



**HAL**  
open science

# The tungsten-gold veins of Bonnac (French Massif central): new constraints for a Variscan granite-related genesis

Florent Cheval-Garabédian, Michel Faure, Eric Marcoux, Marc Poujol

## ► To cite this version:

Florent Cheval-Garabédian, Michel Faure, Eric Marcoux, Marc Poujol. The tungsten-gold veins of Bonnac (French Massif central): new constraints for a Variscan granite-related genesis. Bulletin de la Société Géologique de France, In press, 10.1051/bsgf/2020041 . insu-03079023v1

**HAL Id: insu-03079023**

**<https://insu.hal.science/insu-03079023v1>**

Submitted on 16 Feb 2021 (v1), last revised 15 Mar 2021 (v2)

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

1 **The tungsten-gold veins of Bonnac (French Massif central): new**  
2 **constraints for a Variscan granite-related genesis**

3

4 **Les filons à tungstène-or de Bonnac (Massif central français) :**  
5 **nouvelles contraintes pour une genèse reliée aux granites**  
6 **varisques**

7

8

9 Florent Cheval-Garabédian<sup>1-2\*</sup>, Michel Faure<sup>1</sup>, Eric Marcoux<sup>1</sup>, Marc Poujol<sup>3</sup>

10 1: Institut des Sciences de la Terre d'Orléans (ISTO), UMR 7327-CNRS/Université  
11 d'Orléans/BRGM, 1A Rue de la Férollerie 45071 Orléans Cedex 2, France

12

13 2: Present address: Société Minière Georges Montagnat, 30 route de la Baie des Dames,  
14 98800 Nouméa, Nouvelle-Calédonie

15

16

17 3: Université Rennes, CNRS, Géosciences Rennes – UMR 6118, F-35000 Rennes, France

18

19 \* Corresponding author: florent-cg@hotmail.fr

20

21

22

23

24 **Abstract**

25 In the Brioude-Massiac district (French Massif Central: FMC), a network of W-As-Bi-Au  
26 quartz veins constitutes the Bonnac deposit, where tungsten is the major economic element,  
27 together with high-grade gold (up to 15 g/t Au). The evolution of this mineralization has been  
28 divided into 3 stages: i) an early deep-seated wolframite-löllingite stage formed between 12 to  
29 9 km, at up to 400°C, ii) a ductile/brittle deformation stage associated with scheelite and  
30 arsenopyrite deposition, with an estimated temperature of 480-300 °C; iii) a late stage controlled  
31 by fluid-overpressure potentially triggered by fault-valve mechanism, at a depth of 7 to 5 Km,  
32 and a temperature estimated between 266 to 240 °C, is marked by micro-fracturing infilled by  
33 native bismuth, bismuthinite, hedleyite, electrum, pyrite and base-metals. Structural analysis,  
34 and apatite LA-ICP-MS U/Pb dating, demonstrate a spatial and temporal link between the  
35 emplacement of the peraluminous leucogranitic dykes and the Bonnac mineralization. In more  
36 details, the mineralization was deposited between 321-316 Ma, during, or just after, the  
37 emplacement of the peraluminous dykes estimated around 329-315 Ma, suggesting a magmatic-  
38 hydrothermal transition for the ore-forming process. In the proposed model, the cooling of a  
39 hidden two-mica granitic pluton could have generated a magmatic fluid, and acted as the heat  
40 source responsible for fluid flow towards inherited permeability zones. The magmatic fluid  
41 could have then re-equilibrated at high temperature by fluid-rocks interaction. The sharp  
42 changes in pressure, associated with the decrease of the temperature, and sulfide-fugacity  
43 generated by a late input of meteoric fluid were responsible for the deposition of the late gold-  
44 stage. At the regional scale, the tungsten-gold event is ascribed to an early hydrothermal stage,  
45 dissociated from the formation of the antimony event in the district. The leucogranitic dykes  
46 and Bonnac quartz veins are controlled by a NW-SE stretching direction, interpreted as an  
47 expression of the Serpukhovian-Bashkirian syn-orogenic extension (D4 event of the FMC).  
48 These new data provide evidence for an early tungsten and gold metallogenic event in the FMC,

49 prior the “Or300” event. The genetic classification of the Bonnac mineralization is equivocal.  
50 The W-As-Bi-Au-quartz veins exhibit the features of both an “orogenic gold” deposit at a  
51 relatively deep emplacement level (mesozonal), and an Intrusion-Related-Gold-Deposit  
52 (IRGD) type with a spatial-temporal link with the peraluminous intrusion emplacement. We  
53 propose that the Bonnac deposits represent an intermediate type between a typical orogenic-  
54 gold deposit and an IRGD. We argue that the presence of economic high-grade gold content in  
55 tungsten vein-type, and more generally the IRGD deposits, have been underestimated in the  
56 Variscan French Massif Central.

57

58 **Keywords.** Tungsten-Gold ore deposit, French Massif Central, IRGD, Variscan metallogeny,  
59 Brioude-Massiac district, Apatite U-Pb dating.

60

61

## 62 **Résumé**

63 Dans le district de Brioude-Massiac (Massif Central Français ; FMC), les gîtes de Bonnac  
64 correspondent à un réseau de veines de quartz à W-As-Bi-Au. Le tungstène y est le principal  
65 métal économique, et est associé à de fortes teneurs en or (entre 1 et 15 g / t Au). L'évolution  
66 de cette minéralisation peut être divisée en 3 étapes: i) un stade précoce à wolframite et  
67 löllingite, formé en profondeur, entre 12 et 9 km, et à des températures supérieures à 400 °C,  
68 ii) un stade de déformation ductile / cassant qui contrôle le dépôt de scheelite et d'arsénopyrite,  
69 estimé entre 480-300 °C; iii) un stade tardif, contrôlé par des surpressions de fluide marquées  
70 par une micro-fracturation colmatée par une paragenèse à bismuth natif, bismuthinite, hedleyite,  
71 électrum, pyrite associée à des métaux de base. Les surpressions de fluide seraient possiblement

72 provoquées par un mécanisme de valve-sismique, à des températures comprises entre 266 et  
73 240 ° C, à une profondeur estimée entre 7 et < 5 km. L'analyse structurale, et les datations U/Pb  
74 sur apatite par la méthode LA-ICP-MS démontrent un lien spatial et temporel entre les dykes  
75 leucogranitiques peralumineux et les gîtes de la région de Bonnac. La formation de la  
76 minéralisation entre 321-316 Ma est contemporaine à légèrement plus jeune que celle des dykes  
77 peralumineux mis en place autour de 329-315 Ma, ce qui suggère une genèse lors d'une  
78 transition magmatique-hydrothermal. Dans ce modèle, le refroidissement d'un pluton granitique  
79 à deux micas sous-jacent, pourrait générer des fluides magmatiques et servir de source de  
80 chaleur activant une circulation du fluide vers des zones à haute perméabilité comme des  
81 fractures préexistantes. Le fluide magmatique aurait ensuite été rééquilibré à haute température  
82 par des processus d'interaction fluide-roches. Les changements brusques de pression, la baisse  
83 des températures, et de fugacité du soufre générés par un apport tardif de fluides météoriques  
84 semblent responsables du dépôt du stade aurifère tardif. À l'échelle régionale, l'événement or-  
85 tungstène est attribué à un stade hydrothermal précoce, et dissocié de la formation de  
86 l'événement à antimoine du district. La mise en place des dykes leucogranitiques et des veines  
87 de quartz de Bonnac est contrôlée par une direction d'étirement NW-SE, interprétée comme une  
88 expression de l'extension syn-orogénique d'âge Serpukhovien-Bashkirien (événement D4 du  
89 Massif Central français). Ces nouvelles données fournissent des preuves d'une première période  
90 métallogénique à tungstène et or dans le FMC avant l'événement «Or 300». La classification  
91 génétique des minéralisations de Bonnac est équivoque. Les veines de quartz à W-As-Bi-Au  
92 présentent à la fois les caractéristiques du modèle de "l'or orogénique", avec un niveau  
93 relativement profond de mise en place (mésozonal), et celles du modèle Intrusion-Related-  
94 Gold-Deposit (IRGD) avec un lien spatio-temporel entre la minéralisation et une intrusion  
95 peralumineuse. Nous proposons que Bonnac soit un type intermédiaire entre un modèle typique  
96 de l'or orogénique, et un IRGD. Nous soutenons que la présence de teneurs économiques en or

97 dans les gisements de tungstène de type filonien, et plus généralement ceux de type IRGD, ont  
98 été sous-estimés dans la partie varisque du Massif Central Français.

99 **Mot clés :** Minéralisation à Tungstène-Or, Massif-Central-Français, IRGD, métallogénie  
100 Varisque, district de Brioude-Massiac, Age U-Pb sur apatite.

101

102

### 103 **1. Introduction**

104 The French Massif Central (FMC) represents a prominent metallogenic province for gold  
105 (Bouchot *et al.*, 2005) but only a few tungsten deposits have been found, although resources of  
106 at least 45,000t of WO<sub>3</sub> have been estimated, (Audion and Labbé, 2012), this is probably the  
107 consequence of an under-exploration for this metal in the FMC. The ubiquity of the quartz-  
108 wolframite hydrothermal veins makes it the main source of tungsten in the FMC. Some deposits  
109 with still a strong economic potential were formerly mined, such as Leucamp, Engualès and  
110 Echassières (Marignac and Cuney, 1999; Fig. 1).

111 Among the wolframite-bearing veins of the FMC, some display a polymetallic content with  
112 bismuth and gold in sub-economic grade (W-As-Bi-Au). They are ascribed either to the  
113 perigranitic wolframite vein-type (Marignac and Cuney, 1999) or to orogenic gold deposit  
114 (Bouchot *et al.*, 2005). In the FMC, occurrences of W-As-Bi-Au are known in gold mining  
115 districts such as the Limousin (Marcoux and Bonnemaïson, 1988), Pontgibaud (Marcoux and  
116 Picot, 1985), Brioude-Massiac (Périchaud, 1970; Bril, 1982; Marcoux and Bril, 1986; Sandras,  
117 1988; Bril and Beaufort, 1989; Bril *et al.*, 1991), Montredon (Béziat *et al.*, 1980), S<sup>t</sup>-Mélany  
118 (Charonnat, 2000; Chauvet *et al.*, 2012), and Leucamp districts (Derré, 1983; Bogdanoff *et al.*,  
119 1987; Demange *et al.*, 1988; Bouchot *et al.*, 2005; Lerouge and Bouchot, 2009). The spatial  
120 association of the wolframite-quartz veins with Carboniferous peraluminous two-mica granites

121 argues for an important role of this crustal magmatism in the genesis of the tungsten  
122 mineralization (Marignac and Cuney, 1999, Cuney *et al.*, 2002; Bouchot *et al.*, 2005; Harlaux  
123 *et al.*, 2018). However, the formation of these peri-granitic deposits is still debated. In particular,  
124 the temporal and genetic links between the episodes of magmatism, deformation, and  
125 hydrothermal mineralization are not fully clarified.

126 U-Pb TIMS dating on wolframite from the Limousin, Echassières, Montredon, and S<sup>t</sup>-Mélany  
127 districts (Fig. 1) has been recently performed (Harlaux *et al.* 2018). The obtained U-Pb ages  
128 define the existence of three tungsten mineralizing events closely related to magmatic activity:  
129 i) Visean to Serpukhovian mineralization (333 – 327 Ma) coeval with the emplacement ages of  
130 large peraluminous two-mica plutons (ca. 335 – 325 Ma) during the syn-orogenic extension, ii)  
131 Serpukhovian to Bashkirian mineralization (317 – 315 Ma) synchronous with the emplacement  
132 of syn-tectonic granites (ca. 315 – 310 Ma) during the late-orogenic extension, iii) Gzhelian to  
133 Asselian mineralization (around 300 – 298 Ma), formed during the post-orogenic extension,  
134 coeval with the metallogenic peak of the Or300 event during which the main orogenic gold  
135 deposits were emplaced in the FMC (Bouchot *et al.*, 2005).

136 In the central part of the FMC, i.e. in the Pontgibaud, Brioude-Massiac, and Leucamp  
137 districts, the timing for the emplacement of the wolframite bearing veins remains poorly  
138 constrained. Furthermore, the genetic relationships between the ore deposits and the granitic  
139 emplacement is not yet demonstrated. The Bonnac area, in the central part of the Brioude-  
140 Massiac district is a good target to address these questions (Fig. 1). Indeed, in this area, a dozen  
141 of W-As-Bi-Au bearing quartz veins from the South of the Bonnac village to the Scoufour  
142 hamlet (Fig. 3) further north (Périchaud, 1970; Sandras, 1988) are spatially associated with a  
143 leucogranitic dyke swarm dated at  $322 \pm 7$  Ma (K/Ar on muscovite, Bril *et al.*, 1991), while the  
144 W-As-Bi-Au mineralization yields late Permian age of about 250 Ma (K/Ar on muscovite from  
145 Bonnac; Bril *et al.*, 1991). Variable gold grades ranging from 1 to 15 g/t have been reported in

146 ore samples from the region (Périchaud, 1970; Sandras, 1988), but the relationship between gold  
147 and tungsten ore is not clearly documented.

148 The aim of this study is to better understand the W-As-Bi-Au quartz vein deposits in the  
149 FMC, and more particularly in the Bonnac area. It focuses on the structural control and the  
150 timing of these ore deposits, and their relationships with the Carboniferous tectonics and  
151 magmatism, and will be integrated within the hydrothermal framework of the Variscan FMC.  
152 Detailed field structural studies, and in-situ apatite LA-ICP-MS U/Pb dating were carried out.  
153 Mineralogical and geochemical studies were also performed to decipher the tungsten-gold  
154 relationships and propose an updated metallogenic model.

155

## 156 **2. Geological and metallogenic background**

### 157 2.1 The Haut-Allier area in the FMC Variscan framework

158 Located in the central part of the FMC, the 1000 km<sup>2</sup> Brioude-Massiac polymetallic district  
159 is covered by Cenozoic basaltic flows, and bounded to the northeast by the Oligocene Limagne  
160 graben. The district that belongs to the Variscan orogen, is a N120-130°E trending antiform  
161 that refolds the stack of metamorphic nappes recognized in the entire Massif Central (e.g. Burg  
162 and Matte, 1978; Ledru *et al.*, 1989; Faure *et al.*, 2005, 2009; Fig. 1, 2). The core of the area is  
163 occupied by the Lower Gneiss Unit (LGU) represented by biotite-sillimanite paragneiss,  
164 intruded by the Céroux orthogneiss derived from a Cambro-Ordovician alkaline granite (Burg  
165 and Matte, 1978; Lasnier *et al.*, 1982; Mathonnat, 1983; Thonat *et al.*, 2014). The LGU is  
166 tectonically overlain by the Upper Gneiss Unit (UGU), which is formed by migmatitic  
167 paragneiss with rare orthogneiss, and a felsic-mafic association called the “leptynite-  
168 amphibolite complex”. The mafic rocks experienced an eclogite-facies or granulite-facies  
169 metamorphism during the eo-Variscan evolution (Marchand, 1974; Lasnier, 1977; Bernard-  
170 Griffiths *et al.*, 1980).



171 The nappe stacking in the Haut-Allier area was probably acquired during the early  
172 Carboniferous, around 350-340 Ma (monazite U/Pb dating on syntectonic granulite; Pin and  
173 Peucat, 1986). Then two extensional events, coeval with granitic intrusions accommodated the  
174 crustal thinning widely observed in the FMC (e.g. Malavieille *et al.*, 1990; Faure and Pons,  
175 1991; Faure, 1995). i) The syn-orogenic extension at ca 330-310 Ma, called D4 event (Faure *et*  
176 *al.* 2009), is characterized by a NW-SE maximum stretching recorded by the syn-tectonic  
177 biotite monzogranite and the two-mica granite plutons and their country rocks. In the Brioude-  
178 Massiac area, andalusite-leucogranitic dykes and their related two-mica granites (Sandras,  
179 1988; Bril *et al.*, 1991) belong to this D4 event. ii) The late-orogenic extension (D5 event,  
180 between 310 to 299 Ma; Faure *et al.*, 2009), with a NNE-SSW maximum stretching direction,  
181 was contemporaneous with the emplacement of highly differentiated peraluminous intrusions  
182 and pegmatites, and rare-metal granites (Cuney *et al.*, 2002). The opening of the Late  
183 Carboniferous coal basins belongs to the D5 event (Faure, 1995).

184

## 185 2.2 The Bonnac W-As-Bi-Au deposits

186 The study area is located in the central part of the Brioude-Massiac polymetallic district  
187 which contains more than 200 veins-type deposits and occurrences with variable ore content:  
188 W, Sn or W-As-Bi-Au (Bonnac, Vèze-Bosberly veins), Sb (Au), Pb-Zn or F and Ba (Fig. 2).  
189 Antimony veins have been the main economic substance mined between 1850 and 1978 with  
190 an historical production of 43 000 t Sb metal (Périchaud, 1970; De Gramont *et al.*, 1990). The  
191 Bonnac area was only mined for gold between 1880 and 1911 with a production of only 2 kg  
192 of gold, and never for tungsten (Périchaud, 1970; De Gramont *et al.*, 1990).

193 The Bonnac W-As-Bi-Au quartz-veins are spatially associated with Sb (Au) quartz veins  
194 (Fig. 2) and are located in the southwestern limb of a regional N120-130°E antiform. All veins  
195 seem to crosscut the foliation of the LGU paragneiss (Fig. 2 and 3). Some quartz veins develop

196 immediately at the contact with andalusite leucogranitic dykes (Périchaud, 1970; Sandras,  
197 1988). The ore mineralogy, is mainly represented by arsenopyrite-löllingite with wolframite,  
198 minor scheelite, associated with bismuthinite, native bismuth, tetradymite and visible gold in a  
199 quartz gangue with muscovite clusters (Périchaud, 1970; Bril, 1982; Bril and Beaufort, 1989).

200 Detailed studies on fluid inclusions (Bril, 1982), hydrothermal alteration (Bril and Beaufort,  
201 1989), and lead isotopic signature (Marcoux and Bril, 1986) allow to constrain the P-T  
202 conditions of vein deposition. The Bonnac veins display two successive hydrothermal stages  
203 with an early high temperature (homogenization temperatures between 350-400 °C) CO<sub>2</sub>-CH<sub>4</sub>-  
204 rich ± N<sub>2</sub> aqueous fluid with low-salinity (about 5 equiv wt % NaCl), interpreted as of  
205 metamorphic origin, and a late low temperature (homogenization temperatures between 200 –  
206 300 °C) aqueous fluid, with low-salinity, of meteoric origin, similar to the ore forming fluid  
207 from the Sb (Au) deposits. According to the same authors, the formation of the W-As-Bi-Au  
208 and Sb (Au) veins could be contemporaneous, the result of a single hydrothermal system coeval  
209 with the emplacement of an underlying, albeit hidden, Permian pluton. The ore veins were  
210 considered to show a zonal distribution, with W-As-Bi-Au occurring in a limited area, near the  
211 intrusion, the Sb (Au) veins being more distal.

### 212 2.3 The intrusive rocks

213 Leucogranitic dykes, striking N30°E, N60°E and sometimes N100°E, with a variable  
214 thickness (between 50 cm to 20 m), and small extension (less than 3 km), are cropping out in a  
215 few clusters in the district, the Bonnac area being one of the most important (Fig. 2 and 3).  
216 These dykes display a homogeneous mineralogical and chemical composition in the overall  
217 district (Sandras, 1988). Quartz is the most abundant mineral, associated with plagioclase, and  
218 sub-euhedral K-feldspar (< 5 mm) with biotite aggregates and muscovite. Andalusite is  
219 observed as small sized grains (0.6 to 0.8 mm), associated with the K-feldspar and quartz. A  
220 temperature emplacement of ca 600-650 °C, and a pressure of 0.4 GPa, was estimated from the

221 andalusite-quartz assemblage (Sandras, 1988). An emplacement age of  $322 \pm 7$  Ma was  
222 documented by K/Ar radiometric dating on muscovite (Bril *et al.*, 1991).

223 The dykes chemical compositions correspond to a peraluminous two-mica granite with 74  
224 to 76 % SiO<sub>2</sub>, and a Al<sub>2</sub>O<sub>3</sub>/CaO+Na<sub>2</sub>O+K<sub>2</sub>O ratio up to 1.6 (see EDM. 1 for analytical details).  
225 This bulk chemistry is similar to those found in the Chatelet gold district, and other Visean to  
226 Serpukhovian leucogranites from the Limousin district (e.g. S<sup>1</sup>-Sylvestre massif; Scaillet *et al.*,  
227 1996). A local partial melting of the LGU paragneiss could be responsible for the genesis of  
228 those intrusive rocks (Sandras, 1988). A spatial and potentially genetic link with the W-As-Bi-  
229 Au deposits of the Brioude-Massiac district is assumed. At Bonnac, the dykes are interpreted  
230 as the shallow expression of an underlying pluton (Sandras, 1988; Bril and Beaufort, 1989).

### 231 **3. Materials and methods**

232 The accessory mineral phases were identified using a Merlin compact Zeiss Scanning  
233 Electron Microscopy (SEM), co-operated by BRGM-CNRS-Orléans University, and equipped  
234 with Energy Dispersive System (EDS) for qualitative analyses. In addition, SEM-  
235 cathodoluminescence images have been made using MEB-CL MIRA-3 Tescan (BRGM-  
236 CNRS-Orléans University). Chemical analyses of arsenopyrite were obtained with the Cameca  
237 SX-Five Electron Probe Micro-Analyzer (EPMA) at the Institut des Sciences de la Terre  
238 d'Orléans (ISTO). Analyses were performed using an accelerating voltage of 20 kv, a beam  
239 current at 40 nA, a beam diameter of 3 µm, and a counting time of 30 s for Fe, Ni, Co, Sb, Pb,  
240 Cu, As, Zn, Ag, Bi, and 60 s for gold. Details on the method, parameters and analytical data are  
241 given in ESM2.

242 U/Pb dating on hydrothermal apatite from the mineralization was conducted in-situ by laser  
243 ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the GeOHeLiS  
244 analytical platform (Géosciences Rennes/OSUR, Univ. Rennes) using an ESI NWR193UC

245 Excimer laser coupled to an Agilent 7700x quadrupole ICP-MS equipped with a dual pumping  
246 system to enhance sensitivity (Paquette *et al.*, 2014). The analytical procedure followed the  
247 method described in Pochon *et al.* (2016). Details, standards analyses and analytical data are  
248 provided in ESM3. All errors are listed at  $2\sigma$  level. Concordia diagrams and calculated ages  
249 have been produced using IsoplotR (Vermeesch, 2018).

#### 250 **4. Field characterization of the W-As-Bi-Au quartz veins**

251

##### 252 4.1 Field and structural features from the Bonnac area

253 The strike of the mineralized quartz veins displays three different orientations similar to  
254 those of the leucogranitic dykes. The N30°E trend is represented by the Riolet, Androl, Rode,  
255 Borie veins), the N60°E by the Costillon one, while few veins strike N90°E and N160-170°E  
256 (Fig. 3). The vein dip varies between 30° to 45° to the SE whatever their strike. Mineralized  
257 quartz veins are located in the hangingwall or footwall of the leucogranitic dykes (Fig. 4, 5).  
258 They display similar features all around the area, with a lenticular shape, and a narrow width of  
259 1 to 20 cm. The host-rocks are weakly affected by the hydrothermal alteration. The geometric  
260 relationships show that the leucogranitic dykes crosscut the paragneiss foliation, and are cut by  
261 the mineralized veins (Fig. 4B, 5) with locally developed breccias (Fig. 4B).

262 Most of the vein wallrocks are fault planes with a down-dip striation, indicating a normal  
263 motion (Fig. 5). Some veins display also a striation with a NE 40-50° pitch, in which quartz  
264 steps indicate a normal component of displacement (Fig. 5C, D). The observed kinematics of  
265 the Costillon vein (Fig. 4A) also indicate a normal motion that complies with the drag folds  
266 asymmetry developed around the leucogranitic dykes (Fig. 5B). Late N60-65°E striking sub-  
267 vertical barren faults, with gouge, offset the quartz veins (Fig. 4A).

268

## 269 4.2 Field and structural features from the Scoufour-area

270 The Scoufour mineralized quartz veins exhibit some differences with the Bonnac ones. Three  
271 N10-30°E striking low-angle veins with a dip between 10 and 20° to the SE are observed (Fig.  
272 6). Their thickness is comprised between 30 and 50 cm, but may exceed 1m. Here, leucogranitic  
273 dykes are absent, and the host-rock underwent a hydrothermal alteration related to the  
274 mineralization. A greisen-type alteration is thus observed up to 1 or 2 m from the vein, resulting  
275 in the bleaching of the paragneiss by transformation of biotite into muscovite with associated  
276 silicification. Drag folds observed near the Ferbert vein show a normal motion (Fig. 6B). A late  
277 fracturing event, represented by N20-25°E steeply NW dipping barren faults with gouge, is also  
278 recognized (Fig. 6A).

279 All the structural features observed in the Bonnac and Scoufour areas are summarized in  
280 Figure 7. In both cases, the emplacement of the mineralized quartz veins occurred during a  
281 single deformation phase coeval with a hydrothermal event. The magmatic event responsible  
282 for dyke emplacement post-dated the regional metamorphism but preceded the ore veins  
283 emplacement. Furthermore, normal faults rework the pre-existing faults that controlled the  
284 emplacement of the leucogranitic dykes. Lastly, both dykes and mineralized veins are cut by  
285 NE-SW subvertical faults with subhorizontal striation indicating a sinistral motion.

## 286 **5. Mineralogy and geochemistry of the W-As-Bi-Au ore veins**

### 287 5.1 The mineralized facies

288 All the mineralized veins of the study area have similar habitus, with a massive infill of  
289 coarse white-grey quartz gangue with parallel ribbons of a few centimeters, or aggregates of  
290 arsenopyrite and coarse wolframite (Fig.4A and 8). Secondary scheelite is common in cm-scale  
291 pseudomorphic aggregates of early wolframite that may appear as rare relicts and rarely  
292 observed as isolated, coarse grains or infilling fractures. (Fig. 8).

293 On the basis of gangue and ore mineral textural observations, 3 stages have been recognized,  
294 namely: i) stage 1 with tungsten and arsenic, ii) stage 2 with arsenic, and tungsten, iii) stage 3  
295 with bismuth, gold, and base metals.

#### 296 5.2 Stage 1: early tungsten and arsenic

297 The first opening of the veins corresponds to the deposition of a wolframite and löllingite  
298 assemblage in a macrocrystalline Qz1 quartz (crystal size > 500  $\mu\text{m}$ ; Fig. 9A, B). Observed with  
299 cathodoluminescence, Qz1 displays a blocky habitus with regular growth bands without  
300 significant deformations (Fig. 9B), and numerous fluid inclusions. Coarse euhedral wolframite  
301 crystals (up to 1 cm) are associated with cm-size aggregates of löllingite (Fig. 9A). SEM  
302 analyses of wolframite exhibits a high iron grade (6-8 wt %) and a lower manganese one  
303 suggesting a ferberite. Large apatite crystals (> 100  $\mu\text{m}$ ) have been observed within Qz1 in  
304 close association with wolframite (Fig. 9C). Their euhedral shape and straight grain boundaries  
305 suggest it is coeval with Qz1.

#### 306 5.3 Stage 2: arsenic and late tungsten

307 The beginning of stage 2 is marked by an intense and heterogenous episode of deformation  
308 (Fig. 9A, B, C, D) which has affected the previous stage 1 assemblage. Qz1 grains experienced  
309 a dynamic recrystallization (Stipp *et al.*, 2002) shown by undulose extinction, subgrain rotation  
310 and recrystallization with golfed or jagged shape of the Qz1 boundary, bulging and quartz  
311 neograin (Qz2) formation at the expense of the early Qz1 (Fig. 9 B, D and Fig. 10 A and B).  
312 Qz2 displays undulose extinction and grain size reduction and is located along 10 to more than  
313 500  $\mu\text{m}$  shear bands that surround the edges of Qz1, or crosscut it.

314 The crystallization of arsenopyrite (Fig. 9 B) and scheelite are coeval with the deformation  
315 episode. Arsenopyrite forms small rhombic crystals (up to 100  $\mu\text{m}$ ) and fills the fracture  
316 network of the stage 1 löllingite or wolframite and sometimes totally pseudomorphs after

317 löllingite. Xenomorphic scheelite forms at this stage by partial or total pseudomorphosis of  
318 previous wolframite (Fig. 9 A, C). The scheelites, show rare inclusions of niobium oxides rich  
319 in niobium as on the Ferbert vein, (65 wt % Nb<sub>2</sub>O<sub>5</sub>), iron (25 wt % FeO), manganese (4.5 wt %  
320 MnO), tungsten (2.4 wt % WO<sub>3</sub>), titanium (2.2 wt % TiO<sub>2</sub>) and scandium (0.9 wt % Sc<sub>2</sub>O<sub>3</sub>).  
321 Those uncommon oxides have been observed in the Puy-Les-Vignes tungsten deposit (Harlaux  
322 *et al.*, 2015).

323 The 56 EPMA analyses of arsenopyrite (see Table 1 and ESM 2 for detail) have been  
324 compared with previous study of Bril (1983) from the Bonnac area and from other W-As-Au  
325 regional veins (Vèze and Bosberly, see Fig. 2 for localization). Arsenopyrite has a very similar  
326 composition in all deposits with As % average values of 33.4 %, 32.8%, and 33.0 % for Bonnac,  
327 Vèze, and Bosberly veins, respectively. Minor elements, e.g. Co, Ni, Sb, Au are under the  
328 detection limit of the method. According to Kretschmar and Scott (1976), and Sharp *et al.*  
329 (1985), the use of the arsenopyrite chemical compositions to assess ore formation temperatures  
330 may be considered with a good confidence level, because of the absence of minor element.  
331 Assuming the arsenopyrite-pyrrhotite equilibrium, the calculated formation temperature was  
332 around 480 °C. These values are in the same range than those deduced from the H<sub>2</sub>O-CO<sub>2</sub> L1-  
333 type fluid-inclusions (homogenization temperature between 300 and 420 °C; Bril, 1982).

334

#### 335 5.4 Stage 3: Bi-Te-Au and base metals

336 This stage is marked by the deposition of a new discrete quartz generation (Qz3) in the  
337 fractures of arsenopyrite or löllingite (Fig. 10 C, D). The medium grain-size (around 100 µm)  
338 Qz3 displays a subeuhedral shape or elongate-fibrous habitus. Its hyaline aspect is due to the  
339 scarcity of fluid and solid inclusions. This Qz3 never experienced dynamic recrystallization  
340 (Fig. 10 C, D) and is coeval with a bismuth-telluride-gold-base metals assemblage (Fig. 10 C,  
341 D, E). Rhombic arsenopyrite crystals are commonly crosscut by large mm-size, subeuhedral

342 pyrite, associated with bismuth-telluride and base-metals minerals (Fig. 11 D, E). The EPMA  
343 chemical analysis of the pyrite from Bonnac veins does not show minor element.

344 Bismuthinite and native bismuth are the dominant minerals species of this stage 3. They  
345 occur as 2 to 80  $\mu\text{m}$  inclusions aligned along the cleavage plane of löllingite (Fig. 11A), also  
346 within arsenopyrite, or wolframite (Figs. 10 C, D; 11 A, B, C), and as small-size aggregates (<  
347 500  $\mu\text{m}$ ) or in fractures crosscutting löllingite or arsenopyrite (Fig. 10E, F). Native bismuth is  
348 frequently observed as ovoidal inclusions within bismuthinite (Figs. 10 F; 11 C). Xenomorphic  
349 hedleyite ( $\text{Bi}_7\text{Te}_3$ ) is the main tellurium mineral, always closely associated with the  
350 bismuthinite and native bismuth. Tetrahedrite  $[(\text{Cu},\text{Fe})_{12}\text{Sb}_4\text{S}_{13}]$  and a bismuth-antimony-  
351 sulfide, close to the chemical composition of the horobetsuite  $[(\text{Bi},\text{Sb})_2\text{S}_3]$ , have been identified  
352 as inclusions in a hedleyite aggregate (Fig. 10 F). In the Ferbert vein, a late deposition of Cu-  
353 Zn-Pb minerals overprints and brecciating all the previous minerals. Chalcopyrite is the main  
354 mineral, with small tetrahedrite inclusions (50  $\mu\text{m}$ ). Sphalerite and minor galena complete this  
355 assemblage. This late deposition stage is associated with a Qz4 quartz generation displaying  
356 undeformed pyramidal grains (Fig. 11E).

357 Visible gold has been commonly observed in thin-sections from all veins of the Bonnac area.  
358 Most of the gold intergrowths with the Bi-Te minerals, (Fig. 10 B, 11 A, B, C), or more rarely  
359 appears within sulfides (mainly chalcopyrite, Fig. 11 D, E), or sometimes pyrite or isolated  
360 between Qz2 grains. Gold patches range between 1  $\mu\text{m}$  to 25  $\mu\text{m}$  in size but can reach 50  $\mu\text{m}$   
361 within sulfides. All display a xenomorphous rounded shape (Fig. 11). Rare maldonite ( $\text{Au}_2\text{Bi}$ )  
362 has been observed by SEM analysis as a few microns inclusions intergrowths with native  
363 bismuth.

364 Ten EPMA analyses of gold grains intergrowths with native bismuth and within chalcopyrite  
365 from the Ferbert vein are provided in Table 1 (see EDM 2 for detailed analyses). The small size



366 of the gold grains explains why the analyses do not reach 100 %. Silver is the only element  
367 present with gold (average of 16.7 wt % Ag). “Gold” of Bonnac area is thus an electrum with  
368 a gold fineness of 830 (Morisson *et al.*, 1991).

369 The three economic-stages described above are summarized in figure 12, however, this  
370 evolution represents increments of a single progressive crystallization-deformation event.

371  
372 It should be noted that, a poorly developed and uneconomic post-ore stage, macroscopically  
373 highlighted by a dark-gray quartz facies, has been only observed in the Ferbert vein. All the  
374 previous stages are brecciated and cemented by a chalcedonic quartz gangue with minor  
375 carbonates. The associated metallic-minerals are pyrite-marcasite aggregates with pyrrhotite  
376 relics, with a new generation of chalcopyrite, and sphalerite. This does not greatly affect the  
377 previous assemblages.

378

## 379 **6. LA-ICP-MS U/Pb geochronology on apatite**

380 Hydrothermal apatite from the early tungsten-arsenic stage 1 (Fig. 9C and Fig. 12) of the  
381 Androl (Bonnac area) and Ferbert veins (Scoufour area) have been carefully characterized and  
382 15 grains have been selected for dating. Namely, 9 from the Ferbert vein (mineralized quartz  
383 vein sample BM46D) and 6 from Androl vein (mineralized quartz vein sample BM39A; ESM  
384 3 for analytical details). The cathodoluminescence image shows growth zones without evidence  
385 complex zoning (Fig. 13 A, B). Between 2 and 6 U/Pb analysis have been performed on each  
386 grain (Fig. 13C, D). Apatite grains from the Ferbert vein have variable  $^{207}\text{Pb}/^{206}\text{Pb}$  ratios,  
387 ranging between 0.1849 and 0.7010. The discordant points plot along a discordia line that yields  
388 a lower intercept date of  $315.6 \pm 2.8$  Ma (MSWD = 3.7; Fig. 13C). The data plot along a  
389 discordia line yielding a lower intercept date of  $323.4 \pm 3.2$  Ma (MSWD = 2.4, Fig. 13D). The  
390 intersect point of the discordia give the isotopic composition of the initial lead of the dated

391 apatite (Fig. 13C, D). Their composition shows some difference between the Ferbert vein and  
392 the Androl vein with respectively  $0.823 \pm 0.005$  and  $0.853 \pm 0.013$ . Those results are consistent  
393 with initial  $^{207}\text{Pb}/^{206}\text{Pb}$  ratios measured in different nearby mineralized veins, and main  
394 lithological formations of the Brioude-Massiac area (Marcoux and Bril, 1986). Thus, the  
395 Fournial (Pb-Ag-Sn-As veins) have  $^{207}\text{Pb}/^{206}\text{Pb}$  ratios different  $0.86234 \pm 0.00027$  (n=14), but  
396 that of the Sb-(Au) vein of the Céroux is closer  $0.8598 \pm 0.0014$  (n=1). On the other Sb-(Au)  
397 veins, the isotopic compositions of the lead remain variable within de district. The aplitic dykes  
398 close to a leucogranitic composition from the la Margeride pluton, in the southern part of the  
399 district, show the strongest correlation with the Androl vein with a  $^{207}\text{Pb}/^{206}\text{Pb}$  ratio of 0.8569  
400 (n=1, composition recalculated at 320 Ma).

## 401 7. Discussion

### 402 7.1 Mechanisms of ore-vein formation and chemical-thermal evolution

403  
404 During **stage 1**, the initial vein opening, coeval with the massive crystallization of the Qz1  
405 under low-strain, was contemporaneous with a high temperature (up to 400 °C) paragenesis  
406 with wolframite and löllingite from an As and W enriched fluid with low-salinity (about 5 equiv  
407 wt % NaCl) CO<sub>2</sub>-CH<sub>4</sub>-rich  $\pm$  N<sub>2</sub> aqueous fluid (V-type fluid inclusions in the classification of  
408 Bril, 1982).

409 A ductile/brittle deformation episode marks the beginning of **stage 2** (Fig. 12). The first Qz1  
410 experienced a dynamic recrystallization shown by undulose extinction, subgrain rotation  
411 recrystallization, bulging and quartz neograin (Qz2) formed at the expense of the early Qz1.  
412 Ductile/brittle deformation features argue for a deep-seated formation between 12 to 9 km  
413 (Scholz, 1988). This is supported by the range of temperature for this stage, estimated around  
414 480 °C, based on the arsenopyrite thermometry and, in agreement with the estimated  
415 temperature range (400 to 500 °C) deduced from the quartz textural observations (e.g. Stipp *et*

416 *al.*, 2002). Those depth and temperature estimation are in good agreement with the estimated  
417 emplacement conditions of the leucogranitic dykes of Bonnac (see part 2.3). The  
418 transformations of wolframite into scheelite, and löllingite into arsenopyrite suggest a change  
419 in fluid chemistry, still rich in As and W, and marked by an increase in sulfur fugacity and in  
420 the calcium activity. The pseudomorphic textures argue for a remobilization of the tungsten  
421 from the previous ferberite. The increase of the Ca/Fe ratio in the fluid, associated with a  
422 slightly decrease of the temperature, as predicted by Wood and Samson, (2000) could possibly  
423 correspond to higher fluid interaction with the surrounding metamorphic formations. This fluid  
424 could correspond to the L1-type fluid inclusions defined by Bril, (1982), with low-salinity (3.5-  
425 0 equiv wt % NaCl), lower CO<sub>2</sub> aqueous fluid, and trapping temperature estimated around 300  
426 to 400 °C (Fig. 14).

427 The onset of **stage 3** (Fig. 12) was marked by brittle fracturing. The previous assemblage  
428 was micro-brecciated, and invaded by a hyaline, low-strain Quartz (Qz3). This new quartz  
429 generation was coeval with the deposition of native bismuth, bismuthinite, hedleyite, electrum,  
430 pyrite, and base-metals minerals (chalcopyrite, sphalerite, galena). The microcrack infill as well  
431 as fluid and solid-inclusions bands (Fig. 10 A, B) suggest fluid-assisted fracturation under a  
432 hydrostatic regime at a depth comprised between 7 and < 5 km (Scholz, 1988). This stage 3  
433 might be interpreted as a consequence of a crack-and-seal triggered by a fluid overpressure  
434 mechanism (Ramsay, 1980). The emplacement of the previous massive quartz generations  
435 could have sealed the porosity in the fault zone and act like an impermeable barrier to fluid flow  
436 allowing an increase in the fluid pressure. The crack-and-seal process has triggered pressure  
437 drop from lithostatic to hydrostatic regime, and might be interpreted as a consequence of a fault-  
438 valve mechanism (Sibson *et al.*, 1988; Cox *et al.*, 1991; Robert *et al.*, 1995; Gaboury and  
439 Daigneault, 2000). The textural evolution reflects the transition from a lithostatic pressure  
440 context during stages 1 and 2 with a limited permeability to pervasive fluid circulation in

441 connected fractures, therefore implying a transition from, an aseismic to, a seismic environment  
442 (Cox, 1987; Cox *et al.*, 1991).

443 The deposition temperature of gold during stage 3 can be deduced from the paragenetic  
444 association of native bismuth and bismuthinite. According to Barton and Skinner (1979), a  
445 range of temperature between 320 to 240 °C can be proposed. However, the association of  
446 native bismuth and hedleyite can only be stable below a temperature of 266°C (Dimitrova and  
447 Kerestedjian, 2006). Therefore, we propose a temperature range between 266 to 240 °C for the  
448 deposition of stage 3, which is in good agreement with a ca 200 °C homogenization temperature  
449 deduced from the L2-type secondary aqueous fluid inclusions (Bril, 1982). This relatively low  
450 temperature accounts for the deposition of antimony-rich Bi-Te minerals like the horobetsuite  
451 or the tetrahedrite.

452

## 453 7.2 Possible mechanisms for gold deposition

454 The common occurrence of electrum within Bi-Te minerals might emphasize the role of a  
455 polymetallic melt/liquid for the concentration of precious metal, as already reported for similar  
456 mineralization (Ciobanu *et al.*, 2006; Cook *et al.*, 2007; Ciobanu *et al.*, 2010; Zacharias *et al.*,  
457 2014). The polyphase character of the ore-inclusions (electrum intergrowth in native bismuth,  
458 or electrum, native bismuth intergrowths in hedleyite), the ovoidal shape of the electrum inside  
459 native bismuth, and the presence of minerals such as maldonite or horobetsuite might support  
460 this mechanism (Ciobanu *et al.*, 2006; Zacharias *et al.*, 2014). But our deposition temperature  
461 estimate, between 266 to 240 °C, is too close to, or even below, the bismuth solidus temperature,  
462 and the eutectic temperature of the Au-Bi system (241 °C). This leads us to suggest that a large  
463 part of the gold and Bi-Te phases probably precipitated directly from a hydrothermal fluid  
464 enriched in Bi-Te-Au and were not scavenged by a bismuth-rich liquid/melt.

465 Between stages 1 and 3, a temperature decrease is observed (Fig. 14). In addition, the stage  
466 3 underwent a significant pressure drop associated with a change in tectonic regime, which  
467 might have triggered the input of a meteoritic fluid (Bril, 1982; Fig. 14). Furthermore, the  
468 decrease in the sulfide activity in the ore-fluid could be responsible for the gold deposition by  
469 destabilization of gold-sulfide complexes associated with the ongoing sulfide precipitation  
470 (Williams-Jones *et al.* 2009).

471

### 472 7.3 Tectonic control and timing of ore deposits within the Variscan evolution framework for 473 the French Massif Central

474

475 The vein geometry observed in the field is controlled by the inherited structures. The medium  
476 dip (30-50° SE) of the Bonnac veins reused the previous fault system coeval with dyke  
477 emplacement, whereas the low-angle dip Scoufour veins are controlled by the host-rock  
478 foliation. These anisotropy surfaces can be easily reactivated during faulting, and channeled the  
479 ore-bearing fluids.

480 Kinematic data on the striated fault planes coeval with W-As-Bi-Au veins allowed us to  
481 derive the stress tensor by an optimized inversion method (Delvaux and Sperner, 2003). The  
482 result indicates an extensional tectonic regime with the maximum ( $\sigma_1$ ), intermediate ( $\sigma_2$ ), and  
483 minimum ( $\sigma_3$ ) principal stress axes oriented 39°E/86°, 37°E/04° and 127°E/0°, respectively  
484 (Fig. 15). The W-As-Bi-Au quartz veins deposition was controlled by a NW-SE horizontal  
485 extension direction, consistent with the NW-SE stretching direction documented for the D4  
486 tectono-magmatic event in the FMC (Faure, 1995). This widespread event, related to the syn-  
487 orogenic Variscan extension in the FMC, dated between 325 and 310 Ma, is contemporaneous  
488 with the emplacement of the leucogranitic and monzogranitic syn-tectonic plutons (Figs. 1, 16;

489 Faure and Pons, 1991; Faure 1995; Faure *et al.*, 2009; Talbot *et al.*, 2005a, 2005b; Joly *et al.*,  
490 2007, 2009).

491 The hydrothermal apatite grains from two localities in the Bonnac area yield LA-ICP-MS  
492 U/Pb dates of  $315.6 \pm 2.8$  for the Ferbert vein (Scoufour area) and  $323.4 \pm 3.2$  Ma for the Androl  
493 vein (Bonnac area), respectively interpreted as the emplacement age of the W-As-Bi-Au veins.  
494 This age of ca. 320 Ma is consistent with the D4 tectonic, which is also coeval with the  
495 Serpukhovian-Bashkirian generation of tungsten ore deposits with minor gold in the FMC as  
496 the Puy-les-Vignes or S<sup>1</sup>-Mélany (Fig. 16; Harlaux *et al.*, 2018). Closer to the Brioude-Massiac  
497 district, the Leucamp and Engualès ore deposits in the Châtaigneraie district yielded the most  
498 important tungsten resources of the FMC (Derré, 1983; Bogdanoff *et al.*, 1987; Demange *et al.*,  
499 1988; Lerouge and Bouchot, 2009) are other examples of this tungsten ore deposition event.

500 All previous works (Périchaud, 1970; Bril et Beaufort, 1989) in the Brioude-Massiac district,  
501 proposed a single hydrothermal event, responsible for the formation of both antimony and  
502 tungsten-gold from a perigranitic metal zonation. This model seems to be challenged by our  
503 results. Despite their spatial link with the antimony veins, the W-As-Bi-Au ones yield a distinct  
504 age, since the antimony veins of the Brioude-Massiac district belong to a younger hydrothermal  
505 event referred to as the “Or 300” event (Bouchot *et al.*, 2005; Cheval-Garabédian, 2019). We  
506 have shown that the Bonnac W-As-Bi-Au mineralizations have a polyphased history in a  
507 continuum of time (Fig. 12), which fits with a unique deformation event, decorrelated with the  
508 Or300 event. The three mineralized stage are all trapped in quartz-veins with same and distinct  
509 structural control (D4 tectonic event), same kinematics, a same infilling chronology with a  
510 continuity from a ductile/brittle to only-brittle regime, associated with a progressive cooling of  
511 the ore-fluid (Fig. 12 and 14), and by the absence of late remobilization textures during the gold  
512 stage 3. This, is also attested by the obvious age difference.

513 Our results, together with the emplacement ages obtained on the gold-bearing quartz  
514 veins from the Cévennes district (Chauvet *et al.*, 2012) argue for an earlier Bashkirian-  
515 Moscovian gold-hydrothermal event, sometimes associated with tungsten, during the D4 event.  
516 Our data allow us to propose a polyphase history in the FMC characterized by two distinct  
517 hydrothermal events carrying gold, namely: i) a first Serpukhovian to Bashkirian, and, ii) a  
518 second, Gzhelian-Asselian, as the Or300 event, that might have re-used the structural  
519 discontinuities that controlled the early event. Recent new data obtain on the orogenic-gold  
520 deposit of the la Bellière district (Armorican Massif) argue also for a tectonic-hydrothermal  
521 gold event earlier than the Or300 event around 340-325 Ma (Cheval-Garabédian *et al.*, 2020).

522

#### 523 7.4 Genetic link with the Serpukhovian leucogranites and ore deposit model for the Bonnac 524 area

525

526 Based on our results, the genetic relationships between the mineralization and the  
527 leucogranitic dykes can also be re-assessed. The leucogranitic dykes from Brioude-Massiac,  
528 dated at  $322 \pm 7$  Ma (Bril *et al.*, 1991) were emplaced contemporaneously with the D4 event  
529 and are spatially related to the W-As-Bi-Au deposits. The mineralizing event that followed the  
530 intrusive rocks emplacement could be interpreted as a magmatic-to-hydrothermal evolution  
531 (Fig. 17; Linnen and Cuney, 2005; Gloaguen, 2006) with a relatively long-time duration, around  
532 329-316 Ma (dating of the leucogranitic magmatic event). Several lines of evidence support  
533 this interpretation as: i) the spatial and temporal link between dykes and mineralized veins; ii)  
534 their formation during the D4 tectonic event; iii) the high temperature paragenesis of stage 1 at  
535 400-500 °C, close to the 600-650 °C emplacement temperature estimated for the andalusite-  
536 leucogranitic dykes, iv) their close emplacement depths estimated around 10 km (Sandras,  
537 1988), v) the reworking of previous structural discontinuities. Throughout the Variscan Orogen,

538 there are examples of W-Au deposits that were emplaced within a time gap of ca. 10 Ma after  
539 the intrusions of peraluminous magmas (Romer and Kroner, 2016). In France, the Puy les  
540 Vignes deposit (Harlaux *et al.*, 2018), and the Salau deposit in the French Pyrenees (Poitrenaud  
541 *et al.*, 2019), or in the Bohemian Massif, the Mokrsko deposit (Zacharias *et al.*, 2014), are good  
542 examples of this relation.

543 A two-stage evolutive model for the magmatic-hydrothermal system in the Bonnac area is  
544 proposed in a continuum of time (Fig. 17). Between 329 and 315 Ma, the emplacement of  
545 leucogranitic dykes, related to an underlying pluton, was controlled by normal faulting in the  
546 regional NW-SE extensional regime. Slightly younger from the dyke crystallizations, between  
547 321 to 316 Ma, the deformation became more localized and contemporaneous with quartz veins  
548 emplacement that recorded a magmatic-to-hydrothermal transition (Fig. 17 stage 2). These  
549 hydrothermal fluids have reused the previous discontinuities as feeder channels.

550 The metamorphic or magmatic origin of the ore-forming fluid for peri-granitic ore deposits  
551 is still a matter of debate (Lang and Backer, 2001; Boiron *et al.*, 2001; Hart *et al.*, 2002; Bouchot  
552 *et al.*, 2005; Hart, 2007; Zacharias *et al.*, 2014; Marcoux *et al.*, 2015). In the Bonnac area, the  
553 magmatic origin of the fluid is not fully demonstrated by the existing fluid inclusion study (Bril,  
554 1982) as they rather display a metamorphic origin (low salinity, complex chemistry enriched in  
555 CO<sub>2</sub>). However, a magmatic fluid affinity is pointed out by: i) the presence of magmatic affinity  
556 element such as the W and the Bi-Te-Au association (Lang and Backer, 2001; Blevin, 2004)  
557 and by ii) the spatial and temporal link with leucogranitic dykes. In addition, the lead isotopic  
558 compositions measured for different mineralized veins and main lithological formations of the  
559 Brioude-Massiac area support such magmatic origin of the metals (Marcoux and Bril, 1986).  
560 The <sup>207</sup>Pb/<sup>206</sup>Pb ratios estimated on our dating are close to those obtained on the aplitic dykes  
561 of leucogranitic composition of the la Margeride granite (see part 6 for the data).



562 To take into account all those features, we propose a genetic link between those mineralized  
563 veins and the leucogranitic dykes, where the initial magmatic fluids were derived from the  
564 crystallization of an underlying granitic pluton. The heat source supplied by the pluton was  
565 responsible for fluid migration toward the high permeability zones. The high temperature (400-  
566 500 °C) interaction between the fluid and the host-rocks (greisen type alteration in the vein  
567 hanging walls) could have re-equilibrated the fluid, overprinting its initial magmatic signature  
568 Then fault-valve mechanisms channeled the ore-fluids into structural discontinuities (Sibson *et*  
569 *al.*, 1988), and fluid overpressure associated with potential fault-valve mechanism could be  
570 responsible for vein opening and the gold-stage 3 deposition, in a shallow crustal environment.

571

572 The chemical composition of the Brioude-Massiac andalusite-leucogranitic S-type magma  
573 dykes (EDM 1) is characterized by an oxidizing redox state (Fig. 18), although a reduce redox  
574 state is more commonly observed. These characteristics are considered as more favorable than  
575 a reduce redox state to form a tungsten ore deposit. Indeed the early magnetite precipitation  
576 allows the preservation of Au in the melt fraction of granitic magmas (Blevin, 2004).

577

578 7.5 A new ore deposit model for the Bonnac deposits?

579

580 Because of the metamorphic origin of fluids, the Bonnac deposits was previously classified as  
581 an orogenic gold deposit (Bouchot *et al.*, 2005), although they do not fulfil all the necessary  
582 criteria (Groves *et al.*, 1998).

583 The Bonnac deposits share some of the characteristics of the IRGD type (Thompson *et al.*,  
584 1999; Lang and Baker, 2001; Hart *et al.*, 2002; Gloaguen, 2006; Hart, 2007; Zacharias *et al.*,  
585 2014; Marcoux *et al.*, 2015) such as: i) the spatial and temporal relationships between ore-

586 deposition and peraluminous granite emplacement, ii) the peculiar relation between magmatic-  
587 source-related ore phases such as bismuth, tellurides, wolframite, löllingite or molybdenite, iii)  
588 the contemporaneous bismuth-telluride-gold deposition, iv) the vein deposition during the syn-  
589 orogenic extensional period. The redox state of the leucogranitic dykes that spans the boundary  
590 of the ilmenite series (Fig. 18) is also a favorable context for IRGD deposits (Lang and Backer,  
591 2001; Blevin, 2004).

592 On the other hand, the structural evolution from a ductile/brittle deformation to a brittle one,  
593 fault-valve mechanism features, and the presence of a late meteoric fluid input, are classical  
594 features found for the orogenic gold type deposits (Boiron *et al.*, 1990, 2003; Groves *et al.*,  
595 1998; Bouchot *et al.*, 2005).

596 Therefore, the Bonnac ore-zone represents a mineralization type intermediate between the  
597 orogenic-gold and IRGD models as already demonstrated for the Mokrsko gold deposit in the  
598 Bohemian-Massif for example (Zacharias *et al.*, 2014).

## 599 **8. Conclusions**

600 The Bonnac veins show a W-As-Bi-Au paragenesis that results from polyphase  
601 hydrothermal and magmatic events. Three stages of ore deposition have been identified starting  
602 with wolframite and löllingite in a deep-seated setting, between 12 to 9 km and up to 400 °C.  
603 The second ductile/brittle deformation stage was responsible for scheelite and arsenopyrite  
604 deposition at 480-300 °C. The late stage was marked by brittle micro-fracturing infilled with  
605 native bismuth, bismuthinite, hedleyite, electrum, pyrite and Cu-Zn-Pb minerals at 266 to 240  
606 °C and 7 to <5 km depth. This could be the result of fault-valve mechanism. The decrease of  
607 the temperature-pressure and the sulfide activity caused by ongoing sulfide precipitation seems  
608 to be the major factors responsible for the gold deposition during the late stage of deposition.

609 The mineralized veins are spatially and temporally linked to the emplacement of the  
610 andalusite-leucogranitic dykes of the Brioude-Massiac district around 329-315 Ma. Our new  
611 LA-ICP-MS U/Pb dating on hydrothermal apatite from the deposit documents an emplacement  
612 age around 320 Ma. This genetic link suggests a magmatic-to-hydrothermal transition for the  
613 Bonnac ore-forming process. In the newly proposed model, the cooling of a peraluminous  
614 pluton might have supplied magmatic fluids, and heat source for mineralized fluid flows toward  
615 high permeability zones such as previous discontinuities. The magmatic origin of the fluid has  
616 been partly overprinted by fluid-rocks interaction.

617 The emplacement of both the andalusite-leucogranitic dykes and quartz veins was controlled  
618 at the regional scale by a NW-SE extensional direction, consistent with the tectono-magmatic  
619 D4 event corresponding to the syn-orogenic extension in the FMC Variscan orogen. This  
620 geodynamic event is older than the “Or 300” one, suggesting therefore an earlier fertile  
621 metallogenic period at ca. 320 Ma for tungsten and gold deposition in the FMC.

622 The genetic classification of the Bonnac mineralization is equivocal. The W-As-Bi-Au-  
623 quartz veins exhibit the features of both orogenic gold (relatively deep level of emplacement)  
624 and IRGD model (spatial-temporal link between the mineralization and the peraluminous  
625 intrusion). We propose that it represents an intermediate type between the typical orogenic-gold  
626 and IRGD model.

627 The Serpukhovian to Bashkirian peraluminous andalusite-leucogranitic dyke swarms appear  
628 as a favorable metallotect for future mining exploration in the FMC. The widespread  
629 occurrences related to this type of magmatism in the FMC suggest that other Bonnac-like, or  
630 IRGD-like, deposits probably exist. IRGD deposits, and the economic high-grade gold content  
631 in tungsten vein-type, might have been underestimated in the FMC.

632

633

634 *Acknowledgements.*

635 This work was funded by e-Mines Company through its R&D activity, and the ISTO with  
636 contribution from ANRT. The authors thank the following persons for their technical support  
637 and valuable advices: T. Poitrenaud, B. Cochelin, A. Beaudoin, R. Augier, C. Montmartin J.  
638 Gouin, M. Picault. We particularly thank I. Di-Carlo (ISTO) for the SEM, cathodoluminescence  
639 and microprobe analyses and for valuable advices. S. Janiec, G. Badin, and P. Benoist-Julliot  
640 (ISTO) for thin sections preparation, and technical assistance, and the GeOHeLiS platform for  
641 the LA-ICP-MS dating.

642

#### 643 **References**

- 644 Audion AS, Labbé JF. 2012. Panorama mondial 2011 du marché du tungstène. Rapport  
645 Public BRGM, RP-61341-FR 108p.
- 646 Barton P.B, Skinner B.J. 1979. Sulfide mineral stabilities. In: Barnes, H.L. (Ed.), *Geochemistry*  
647 *of Hydrothermal ore Deposits*. John Wiley, New York, pp. 278–403.
- 648 Bernard-Griffiths J, Lasnier B, Marchand J, Vidal P. 1980. Approche par la méthode Rb/Sr de  
649 l'étude de granulites acides en Haut-Allier (Massif Central français). *Réun Ann Sci Terre*  
650 8 : 41 p.
- 651 Béziat P, Prouhet JP, Tollon F. 1980. Le district de Montredon-Labessonnié (Tarn): W, Sn, F.  
652 Publications du 26e Congrès Géologique International (Paris): Gisements français 7, 42 p.
- 653 Bogdanoff S, Cirodde JL, Ploquin A, Ramboz C, Le Chapelain JR, Mignon R. 1987.  
654 Exploration for tungsten in the Châtaigneraie district. *Chron Rech Min* 487: 11–30.
- 655 Blevin P.L. 2004. Redox and compositional parameters for interpreting the granitoid  
656 metallogeny of eastern Australia: Implications for gold-rich ore systems: *Resource*  
657 *Geology* 54: 241–252.
- 658 Boiron M.C, Cathelineau M, Dubessy J, Bastoul A.M. 1990. Fluids in Hercynian Au veins of  
659 from the French Variscan belt. *Mineralogical Magazine* 54: 231–243.
- 660 Boiron M.C, Barakat A, Cathelineau M, Banks D.A, Durisova J, Moravek P. 2001. Geometry  
661 and P-V-T-X conditions of microfissural ore fluid migration: the Mokrsko gold deposit  
662 (Bohemia). *Chem Geol* 173: 207–225.
- 663 Boiron M-C, Cathelineau M, Banks DA, Fourcade S, Vallance J. 2003. Mixing of metamorphic  
664 and surficial fluids during the uplift of the Hercynian upper crust: consequences for gold  
665 deposition. *Chem Geol* 194: 119–141.

- 666 Bouchot V, Ledru P, Lerouge C, Lescuyer J-L, Milesi J-P. 2005. Late Variscan mineralizing  
667 systems related to orogenic processes: the French Massif Central. *Ore Geol Rev* 27: 169–  
668 197.
- 669 Bril H. 1982. Fluid inclusions study of Sn-W-Au, Sb- and Pb-Zn mineralizations from the  
670 Brioude-Massiac district (French Massif Central). *Tschermaks Min Petr Mitt* 30: 1-16.
- 671 Bril H. 1983. Etude métallogénique des minéralisations à antimoine et associées du district de  
672 Brioude-Massiac (Massif Central français) ; conditions géochimiques de dépôt,  
673 implications génétiques, PhD thesis : Université Clermond-Ferrand, 341pp.
- 674 Bril H, Beaufort D. 1989. Hydrothermal alteration and fluid circulation related to W, Au, and  
675 Sb vein mineralizations, Haut-Allier, Massif Central, France: *Econ Geol* 84: 2237–2251.
- 676 Bril H, Bonhomme M.G, Marcoux E, Baubron J.C. 1991. Ages K/Ar des minéralisations de  
677 Brioude-Massiac (W-Au-As-Sb; Pb-Zn), Pontgibaud (Pb-Ag; Sn), et Labessette (As-Pb-  
678 Sb-Au): Place de ces districts dans l'évolution géotectonique du Massif Central français:  
679 *Miner Deposita* 26: 189-198.
- 680 Burg J-P, Matte P. 1978. A cross section through the French Massif Central and the scope of  
681 its Variscan geodynamic evolution. *Z. dt. Geol. Ges.* 129 : 429-460.
- 682 Chantraine J, Autran A, Cavelier C. 1996. Geological map of France, 1/1 000 000. BRGM,  
683 Orléans.
- 684 Charonnat X. 2000. Les minéralisations aurifères tardi-hercyniennes des Cévennes, PhD thesis,  
685 Université d'Orléans, 1 Vol, 259 pp.
- 686 Chauvet A, Volland-Tuduri N, Lerouge C, *et al.* 2012. Geochronological and geochemical  
687 characterization of magmatic-hydrothermal events within the Southern Variscan external  
688 domain (Cévennes area, France). *Int J Earth Sci.* 101: 69-86.
- 689 Cheval-Garabédian F. 2019. Les minéralisations à Sb et Au tardi-varisques : vers un modèle  
690 génétique unifié ? Exemples du Massif armoricain et du Massif central, PhD thesis,  
691 Université d'Orléans, 1 Vol, 498pp.
- 692 Cheval-Garabédian F, Faure M, Marcoux E, Gouin J, Picault M. 2020. The La Bellière gold  
693 and antimony district (French Armorican Massif): A two-stage evolution model controlled  
694 by Variscan strike-slip tectonic. *Ore Geol Rev* 125: 103–681.
- 695 Chew D.M, Petrus J.A, Kamber B.S. 2014. U-Pb LA-ICPMS dating using accessory mineral  
696 standards with variable common Pb. *Chem Geol* 363: 185–199.
- 697 Ciobanu C.L, Cook N.J, Damian F, Damian G. 2006. Gold scavenged by bismuth melts: an  
698 example from Alpine shear-remobilizations in the Highis Massif Romania. *Mineral Petrol*  
699 87: 351–384.
- 700 Ciobanu C L, Birch W D, Cook N J, Pring A, Grundler P. V. 2010. Petrogenetic significance  
701 of Au–Bi–Te–S associations: the example of Maldon, Central Victorian gold province,  
702 Australia. *Lithos* 116: 1-17.
- 703 Cook N.J, Ciobanu C.L, Wagner T, Stanley C.J. 2007. Minerals of the system Bi–Te–Se–S  
704 related to the tetradymite archetype: review of classification and compositional variation.  
705 *Can Mineral* 45: 665–708.
- 706 Cox S.F. 1987. Antitaxial crack-seal vein microstructures and their relationships to  
707 displacement paths. *J Struct Geol* 9: 79–787.
- 708 Cox S.F, Wall V.J, Etheridge M.A, Potter T.F. 1991. Deformation and metamorphic processes  
709 in the formation of mesothermal vein-hosted gold deposits, examples from the Lachlan  
710 Fold Belt in central Victoria Australia. *Ore Geol Rev* 6: 391–423.
- 711 Cuney M, Alexandrov P, Le Carlier de Veslud C, *et al.* 2002. The timing of W Sn rare metals  
712 mineral deposit formation in the Western Variscan chain in their orogenic setting: the case  
713 of the Limousin area (Massif Central, France). In: Blundell, D.J., Neubauer, F., von Quadt,  
714 A. (Eds.), *The Timing and Location of Major Ore Deposits in an Evolving Orogen*,  
715 *Geological Society, London, Special Publications* 204: 213–228.

- 716 Debon F, Le Fort P. 1988. A cationic classification of common plutonic rocks and their  
717 magmatic associations: principles, method, applications. *Bulletin de Minéralogie* 111 :  
718 493-510.
- 719 De Gramont X, Feybesse J.L, Lambert A. 1990. Synthèse du district de Brioude-Massiac et des  
720 confins nord de la Margeride (Massif Central). Rapp BRGM DAM/DL/C/ R-30695. 191  
721 p.
- 722 Delvaux D, Sperner B. 2003. Stress tensor inversion from fault kinematic indicators and focal  
723 mechanism data: the TENSOR program. *New insights into structural interpretation and*  
724 *modelling*, 212: 75-100.
- 725 Demange M, Nicolas V-A, Soler P, Giouse H. 1988. Le gisement tungstifère de Leucamp  
726 (Cantal, France). Contrôles géologiques et minéralisations. *Bull. Soc. Géol. France*, 4 :  
727 559-570.
- 728 Derré C. 1983. La province à Sn-W ouest-européenne. Histoire de divers types de gisements  
729 du Massif Central, des Pyrénées et du Portugal. Distributions des gisements, PhD thesis:  
730 Université Paris VI, 2 vol., I, 345p., II, 421p.
- 731 Dimitrova D, Kerestedjian T. 2006. Bismuth minerals in the postkarn sulphide-arsenide  
732 mineralization in the Martinovo iron deposit, NW Bulgaria: Geochemistry, Mineralogy and  
733 Petrology, Sofia, v. 44, 19-32.
- 734 Faure M. 1995. Late orogenic carboniferous extensions in the Variscan French Massif Central.  
735 *Tectonics* 14: 132–153.
- 736 Faure M, Pons J. 1991. Crustal thinning recorded by the shape of the Namurian-Westphalian  
737 leucogranites in the Variscan belt of the Northwest Massif Central, France. *Geology* 19:  
738 730-733.
- 739 Faure M, Be Mézème E, Duguet M, Cartier C, Talbot J-Y. 2005. Paleozoic tectonic evolution  
740 of medio-Europa from the example of the French Massif Central and Massif Armorican.  
741 In: (eds.) Carosi, R., Dias, R., Iacopini, D., and Rosenbaum, G., The southern Variscan  
742 belt, *Journal of the Virtual Explorer*, Electronic Edition, ISSN 19: 1441–8142.
- 743 Faure M, Lardeaux J.-M, Ledru P. 2009. A review of the pre-Permian geology of the Variscan  
744 French Massif central. *Comptes Rendus Geoscience* 341 : 202-213.
- 745 Gaboury D, Daigneault R. 2000. Flat vein formation in a transitional crustal setting by self-  
746 induced fluid pressure equilibrium, an example from the Géant Dormant gold mine Canada.  
747 *Ore Geol Rev* 17: 155-178.
- 748 Gloaguen E. 2006. Apport d'une étude intégrée sur les relations entre granite et minéralisations  
749 filoniennes (Au et Sn-W) en contexte tardi-orogénique, PhD thesis: Université d'Orléans.
- 750 Groves D.I, Goldfar, R.J, Gebre-Mariam M, Hagemann S.G, Robert F. 1998. Orogenic gold  
751 deposits, a proposed classification in the context of their crustal distribution and  
752 relationship to other gold deposit types. *Ore Geol Rev* 13: 7–27.
- 753 Harlaux M, Marignac C, Cuney M, Mercadier J, Magott R, Mouthier B. 2015. Nb-Ti-Y-HREE-  
754 WU oxide minerals with uncommon compositions associated with the tungsten  
755 mineralization in the Puy-les-Vignes deposit (Massif central, France): Evidence for rare-  
756 metal mobilization by late hydrothermal fluids with a peralkaline signature. *Can Mineral*  
757 53: 653-672.
- 758 Harlaux M, Romer R. L, Mercadier J, Morlot C, Marignac C, Cuney M. 2018. 40 Ma of  
759 hydrothermal W mineralization during the Variscan orogenic evolution of the French  
760 Massif Central revealed by U-Pb dating of wolframite. *Miner Deposita* 53: 21-51.
- 761 Hart C.J.R, McCoy D, Goldfarb R.J, et al. 2002. Geology, exploration and discovery of the  
762 Tintina gold province, Alaska and Yukon. Society of economic geologists special  
763 publication 9: 241-274.

- 764 Hart C. J. 2007. Reduced intrusion-related gold systems. Geological Association of Canada,  
765 Mineral Deposits Division, 5: 95-112.
- 766 Joly A, Chen Y, Faure M, Martelet G. 2007. multidisciplinary study of a syntectonic pluton  
767 close to a major lithospheric-scale fault: relationships between the Montmarault granitic  
768 massif and the Sillon Houiller Fault in the Variscan French Massif Central. Part I:  
769 Geochronology, mineral fabrics and tectonic implications, *J Geophys Res*: 112, B10104,.  
770 Joly A., Faure M, Chen Y, Martelet G. 2009. Gravity inversion, AMS and geochronological  
771 investigations of syntectonic granitic plutons in the southern part of the Variscan French  
772 Massif Central. *J. Struct. Geol.*, 31: 421-443.
- 773 Kretschmar U, Scott S.D. 1976. Phase relations involving arsenopyrite in the system Fe-As-S  
774 and their application: *Can Mineral* 14: 364–386.
- 775 Lang J-R, Baker T. 2001. Intrusion related gold systems: the present level of understanding.  
776 *Miner Deposita* 36: 477–489.
- 777 Lasnier B. 1977. Persistance d'une série granulitique au cœur du Massif central français (Haut  
778 Allier). Les termes basiques, ultrabasiques et carbonatés. PhD. Thesis, Université de  
779 Nantes, 341pp.
- 780 Lasnier B, Marchand J, Bouilkler R, Burg J-P, Cornen G, Forestier F.H Leyreloup A. 1982.  
781 Notice de la carte géologique de France (1/50 000), feuille de Brioude (766) – BRGM,  
782 Orléans.
- 783 Ledru P, Lardeaux J. M, Santallier D A, *et al.* 1989. Où sont les nappes dans le Massif central  
784 français ? *Bulletin de la Société géologique de France* 3 : 605-618.
- 785 Lerouge C, Bouchot V .2009. Conditions of formation and origin of fluids of quartz-tourmaline  
786 veins in the La Châtaigneraie tungstiferous district (Massif Central, France): fluid inclusions  
787 and stable isotopes. *B Soc Geol Fr* 180: 263-270.
- 788 Linnen RL, Cuney M. 2005. Granite-related rare-element deposits and experimental  
789 constraints on Ta-Nb-W-Sn-Zr-Hf mineralization. In: Rare-element geochemistry and  
790 mineral deposits (eds. R.L. Linnen and I.M. Samson). *Geological Association of Canada,*  
791 *GAC Short Course Notes* 17: 45 – 68.
- 792 Malavieille, J., P. Guihot, S. Costa, J.M. Lardeaux, and V. Gardien, 1990. Collapse of the  
793 thickened Variscan crust in the French Massif Central: Mont Pilat extensional shear zone  
794 and St.-Etienne Late Carboniferous basin. *Tectonophysics* 177: 139-149.
- 795 Marchand J. 1974. Persistance d'une série granulitique au cœur du Massif central français  
796 (Haut Allier). Les termes acides. PhD. Thesis, Université de Nantes, 267pp.
- 797 Marcoux E, Picot P. 1985. Les minéralisations de Pontgibaud (Puy-de-Dôme): Une approche  
798 complémentaire par géochimie isotopique du plomb et les paragenèses. *Chronique de la*  
799 *Recherche Minière* 481 : 27-38.
- 800 Marcoux E, Bril H. 1986. Héritage et sources de métaux d'après la géochimie isotopique du  
801 plomb ; Etude des minéralisations filoniennes du Haut-Allier (Massif Central, France).  
802 *Miner Deposita* 21 : 35-43.
- 803 Marcoux E, Bonnemaïson M. 1988. La géochimie isotopique du plomb et la prospection de l'or  
804 en France. In: Johan Z, newstetter D (eds) Gisements métallifères dans leur contexte  
805 géologique. Doc BRGM 158: 489–508.
- 806 Marcoux E, Nerci K, Branquet Y, *et al.* 2015. Late-Hercynian Intrusion-related gold deposits:  
807 an integrated model on the Tighza polymetallic district, central Morocco. *Journal of African*  
808 *Earth Sciences* 107: 65-88.
- 809 Marignac C, Cuney M (1999) Ore deposits of the French Massif Central: insight into the  
810 metallogenesis of the Variscan collision belt. *Miner Deposita* 34: 472 – 504.

811 Mathonnat M. 1983. La série métamorphique du Cézallier, Massif central français, PhD thesis:  
812 Université de Clermont-Ferrand.

813 McDowell F.W, McIntosh W.C, Farley K.A. 2005. A precise  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  reference age for the  
814 Durango apatite (U–Th)/He and fission-track dating standard. *Chem Geol* 214: 249–263.

815 Monié P, Bouchot V, Faure M, Charonnat X, Najoui K. 1999.  $^{40}\text{Ar}/^{39}\text{Ar}$  Laser-Probe Dating  
816 of W, Au and/or Sb Deposits and associated granites in the Southern French Massif Central  
817 (Cévennes, Châtaigneraie), EUG 10, abstract volume, Strasbourg, Terra Abstracts, p 477.

818 Monié P, Respaut J.-P, Brichaud S, Bouchot V, Faure M, Roig J.-Y. 2000.  $^{40}\text{Ar}/^{39}\text{Ar}$  and U–  
819 Pb geochronology applied to Au–W–Sb metallogenesis in the Cévennes and Châtaigneraie  
820 districts (Southern Massif Central, France). In: Bouchot, V., Moritz, R. (Eds.), A Geode–  
821 GéoFrance 3D Workshop on Orogenic Gold Deposits in Europe with Emphasis on the  
822 Variscides; Extended Abstracts. Documents du BRGM, 297 : 77–79.

823 Morisson G W, Rose W J, Jaireth S. 1991. Geological and geochemical controls on the silver  
824 content (fineness) of gold in gold-silver deposits. *Ore Geol Rev* 6: 333–364.

825 Nicaud J. 2001. Contrôle structural de la mise en place des minéralisations aurifères du district  
826 de Saint-Yrieix : analyse de la fracturation, étude des altérations hydrothermales, PhD  
827 thesis: Université de Limoges. 252p.

828 Paquette J.L, Piro J.L, *et al.* 2014. Sensitivity enhancement in LA-ICP-MS by N<sub>2</sub> addition to  
829 carrier gas: Application to radiometric dating of U-Th-bearing minerals. *Agilent ICP-MS J*  
830 58: 4–5.

831 Paton C, Woodhead J.D, Hellstrom J.C, Hergt J.M, Greig A, Maas R. 2010. Improved laser  
832 ablation U-Pb zircon geochronology through robust downhole fractionation correction.  
833 *Geochem. Geophys. Geosyst.* 11 Q0AA06.

834 Périchaud J.J. 1970. Les gisements métalliques du district d’antimoine de Brioude-Massiac  
835 (Massif central français), PhD thesis: Université de Clermont Ferrand. 771 p.

836 Pin C, Peucat J.-J. 1986. Ages des épisodes de métamorphisme paléozoïques dans le Massif  
837 central et le Massif armoricain. *Bull. Soc. Géol. France*, 8, t. II, n°3, 461–469.

838 Pochon A, Gapais D, Gloaguen E, *et al.* 2016. Antimony deposits in the Variscan Armorican  
839 belt, a link with mafic intrusives? *Terra Nova* 28: 138-145. doi: 10.1111/ter.12201.

840 Poitrenaud T, Poujol M, Augier R, Marcoux E. 2019. The polyphase evolution of a late  
841 Variscan W/Au deposit (Salau, French Pyrenees): insights from REE and U/Pb LA-ICP-  
842 MS analyses. *Miner Deposita*: 1-21.

843 Ramsay J.G. 1980. The crack-seal mechanism of rock deformation. *Nature* 284: 135–139.

844 Robert F, Boullier A.M, Firdaous K. 1995. Gold–quartz veins in metamorphic terranes  
845 and their bearing on the role of fluids in faulting. *J. Geophys. Res.* 100: 12841-12859.

846 Romer RL, Kroner U. 2016. Phanerozoic tin and tungsten mineralization–tectonic controls on  
847 the distribution of enriched protoliths and heat sources for crustal melting. *Gondwana Res*  
848 31: 60 – 95.

849 Sandras A. 1988. Les structures auro-antimonifères du district de Brioude–Massiac. Gîtologie  
850 et métallogénie des concentrations aurifères, PhD thesis: Université de Nancy. 211 p.

851 Scaillet S, Cheilletz A, Cuney M, Farrar E, Archibald DA. 1996. Cooling pattern and  
852 mineralization history of the saint Sylvestre and western Marche leucogranite pluton,  
853 French massif central: I. $^{40}\text{Ar}/^{39}\text{Ar}$  isotopic constraints. *Geochim Cosmochim Acta* 60:  
854 4653 – 4671.

855 Schoene B, Bowring S.A. 2006. U-Pb systematics of the McClure Mountain syenite:  
856 thermochronological constraints on the age of the  $^{40}\text{Ar}/^{39}\text{Ar}$  standard MMhb. *Contrib.*  
857 *Mineral Petrol* 151: 615–630.

858 Scholz C. H. 1988. The brittle-plastic transition and the depth of seismic faulting.  
859 *Geologische Rundschau* 77: 319-328.



860 Sibson R.H, Robert F, Poulsen K.H. 1988. High-angle reverse faults, fluid pressure cycling,  
861 and mesothermal gold–quartz deposits. *Geology* 16: 551–555.

862 Sharp Z. D, Essene E. J, Kelly W. C. 1985. A re-examination of the arsenopyrite  
863 geothermometer; pressure considerations and applications to natural assemblages. *Can.*  
864 *Mineral.* 23: 517-534.

865 Stipp M, Stünitz H, Heilbronner R, Schmid S.M. 2002. The eastern Tonale fault zone: a natural  
866 laboratory for crystal plastic deformation of quartz over a temperature range from 250 to  
867 700 °C. *Journal of Structural Geology* 24: 1861–1884.

868 Talbot J. Y. Faure M, Chen Y, Martelet G. 2005a. Pull-apart emplacement of the Margeride  
869 granitic complex (French Massif Central). Implications for the late evolution of the  
870 Variscan orogen. *Journal of Structural Geology*, 27: 1610-1629.

871 Talbot JY, Chen Y, Faure M. 2005b. Pluton-dykes relationships from AMS and microstructural  
872 studies in a Variscan granite from French Massif Central, *J Geophys Res* 110.

873 Thompson J.F.H, Sillitoe R.H, Baker T, Lang J.R, Mortensen J.K. 1999. Intrusion related  
874 gold deposits associated with tungsten–tin provinces. *Miner Deposita* 34: 323–334.

875 Thomson S.N, Gehrels G.E, Ruiz J, Buchwaldt R. 2012. Routine low-damage apatite U-Pb  
876 dating using laser ablation–multicollector–ICPMS. *Geochem Geophys Geosyst* 13:  
877 Q0AA21.

878 Thonat A, Mathonnat M, Pin C, Rocher P, Bertin C, Chèvremont P. 2014. Notice de la carte  
879 géologique de France au 1/50 000°, 765, Massiac. 141p.

880 Vermeesch, P., 2018. IsoplotR: A free and open toolbox for geochronology. *Geosci. Front.* 9,  
881 1479–1493. <https://doi.org/10.1016/J.GSF.2018.04.001>

882 Williams-Jones A. E, Bowell R. J, Migdisov A. A. 2009. Gold in solution. *Elements* 5: 281-  
883 287.

884 Wood, S.A. Samson, I.M. 2000. The Hydrothermal Geochemistry of Tungsten in Granitoid  
885 Environments: I. Relative Solubilities of Ferberite and Scheelite as a Function of T, P, pH,  
886 and mNaCl. *Econ Geol* 95: 143-182.

887 Zachariáš J, Moravek P, Gadas P, Pertoldova J. 2014. The Mokrsko-West gold deposit,  
888 Bohemian Massif, Czech Republic: mineralogy, deposit setting and classification. *Ore*  
889 *Geol Rev* 58: 238-263.

890

891

892

893

894

895

896

897

898

899

900

901

902

903

904

## 905 **Figures captions**

906 **Fig. 1.** Geological map of the French Massif Central (modified from Faure *et al.*, 2009), with  
907 the location of, the tungsten deposits and occurrences (from Audion and Labbé, 2012), and the  
908 study area. Tungsten district name abbreviations: ECH: Echassières; ENG: Engualès; FUM:  
909 Fumade; GOU: St-Goussaud; LCP: Leucamp; MAN: Mandesle; ML: Montredon-  
910 Labessonniè; NF: Neuf-Jours; PLV: Puy-les-Vignes; SM: St-Mélany; VAU: Vaulry.

911 **Fig. 2.** Location of the study area within the geological and metallogenic framework of the  
912 Brioude-Massiac district. The simplified geology modified from Lasnier *et al.* (1982) and  
913 Thonat *et al.* (2014). Location and extension of mineralized veins are from Périchaud, (1970).

914 **Fig. 3.** Geological and structural map of the Bonnac area with the location of most interesting  
915 outcrops.

916 **Fig. 4.** A) Representative arsenopyrite (Asp) and wolframite (Wolf) bearing quartz vein from  
917 the Costillon vein (outcrop A in Fig.3) showing the structural features and the relationships  
918 with the paragneiss host-rock and the leucogranitic dykes. B) Detail of drag folds developed in  
919 the country-rock paragneiss along the contact between the arsenopyrite (Asp) and wolframite  
920 (Wolf) bearing quartz veins and leucogranitic dyke. La Borie vein (outcrops B in Fig.3).

921 **Fig. 5.** A) Detail picture of the Fig.4B W-As-Bi-Au bearing quartz vein crosscutting  
922 leucogranitic dykes, (La Borie vein, outcrops B in Fig.3). B) Fault plane seen on Fig. 5A with  
923 high angle pitch striation. C) Cm-sized mineralized quartz veins network crosscutting the  
924 leucogranitic dyke (the Rode vein, outcrops C on Fig.3). D) Focus on the fault plane in the  
925 mineralized vein of the figure 5C showing a normal kinematics.

926 **Fig. 6.** Mine gallery opened in the Ferbert vein. A) Low angle wolframite (Wolf) and  
927 arsenopyrite (Asp)-bearing quartz vein (outcrops D in Fig.3). The vein is cut by late sub-vertical  
928 barren fault. B) Detail of the quartz vein showing normal kinematics.

929 **Fig. 7.** A) 3D block showing the main structural observations made on the mineralized quartz  
930 veins from Bonnac area. They allow us to propose a relative chronology of the structures  
931 developed in the paragneissic host-rock, the leucogranitic dykes and the quartz veins. B)  
932 Stereogram (lower hemisphere projection) of the poles of the fault planes coeval with the  
933 emplacement of the mineralized veins, leucogranitic dykes, and late faults measured in the field.

934 **Fig. 8.** Representative W-As-Bi-Au-bearing quartz hand sample from the Androl vein (see  
935 Fig.3 for localization), with arsenopyrite, wolframite, scheelite, and muscovite. Sample is  
936 observed in natural light (left) and UV light (254 nm, right).

937 **Fig. 9.** Microphotographs showing the mineralogy of the stages 1 and 2 at Bonnac. A) Coarse  
938 wolframite (Wolf) with lollingite (Lo) fractured and cemented by rhombic arsenopyrite (Asp).  
939 Secondary scheelite (Sch) pseudomorphs after wolframite. Arsenopyrite is fractured and  
940 cemented by bismuthinite (Bit), (Androl vein). B) Cathodoluminescence view showing the  
941 relationships between lollingite (Lo), weakly deformed macrocrystalline quartz (Qz1), and  
942 arsenopyrite (Asp) rhombic crystals cutting Qz1, (Costillon vein). C) Wolframite (Wolf) and

943 coarse hydrothermal apatite (Ap) assemblage fractured and cemented by secondary scheelite  
944 (Sch) and minor pyrite (Py), (Ferbort vein). D) Highly sheared macrocrystalline quartz (Qz1)  
945 crosscut by a second quartz generation (Qz2), (see text for further explanation). Relics of Qz1  
946 clasts are present in the upper right part of the photograph, (Ferbort vein).

947 **Fig. 10.** Microphotographs showing the mineralogy of stage 3. A) Macrocrystalline quartz  
948 (Qz1) and highly sheared quartz (Qz2) crosscut by microcracks with fluid inclusions and  
949 bismuth minerals (Bi minerals), (Ferbort vein). B) Relationships of sheared quartz (Qz1) with  
950 neoformed quartz (Qz2), crosscut by microcracks with bismuthinite (Bit) and electrum (El),  
951 (Ferbort vein. C) Lollingite aggregates (Lo) highly fractured and cemented by hyaline quartz  
952 (Qz3) with bismuthinite (Bit), (La-Rode vein. D) Same picture as C) in transmitted, polarized  
953 light. E) Lollingite (Lo) crosscut by an assemblage of native bismuth (Bi) and bismuthinite  
954 (Bit), (Androl vein). F) back scattered electron image of the complex Bi-Te assemblage formed  
955 in stage 3. Native rounded shape bismuth (Bi) with bismuthinite (Bit) and tetrahedrite (Trt),  
956 horobetsuite (Hor) in a hedleyite (Hed) crystal. Ox: unknown oxydes, (Ferbort vein).

957 **Fig. 11.** Microphotographs showing gold habits of stage 3 at Bonnac. A) Lollingite (Lo) with  
958 inclusions of electrum (El) within a native bismuth (Bi) - bismuthinite (Bit) patch, (Androl  
959 vein). B) Fractured wolframite (Wolf) cemented by bismuthinite (Bit), electrum (El), hedleyite  
960 (Hed) and native bismuth (Bi), (Ferbort vein). C) Residual lollingite (Lo) fractured and  
961 cemented by arsenopyrite (Asp) at its turn fractured and cemented by bismuthinite (Bit),  
962 electrum (El), hedleyite (Hed) and native bismuth (Bi), (Ferbort vein). D) Fractured  
963 arsenopyrite (Asp) cemented by chalcopyrite (Ccp) with bismuthinite (Bit) inclusions,  
964 sphalerite (Sp), electrum (El), (Ferbort vein). E) Fractured arsenopyrite (Asp) cemented by  
965 chalcopyrite (Ccp) with bismuthinite (Bit) inclusions, sphalerite (Sp), tetrahedrite (Trt),  
966 euhedral pyrite (Py) contemporaneous with euhedral quartz (Qz4), (Ferbort vein).

967 **Fig. 12.** Paragenetic succession of the Bonnac W-As-Bi-Au mineralization. See text for details.

968 **Fig. 13.** A) and B) cathodoluminescence images of some of the dated apatite grains from  
969 Bonnac (A, Androl vein, B, Ferbort vein). C) and D) Tera-Wasserburg concordia diagrams for  
970 the hydrothermal apatite from Bonnac. n corresponds to the number of apatite grains analyzed.  
971 Ellipses and errors are reported at  $2\sigma$ .

972 **Fig. 14.** Summary of the evolution of the estimated mineral deposition temperatures for the 3  
973 stages of mineralization of the Bonnac veins, based on all available data. Fluids inclusions data  
974 are from Bril (1982), estimated temperature for quartz textural deformation are from Stipp *et*  
975 *al.* (2002).

976 **Fig. 15.** Stereographic projection of faults planes contemporaneous of mineralized quartz veins  
977 with their kinematics and associated striae.  $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$ : orientation of principal stress axe  
978 calculated from fault-slip data inversion using WinTensor software in Schmidt's lower  
979 hemisphere equal-area projection (Delvaux and Sperner, 2003).

980 **Fig. 16.** A) Synthesis of the structural control and radiometric age compilation of orogenic gold  
981  $\pm$  antimony district, W-Sn and W-Bi-Au vein-type districts (Beziat *et al.*, 1980; Bouchot *et al.*,

982 2005; Harlaux *et al.*, 2018). White boxes correspond to U-Pb dating on wolframite by TIMS  
983 method, from Harlaux *et al.* (2018). Black boxes correspond to Ar/Ar dating on muscovite from  
984 Monier *et al.* (1999, 2000). For the orogenic-gold deposits, le Châtelet dating (K/Ar on illites)  
985 is from Bouchot *et al.* (2005); from Nicaud, (2001) for Saint-Yrieix district (K/Ar on illite);  
986 from Chauvet *et al.* (2012) for the Cévennes district (Ar/Ar on muscovite). District name  
987 abbreviations are the same as in figure 1. Geological map modified after Chantraine *et al.*  
988 (1996). B) The Bonnac hydrothermal event is replaced in the different geodynamic events of  
989 the Variscan orogen in the French Massif Central (Faure *et al.*, 2009).

990 **Fig. 17.** Metallogenic model of the Bonnac W-Bi-Au quartz veins system (not to scale).

991 **Fig. 18.** Fe<sub>2</sub>O<sub>3</sub>/FeO vs SiO<sub>2</sub> diagram for granitoid rocks associated with various mineral  
992 deposits, compiled from Harlaux *et al.* (2018). Data from the leucogranitic dykes of the  
993 Brioude-Massiac district are from Sandras, (1988).

994

995 **Table 1** Summary of the EPMA assays obtained on arsenopyrite from the Brioude-Massiac W-  
996 As-Bi-Au veins and gold from Bonnac. Estimated temperatures of crystallization with the  
997 arsenopyrite geothermometer are compared with the fluid-inclusions data (Bril, 1982).

998

999

1000

1001

1002

1003

1004

1005

1006

1007

1008

1009

1010

1011

1012

1013

1014

1015

1016

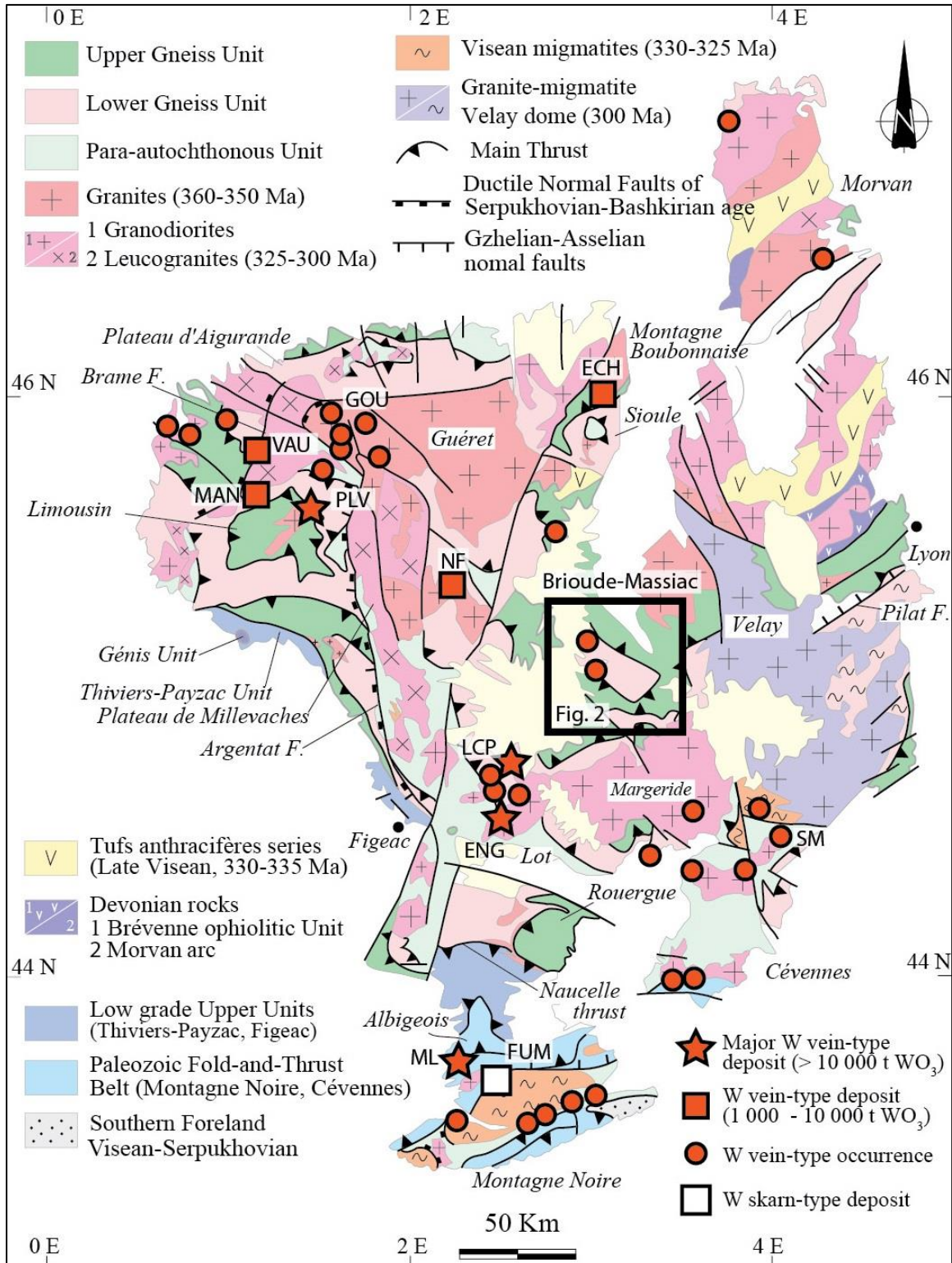
1017

1018

# Figures

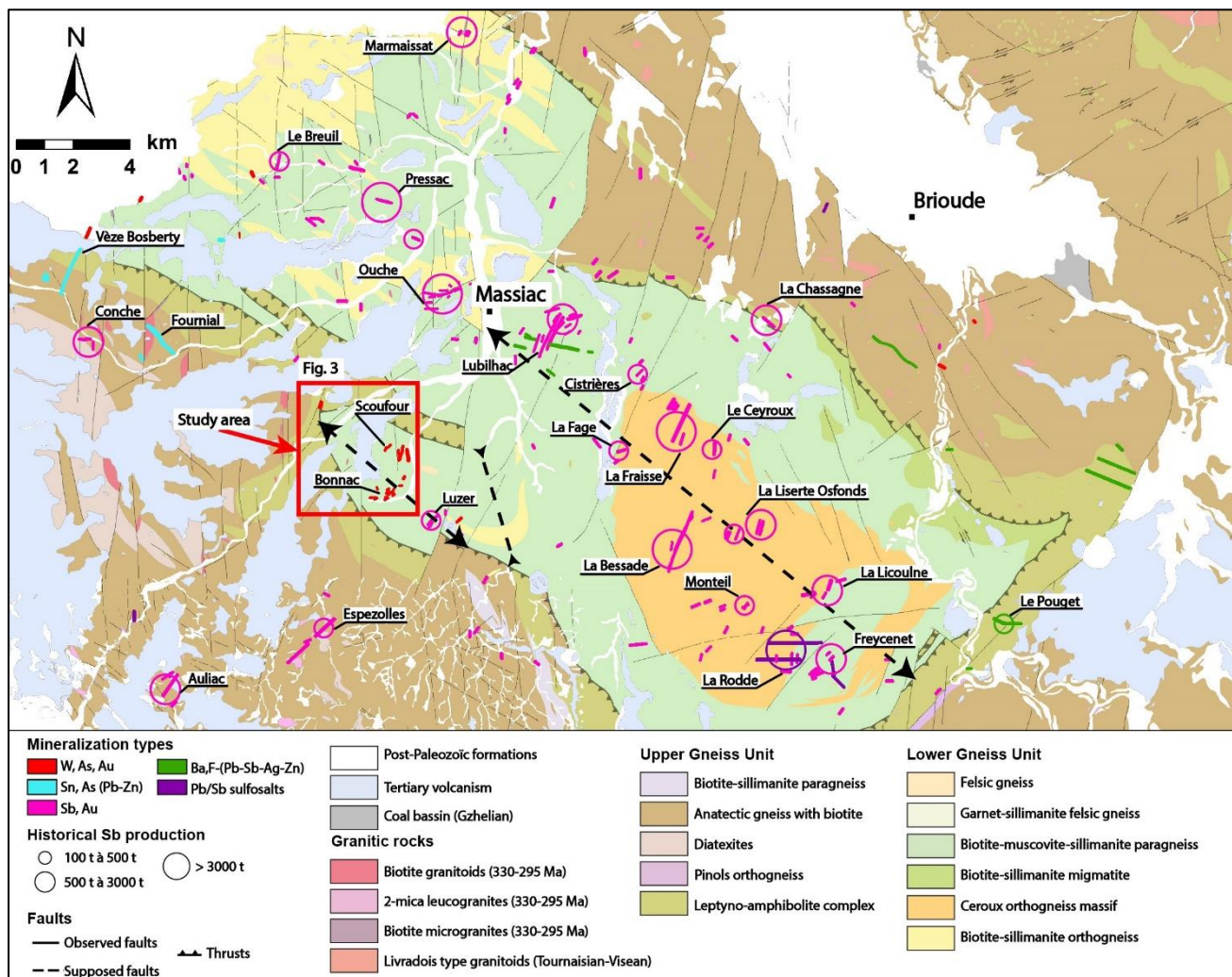
1019

1020 **Figure 1**



1021

1022 **Figure 2**



1023

1024

1025

1026

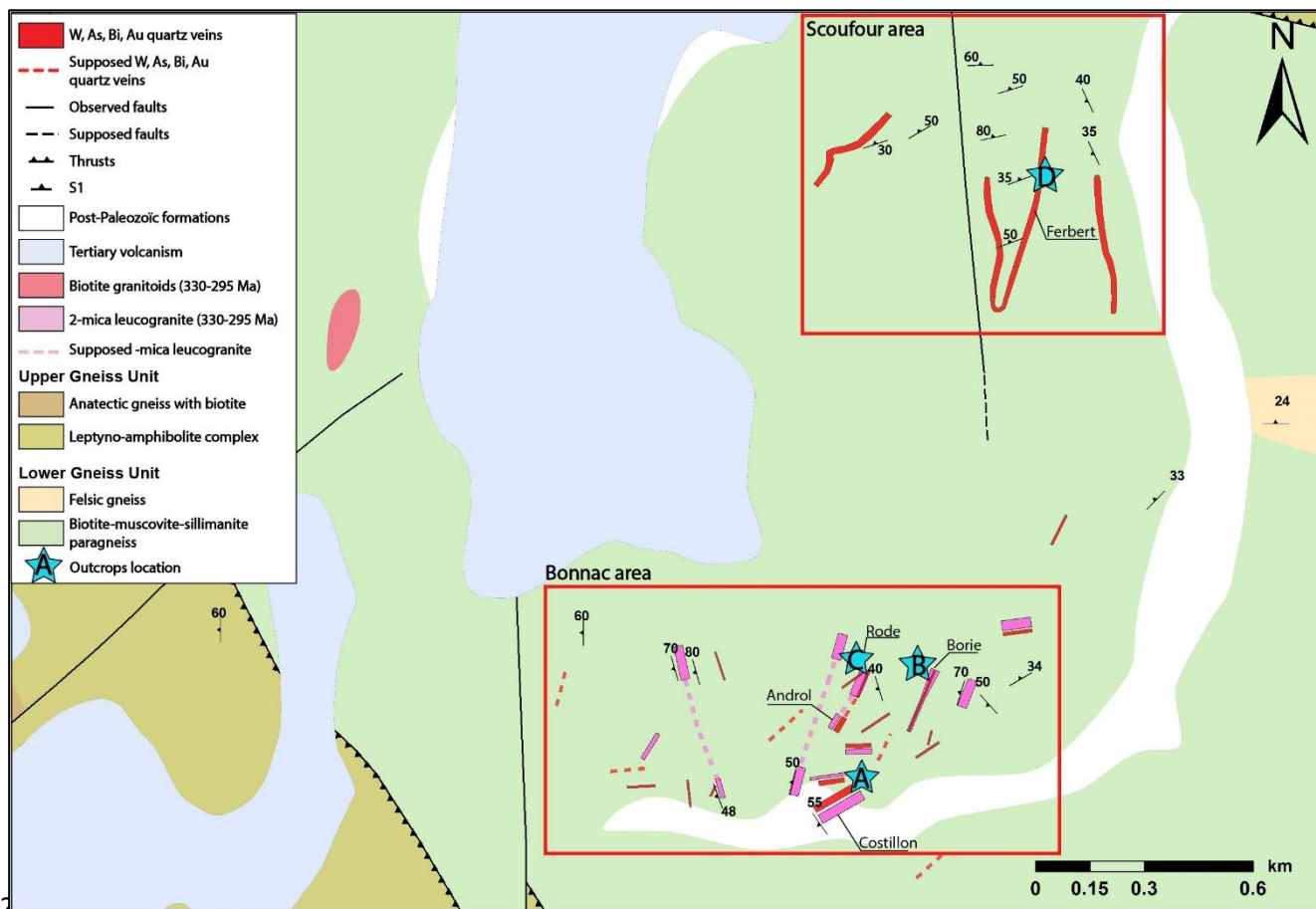
1027

1028

1029

1030

1031 **Figure 3**



1032

1033

1034

1035

1036

1037

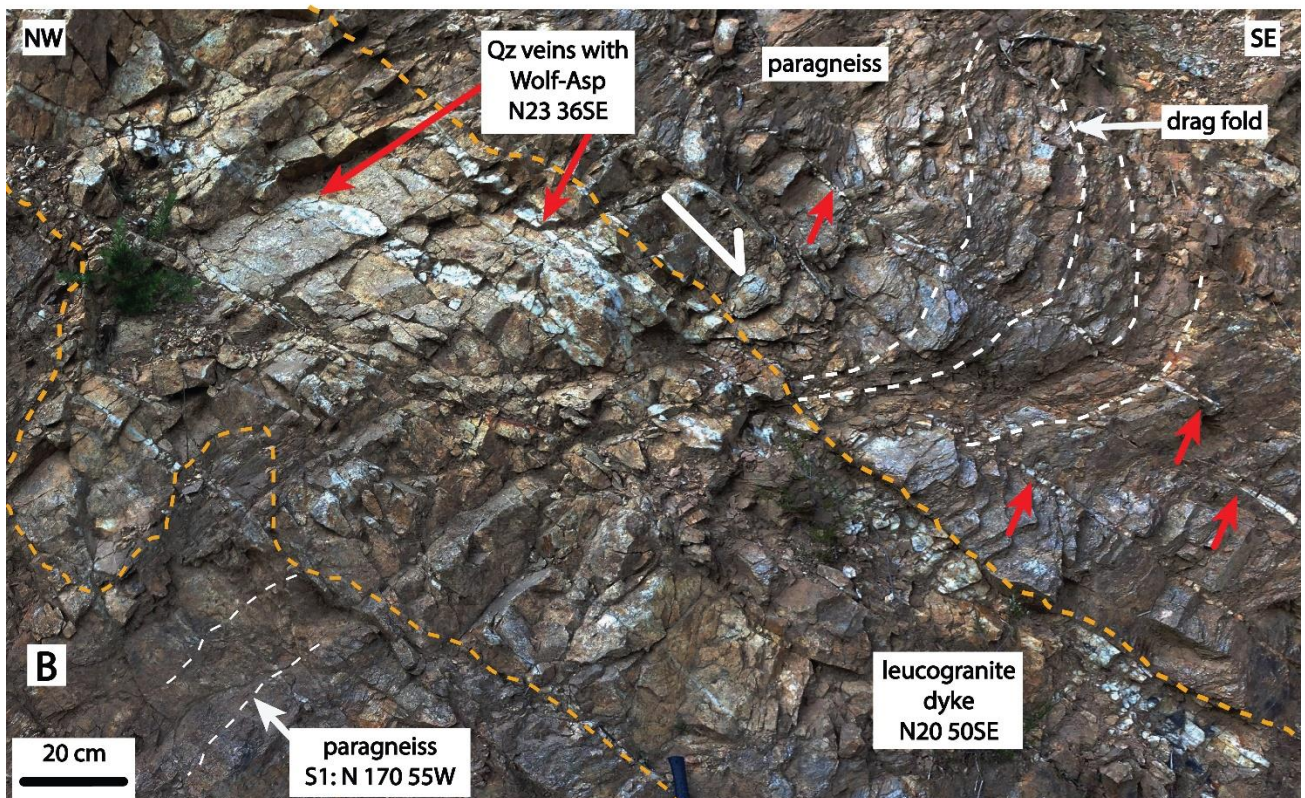
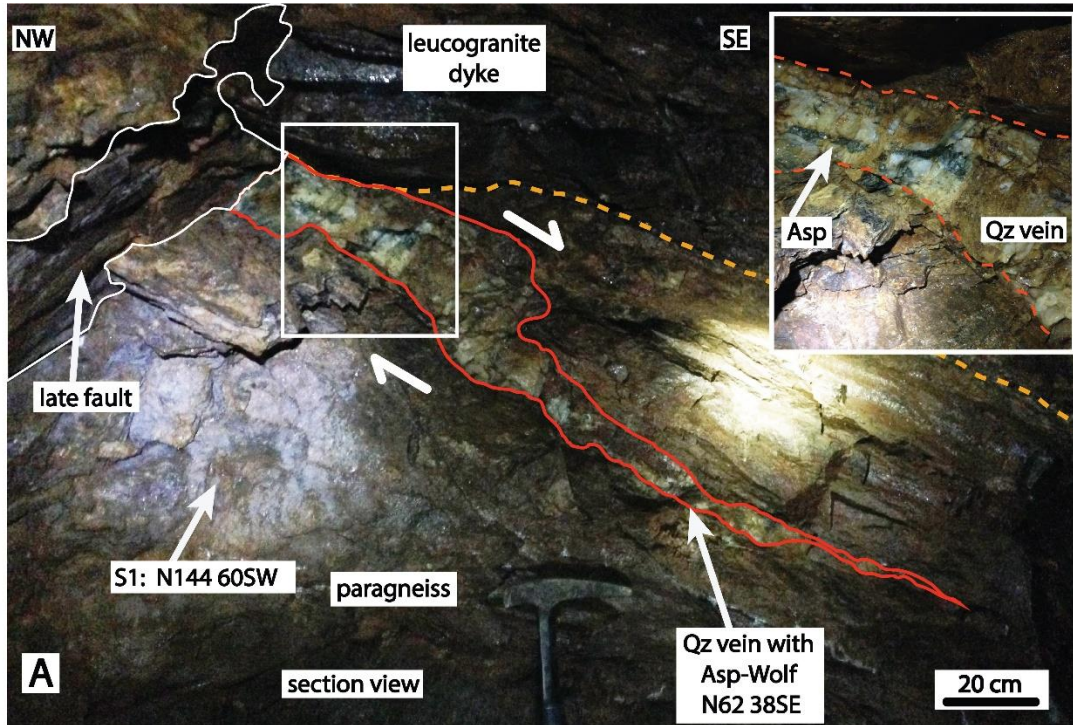
1038

1039

1040

1041 **Figure 4**

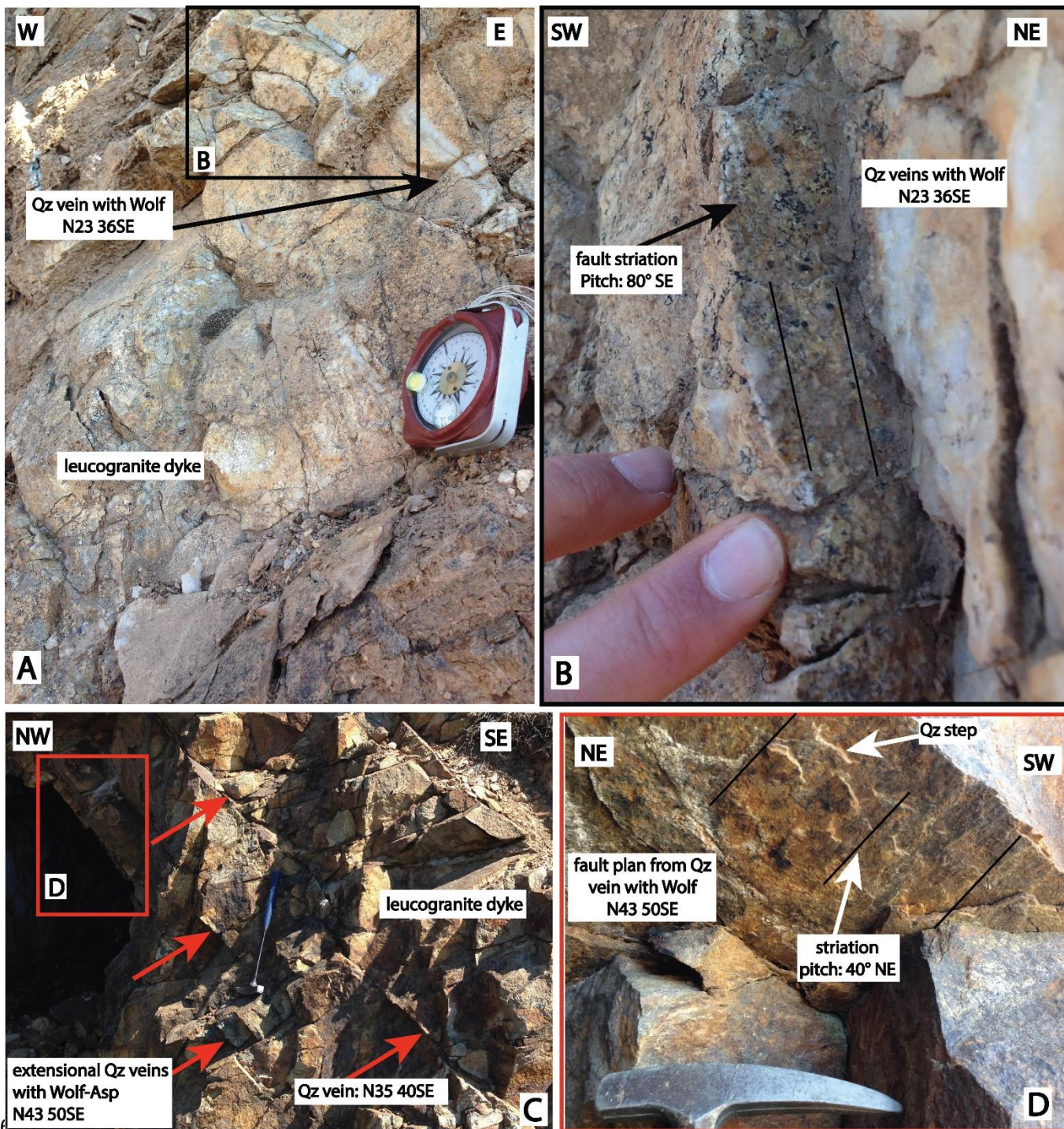
1042



1043

1044





1046

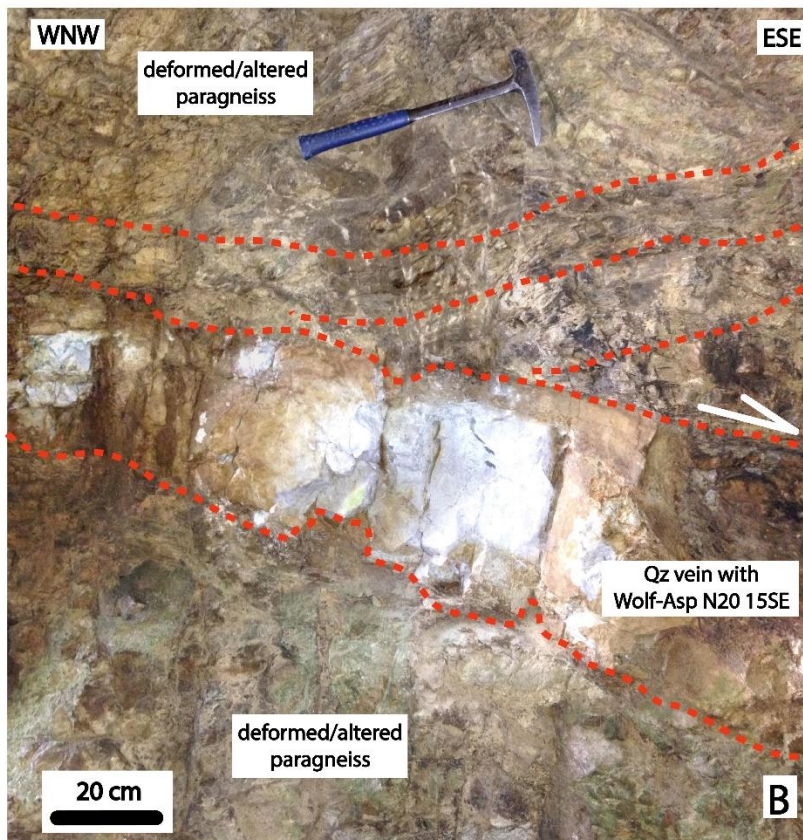
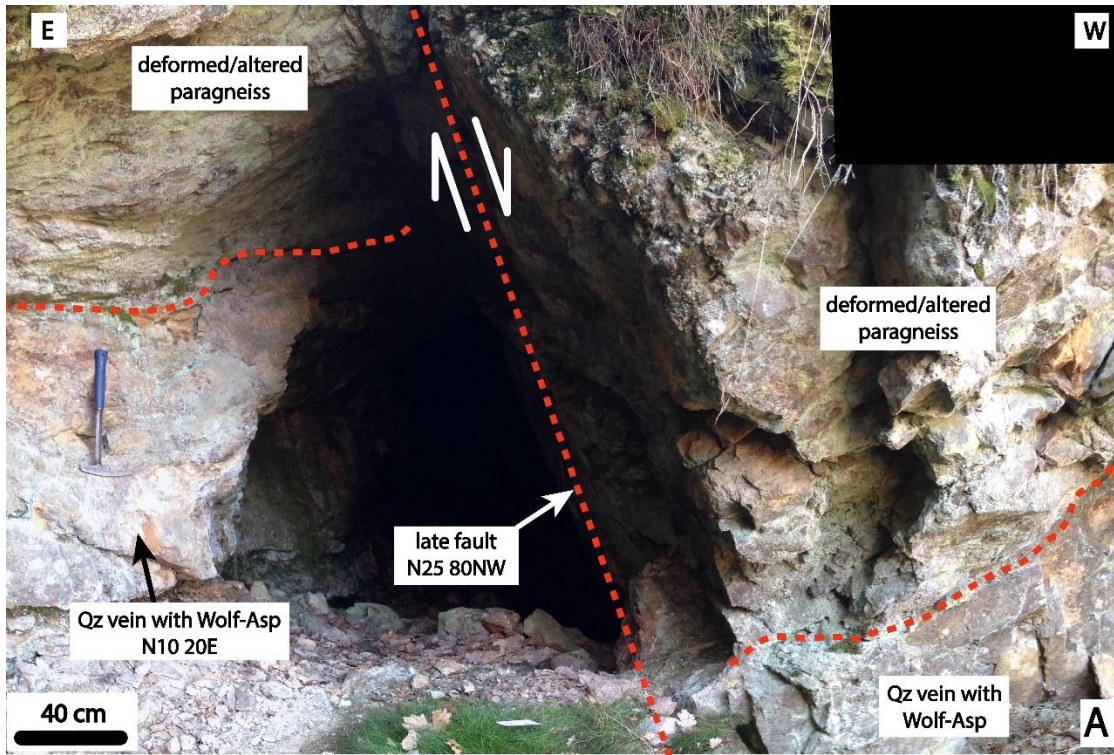
1047

1048

1049

1050 **Figure 6**

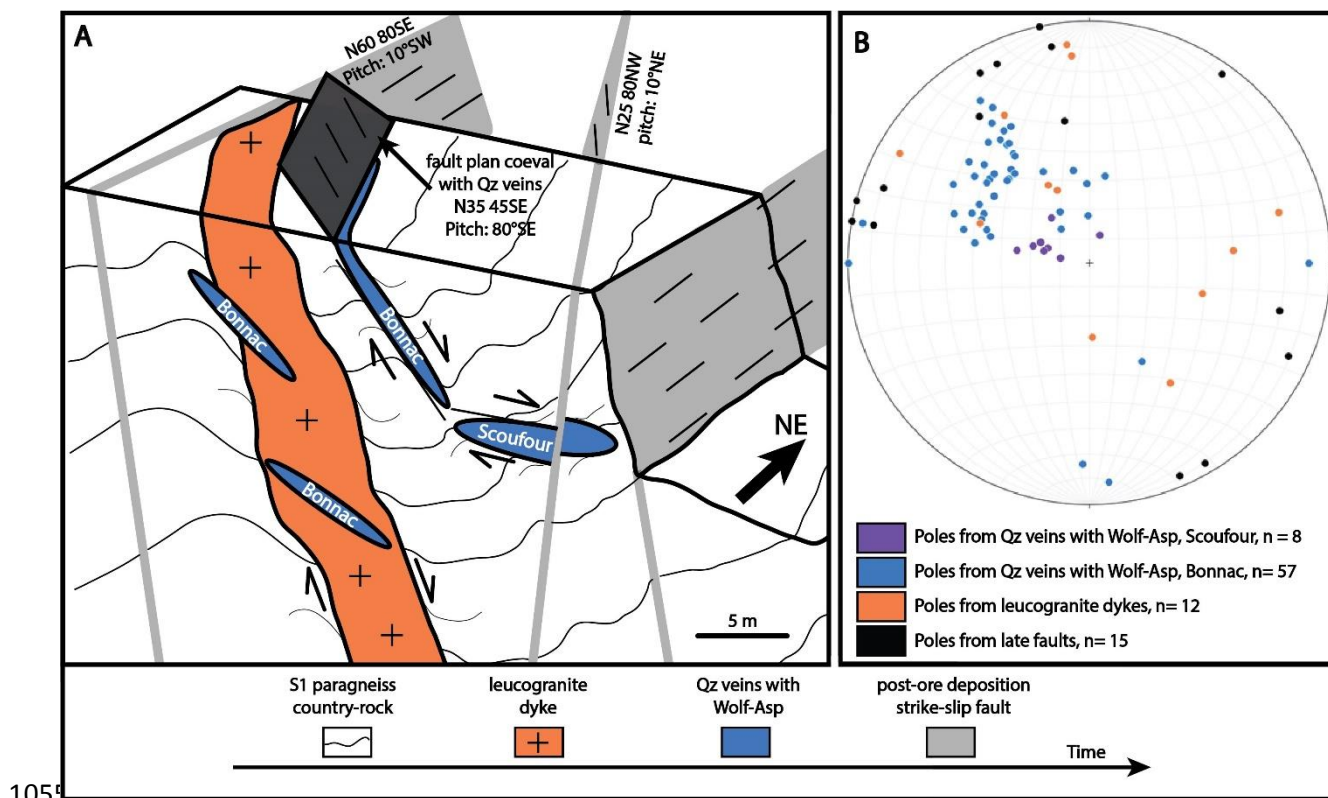
1051



1052

1053

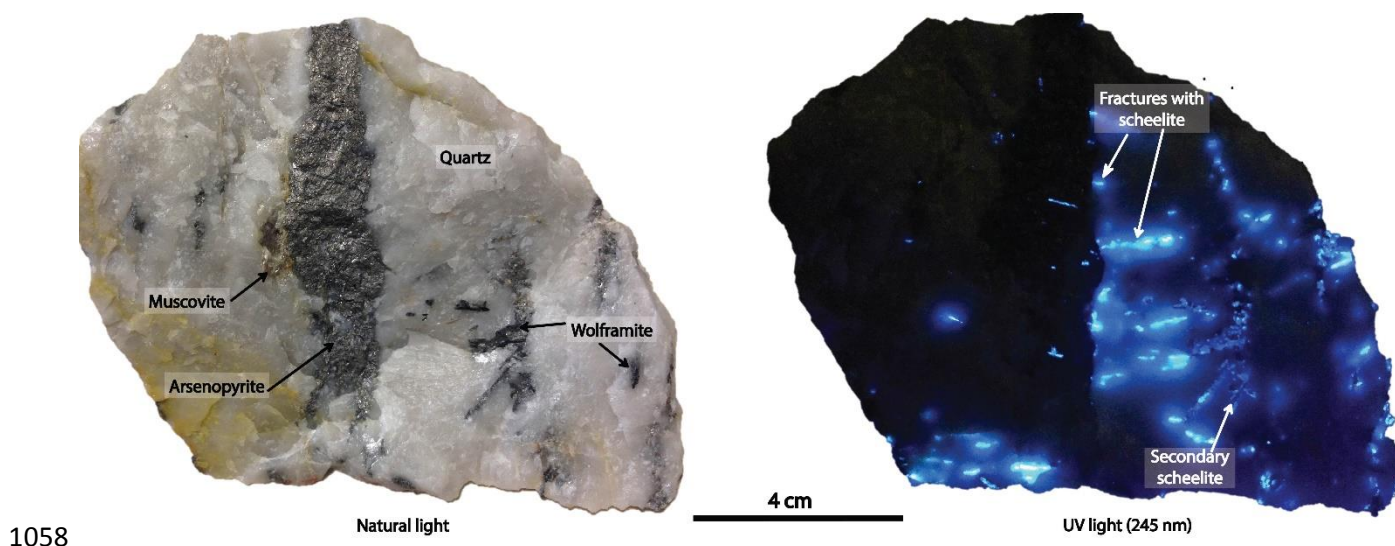
1054 **Figure 7**



1055

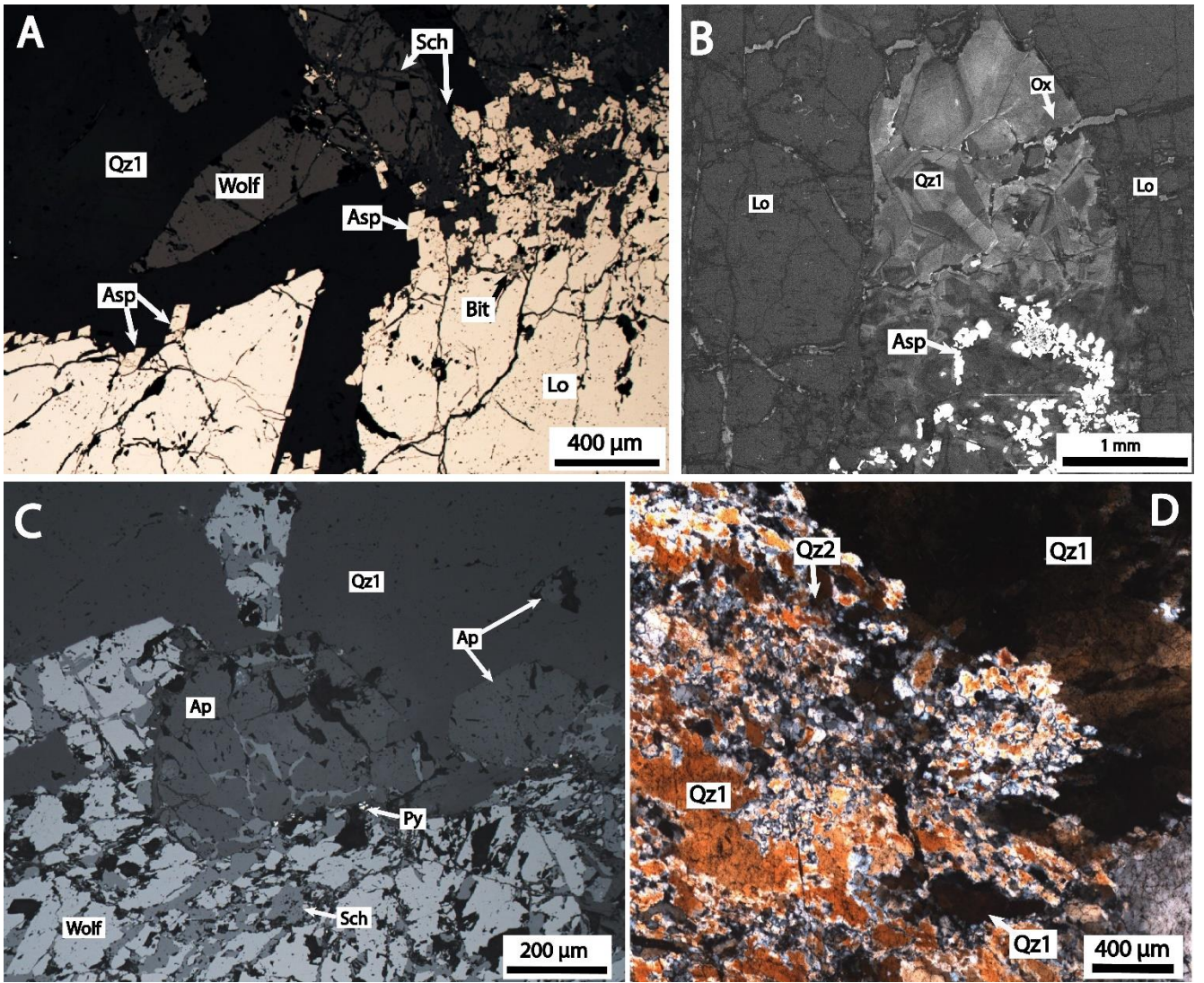
1056 **Figure 8**

1057



1058

1059 **Figure 9**



1060

1061

1062

1063

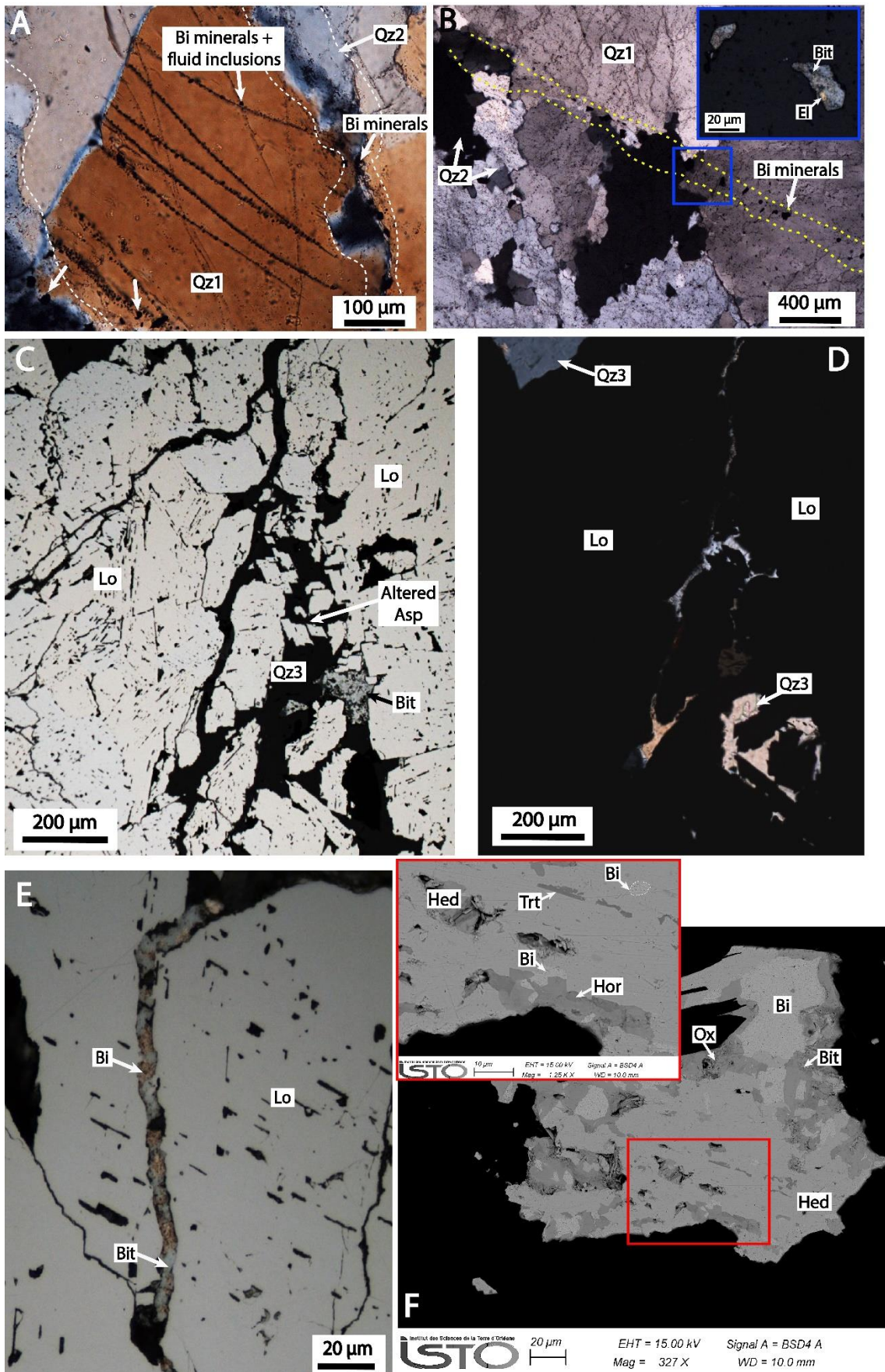
1064

1065

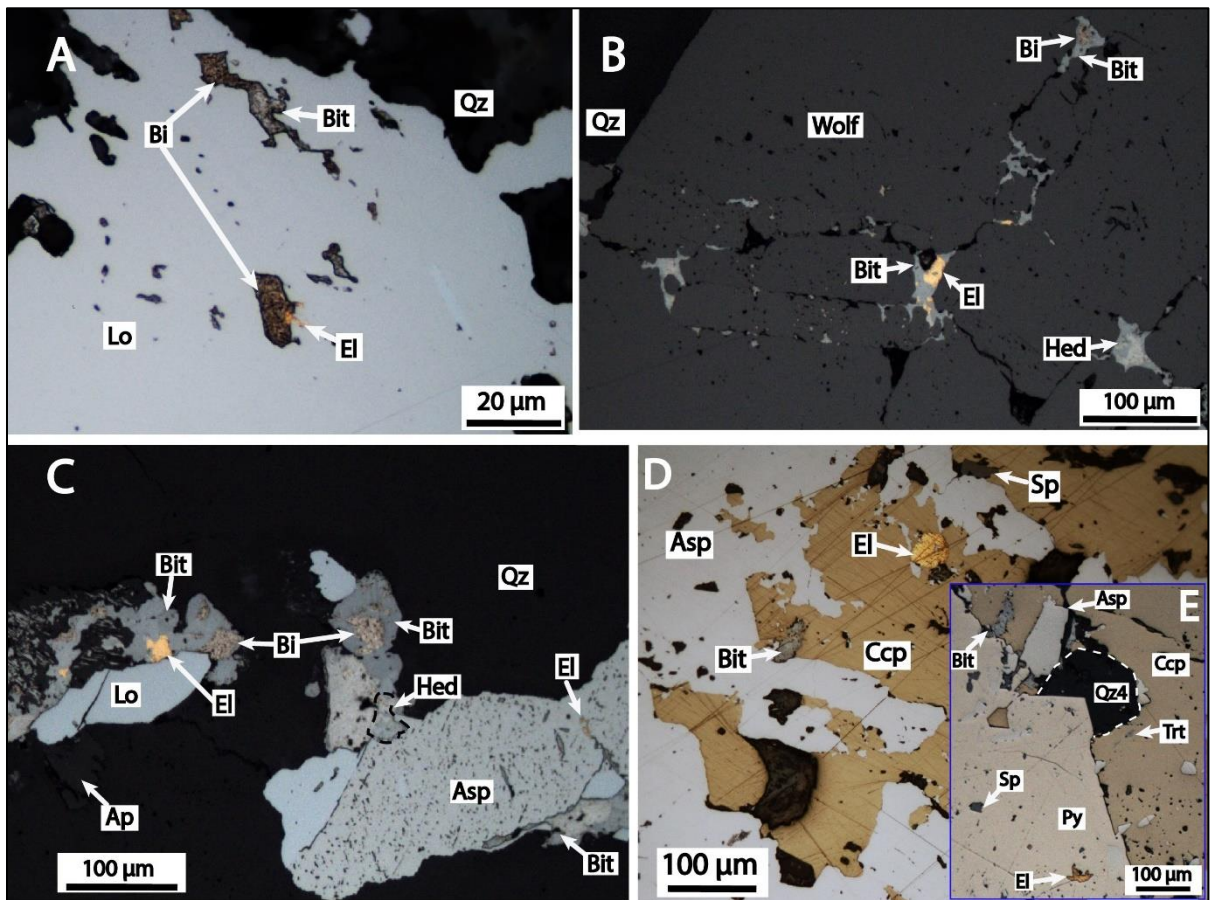
1066

1067

1068 **Figure 10**



1070 **Figure 11**



1071

1072

1073

1074

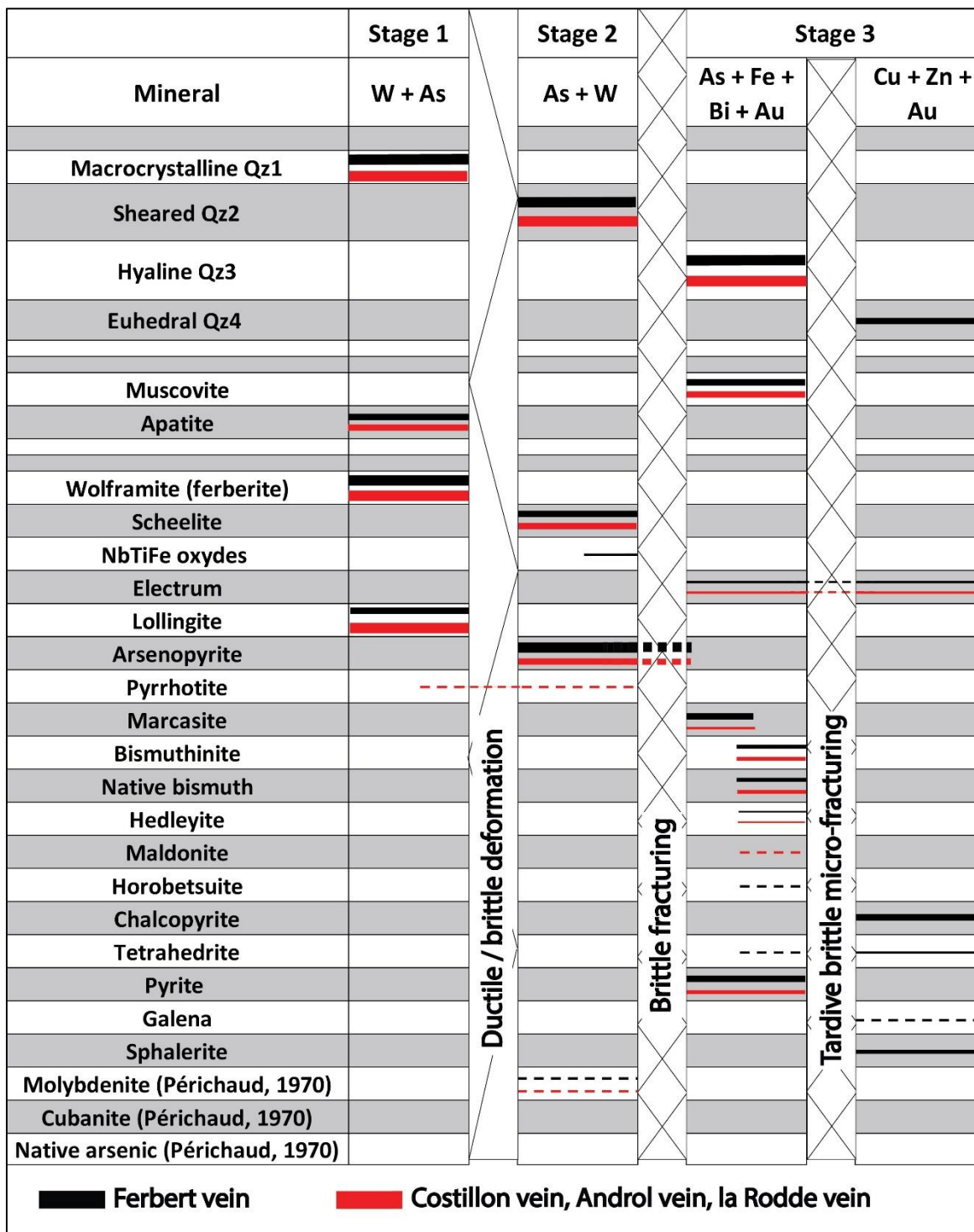
1075

1076

1077

1078

1079



1081

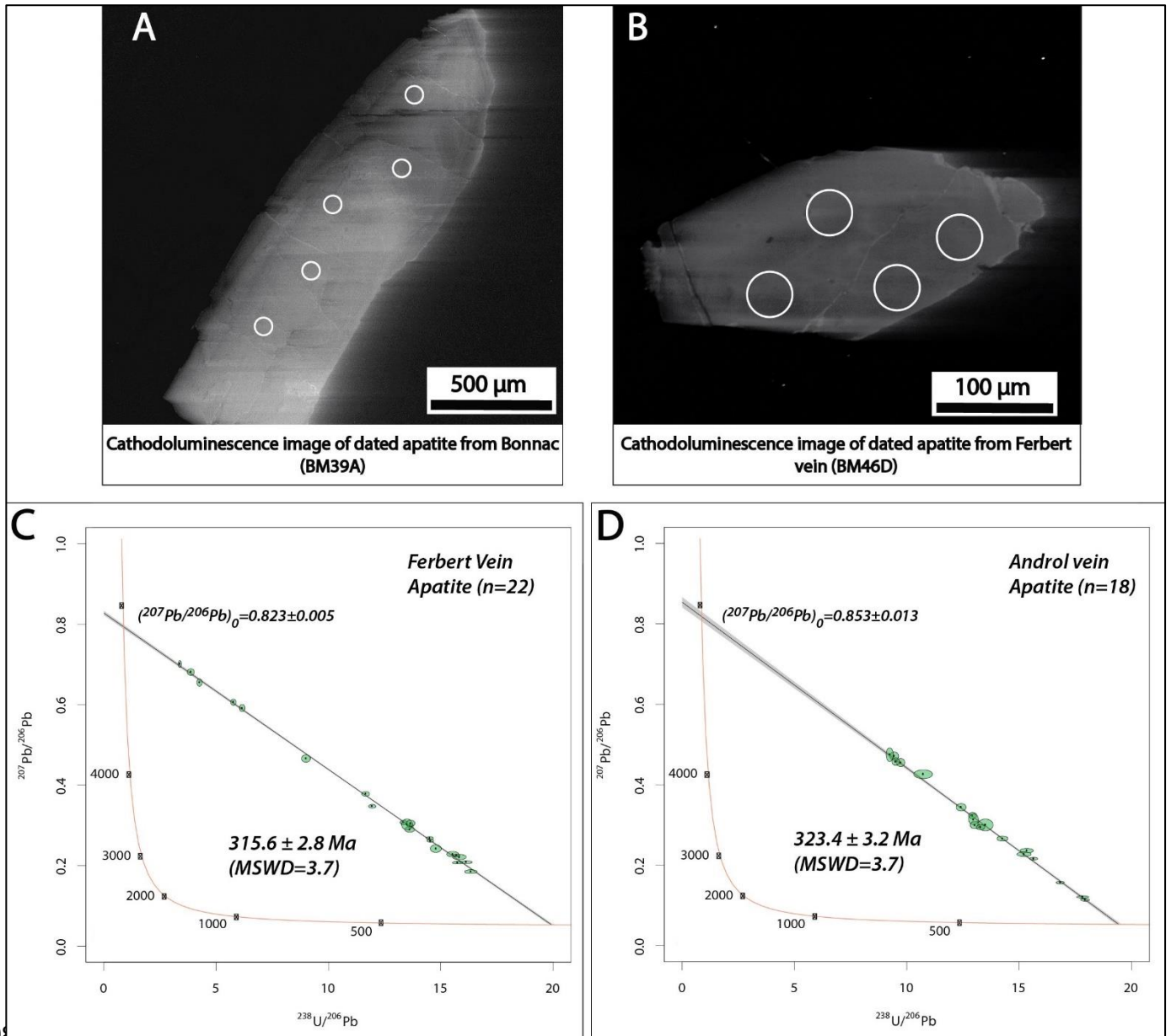
1082

1083

1084

1085 **Figure 13**

1086



1087

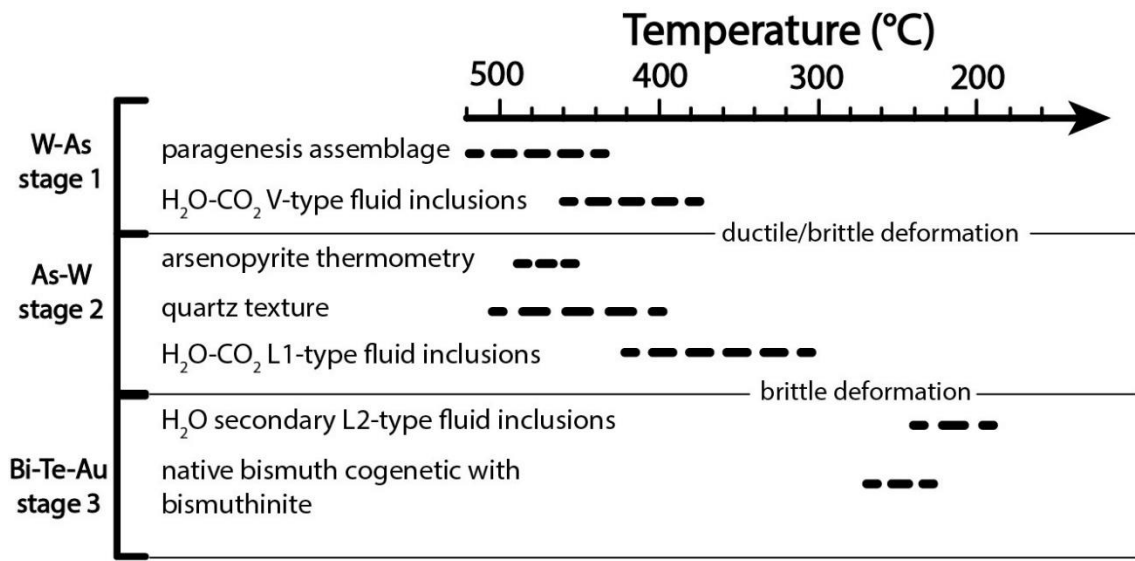
1088

1089

1090



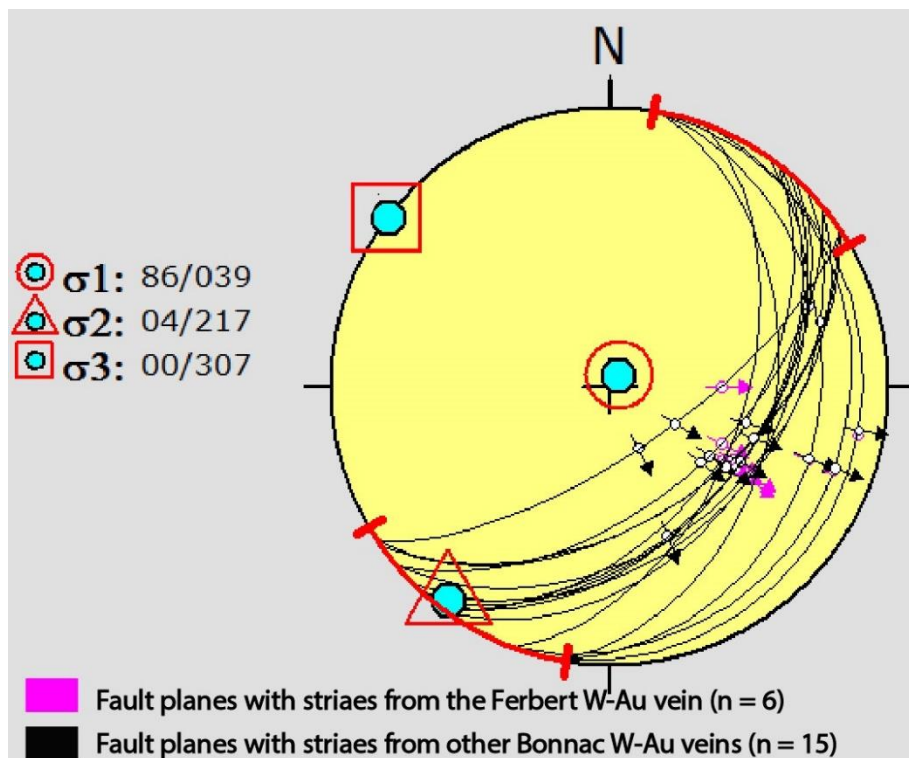
1091 **Figure 14**



1092

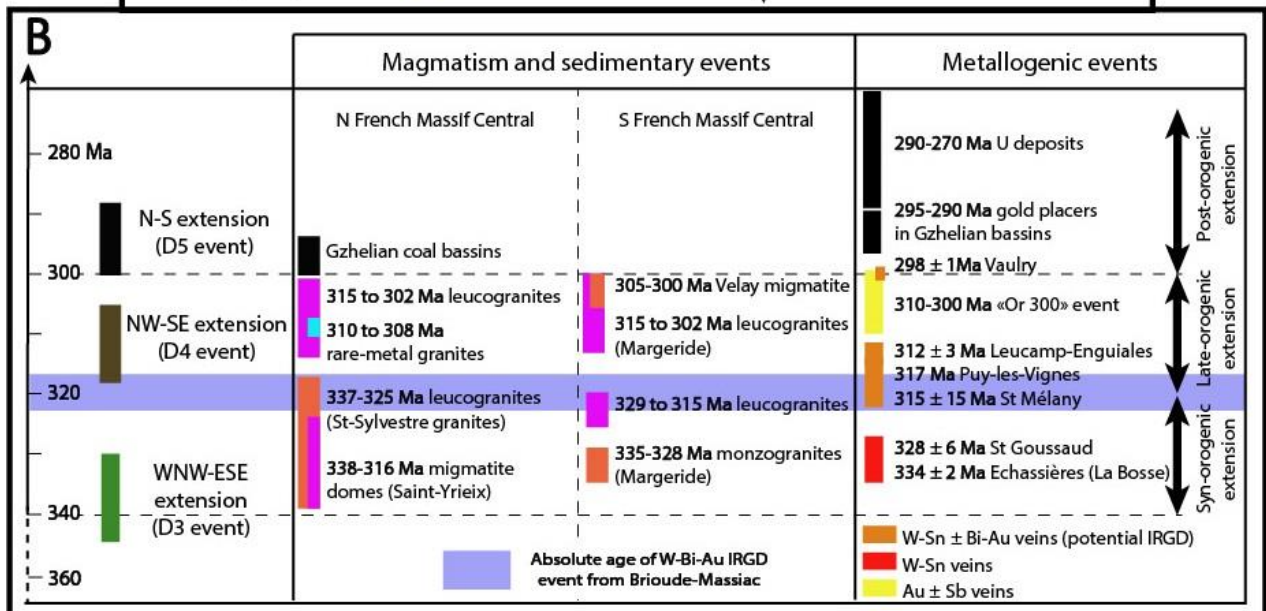
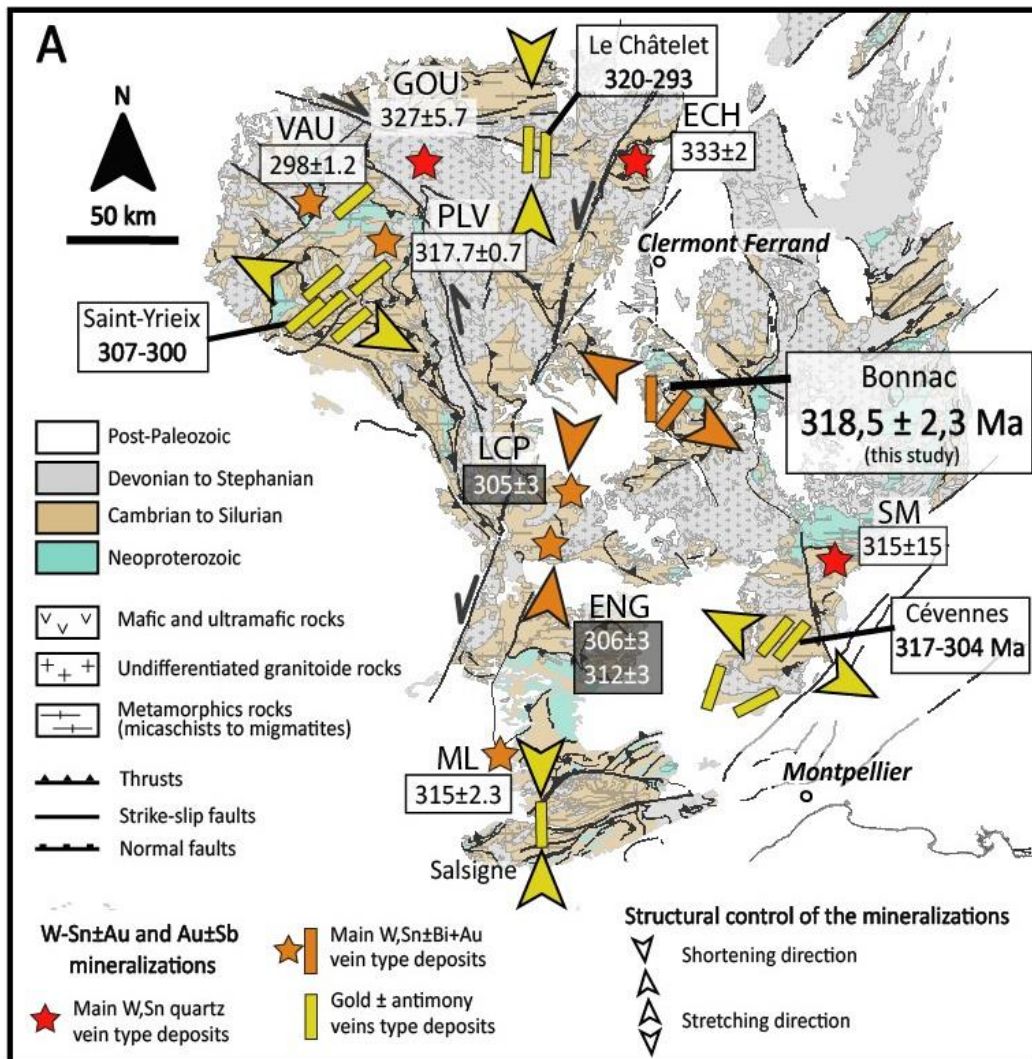
1093

1094 **Figure 15**



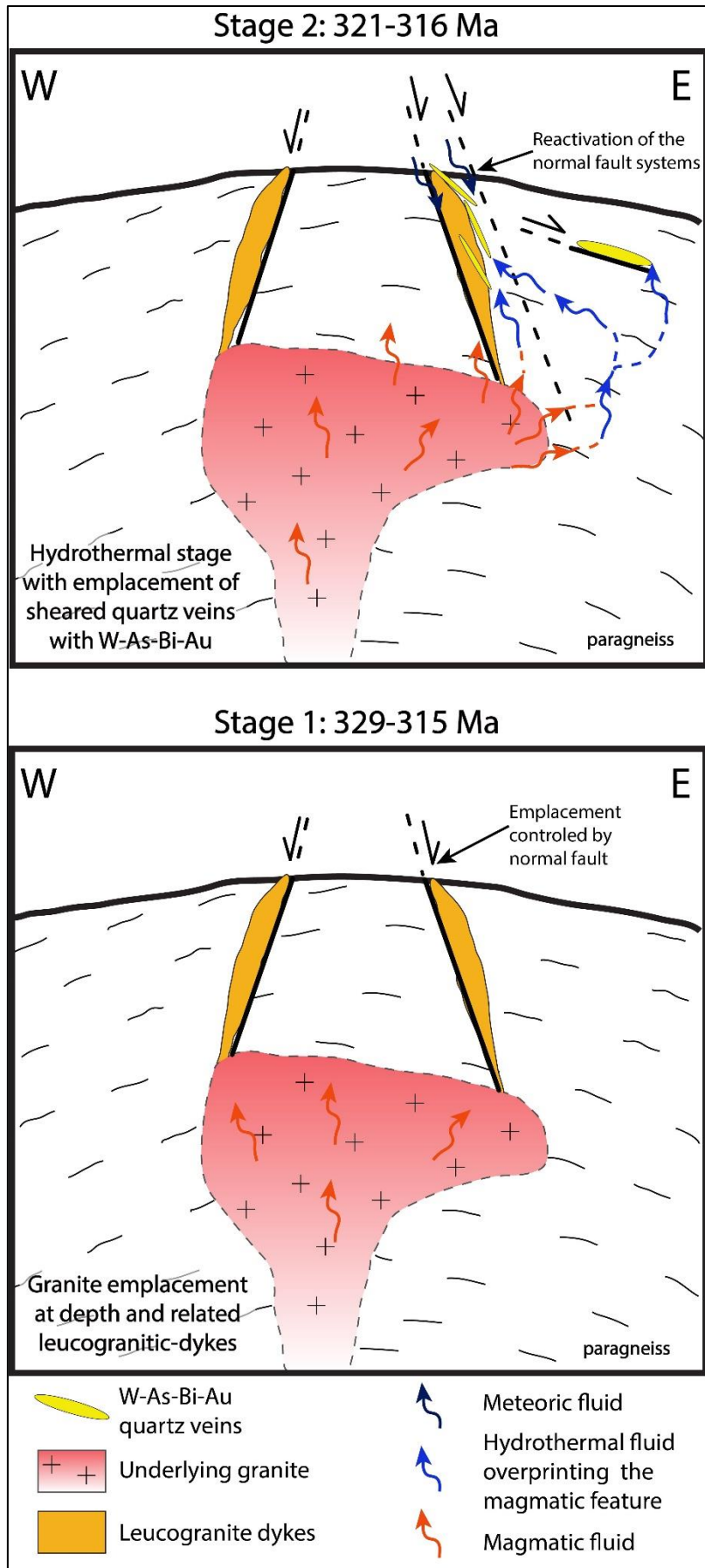
1095

1096 **Figure 16**

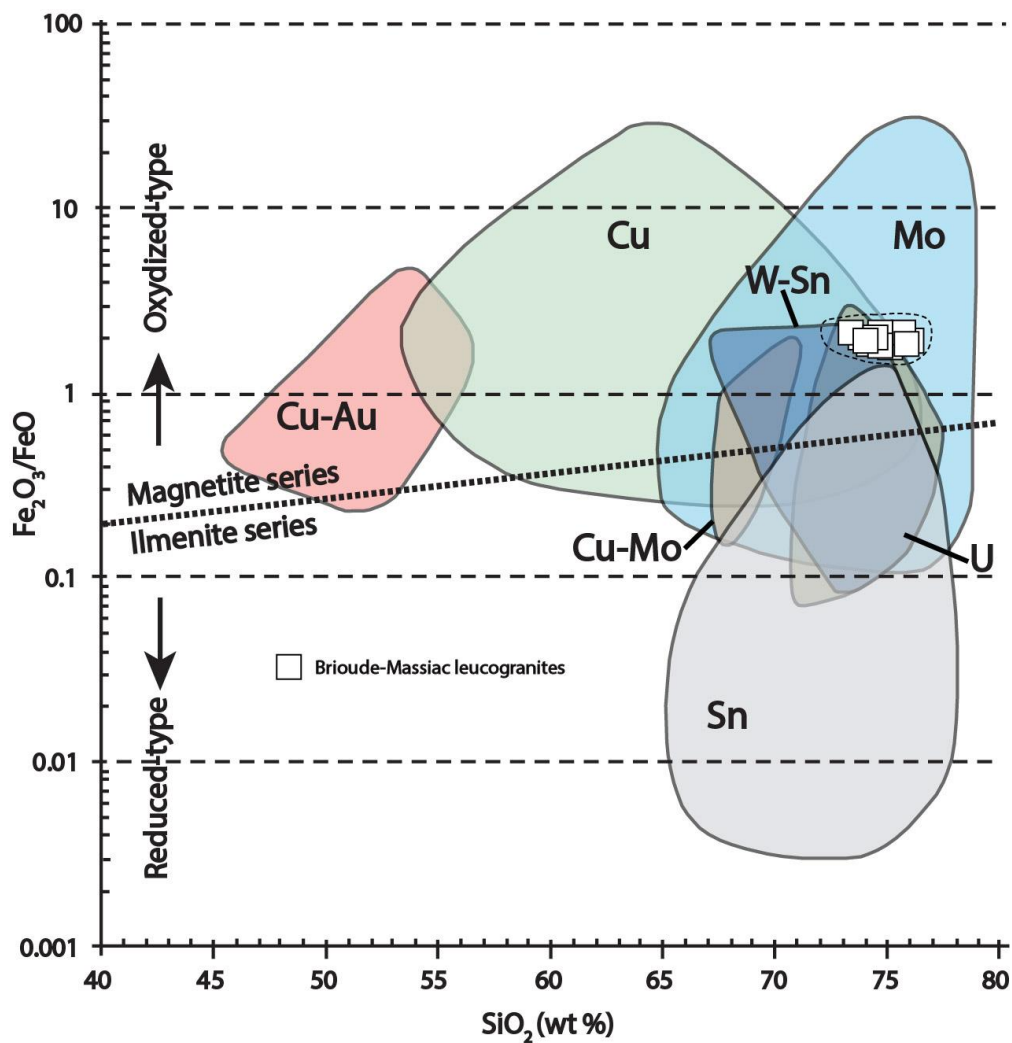


1097

1098 **Figure 17**



1100 **Figure 18**



1101

1102

1103

1104

1105

1106

1107

1108

1109

1110 **Table 1**

Arsenopyrite composition	Number of analysis	S (Wt. %) Std Fe Std As Std Sb Std Au Std Total As (at%) Std												T (°C) Kretschmar and Scott, 1976	Trapping temperature (°C) estimated by fluid inclusions (Bril, 1982)	
		S (Wt. %)	Std	Fe	Std	As	Std	Sb	Std	Au	Std	Total	As (at%)	Std		
Asp from Bonnac W-As-Bi-Au veins (data from this study and Bril, 1983)	60	19.30	0.50	34.40	0.32	45.70	0.68	0.01	0.03	bdl		99.4	33.4	0.66	485°C	> 350°C
Asp from Vèze W-As-Bi-Au veins (data from Bril, 1983)	3	19.74	0.63	34.87	0.26	45.39	0.89	bdl		bdl		100	32.8	0.87	470°C	> 350°C
Asp from Bosberty W-As-Bi-Au veins (data from Bril, 1983)	4	19.10	0.46	35.43	0.19	45.47	0.63	bdl		bdl		100	33.0	0.61	480°C	> 350°C

Gold composition	Number of analysis	Ag (Wt. %) Std Au Std Total				
		Ag (Wt. %)	Std	Au	Std	Total
Gold from W-As-Bi-Au veins	10	16.7	5.70	82.60	6.92	99.30

1111 Std = standard dev bdl = below detection limit

1112

1113

1114

1115

1116

1117

1118

1119

1120

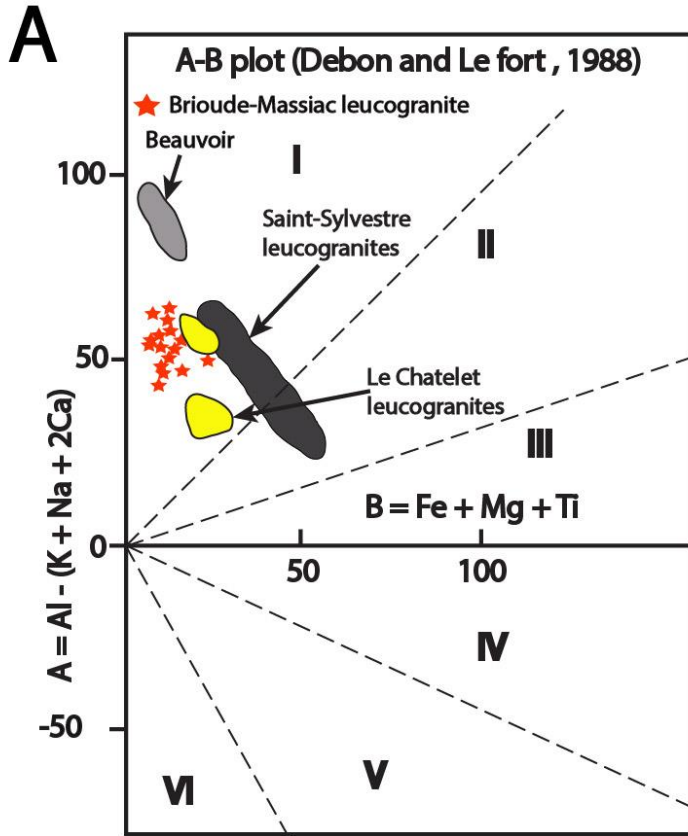
1121

1122

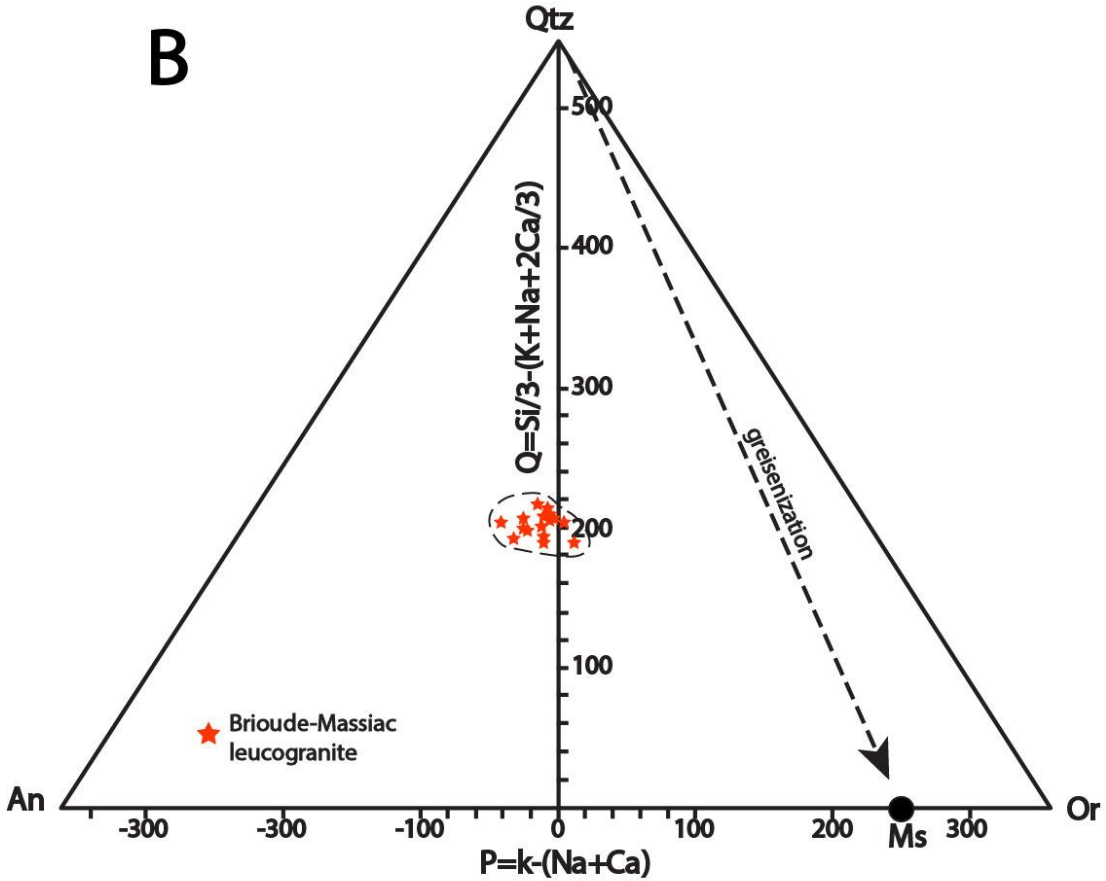
1123 **Supplementary data**

1124

1125 **ESM 1**



**Q-P plot (Debon and Le fort , 1988)**





ESM 3 Table 1: Operating conditions for the LA-ICP-MS equipment

ESM 3 Table 1: Operating conditions for the LA-ICP-MS equipment	
<b>Laboratory &amp; Sample Preparation</b>	
Laboratory name	Géosciences Rennes, UMR CNRS 6118, Rennes, France
Sample type/mineral	apatite
Sample preparation	Thin and polished sections
Imaging	MEB Merlin Compact Zeiss with EDS detector EDS (Bruker, Quantax – Xflash6– 129 eV)
<b>Laser ablation system</b>	
Make, Model & type	ESI NWR193UC, Excimer
Ablation cell	ESI NWR TwoVol2
Laser wavelength	193 nm
Pulse width	< 5 ns
Fluence	6.5 J/cm <sup>2</sup>
Repetition rate	5 Hz
Spot sizes	40 µm (round spot)
Sampling mode / pattern	Single spot
Carrier gas	100% He, Ar make-up gas and N <sub>2</sub> (3 ml/mn) combined using in-house smoothing device
Background collection	20 seconds
Ablation duration	60 seconds
Wash-out delay	15 seconds
Cell carrier gas flow (He)	0.75 l/min
<b>ICP-MS Instrument</b>	
Make, Model & type	Agilent 7700x, Q-ICP-MS
Sample introduction	Via conventional tubing
RF power	1350W
Sampler, skimmer cones	Ni
Extraction lenses	X type
Make-up gas flow (Ar)	0.87 l/min
Detection system	Single collector secondary electron multiplier
Data acquisition protocol	Time-resolved analysis
Scanning mode	Peak hopping, one point per peak
Detector mode	Pulse counting, dead time correction applied, and analog mode when signal intensity > ~ 10 <sup>6</sup> cps
Masses measured	<sup>43</sup> Ca, <sup>204</sup> (Hg + Pb), <sup>206</sup> Pb, <sup>207</sup> Pb, <sup>208</sup> Pb, <sup>232</sup> Th, <sup>238</sup> U
Integration time per peak	10-30 ms
Sensitivity / Efficiency	28 000 cps/ppm Pb (50µm, 10Hz)
Dwell time per isotope	5-70 ms depending on the masses
<b>Data Processing</b>	
Gas blank	20 s on-peak
Calibration strategy	Madagascar apatite used as primary reference material, Durango and McClure apatite standards used as secondary reference material (quality control)
Reference Material info	Madagascar (Thomson et al., 2012) Durango (McDowell et al., 2005) McClure (Schoene and Bowring, 2006)
Data processing package used	Iolite (Paton et al., 2010), VizualAge_UcomPbine (Chew et al., 2014)
Quality control / Validation	Durango: Weighted average <sup>207</sup> Pb corrected age = 31.89 ± 0.70 Ma (MSWD = 0.62) McClure: Weighted average <sup>207</sup> Pb corrected age = 526 ± 14 Ma (MSWD = 1.7)



ESM 3 Table 2: LA-ICP-MS U/Pb analyses for apatites for studied samples									
		U (ppm)	Pb (ppm)	238U/206Pb	Error (2σ)	207Pb/206Pb	Error (2σ)	Final 207 Age	Error (2σ)
	BM46d_1	111.90	7.82	15.830	0.250	0.2212	0.0054	317	16
	BM46d_2	122.60	7.77	16.130	0.220	0.2083	0.0030	316	14
	BM46d_3	115.90	8.24	15.530	0.220	0.2283	0.0053	317	13
	BM46d_4	88.40	8.02	14.510	0.130	0.2680	0.0031	318	17
	BM46d_5	127.60	10.31	15.700	0.130	0.2254	0.0024	316	17
	BM46d_7	66.10	7.61	13.350	0.130	0.3069	0.0044	324	19
	BM46d_8	73.70	7.89	13.620	0.180	0.2896	0.0054	327	16
	BM46d_9	176.80	10.11	16.340	0.230	0.1849	0.0039	324	17
	BM46d_10	64.44	7.24	13.640	0.120	0.2992	0.0037	322	18
	BM46d_11	148.70	10.11	15.750	0.190	0.2071	0.0027	324	16
	BM46d_13	66.79	10.16	11.660	0.140	0.3781	0.0048	323	22
	BM46d_14	158.30	13.75	14.540	0.120	0.2616	0.0031	322	16
	BM46d_15	90.33	14.57	11.950	0.130	0.3472	0.0039	336	21
	BM46d_16	97.10	10.38	13.500	0.200	0.3023	0.0110	322	21
	BM46d_17	41.64	21.18	5.768	0.096	0.6060	0.0063	344	43
	BM46d_18	39.08	40.03	3.384	0.055	0.7010	0.0070	369	63
	BM46d_19	51.83	12.96	9.000	0.160	0.4660	0.0077	343	30
	BM46d_20	51.96	39.50	4.255	0.091	0.6550	0.0077	377	44
	BM46d_21	38.60	33.40	3.870	0.130	0.6810	0.0066	362	40
	BM46d_22	207.80	17.13	14.780	0.200	0.2421	0.0078	327	16
	BM46d_23	204.30	22.95	13.660	0.160	0.3051	0.0062	317	11
Ferbert vein	BM46d_24	68.00	32.18	6.160	0.100	0.5915	0.0075	341	20
Bonnac	BM39a_2	29.06	3.39	12.930	0.150	0.3233	0.0063	324	14
	BM39a_3	30.09	3.58	12.970	0.180	0.3140	0.0110	333	13
	BM39a_4	26.70	2.79	13.030	0.170	0.2997	0.0074	336	16
	BM39a_5	24.32	2.65	13.500	0.280	0.3000	0.0120	325	22
	BM39a_6	11.66	2.86	9.440	0.160	0.4710	0.0085	323	28
	BM39a_7	13.39	3.39	9.730	0.150	0.4550	0.0083	326	23
	BM39a_8	13.13	3.52	9.510	0.140	0.4573	0.0075	333	25
	BM39a_9	13.53	2.97	10.730	0.340	0.4260	0.0090	321	29
	BM39a_10	11.25	3.02	9.240	0.130	0.4747	0.0140	326	24
	BM39a_11	23.39	3.31	12.420	0.180	0.3438	0.0077	324	16
	BM39a_13	138.10	5.24	16.830	0.150	0.1567	0.0027	325	11
	BM39a_14	76.90	5.10	15.340	0.240	0.2360	0.0047	319	12
	BM39a_15	315.50	6.81	17.830	0.220	0.1208	0.0026	324	12
	BM39a_16	79.80	5.17	15.220	0.260	0.2271	0.0045	325	13
	BM39a_17	76.51	4.93	15.650	0.150	0.2160	0.0027	320	12
	BM39a_19	243.20	5.29	17.940	0.160	0.1138	0.0027	324	11
	BM39a_21	34.74	3.53	13.280	0.160	0.2944	0.0052	332	16
	BM39a_24	48.50	4.04	14.260	0.200	0.2660	0.0052	326	15

1132

1133

1134

1135

1136

1137

1138

1139

1140

1141

1142

1143

1144

1145

1146

1147