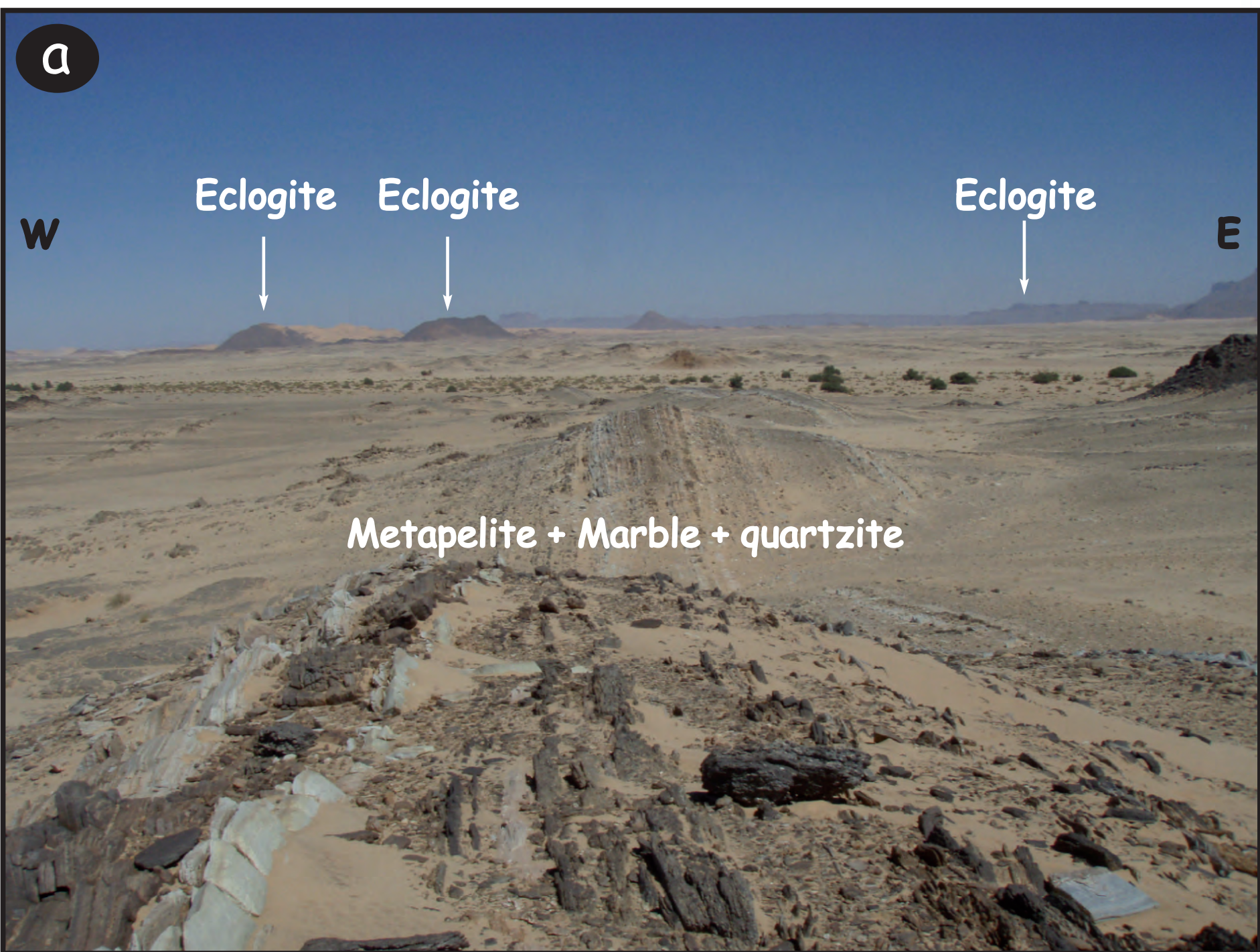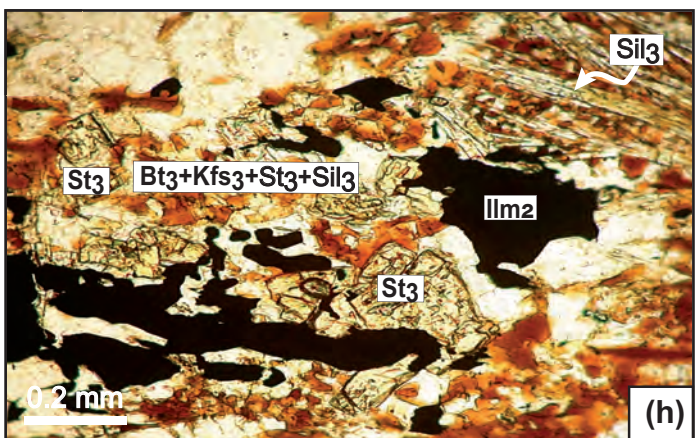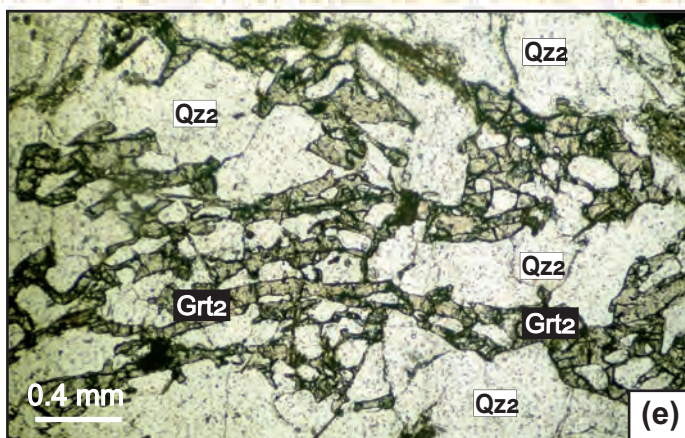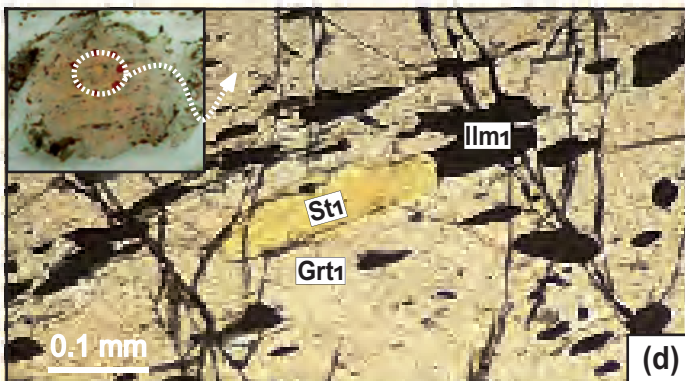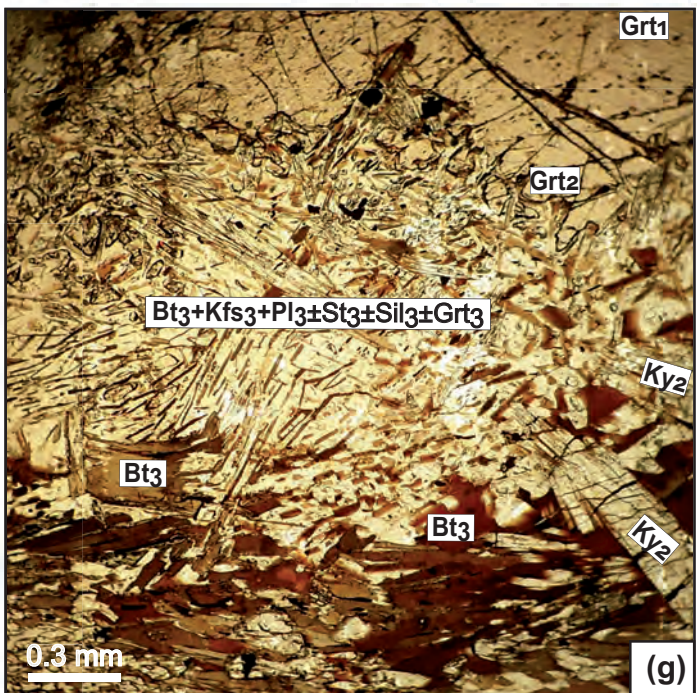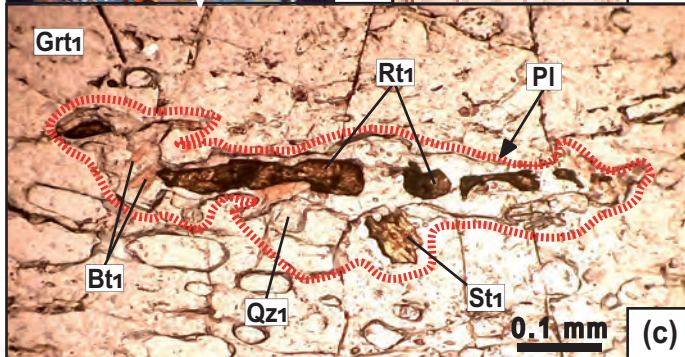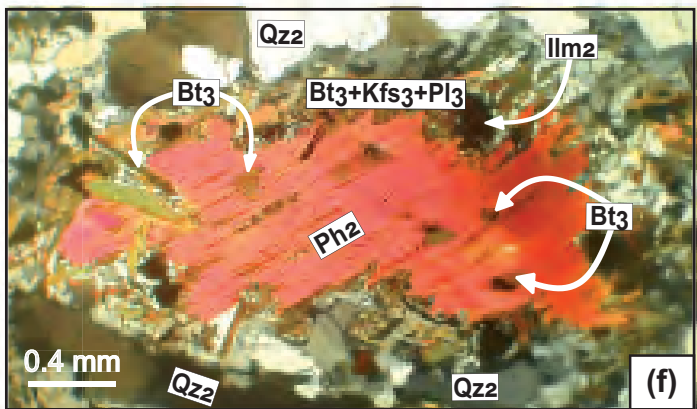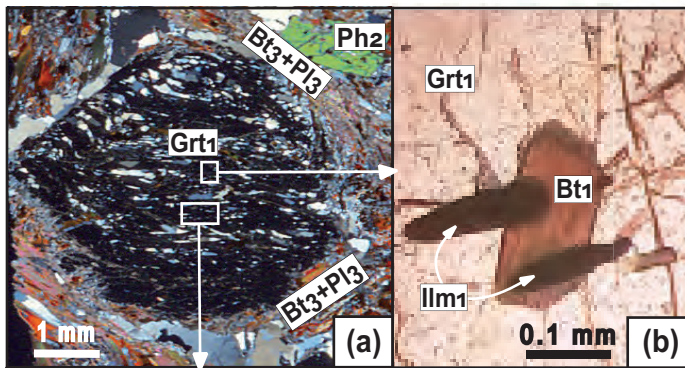
Figure 1

Figure 2

Figure 3
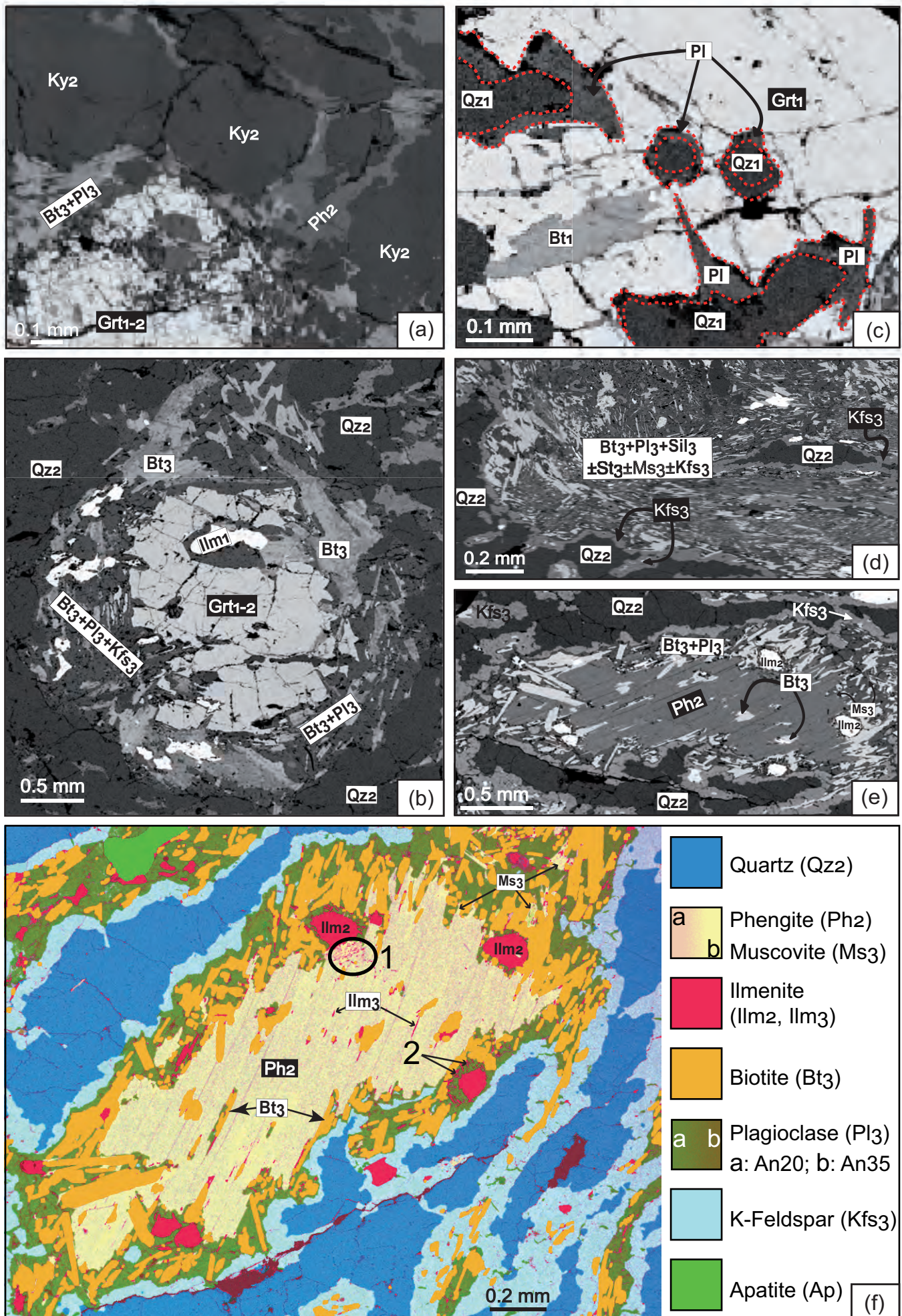
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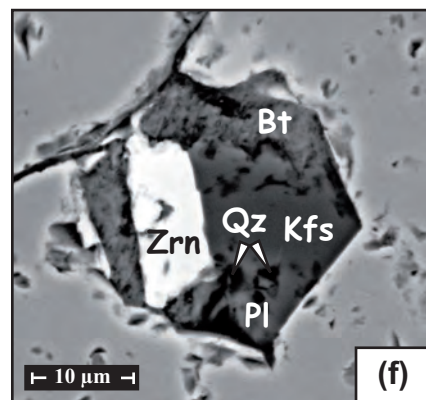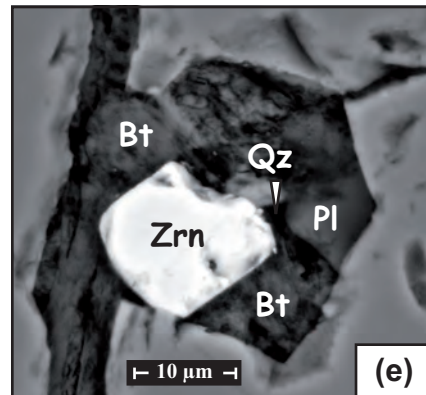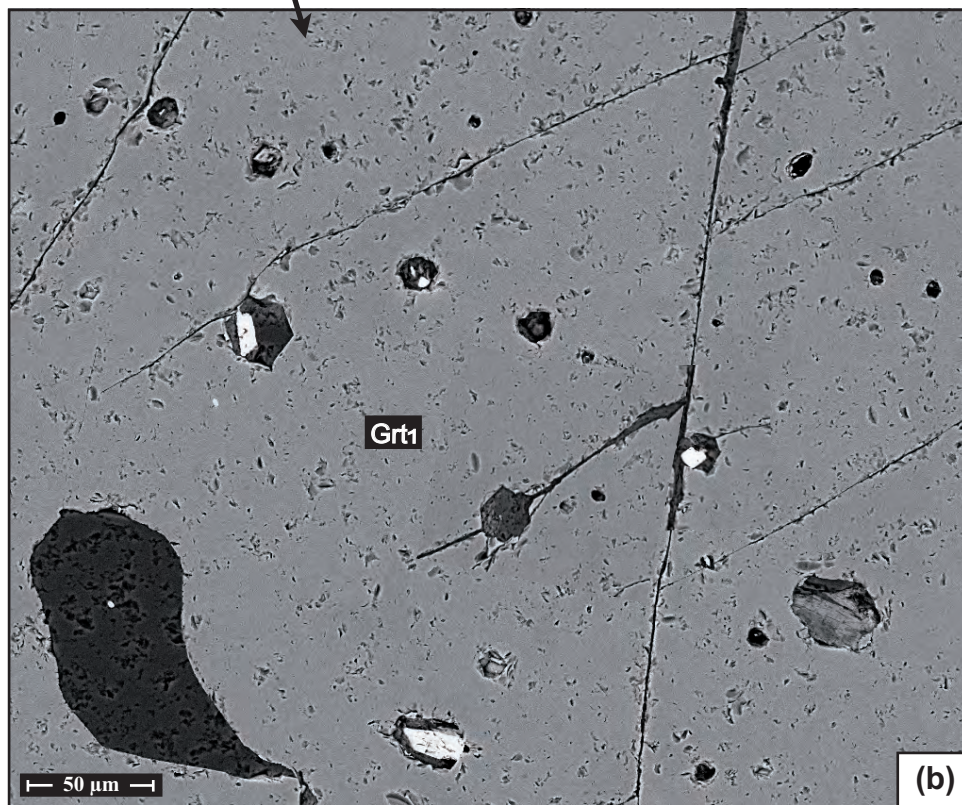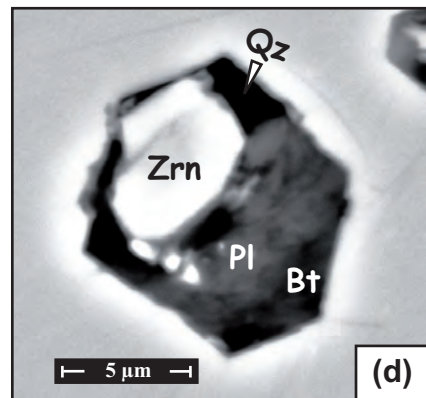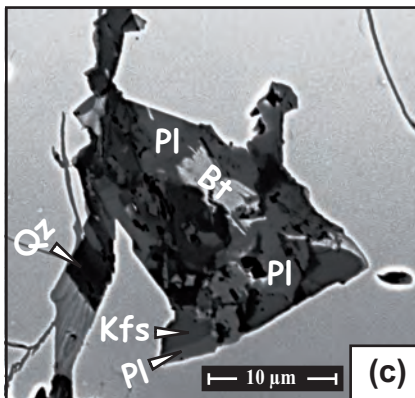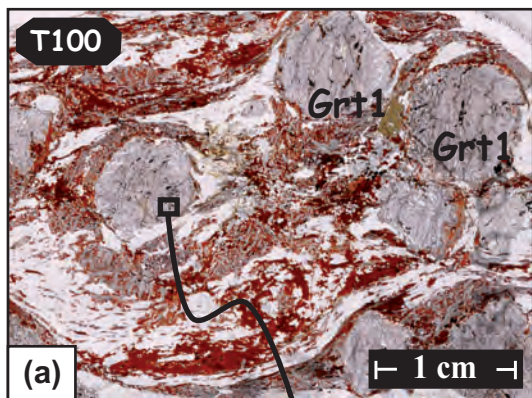
Figure 5

Figure 6

Figure 7