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1 Evaporitic brines and copper-sulphide ore genesis at Jbel Haïmer (Central Jebilet, Morocco)

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24 **Abstract**

25 The Jbel Haïmer copper-sulphide mineralisation occurs at 20 km north of Marrakesh in the  
26 Variscan Jebilet massif, Morocco. Most of the ores (up to 3.9 wt. % Cu,  $\leq$  38 ppm Ag, and up  
27 to 2.9 ppm Au) occur as impregnations of NE-SW fault/fracture zones and related tectonic  
28 breccia. Two independent stages of fluid circulation and mineral deposition are distinguished.  
29 First, Late Variscan high temperature-low pressure metamorphism synchronous of granite  
30 intrusion induced percolation of C-H-O-N hydrothermal fluids throughout faults and shear  
31 zones. The drop in pressure from lithostatic down to hydrostatic values at temperatures around  
32  $350 \pm 50^\circ\text{C}$  triggered quartz precipitation associated with minor Sn-As-(Co-Ni) deposits and  
33 finally brecciation. The second stage, more recent than Triassic, consists in the deposition of  
34 quartz + carbonates, followed by Cu-(Pb-Zn) sulphides ( $\pm$ Ag-Au alloys) in fractures  
35 crosscutting 240 Ma microdiorite dikes. Mixing of evaporitic brines likely coming from  
36 Triassic formations with low salinity aqueous fluids was responsible for Cu-sulphide deposition  
37 at temperatures of around  $220\text{-}280^\circ\text{C}$  at a depth of 4-5 km. These base metal-rich brines are  
38 similar to those from the nearby Roc Blanc Ag-deposit and several other silver and base metal  
39 deposits in Morocco, considered as having circulated during the Central Atlantic Ocean  
40 opening.

41

42 **Keywords:** Cu-(Ag) ores, brines, fluid mixing, Triassic evaporite, Atlantic rifting

43

## 44 **Introduction**

45 Granite-related ore systems, an essential target for the mineral exploration industry (Sial et al.,  
46 2011), were developed as models for several commodities such as Au and W-Sn (granite related  
47 Au-deposits (IRGDs) for instance: Thompson et al., 1999; Hart, 2007; Thompson and  
48 Newberry, 2000; Lang and Baker, 2001). The proximity of the deposits to intrusions or inferred  
49 intrusions marked by contact metamorphic aureoles was one of the main arguments for such  
50 ore deposit models where magmatism plays a significant role at less as a source of heat flow  
51 for fluid convection. In Morocco, base metal (Pb-Zn-Cu), and precious metal (such as Ag)  
52 deposits are however not coeval with Pan-African or Variscan orogenies and related granitoids.  
53 Thus, extensional tectonics associated with the successive stages of Atlantic rifting favoured  
54 the formation of Ag and Pb-Zn deposits in Morocco and Western Europe. Ore deposits formed  
55 either in the Mesozoic sedimentary cover or in the basement where inherited discontinuities are  
56 excellent pathways for sedimentary brines. There, the increased porosity and permeability of  
57 damaged zones developed around faults and shear zones favoured fluid flows (Boiron et al.,  
58 2010; Nadoll et al., 2019).

59 In the Variscan Jebilet massif (Morocco), several vein-type polymetallic deposits occur in close  
60 spatial association with Late Variscan plutons such as the Roc Blanc Ag-(Zn-Pb) deposit where  
61 Ag grades reach 500 – 700 ppm or the Jbel Haïmer Cu occurrences (Huvelin, 1977). Huvelin  
62 (1977) considered these deposits as related to magmatic intrusions. At Roc Blanc, the model  
63 recently proposed by Essarraj et al. (2017a) is very different because it considers that the  
64 introduction of silver is late and not related to the Variscan cycle but synchronous to the Atlantic  
65 rifting after Triassic times. The silver deposit was there superimposed on previous Variscan  
66 mineral assemblages (sulphides and sulpharsenides) and related to the downward circulation of  
67 basinal brines.

68 At Jbel Haïmer, located at most 500 metres from the Roc Blanc deposit, a series of copper  
69 occurrences have been mined before the XX<sup>th</sup> century only in the near-surface weathered part.  
70 Copper was exploited in metre-sized excavations as malachite in breccia affected by intense  
71 oxidation. Oxidised ore breccia from outcrops at Jbel Haïmer have Cu grades up to 3.9 %  
72 (average 0.6 %), up to 38 ppm Ag, and 0.5 ppm to locally 2.9 ppm Au (Krutilin et al., 2013).  
73 The average Cu grade of the Jbel Haïmer ore is similar to those from volcanogenic massive  
74 sulphide deposits that occur a few kilometres towards the South-West and North-West, such as  
75 the Draa Sfar deposit (0.5 wt. % Cu), and the Kettara abandoned mine (0.6 wt. % Cu). There,  
76 Cu-rich quartz-carbonate veins crosscut volcanogenic massive sulphide (Outigua et al., 2020;  
77 N'Diaye et al., 2016).

78 The present study aims to decipher the nature of the mineralising fluids in the Jbel Haïmer Cu-  
79 deposit, in particular the temporal and spatial relationships between the mineralisation and the  
80 geodynamic events. The objective was to test a potential generalisation of the Roc Blanc genetic  
81 model developed for Ag-ores to other base metals such as copper in the Central Jebilet.

82

### 83 **Regional geology**

84 *Variscan units and tectonic-metamorphic stages:* The Jebilet massif extends 170 km E-W and  
85 7 to 40 km N-S (Fig. 1), and consists of three lithotectonic domains, the Western, Central, and  
86 Eastern Jebilet, separated by first-order shear zones: the Marrakesh Shear Zone (MSZ), between  
87 the Eastern and Central Jebilet (Lagarde and Choukroune, 1982) and the West Moroccan Shear  
88 Zone (WMSZ) between the Western and the Central Jebilet (Huvelin, 1977; Piqué et al., 1980;  
89 Lagarde and Choukroune, 1982; Le Corre and Bouloton, 1987) (Fig. 1b). According to Huvelin  
90 (1977) and Aarab and Beauchamp (1987), this massif is an intra-continental rift-basin filled  
91 with marine sediments deposited in an anoxic environment (Beauchamp, 1984; Beauchamp et  
92 al., 1991) from the Late Devonian to Early Carboniferous. During this extensional tectonic

93 regime, cogenetic tholeiitic mafic-ultramafic and calc-alkaline felsic intrusions are the  
94 witnesses of the pre-orogenic bimodal magmatism (Bordonaro, 1983; Aarab, 1984) (Fig. 2a).  
95 Recent U-Pb LA-ICP-MS dating on zircon from granodioritic plutons gave an absolute age of  
96  $358 \pm 7$  Ma (Tabouchent - Bamega) and  $336 \pm 4$  Ma (Oulad Ouaslam) (Delchini et al., 2018).  
97 This age range is older than the former ages obtained for the same rocks ( $330.5 \pm 0.7$  Ma, U-  
98 Pb on zircons, Essaifi et al., 2003; and  $327 \pm 4$  Ma, Rb-Sr on whole rock, Mrini et al., 1992).  
99 These intrusions produced contact metamorphism (M1) in the pyroxene-hornfels facies  
100 (Huvelin, 1977; El Hassani, 1980; Delchini et al., 2018). The Jbel Haïmer Cu-ore bodies occur  
101 in the central part of the Jebilet comprised of the so-called Sarhlef series (Fig. 1). The Sarhlef  
102 metasediments deposited in the rift-basin as a thick succession of argillites overlain by  
103 carbonaceous argillites and limestones (Bordonaro, 1983). These series have a Carboniferous  
104 age (Upper Viséan - Namurian: fossil relative dating by *Posidonomya becheri* Bronn; Huvelin,  
105 1961). In the Sarhlef series, stratabound lenticular Fe-Cu-Pb-Zn volcanogenic massive  
106 sulphides formed during this rifting period (Huvelin, 1977). The structural features of the Jebilet  
107 massif are due to the succession of two deformation events, D1 and D2 that lasted from the Late  
108 Carboniferous to the Early Permian and constituted the Variscan orogeny (Delchini et al.,  
109 2018). During the D1 compressive deformation, the emplacement of superficial allochthonous  
110 nappes resulted in recumbent folds (Delchini et al., 2018), accompanied by rare schistosity  
111 cleavage S1, boudinage of competent layers as well as vertical fractures and veins. The context  
112 is typical of a diagenetic to anchizonal metamorphism transition (low temperature: 150-200°C,  
113 Bamoumen, 1988). The D1 structures trending E-W in the Central Jebilet and the West of the  
114 Eastern Jebilet suggest an N-S shortening (Delchini et al., 2018). The D2 is the major polyphase  
115 deformation event that corresponds to a WNW-ESE to NW-SE transpressional crustal  
116 shortening. During the first D2 stage, NS–N30°E kilometre-size isoclinal folds developed, as  
117 well as a penetrative S2 cleavage and a high temperature–low pressure (HT-LP) thermal

118 metamorphism (greenschist to amphibolite facies; 4 to 5 kbar and 560-485°C; Delchini et al.,  
119 2016). The second stage of D2 deformation corresponds to transpressional shearing that  
120 induced shear zones at all scales, in particular the multi-kilometre-sized WMSZ and the MSZ  
121 (Fig. 1b). HT-LP thermal metamorphism M2, so-called M2a in Delchini et al. (2018), isoclinal  
122 folding D2, high thermal gradients (50°C/km, and up to 95°C/km) and shear zone activity  
123 occurred within the 310-280 Ma period (Delchini et al., 2018). Close to MSZ, leucogranites  
124 such as the Bramram intrusion (Fig. 2a) at  $295 \pm 15$  Ma (Rb/Sr, Mrini et al., 1992) and  $297 \pm 6$   
125 Ma (Tisserant, 1977) intruded the Sarhlef schists. Local contact metamorphism (noted M2b in  
126 Delchini et al., 2018) reached hornblende-hornfel facies with peak conditions about 2–3 kbar  
127 and 620°C (El Hassani, 1980; Delchini et al., 2016) and locally induced the development of  
128 graphite-rich skarns (Fig. 2a) in the Central Jebilet (Bastoul, 1992). The HT-LP metamorphism  
129 coeval with leucogranite intrusions may be explained by the inversion of the thermally  
130 weakened intracontinental domain during the Variscan compression D2 (Delchini et al., 2018).  
131 A final increment of the D2 stage corresponds to the development of a network of regional  
132 brittle conjugate shear zones and brittle reverse faults (ENE, and NW) that locally deform the  
133 S2 major cleavage (Delchini et al., 2018). The Aït Bella OuSaïd kilometre-sized fault located  
134 close to Jbel Haïmer (few hundred metres to the North, Fig. 2a) is one of the longest and thickest  
135 ENE shear zones resulting from the last D2 stage (Delchini et al., 2018).

136 *Post-Variscan microdiorite dikes and sills:* they crosscut both the bimodal magmatic and  
137 granodioritic rocks and leucogranite plutons. They may exceed 1 km in length, strike N-S to  
138 N40°E (Fig. 2a). They formed during a period of distension (Huvelin, 1977; Bordonaro, 1983;  
139 Aarab and Beauchamp, 1987; Bernard et al., 1988; Bouloton and Gasquet, 1995; Essaifi et al.,  
140 2003; Dostal et al., 2005) at ca.  $240 \pm 10$  Ma (K-Ar method on kaersutite: Gasquet and  
141 Bouloton, 1995; Youbi et al., 2001; Dostal et al., 2005, summarised by Bouloton et al., 2019).  
142 They are synchronous with the thermal events which affected the Western Meseta in the 250-

143 210 Ma range (apatite fission track thermal modelling: Ghorbal et al., 2008; Saddiqi et al., 2009;  
144 Barbero et al., 2011).

145 *Mesozoic sedimentation and deformation:* several extensional deformation events occurred  
146 from lower Triassic to Post-Kimmeridgian times. Such events are coeval with the break-up of  
147 Pangea and Central Atlantic opening (Medina, 1991; Jalil, 1999; Tourani et al., 2000; Medina  
148 et al., 2001; El Arabi, 2007). Subsequently, the deposit of thick clastic series alternating with  
149 evaporites and basaltic flows, filled large sedimentary basins. In this time, the Central Jebilet  
150 domain was a part of the West Moroccan Arch (WMA: Hafid, 2006; El Arabi, 2007; Saddiqi  
151 et al., 2009). The latter was a paleogeographic high separating Tethyan domain to the East, i.e.,  
152 the High Atlas rift and the Atlantic rift to the West. Paleogeographic reconstructions and apatite  
153 fission-track data (Saddiqi et al., 2009) showed that the Central Jebilet high was supplied by  
154 sediments that did not exceed 2.4 km in thickness, an estimate slightly lower than that proposed  
155 by Ghorbal et al. (2008). Triassic series, composed of sandstone, argillites, and evaporites  
156 (gypsum and salt), are outcropping at the Southern limit between Central and Eastern Jebilet  
157 (Fig. 2a) as well as in the Western Jebilet (Huvelin, 1977). The pre-Atlasic orogenic period  
158 lasted from the Triassic to the Late Cretaceous. From a structural point of view, the parallelism  
159 of some major Paleozoic trends (NNE, High and Middle Atlas) attests to the reactivation of  
160 former structures during the Atlasic orogeny at the Eocene (Frizon de Lamotte et al., 2008).  
161 Nevertheless, the E-W striking fault systems that crosscut older Paleozoic structures in the  
162 Jebilet did not correspond to reactivated structures (Frizon de Lamotte et al., 2008). Those  
163 newly formed E-W fracture sets are filled with quartz-carbonate and contain Cu and Pb-Zn-  
164 (Cu) ores (Huvelin, 1977).

165 *The Jbel Haïmer Cu-ore deposit:* At Jbel Haïmer, Cu ore bodies (Fig. 2b) are hosted by  
166 greenish-brown to grey Sarhlef schists, split in millimetre thick sheets (S1). Intercalations of  
167 sandy schist and sandstone layers prevail as NE-SW protruding crests at most one metre thick



168 and a few tens of metres long. Grey quartz occurs as boudinaged lenses in the schistosity planes,  
169 derived from metamorphic exsudation. Sarhlef series sometimes present hornfels with  
170 cordierite spots produced by contact metamorphism during granodiorite intrusions (Huvelin,  
171 1977). Granodiorites outcrop a few kilometres to the South of Jbel Haïmer (Fig. 2a). Besides,  
172 contact metamorphism locally transformed sandstones to quartzite. The latter shows  
173 granoblastic mosaic texture and presents millimetre-sized impregnations and veinlets of dark-  
174 brown tourmaline and hyaline quartz that crosscut the schist. When approaching granodiorite,  
175 tourmaline abundance increases up to massive black tourmalinite. Several microdiorite dikes  
176 (< 1m in width and up to one hundred metres in length) are widespread in the Jbel Haïmer  
177 outcrops and throughout the mineralised areas (Fig. 2a).

178 Ore zones occur exclusively in breccia affecting competent formations such as sandy schist and  
179 sandstone - quartzite layers (Fig. 3a to 3c). The old mining works are no longer accessible in  
180 Jbel Haïmer and were confined to a few tens of metres depth over the water table (up to 50 m,  
181 Huvelin, 1977). Most ores are therefore malachite and Fe-oxide impregnations in the oxidised  
182 breccia (Fig. 3a to 3e) and locally in the brecciated microdiorite dikes (Fig. 3f, 3g).

183

## 184 **Methods**

185 Representative samples were collected from the wall rocks (spotted schist, sandy schist-  
186 sandstone, and microdiorite dikes), as well as from the ore breccia and quartz veins for this  
187 study. Petrographic and scanning electron microscope (SEM) investigations were carried out  
188 using twenty selected samples.

189 Nine doubly polished wafers were used for fluid inclusion studies. Fluid inclusion typology  
190 (Table 2) follows notations from Boiron et al. (1992): aqueous (w), carbonic (c), bulk  
191 homogenisation to the liquid phase (L), bulk homogenisation to the vapour (V), presence of  
192 halite cube (h), and unidentified solids (s). Microthermometry was performed using a Linkam

193 THSMG600 freezing-heating stage (Shepherd, 1981). Abbreviations follow the convention  
194 from Roedder (1984) for microthermometric data presentation:  $T_m \text{ CO}_2$ : melting temperature  
195 of volatile phase for carbonic fluid inclusions,  $T_h \text{ CO}_2$ : homogenisation temperature of volatile  
196 phase for carbonic fluid inclusions,  $T_e$ : eutectic or apparent eutectic temperature defined as the  
197 temperature at which the first liquid appears in the frozen fluid inclusion during low-  
198 temperature measurements,  $T_m \text{ hh}$ : temperature of final melting of hydrohalite,  $T_m \text{ ice}$ : final  
199 melting temperature of ice,  $T_m \text{ cl}$ : melting temperature of clathrate,  $T_h \text{ (L or V)}$ : total  
200 homogenisation temperature (L+ V to liquid or L + V to vapour phase respectively) and  $T_m$   
201  $\text{NaCl}$ : melting temperature of halite cube). The precision of phase transitions below  $0^\circ\text{C}$  was  
202  $+0.2^\circ\text{C}$ , whereas the precision of the liquid-vapour homogenisation was  $1^\circ\text{C}$ . Over the range –  
203  $90$  to  $0^\circ\text{C}$ , the accuracy was  $0.4^\circ\text{C}$ , and from  $0$  to  $300^\circ\text{C}$  was  $2^\circ\text{C}$ . For most aqueous fluid  
204 inclusions, salinity calculations have been made in the  $\text{H}_2\text{O-NaCl}$  system using data from  
205 Bodnar and Vityk (1994) based on  $T_m \text{ ice}$  or  $T_m \text{ halite}$  for fluid inclusions containing halite  
206 cube (when  $T_{mh} < T_h$  and no  $T_m \text{ hh}$  is available). When both  $T_m \text{ ice}$  and  $T_m \text{ hh}$  or  $T_m \text{ NaCl}$   
207 values were available, salinity was calculated in the  $\text{H}_2\text{O-NaCl-CaCl}_2$  system using data from  
208 Steele-MacInnis et al. (2011).

209 Molar fractions of gas components ( $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2$ ) were determined on individual carbonic and  
210 aqueous-carbonic fluid inclusions in quartz by Raman spectrometry analysis using a DILOR  
211 LABRAM Raman spectrometer at the GeoRessources laboratory, University of Lorraine,  
212 Nancy, France. Bulk composition, molar volume, volatile/water ratio, and salinity were  
213 calculated from the  $P$ - $V$ - $T$ - $X$  properties of individual fluid inclusions in the C-O-H-S system  
214 (Dubessy, 1984; Dubessy et al., 1989; Thiery et al., 1994; Bakker, 1997). Isochores were  
215 calculated using the program ISOC from the computer package FLUIDS-1 (Bakker, 2003).

216 Laser ablation - inductively coupled plasma - mass spectrometry (LA-ICP-MS) analyses have  
217 been performed at the GeoRessources Laboratory (Nancy, France) on individual fluid

218 inclusions to quantify the ionic composition of fluids involved in the metal deposition. Laser  
219 ablation was carried out with an ESI New Wave Research UC 193 nm excimer laser at 5 Hz  
220 laser frequency. The ablated material was analysed with an Agilent 8900 Triple Quadrupole  
221 ICP-MS, equipped with a collision–reaction cell. The ablated material was carried in helium  
222 gas (0.5 l min<sup>-1</sup>), which was mixed with argon (0.9 l min<sup>-1</sup>) via a cyclone mixer (volume of  
223 9.5 cm<sup>3</sup>) before entering the ICP torch. A straight ablation technique with spot sizes of 30 and  
224 40 µm was applied to obtain overall higher signal-to-background intensity ratios and lower  
225 limits of detection (LOD). Each analytical series consists in the following isotopes: <sup>23</sup>Na, <sup>24</sup>Mg,  
226 <sup>39</sup>K, <sup>44</sup>Ca, <sup>55</sup>Mn, <sup>57</sup>Fe, <sup>63</sup>Cu, <sup>66</sup>Zn, <sup>75</sup>As, <sup>85</sup>Rb, <sup>87</sup>Sr, <sup>109</sup>Ag, <sup>121</sup>Sb, <sup>137</sup>Ba and <sup>208</sup>Pb. The collected  
227 intensity ratios for Na were converted to concentration ratios by external calibration against a  
228 NIST 610 standard reference glass following a bracketing standardisation procedure (Longerich  
229 et al., 1996). <sup>23</sup>Na was used as an internal standard to calculate absolute concentrations and was  
230 obtained via microthermometry. The calculation method for the chemical composition of the  
231 fluid inclusions is based on a combination of the ice-melting temperature, a Pitzer-based  
232 thermodynamic model, and the LA-ICP-MS Na/cation ratios (Leisen et al., 2012a). Limits of  
233 detection for a given element can be calculated, according to Longerich et al. (1996) and  
234 described in Leisen et al. (2012a).

235

### 236 **Barren and ore veins in their geological context**

237 The schistosity cleavage (S1) in the Sarhlef series strikes N30-50°E with an average dip of 20-  
238 60° to the East (Fig. 4a, 5a). Joints and faults are mostly parallel to the schistosity or crosscutting  
239 it (Boutira and Hakkou, 2012; Essarraj et al., 2013; Fig. 4, Fig. 5).

240 *Barren veins*: fractures, a few centimetres to a few metres in length, form a dense network  
241 striking NW-SE (average N130-140°E), dipping 50° (East and West) to sub-vertical. Pale grey  
242 quartz QI infillings are found in fractures crosscutting competent sandy schist and sandstone

243 and are associated with chlorite along the vein walls (Fig. 4b, 5b to 5e). The second set of  
244 fractures and white quartz veins named QII, in general up to a few metres long, strikes from  
245 N160°E to NE-SW and crosscuts the NW-SE QI veins (Fig. 5d) and fractures. The veins show  
246 a geodic texture locally. Decametre length corridors of breccia are oriented N10-30°E to NE-  
247 SW (Fig. 3a to 3e, 4) with an average dip around 60° to the East, and affect all preceding quartz  
248 types. They correspond to open structures sub-parallel to the strike of the regional schistosity,  
249 although schistosity planes are difficult to be observed in sandy schist and sandstone layers  
250 (Fig. 3a, 3c). Microdiorite dikes intruded the schist parallelly to the ore breccia corridors, as they  
251 strike mostly NNE-SSW (Fig. 4). They are locally deformed in particular along the breccia  
252 corridor (Fig. 3g).

253 *Quartz-carbonates veins and Cu-ore bodies:* a set of E-W fractures, feathery quartz and  
254 carbonate veins crosscut the schist and sandstone layers, as well as the microdiorite and most  
255 earlier veins above described (Fig. 5f, 5g). The Cu- ores formed later than E-W fractures and  
256 crosscut as well as the microdiorite. They are found as infillings of new microfracture sets in  
257 the vicinity of the main ore breccia corridor.

258

## 259 **Mineralogy**

260 Table 1 provides the paragenetic succession.

261 *Pre-ore stage:* A biotite-tourmaline-pale-grey quartz QI assemblage constitutes the first stage  
262 of barren vein infillings. Biotite, with tourmaline crystals, are abundant and consistently line  
263 the QI vein walls (Fig. 6a, 6b). Biotite was almost totally replaced later on by chlorite (chlorite  
264 1). The pale-grey quartz QI is coarse-grained and intensively sheared. It shows several  
265 interlocked networks of microfractures (fluid inclusion planes, FIPs) mainly NW-SE and NE-  
266 SW. Cassiterite, as crystals up to 300 µm in size, often with Sb traces, and sulphides (pyrite,  
267 arsenopyrite, and Co-As-Ni minerals, bismuthinite with Se traces) are found in brecciated QI,

268 as well as small disseminated grains (a few  $\mu\text{m}$ ) of native Bi (traces of Se and Ag) (Fig. 7a).  
269 The coarse-grained white quartz QII is locally associated with brecciated tourmaline  
270 agglomerations and followed by pyrite (Fig. 6c).

271 Fe-Co-Ni sulpharsenides fill fractures or cavities of the breccia and postdate pyrite and QII.  
272 They consist of euhedral arsenopyrite, Fe-(Co)-sulphide (Co-pyrite with around 6 wt % Co),  
273 and small size (few  $\mu\text{m}$ ) euhedral crystals of Fe-Co-Ni-sulpharsenides and cobaltite (Fig. 7b).  
274 After the breccia stage, chlorite 2 and QIII formed around the breccia fragments. Locally,  
275 pyrrhotite is spatially associated with chlorite 2 and quartz QIII. In schist, millimetre size clear  
276 quartz (QIII) veins are observed sub-parallelly to the QI veins, and are lined by a newly  
277 crystallised chlorite 2 (Fig. 6d, 6e). They correspond to the re-opening of the QI vein selvage  
278 (Fig. 6e). In these zones, QI-QII quartz crystals present recrystallisation halos or epitaxial  
279 clearer growth bands at the contact of chlorite 2.

280 *Cu-ore stage*: quartz breccia and microdiorite are crosscut by millimetre to centimetre-sized  
281 fractures, lined by feathery comb quartz, siderite and calcite (Fig. 6f to 6h). The late quartz  
282 (QIV) is clear, undeformed, and presents euhedral geodic terminations. It hosts scarce fluid  
283 inclusions and fluid inclusion planes (Fig. 6i). Chalcopyrite occurs later than QIV as  
284 impregnations of the former breccia and microfracture infillings. It sometimes contains traces  
285 of Te, scarce inclusions of Fe-sphalerite (up to 8 wt % Fe), stannite as well as an unidentified  
286 Bi-Te-Se-S mineral (Fig. 7c, 7d and 7e). Galena is found sporadically in microfractures  
287 affecting earlier Fe-As minerals (Fig. 7b and 7f). Selenium rich-galena (up to 3 wt % Se; traces  
288 of Bi) locally crosscuts chalcopyrite (Fig. 7g). Precious metals are present as late Ag-Au alloys  
289 (Ag/Au around 2).

290 *Supergene alteration*: supergene minerals replace sulphides and impregnate breccia fragments  
291 and microfractures (Fig. 6c, 6d, and 7h). Thus, exploited copper ores are mostly malachite (Fig.  
292 7c, 7e, and 7g) that results from the weathering of chalcopyrite from the Cu-ore stage. Fe-

293 oxides/hydroxides are predominant and are accompanied by a few grains of covellite and  
294 cerussite. Native metals (Pb, Zn, Ag, Cu, Bi, Se) are present as minute grains (10 to 30  $\mu\text{m}$ ).

295

### 296 **Fluid inclusion study**

297 Fluid inclusions (FIs) were studied in quartz and carbonate from the mineralised breccia as well  
298 as in most fracture quartz infillings in the Jbel Haïmer area. Fluid inclusions types are defined  
299 in Table 2. Table 3 provides microthermometric data and Table 4 Raman data.

### 300 *Pre-ore stage*

301 *Fluids in tourmaline:* primary FIs are two-phase and water dominated with traces of a low-  
302 density volatile, noted Lw-(c)-tur (Table 3). Their salinity is estimated around 24 – 26 wt%  
303 NaCl equiv. Th, to the liquid phase, ranges between 370 and 390°C. Secondary FIs in quartz  
304 from tourmalinised quartzite are two-phase water dominated FIs with traces of low-density  
305 volatile (Lw-(c)1), salinity ranging between 15.7 to 16.5 wt% NaCl equiv. and Th from 286°C  
306 to above 386°C to the liquid phase.

307 *Fluids in early quartz Q1 – biotite/chlorite 1 stage:* quartz Q1 in NW-SE veins and quartz  
308 fragments in breccia contain dense clouds of FIs (Fig. 8a) where true primary FIs cannot be  
309 easily distinguished. Two types of FIs distribute randomly in Q1 crystals: i) water dominated  
310 FIs with traces of volatiles (Lw1), which are abundant in FIs clouds, have a salinity ranging  
311 from 20 to 26 wt% NaCl+CaCl<sub>2</sub> equiv. and Th from 296° to over 357°C to the liquid, some of  
312 them decrepitating at temperatures above 350°C; ii) one-phase dense carbonic liquid inclusions,  
313 Lc1, found dispersed in Q1 show Tm CO<sub>2</sub> from –78.4 to –67.9°C, indicative of the presence of  
314 significant amounts of other volatiles. Th CO<sub>2</sub> to the liquid phase ranges from –70.2 to –13.7°C  
315 with a mode at –32°C (Table 3).

316 Lw2 aqueous FIs containing relatively high vapour infilling (up to 30%), with small amounts  
317 of gas (low density of the volatile phase), are abundant as regular networks of FIPs crosscutting

318 QI quartz crystals from veins and breccia. The average salinity ranges from 11.8 to 15.8 wt %  
319 NaCl equiv. and Th ranges from 261 to 317°C (Table 3).

320 *Fluids in quartz QII (NS to NE-SW white quartz veins):* scattered one-phase carbonic vapours  
321 (Vc2) and two-phase aqueous carbonic FIs (Lc-w2) coexist in the same QII microdomains (Fig.  
322 8b, 8c). In both FI types, Tm CO<sub>2</sub> ranges from -102.8 to -68.5°C and Th CO<sub>2</sub> from -71.6 to -  
323 60.5°C to the vapour phase (Table 3). The volatile phase is dominated by N<sub>2</sub> (60-70 mol%),  
324 (Table 4). Tm cl and Tm ice for Lc-w2 are respectively from -4.2 to 1°C and from -8.4 to -  
325 3.8°C. Th of Lc-w2 FIs are recorded over 460°C to the liquid phase, but most of the FIs  
326 decrepitate around 350°C. In QII veins, one-phase carbonic vapours (Vc2) and two-phase  
327 aqueous-carbonic inclusions (Lc-w2) coexist in the clear quartz microdomains surrounding  
328 pyrite. Vc2 show Tm CO<sub>2</sub> around -102°C and Th CO<sub>2</sub> around -97°C while Lc-w2 recorded  
329 Tm ice around -10 to -9°C, Tm cl from 6.2 to 9.1°C and Th from 414 to 453°C to the liquid.  
330 Raman spectroscopy analyses show that the volatile phase of Lc-w2 FIs in recrystallised QII is  
331 dominated by CH<sub>4</sub> (60-70% mol%), (Table 4).  
332 Vapour FIs showing roughly similar microthermometric characteristics to Vc2 (Tm CO<sub>2</sub> modes  
333 at -85°C and -65°C and Th CO<sub>2</sub> at -65 to -60°C to the vapour) are present as FIPs crosscutting  
334 QI. They are random FIs in recrystallised QI.

335 *Fluids in quartz from breccia and NW-SE QIII – chlorite 2 veinlets:* carbonic liquids (Lc3) (Fig.  
336 8d to 8h) are monophasic FIs scattered and pseudo-secondary in clear quartz QIII surrounding  
337 chlorite 2 crystals and in QIII from veins (Fig. 9). Lc3 form also sets of FIPs parallel to vein  
338 walls in QI (Fig. 8d and 8e) and crosscutting QII. Tm CO<sub>2</sub> ranges from -65 to -57.6°C, and Th  
339 CO<sub>2</sub> goes from -46.9 to 18.6°C to the liquid phase (Table 3). The Lc3 FIs pseudo-secondary in  
340 QIII (Fig. 8h) display a Tm CO<sub>2</sub> close to those of pure CO<sub>2</sub> (Tm of pure CO<sub>2</sub>: -56.6°C) and Th  
341 CO<sub>2</sub> close or above 0°C. CO<sub>2</sub> dominates Lc3 FIs (59 to 88 mol%), followed by N<sub>2</sub> (10 to 29  
342 mol%) with lower CH<sub>4</sub> content (2 to 14 mol%) (Table 4, Fig. 9).

343

344 *Cu-ore stage fluids*

345 Feathery quartz, calcite, and QIV are devoid of carbonic FIs and show exclusively aqueous FIs  
346 covering a broad range of salinities. The two major FI types are (Fig. 10, Table 3): i) high  
347 salinity FIs with a halite crystal and an unidentified clear solid (noted Lwh), and sometimes a  
348 few additional solids (Lws) and ii) moderate to low salinity FIs (Lw) (Fig. 10, Table 3).  
349 Chalcopyrite is present in the same quartz microdomains as Lwh brines as well as within Lw  
350 FI assemblages from clear quartz QIV microdomains.

351 Almost all of the aqueous FIs present relatively low eutectic temperatures ( $-65^{\circ}\text{C}$ ), likely  
352 corresponding to metastable eutectic of the  $\text{H}_2\text{O}-\text{NaCl}-\text{CaCl}_2$  system (Davis et al., 1990). These  
353 FIs are present as FIPs in early quartz (QI, QII, and QIII).

354 *High salinity brines:* Lws FIs have an irregular shape (Fig. 10a to 10c), and distribute in  
355 recrystallised microdomains of quartz QI-QII from veins and breccia, as well as irregular FIPs  
356 crosscutting QI, QII, and QIII (Fig. 8g). Salinity is around 38 - 39 wt%  $\text{NaCl}+\text{CaCl}_2$  equiv.  
357 Most Lws FIs decrepitate upon heating at temperature from  $230^{\circ}\text{C}$  with an average  
358 decrepitation temperature of  $300-330^{\circ}\text{C}$ . A few Th were recorded between  $174$  and  $252^{\circ}\text{C}$  to  
359 the liquid phase. The dissolution of solids occurs from  $90$  to  $360^{\circ}\text{C}$ , mostly at a temperature  
360 higher than Th.

361 Lwh FIs present regular shape and sometimes one unidentified rounded or rhombic-shape clear  
362 solid in addition to the halite cube (Fig. 10d and 10g), and occasionally a small opaque solid.

363 Lwh FIs are scattered in QIV and form abundant FIPs crosscutting QI, QII, and QIII veins and  
364 previous volatile-rich FIPs (Fig. 10e). Besides, Lws and Lwh FIs are sometimes present in the  
365 same recrystallised early quartz microdomains where Lwh FIPs often crosscut Lws FIPs.  
366 Salinity ranges from 31.3 to 37.3 wt%  $\text{NaCl}+\text{CaCl}_2$  equiv. (average 34 wt%  $\text{NaCl}+\text{CaCl}_2$   
367 equiv.). Th ranges from  $179$  to  $264^{\circ}\text{C}$  (mode around  $220^{\circ}\text{C}$ ), and halite cube melts at



368 temperatures ranging from 155 to 262°C, the second solid remaining unmelted. Some FIs have  
369 decrepitated around 270°C. For most Lwh FIs,  $T_m$  NaCl and  $T_h$  occur roughly in the same  
370 average domain between 220 and 230°C.

371 Lw FIs in feathery quartz and calcite show  $T_m$  ice from -32 (primary in calcite) to -20°C  
372 (secondary in feathery quartz and calcite) and  $T_h$  from 186 to 242°C. Salinity ranges from 22.4  
373 wt% to > 30 wt% NaCl equiv.

374 *High to low salinity fluids:* several types of two-phase aqueous FIs (Lw), sometimes with an  
375 unidentified clear solid and sporadically an opaque solid, form regular networks of FIPs in QI,  
376 QII, QIII and QIV (Fig. 10g and 10h). Most aqueous FIs show a regular shape and have a  
377 vapour infilling around 10%.  $T_m$  ice range from -29.6 to -7.1°C,  $T_m$  hh range between -11.9  
378 and -6.5°C and  $T_h$  range from 139 to 249°C with several modes corresponding to different  
379 FIPs. Salinities range from 10.6 to 28 wt% NaCl+CaCl<sub>2</sub> equiv. Clear solids do not melt until  
380 temperatures over 330°C. FIs in planes crosscutting QIV crystals show salinities from 9 to 15.3  
381 wt% NaCl equiv. and  $T_h$  from 156 to 242°C. Scarce FIs, scattered in the recrystallised quartz  
382 around chalcopyrite (Fig. 10f), have a salinity around 23 wt% NaCl equiv. and  $T_h$  around 150-  
383 160°C.

384 A general trend corresponds to a decrease in salinity at constant or slightly decreasing  $T_h$  from  
385 the Lws brine to Lw FIs (Fig. 11). The salinity evolution is in agreement with chronological  
386 relationships between aqueous fluid inclusion types that start with Lws, crosscut by Lwh FIPs,  
387 and both of them being crosscut by several Lw FIPs that show a gradual decrease in salinity.  
388 The latest Lw FIs that crosscut quartz QIV present the lowest salinities (Fig. 11). Chalcopyrite  
389 deposition occurred when mixing occurred, e.g. when fluids were characterised by intermediate  
390 features between the two end-members of this general trend (i.e., Lws and Lw FIPs in QIV).

391 *Major elements and metal content of the brine inclusions:* LA-ICP-MS data for Lws and Lwh  
392 brines are given in Table 5 and Fig. 12. Lw fluid inclusions were too small to be analysed.

393 Lws brines (FIPs in QI, QII and QIII) show relatively high Na content (average 2735 mmol/kg),  
394 Ca, and K, (average around 941 mmol/kg, and 397 mol/kg respectively) but low Mg content (73  
395 mmol/kg) (Table 5, Table 6). Average molar Na/Ca, Na/K, and Na/Mg ratios are 2.9, 6.9, and  
396 37.7, respectively. Lws FIs display Pb and Zn contents of 72.2 mmol/kg and 159.1 mmol/kg  
397 respectively on average and a Cu content of 19.1 mmol/kg. Ag concentration is around 0.2  
398 mmol/kg (Table 5, Table 6).

399 Lwh FIs (quartz QIV): in Lwh FIs, Na is also the dominant cation (average around 1532  
400 mmol/kg), but they are rich in Ca (1174 mmol/kg), K and Mg (580 mmol/kg and 501 mmol/kg,  
401 respectively) (Table 5, Table 6). The average molar ratios are around 1.3 for Na/Ca, 2.6 for  
402 Na/K and 3.1 for Na/Mg. High amounts of Pb, Zn and especially Cu are present in Lwh brines  
403 (average: 28.8 mmol/kg, 136.8 mmol/kg and 43.9 mmol/kg respectively) as well as Ag  
404 (average: 5.3 mmol/kg) (Table 5, Table 6). In Lwh brines, Cu and Pb concentrations are  
405 correlated with Na. Fe is detected at high concentrations, and is certainly present. Fe  
406 contributions were however not considered in the calculations because of probable  
407 contaminations by solids yielding unrealistic contents.

408 From Lws to Lwh brines, K, Ca, Mg, Cu, As and Ag concentrations increase, together with a  
409 decrease in Na, Zn, Pb, Ba, Rb, and Sr concentrations (Fig. 12, 13). Similar positive correlations  
410 are obtained for Sr–Ba, and As–Cu. By comparison, brines from Jbel Haïmer contain higher  
411 Zn, Cu, Pb and Ag contents than those from the Roc Blanc deposit (Essarraj et al., 2017a),  
412 (Table 6 and Fig. 13). The high chlorinity, the richness in K, Ca and Mg are typical of evaporitic  
413 brines as discussed below (Fig. 14).

414

## 415 **Discussion**

### 416 *Pre-ore stage fluids in the regional metamorphic context*

417 *Early tourmaline-biotite-Sn assemblage:* Tourmaline formed first from hot brines (around 25

418 wt% NaCl equiv.,  $T > 380^{\circ}\text{C}$ ) related to granitoid intrusions, which produced hornfels in the  
419 contact metamorphic aureole where tourmaline-rich pegmatite veins and lenses are abundant.

420 C-H-O-N fluids: NW-SE-striking fractures with quartz QI (biotite) infillings followed by NE-  
421 SW fractures with quartz QII, formed from  $\text{N}_2\text{-CH}_4\text{-(CO}_2\text{-H}_2\text{O)}$  fluids at a temperature ranging  
422 from  $450$  to  $500^{\circ}\text{C}$ . Brecciation occurred in the competent NE-SW sandy schist and sandstone-  
423 quartzite layers later than QI, QII veins and is synchronous with new NW-SE fractures likely  
424 conjugated with NE-SW fractures. Large circulation of  $\text{CO}_2\text{-(H}_2\text{O)}$  dominated fluid produced  
425 the cementation of the breccia and newly formed NW-SE fractures filled with quartz QIII and  
426 chlorite 2.

427 An evolution in the volatile phase composition (Fig. 9) occurred from  $\text{N}_2\text{-CH}_4$  ( $\pm \text{H}_2\text{O}$ ) rich  
428 fluid associated with early quartz (QI, QII) towards  $\text{CH}_4\text{-CO}_2$  ( $\pm \text{H}_2\text{O}$ ) rich fluid associated with  
429 pyrite deposition. Finally,  $\text{CO}_2$ -rich fluid associated with chlorite 2 deposition ends the volatile-  
430 rich fluid series. Aqueous-carbonic fluids ( $\text{N}_2\text{-CH}_4\text{-(CO}_2 \pm \text{H}_2\text{O)}$ ) from Jbel Haïmer are very  
431 similar to those observed in the Roc Blanc and Koudia El Hamra silver-(base metal) deposits  
432 (Essarraïj et al., 2017a; Nshimiyimana et al., 2018, respectively) (Fig. 9). Bastoul (1992)  
433 documented fluids with similar volatile composition in skarns located a few kilometres North  
434 of Jbel Haïmer (Fig. 9). Most volatile-rich fluids were produced during the HT-LP M2a stage  
435 under regional metamorphism conditions ( $500\text{-}650^{\circ}\text{C}$  and  $200 \text{ MPa} \pm 20 \text{ MPa}$ ) (Bastoul, 1992;  
436 Delchini et al., 2018). The production of  $\text{H}_2\text{O-CO}_2\text{-CH}_4$  rich fluids in this P-T range results  
437 typically from water and graphite equilibrium under reduced conditions close to Q-F-M buffer  
438 which constitutes a rather good proxy of the redox conditions in metamorphic series (Huizenga,  
439 2001; Huff and Nabelek, 2007). Additional local sources are needed to explain the mixing  
440 trends among volatiles: i) a mixing trend between  $\text{N}_2$  rich fluids and  $\text{CH}_4$  rich fluids, and ii) a  
441 mixing trend between a  $\text{CO}_2$  rich fluid end-member and the  $\text{N}_2\text{-CH}_4$  mixed fluids. Bastoul  
442 (1992) found the same trends and attributed the formation of  $\text{N}_2$  to the oxidation of  $\text{NH}_4^+$  from

443 micas as also documented by Wright et al. (2012). Both authors have reported the occurrence  
444 of ammonium-rich phyllosilicates in metamorphic series and the related production of N<sub>2</sub>  
445 during their heating. N<sub>2</sub>-CH<sub>4</sub> rich fluids are thus produced in graphite-rich series submitted to  
446 contact or retrograde metamorphism with highly variable N<sub>2</sub>/CH<sub>4</sub> ratio and are in general very  
447 poor in water.

448 *High thermal gradients:* High temperatures recorded by early metamorphic fluids at Jbel  
449 Haïmer (Th > 450°C, this study) are in agreement with several temperature estimates: i) those  
450 proposed for the Central Jebilet (Bastoul, 1992), and ii) the temperatures derived from the  
451 graphite Raman thermometry (based on the structural organisation of the carbonaceous material  
452 to graphite) applied to hornfels (475 to 630°C, Delchini et al., 2016). Isotope data (O, H) of N<sub>2</sub>-  
453 CH<sub>4</sub>-CO<sub>2</sub> ± H<sub>2</sub>O fluids either at the Roc Blanc deposit (δ<sup>18</sup>O of waters in equilibrium with early  
454 quartz: 12.6 - 14.0‰ v-SMOW; δD: -43.2 to -37.1‰ v-SMOW, Essarraj et al., 2017a) or the Kettara  
455 deposit (δ<sup>18</sup>O of waters in equilibrium with chlorite: 6.0 to 7.2‰ v-SMOW; δD: -14.5 to -10.5‰,  
456 N'Diaye et al., 2016), compared to the composition of metamorphic waters from Sheppard  
457 (1986) confirm their metamorphic origin. Whatever their pristine source, a significant part of  
458 the described waters deeply equilibrated with metamorphic series, in particular with graphite  
459 producing H<sub>2</sub>O-CO<sub>2</sub>-CH<sub>4</sub> fluids. Early metal extraction and transport (Fe, Sn, As, Bi, Co, Ni)  
460 at Jbel Haïmer were probably favoured at that stage by aqueous-carbonic fluids set in motion  
461 in close connection with the HT-LP thermal metamorphism (M2a) and the late granites  
462 intruding the Sarhlef series (M2b). Aqueous-carbonic fluids play a significant role in metal  
463 transport and deposit in a great variety of Variscan deposits (Wilkinson et al., 1990; Cathelineau  
464 et al., 2020). N<sub>2</sub>-rich fluids may be the main ore fluids in scheelite deposits (Wang et al., 2018)  
465 and CH<sub>4</sub>-rich fluids in C-rich formations close to Au-As deposits (Guedes et al., 2002; Boiron  
466 et al., 2003).

467 *P-T evolution*: the pressure and temperature of trapping were estimated using isochores for most  
468 fluid types (Fig. 15A). The earliest fluids, Lw-(c)-tur FIs in tourmaline, were trapped at  
469 conditions close or slightly below those estimated for the thermal metamorphism (M2a). A  
470 significant temperature increase of approximately 250-300°C was therefore reached from  
471 regional metamorphic conditions, leading to thermal gradients of around 70°C/km (P-T box  
472 from Bastoul, 1992, Fig. 15A). Their isochores crosscut the P-T box for the HT-LP  
473 metamorphic conditions, which constitutes the maximal estimate. Isochores for the earliest FIs  
474 in quartz QI (Lw1) are subparallel to those of tourmaline FIs, while Lc1 isochores define a  
475 broad pressure range in between 70 and 150 MPa. Both fluids are considered as sub-  
476 synchronous. The intersection of their isochores provides an estimated pressure range of 70 to  
477 150 MPa, and temperatures ranging from 360 to 460°C. For the second stage of quartz QII,  
478 consideration of the assemblage Lc-w2 and Vc2 yield to the following P-T estimate: 70-110  
479 MPa, 450-520°C. The values are close to those of unmixing defined by the isopleths in the H<sub>2</sub>O-  
480 CO<sub>2</sub>-NaCl system for two different CO<sub>2</sub> contents. Such a process can explain the presence of  
481 Vc2 fluids. The third stage QIII is characterised by carbonic liquids that do not provide strong  
482 constraints on their trapping P-T box except the temperature estimate for the chlorite (300-  
483 350°C), which are similar to those of the Roc Blanc deposit. Carbonic liquids are thus trapped  
484 under higher pressure than in the preceding stage, in between 120 and 170 MPa.

485 The evolution of fluids from the tourmaline stage to QI and QII suggests a significant pressure  
486 decrease from lithostatic conditions towards hydrostatic conditions, in agreement with the  
487 pressure release expected after the breccia formation. During stage QIII, pressure increased  
488 again up to values close to those of the lithostatic regime. In both cases, the P-T box is  
489 intersected by a thermal gradient of around 60 and 70°C/km indicative of high thermal gradients  
490 in agreement with the thermal metamorphism and late intrusions of magmatic bodies defined  
491 by Delchini et al. (2018).

492 Most fluids from the early stages are therefore related to both abnormal thermal fluxes linked  
493 to HT-LP metamorphism and late granite magmatism during deformation stage D2. The  
494 presence of drainage zone, such as the MSZ and the Aït Bella OuSaïd shear zone, favoured  
495 collect and mixing of the different types of volatile-rich fluids generated during the thermal  
496 event (Fig. 16A). Fluids under lithostatic pressure may have produced brecciation and  
497 subsequent fluid decompression and precipitation of quartz QIII.

498

#### 499 *Cu brine circulation during post Variscan events in the Jebilet massif*

500 *P-T conditions:* the intersection between the isochores calculated for the three FI types (Lws,  
501 Lwh, and Lw), and the thermal gradients expected in basins during extensional stages linked to  
502 rifting (see discussion below), provides an estimate P-T pair of 40-50 MPa and 220-280°C (Fig.  
503 15B). Considering hydrostatic conditions and abnormal thermal gradient of 40°C/km and  
504 50°C/km during this particular period, pressures correspond to a depth of around 4 to 5 km.  
505 Such a depth comprises the thickness of the Mesozoic series in the Jebilet (up to 2.4 km), and  
506 therefore yield to an estimate of the depth below the unconformity of 1.6 to 2.6 km.

507 *Triassic formations as brine source:* The Jbel Häïmer brines are characterised by high salinities  
508 from 31 to 37 wt% NaCl+CaCl<sub>2</sub> equiv. (average 34 wt% NaCl+CaCl<sub>2</sub> equiv.), are trapped  
509 around 220-280°C, and are enriched in K, Mg and Ca. They are similar to those of the Roc  
510 Blanc Ag-deposit (20 wt% to 35 wt% NaCl equiv., trapping temperature around 200°C and  
511 pressure of 50 MPa, Essarraï et al., 2017a) and the Koudia El Hamra Ag-deposit (Nshimiyimana  
512 et al., 2018).

513 The major element contents of the two brines Lwh and Lws were compared to those of seawater  
514 and evaporated seawater after the halite saturation. The high chlorinity, the richness in K (and  
515 Mg) are typical of brines having passed halite saturation (Fontes and Matray, 1993) (Fig. 14).  
516 They are similar to those described for evaporitic brines found either in a variety of sedimentary

517 basins or in basement faults (Poitou high (France): Boiron et al., 2002; Black Forest (Germany):  
518 Walter et al., 2019; Catalan coastal range (NE Spain): Piqué et al., 2018). The calcium  
519 enrichment, common to fluids from all sites, is generally interpreted as the result of water-rock  
520 interactions such as albitisation (Black Forest, Walter et al., 2016), and the relatively broad  
521 range of Mg contents as the result of Mg uptake by the crystallisation of dolomite in the  
522 sedimentary cover, and talc or other Mg silicates in the basement (Trimouns (Pyrénées, France):  
523 Leisen et al., 2012b).

524 Evaporites within the sedimentary clastic sequences, up to 8 km thick, from Atlasic basins,  
525 constitute good candidates for the source of brines. These subsident basins formed in relation  
526 with the Early Triassic to Early Jurassic extension stages (Studer, 1987; Warme, 1988), and  
527 constituted the High Atlas Belt. In the Central Jebilet, Triassic evaporite series outcrop a few  
528 kilometres South-East of Jbel Haïmer (Fig. 2a), and layers with sufficient thickness to be mined,  
529 about 100 km West of Jbel Haïmer in the Western Jebilet. The basement, now stripped of its  
530 Mesozoic cover as a result of erosion, was most probably continuously covered by Triassic  
531 evaporites during the Mesozoic.

532 *Metal concentrations in brines:* brines have high concentrations in Cu, Pb, Zn, (and Ag for  
533 Lwh) which were probably extracted from basement rocks (Fig. 16B). Among other potential  
534 source rocks present in the region, the black shales may release Ag, As, basic intrusions and  
535 some VMS lenses, Cu and Zn. These lithologies (metal sources) occur as weathered rocks just  
536 below the Triassic formations (brine source). Regoliths are generally considered as reserves of  
537 easily extractible metals by brines coming from upper levels (Boiron et al., 2010; Cathelineau  
538 and Boiron, 2019). Base metal contents in brines (Cu, Pb, Zn) are higher at Jbel Haïmer than at  
539 Roc Blanc (Table 6). Brines transported, therefore, specific metal contents depending on the  
540 deposit.

541 *Mechanisms of Cu-ore deposition:* metals might have been transported as chloride complexes  
542 owing to the high salinity of brines and the high Cu, Zn, and Pb of the Lwh brine (Yardley,  
543 2005; Wilkinson et al., 2009). Thus, at temperatures below 300°C, chloride complexes are the  
544 predominant Cu, Pb, and Zn species, whereas hydrosulphides predominate at a higher  
545 temperature (> 400°C) in sulphide-saturated systems (Zhong et al., 2015).

546 Tm ice - Th pairs distribute between two end-members, the Lws and Lwh brines on the one  
547 hand, and a low salinity water end-member (Lw) on the other hand (Fig. 11). This trend  
548 corresponds to mixing between brine and a low-salinity fluid. The mixing is synchronous with  
549 the chalcopyrite deposition. The chlorinity decrease due to mixing may have destabilised metal  
550 (Zn, Cu, Pb) chloride complexes, and caused metal deposition (Wilkinson, 2001; Heijlen et al.,  
551 2003; Boiron et al., 2002, 2010; Neiva et al., 2015; Richard et al., 2016).

552 Moreover, Walter et al. (2019) emphasise on the example of the Schwarzwald district (SW  
553 Germany) that base metal (sulphide) ores form only if fluid mixing and sulfate reduction occur  
554 at the same time, TSR being the main process reducing sulfates from Triassic evaporites to  
555 produce H<sub>2</sub>S. For those authors, a reducing agent (methane, for instance, or graphite in close  
556 host rocks) is required to precipitate ores. For example, Heijlen et al. (2008) noticed that the  
557 distribution of organic material determines the location of mineralisation in some parts of the  
558 Central African copper belt (DR Congo). At Jbel Haïmer, as at several studied areas in the  
559 Central Jebilet, graphite is abundant, and gas (CH<sub>4</sub>, CO<sub>2</sub>) storage in schist microporosity was  
560 documented (Bastoul, 1992). Thus, fluid mixing and reduction are the main factors controlling  
561 metal deposit at Jbel Haïmer. Likewise, Essarraïj et al. (2017a) and Nshimiyimana et al. (2018)  
562 evoked a fluid reduction in graphite-rich black shale as a deposition mechanism for base metal  
563 and silver mineralisation at the Roc Blanc and Koudia El Hamra deposits, respectively.

564 *Relative age of Cu-ore deposition:* As Cu mineralisation at Jbel Haïmer occurs after the  
565 intrusion and deformation of the microdiorite dikes dated at 240 ± 10 Ma (Bouloton et al.,



566 2019), Triassic brine circulation during Mesozoic is, therefore, the most likely hypothesis. The  
567 thermal and tectonic stages related to the Central Atlantic Rifting are the main periods already  
568 proposed in a variety of other deposits for such brine migration (Jbel Ighoud barite deposit,  
569 Eastern Jebilet: Valenza et al., 2000; Roc Blanc Ag deposit: Essarraj et al., 2017a; Koudia El  
570 Hamra Ag deposit: Nshimiyimana et al., 2018). Furthermore, large basaltic flows, coeval with  
571 the Central Atlantic Ocean opening are reported in the region (Frizon de Lamotte et al., 2008,  
572 2009). They are witnesses of abnormal thermal gradients recorded in the Western Meseta  
573 between 250 and 210 Ma (Ghorbal et al., 2008; Saddiqi et al., 2009; Barbero et al., 2011), and  
574 around  $195 \pm 4$  Ma (Huon et al., 1993).

575 At Jbel Haïmer, tectonic traps consist of clusters of reactivated and re-opened Variscan (N-S to  
576 NE-SW and NW-SE) discontinuities during post-Variscan events. The nearby presence of the  
577 MSZ and the Aït Bella OuSaïd shear zone may constitute drainage zones for brines (Fig. 2a and  
578 16B), as they are reactivated during the Central Atlantic rifting (Laville and Piqué, 1991; Piqué  
579 and Laville, 1993, 1996).

580 *Similar ore deposition processes in Morocco:* Early fluid stages synchronous with the  
581 Panafrican magmatism and metamorphism, followed by later migration of evaporitic brines  
582 during the Mesozoic are typical of most Anti-Atlas deposits: Zgounder (Ag-Hg), Bou Azzer  
583 (Co-Ni-Ag-Au), and Imiter (Ag-Hg) deposits (Essarraj et al., 1998, 2005, 2016, 2017b).  
584 Similarly, fluid flows induced by extensional tectonics, contemporary with the first stages of  
585 the Atlantic Ocean opening, are proposed for the Assif El Mal deposit, High Moulouya district  
586 and Tirhza-Jbel Aouam district (base metal – polymetallic, Morocco) (Bouabdellah et al., 2009;  
587 Margoum et al., 2015; Rossi et al., 2016 respectively).

588

589 **Conclusion**

590 This study concludes a general framework of fluid circulations and mineral deposition at the  
591 Jbel Haïmer area summarised as follows:

- 592 - The first stage is related to fluid convection induced by Late Variscan magmatism.  
593 High-temperature fluids having a typical metamorphic signature (C-O-N-H) deposited  
594 minor concentrations of Sn-As-(Co-Ni) in quartz veins.
- 595 - The second stage occurs much later and is independent of the first stage. It is  
596 characterised by the introduction of metals (Cu – (Zn – Pb), Ag) in the system by  
597 primary evaporitic brines characterised by their salinity and enrichment in K, Mg. The  
598 likely origin of the brines is the Triassic evaporitic levels deposited above the basement  
599 unconformity. The high metal concentrations in fluid inclusions are considered as an  
600 excellent pathfinder of exploration targets. The high chlorinity of the brines favoured  
601 the extraction of metals from basement rocks, especially those affected by weathering  
602 (regolith) located just below the unconformity and Triassic formations.
- 603 - Cu-ores deposited at medium temperatures (220-280°C) corresponding to a burial of  
604 around 4-5 km. The main driving force for Cu-deposition is the dilution of ore-forming  
605 brines by low salinity fluids, probably of meteoric origin.
- 606 - Tectonic traps are issued in part from Variscan deformation which developed damaged  
607 zone along shear zones. Mesozoïc extensional tectonics reactivated inherited shear  
608 zones during post-240 Ma events. Although the absolute age of the Cu-ore stage is not  
609 available, it is likely related to the Atlantic Ocean rifting stages. The latter favoured the  
610 downward migration of Triassic brines into the basement. Such processes are very  
611 similar to those proposed for the Anti-Atlas, High Atlas and Meseta silver and base  
612 metal deposits.

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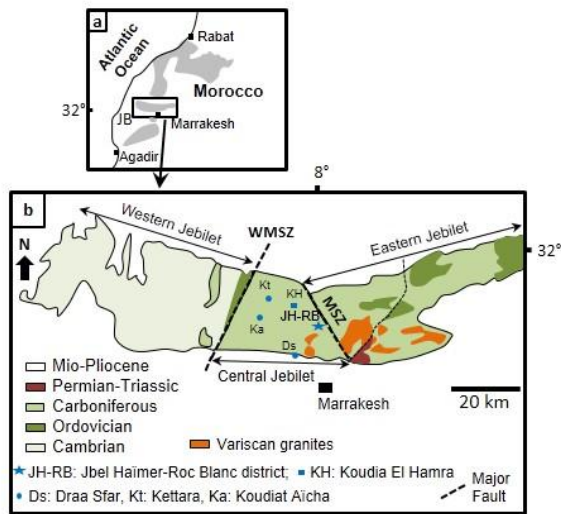
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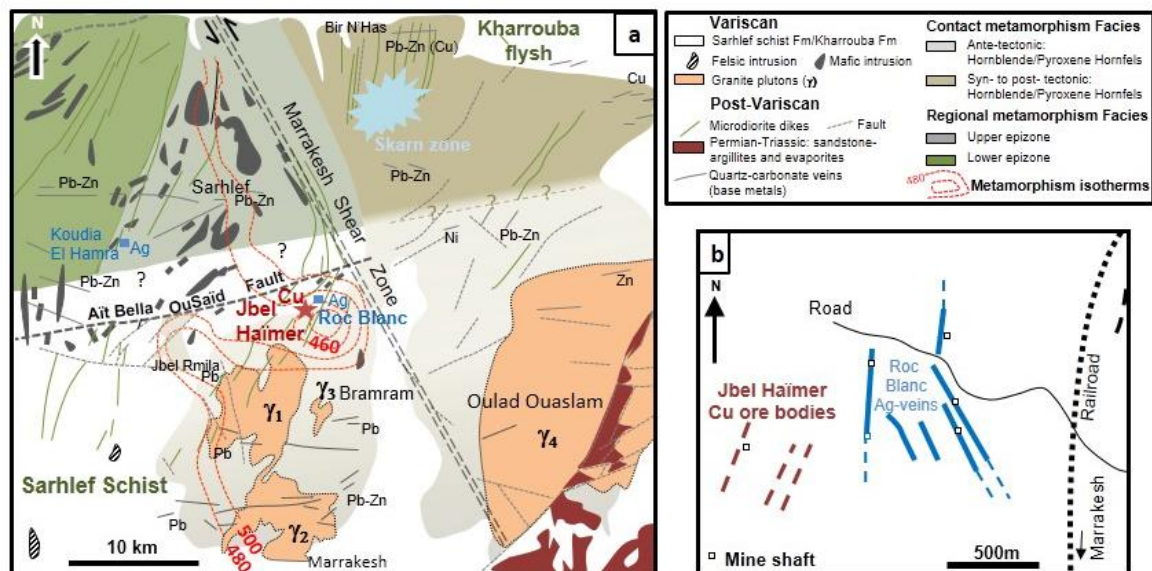


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935 **Fig. 1. a** Location of the Variscan massifs in Morocco (in grey: central-meridional domain), JB:  
 936 Jebilet. **b** Geology of the Jebilet massif (Huvelin, 1977; in Bernard et al., 1988), and location  
 937 of the main deposits: the Jbel Haïmer and Roc Blanc (Ag) district, the Koudia El Hamra Ag  
 938 deposit, and the main volcanogenic massive sulphide deposits (VMS pyrrhotite-polymetallic  
 939 lenses): Draa Sfar, Koudiat Aicha and Kettara, from Huvelin (1977). (MSZ: Marrakesh Shear  
 940 Zone; WMSZ: West Moroccan Shear Zone, see text for references).

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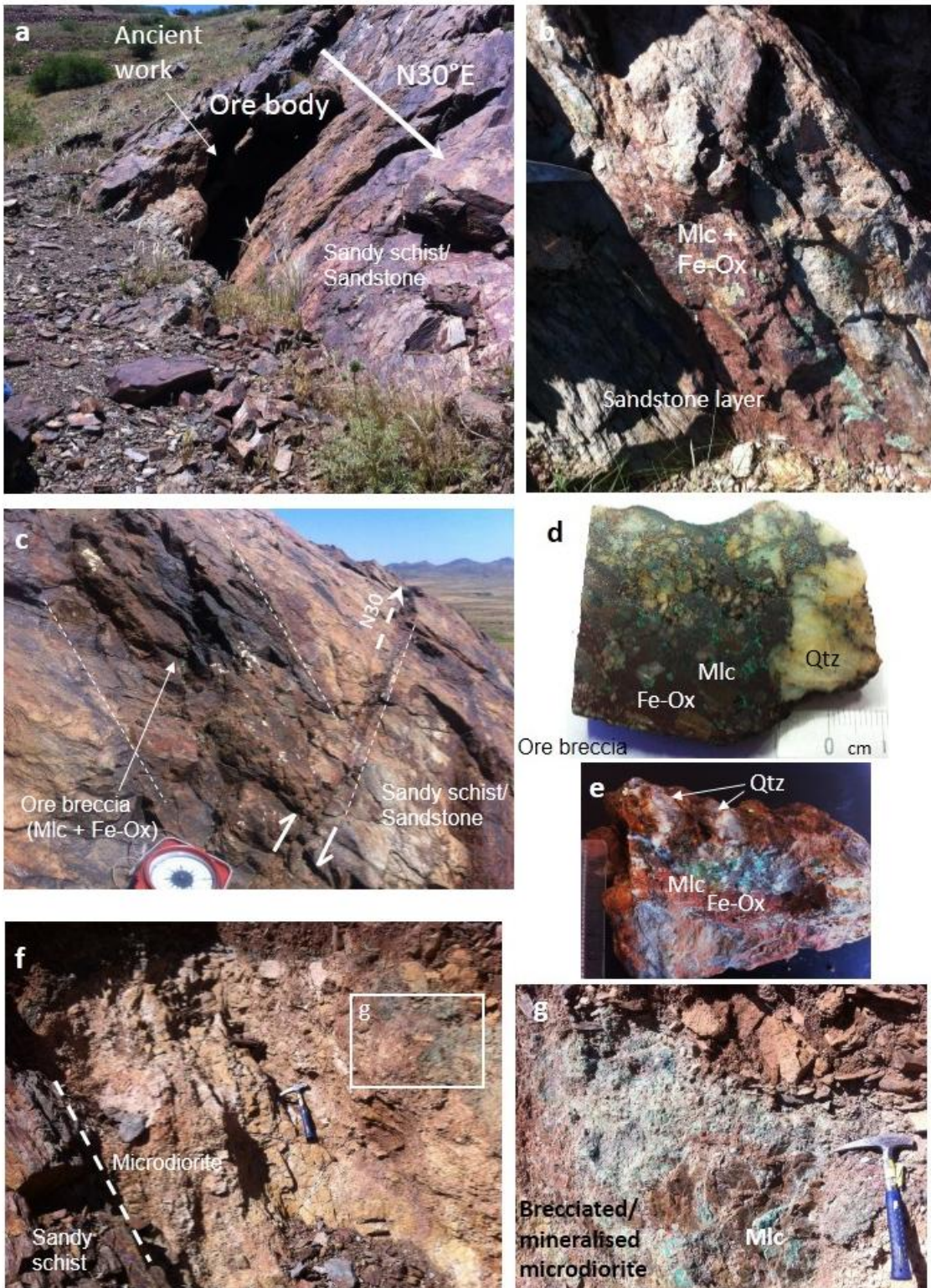
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945 **Fig. 2. a** Location of base metal and silver ore veins (deposits and occurrences) with the  
 946 indication of major faults in the Central Jebilet around Jbel Haïmer and Western part of the

947 Eastern Jebilet (from Huvelin, 1972); only kilometre size faults are represented.  $\gamma$ : granites 1,  
948 2, 3 and 4: Tabouchennt, Bamega, Bramram and Oulad Ouaslam respectively. The Jbel Haïmer–  
949 Roc Blanc district is detailed in b. Metamorphism facies and isotherms of thermal  
950 metamorphism M2 are reported from Delchini et al. (2018) and Delchini (2018); skarn zone:  
951 from Huvelin (1977), studied by Bastoul, (1992). **b** Schematic map of the mining works of the  
952 Jbel Haïmer (main ore bodies) and Roc Blanc Ag- ore bodies (From Huvelin 1977).

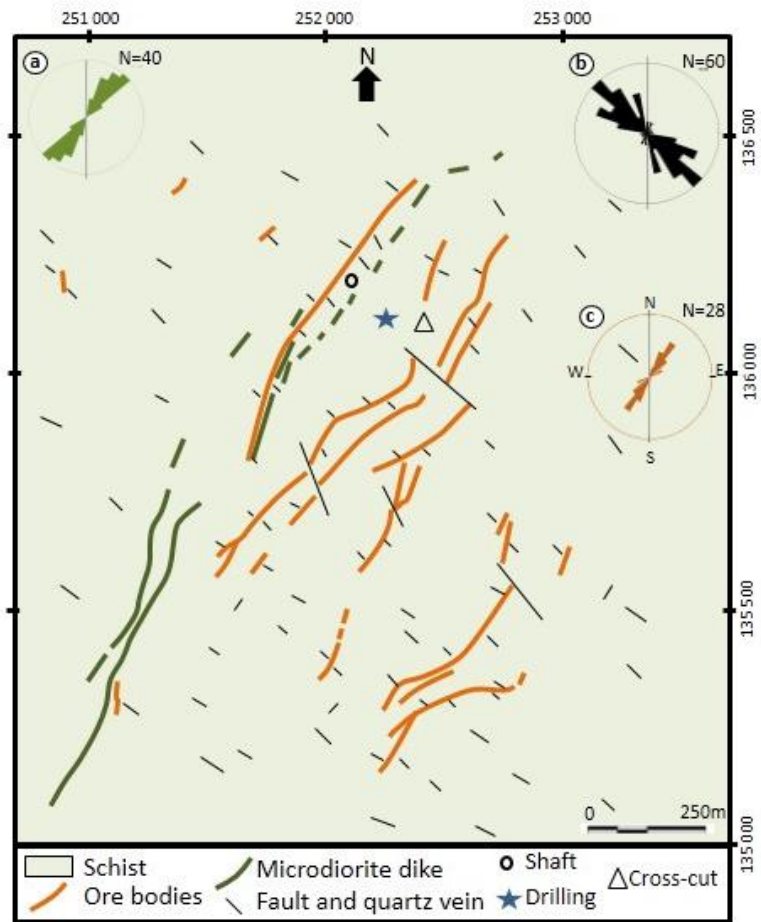




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954 **Fig. 3. a, b, c, f, g** Field exposures of the Jbel Haïmer area showing gossan: oxidised ores  
 955 (malachite (Mlc) and Fe-oxides (Fe-Ox) sandy schist/sandstone and brecciated/alterned  
 956 microdiorite dike. **d** and **e**: hand specimens showing ore breccia with quartz (Qtz) fragments  
 957 impregnated with malachite and Fe-oxides





958

959 **Fig. 4.** Representation of fractures, main ore bodies, and microdiorite dikes subparallel to local  
 960 schistosity (S1) in the Jbel Haïmer area. **a**, **b**, **c** rose-diagrams corresponding respectively to  
 961 schistosity, fractures, and veins, and ore bodies (Boutira and Hakkou, 2012; in Essarraj et al.,  
 962 2013), N: number of measurements.



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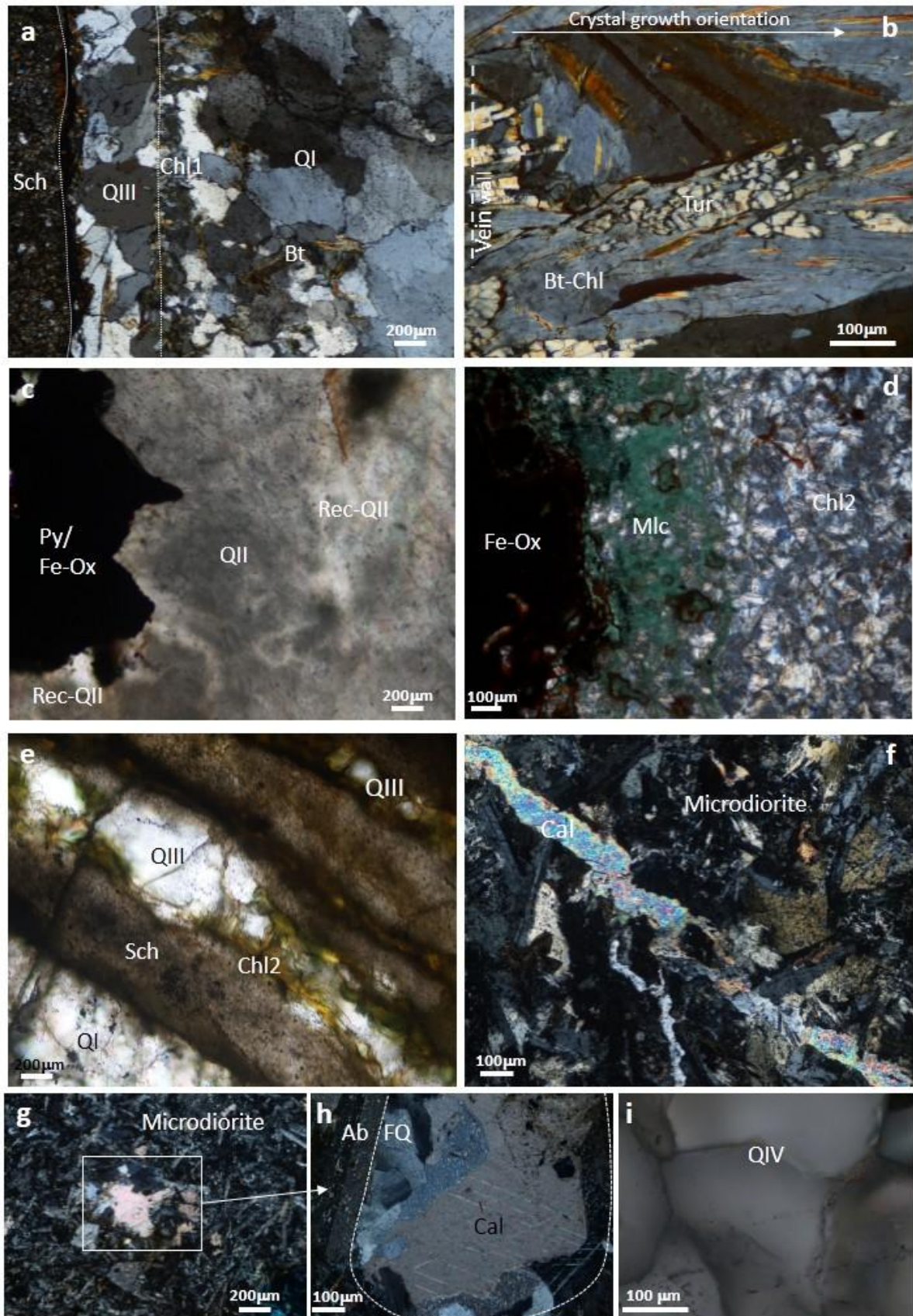
964 **Fig. 5. a, b, c, d** Relationships between schistosity, fractures and veins crosscutting sandy schist

965 and sandstone layers; QI and QII: early quartz (see text for description). **e** fractures in

966 microdiorite, **f** Calcite veinlet crosscutting microdiorite, **g** Feathery quartz veinlets crosscutting

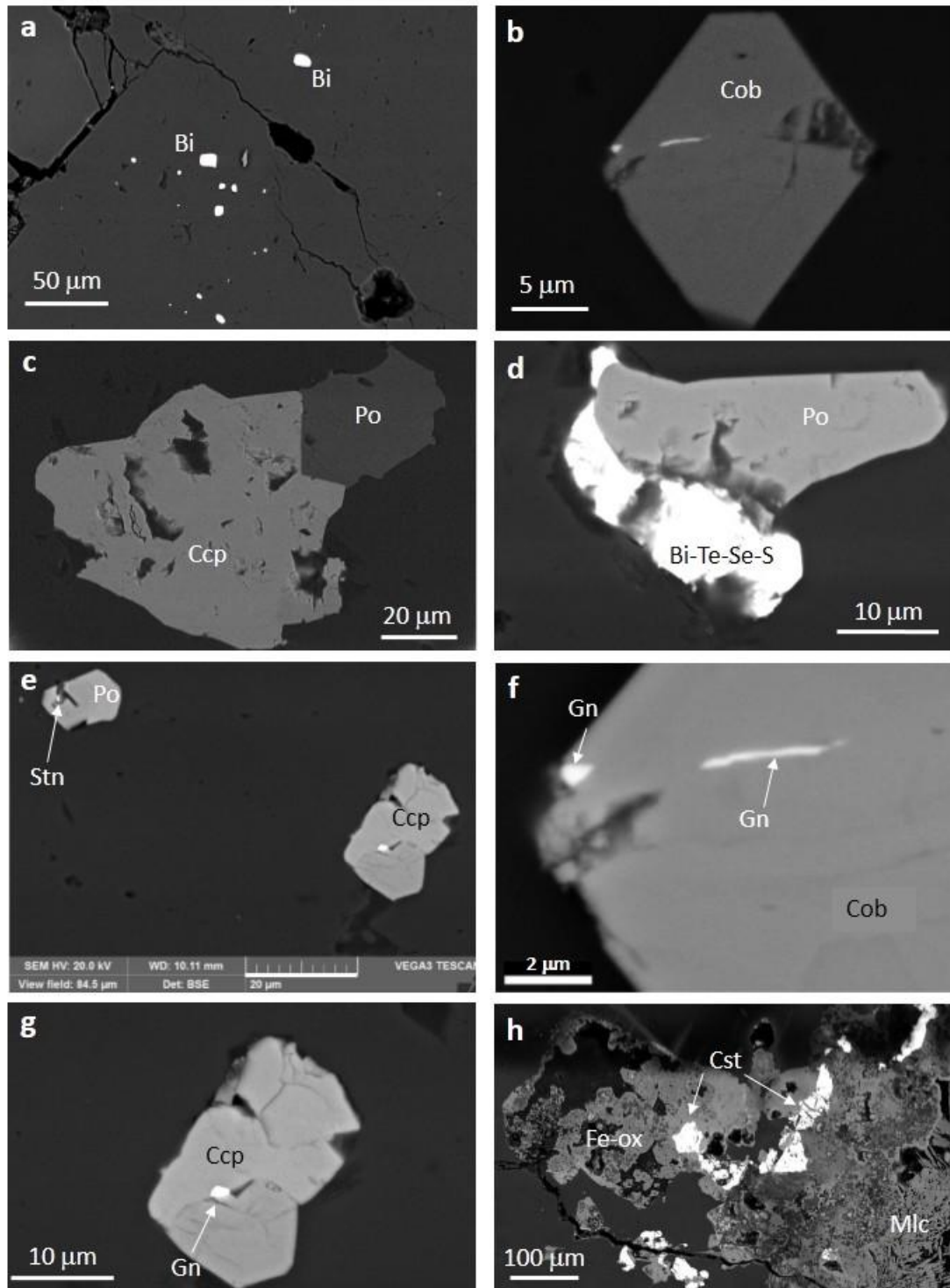
967 microdiorite.





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 969 **Fig. 6.** Mineralogy of Jbel Haïmer. **a** NW-SE vein with deformed and cloudy quartz (QI) and  
 970 chloritised biotite (Chl1)-(Bt), crosscutting schist (Sch), and newly formed quartz veinlet with

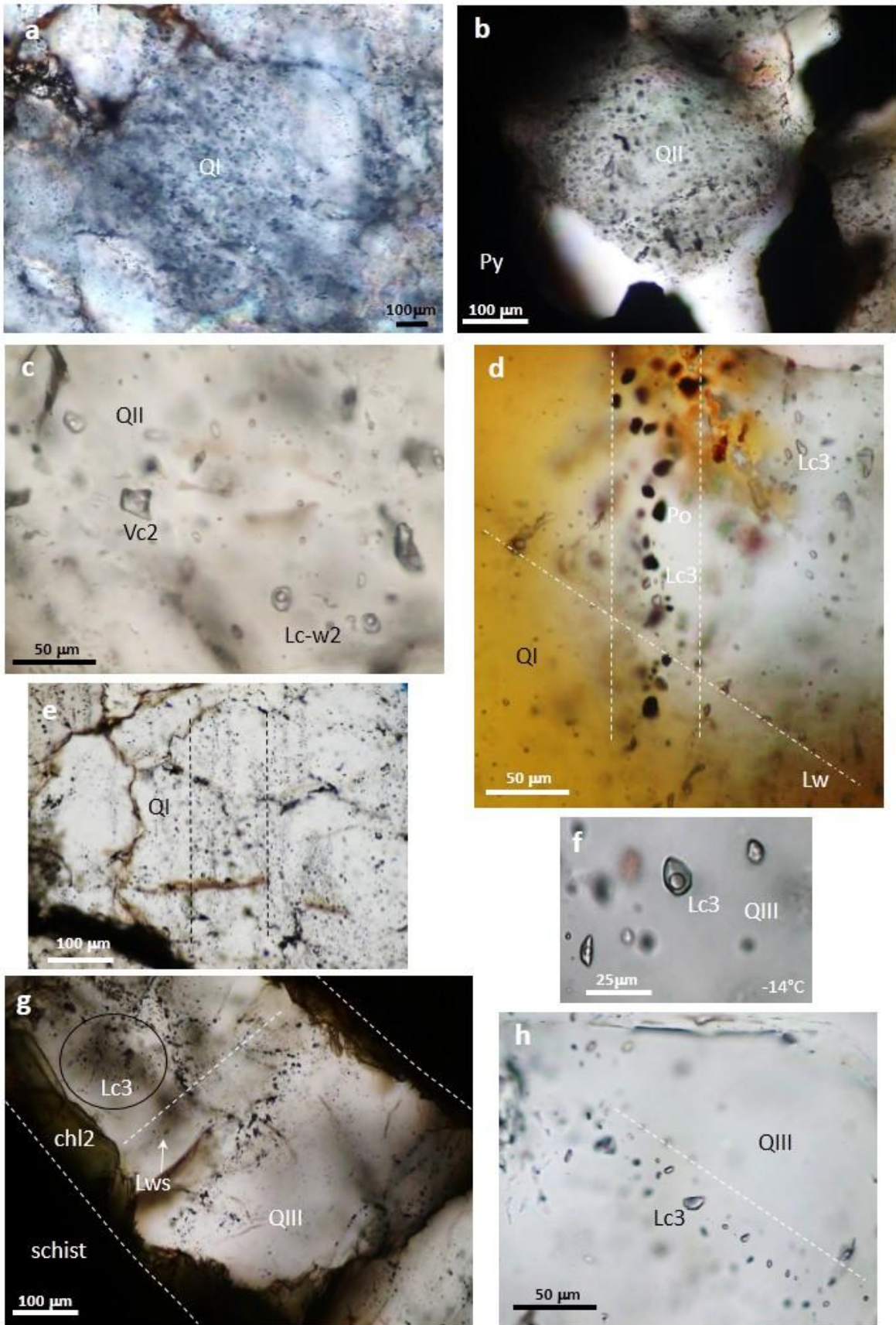
971 undeformed quartz (QIII). **b** chloritised biotite (Bt-Chl) and brecciated tourmaline crystals (Tur)  
972 perpendicular to the QI vein wall. **c** Cloudy QII quartz with strongly oxidised pyrite (Py/Fe-  
973 Ox) in the core of QII vein, Rec-QII: recrystallisation microdomains in QII around pyrite. **d**  
974 Malachite (Mlc), Fe-oxides (Fe-Ox), and chlorite 2 (Chl2) invading the QI vein core. **e**  
975 Undeformed QIII-chlorite 2 (Chl2) veinlet parallel to QI (deformed) vein, both crosscutting  
976 schist (Sch). **f** calcite veinlet crosscutting microdiorite. **g** Micro-vacuole in microdiorite filled  
977 with late minerals (detail in H). **h** Undeformed feathery quartz (FQ), then calcite (Cal) filling a  
978 vacuole in microdiorite, Ab: albite from microdiorite. **i** Late geodic quartz QIV poor in fluid  
979 inclusions and FIP.



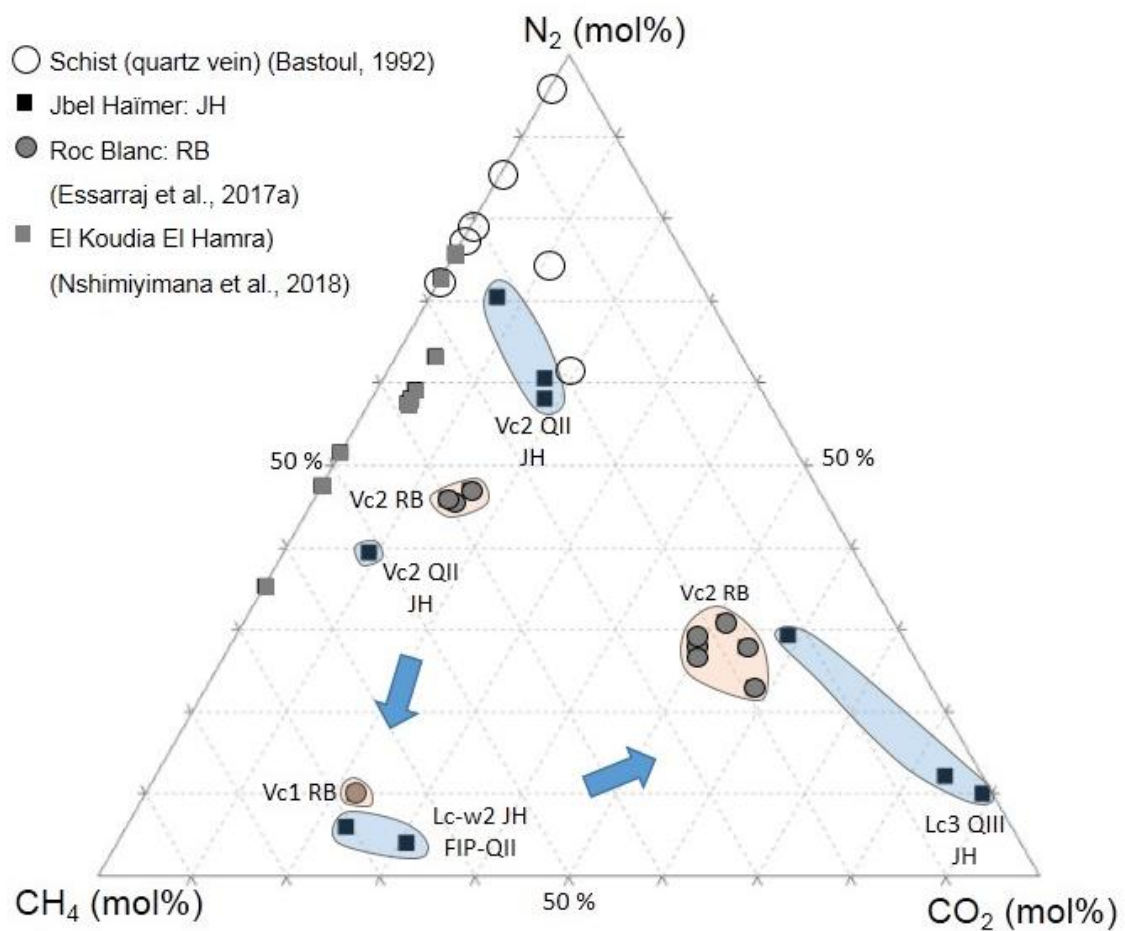
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981 **Fig. 7.** Ore minerals from Jbel Haïmer observed by scanning electron microscope. **a** Bismuth  
 982 and bismuthinite blebs (Bi). **b** cobaltite euhedral crystal (Cob). **c** Chalcopyrite (Ccp)  
 983 crystallising over pyrrhotite (Po). **d** Bi-Te-Se-S mineral growing over pyrrhotite (Po). **e** Stannite  
 984 (Stn) in fracture of pyrrhotite (Po). **f** galena (Gn) in microfracture crosscutting cobaltite (Cob).  
 985 **g** Galena (Gn) in microfracture crosscutting chalcopyrite (Ccp). **h** Malachite (Mlc), Cassiterite  
 986 (Cst), and Fe-oxides in oxidised ore.

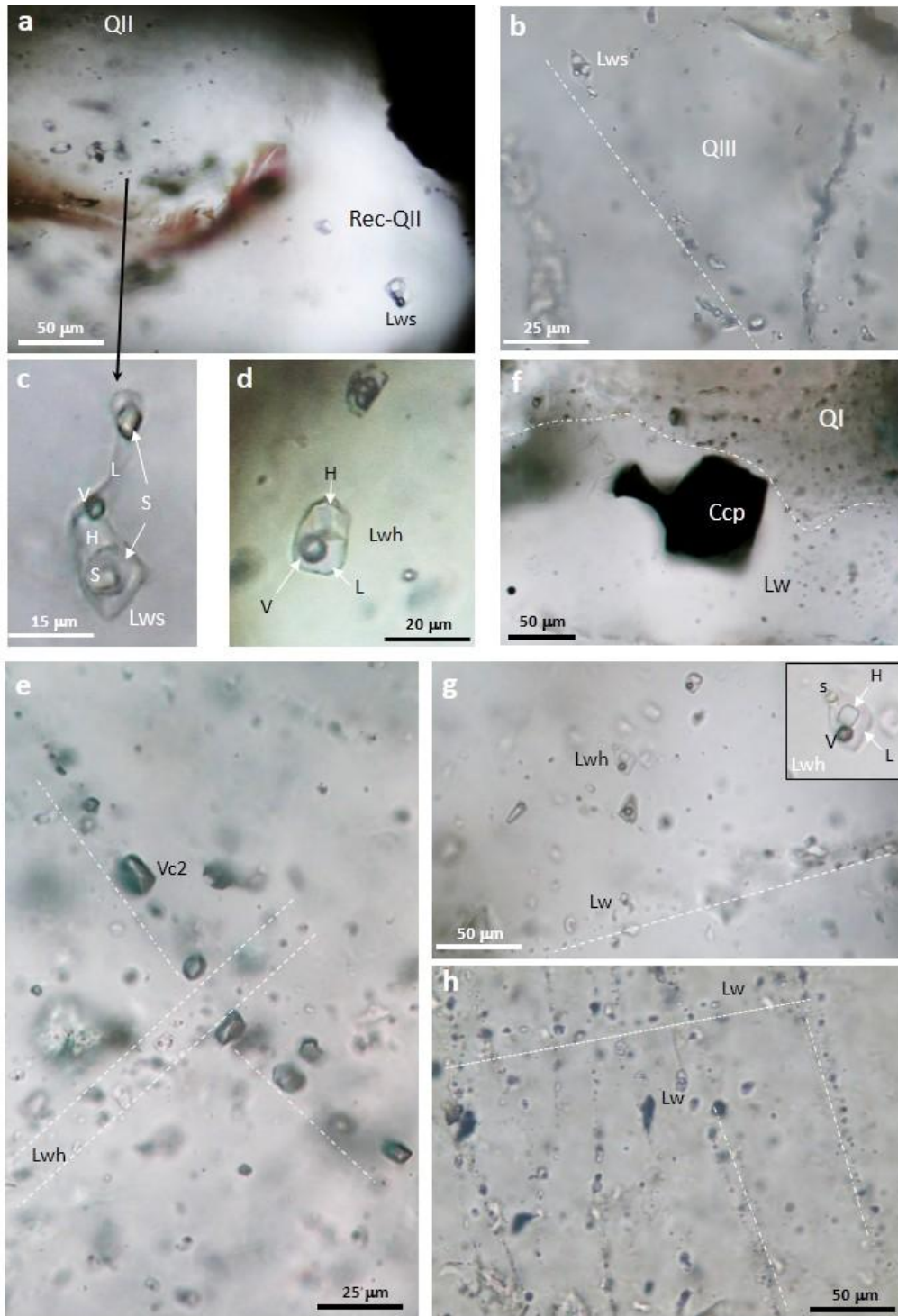




989 **Fig. 8.** Fluid inclusions (FIs) from Jbel Haïmer: early stages. **a** QI darkened by FIs clouds from  
 990 different generations. **b** QII quartz recrystallised around pyrite crystals (Py) and late sulphides  
 991 assemblages. **c** FIs in QII. **d** Lc3 FIs synchronous with small pyrrhotite crystals: Lc3 FIs and  
 992 pyrrhotite microcrystals are trapped in the same microfracture crosscut by an aqueous fluid  
 993 inclusion (Lw) plane. **e** Lc3 FIP network parallel to NW-SE QI veins. **f** Lc3 FIs (two-phase at -  
 994 14°C). **g** Lc3 FIs cloud (circle) in NW-SE QIII – chlorite 2 (Chl2) vein, and Lws aqueous FIP  
 995 perpendicular to QIII vein. **h** Lc3 FIs pseudo-secondary in QIII vein. See text for description  
 996 of fluid inclusion types.  
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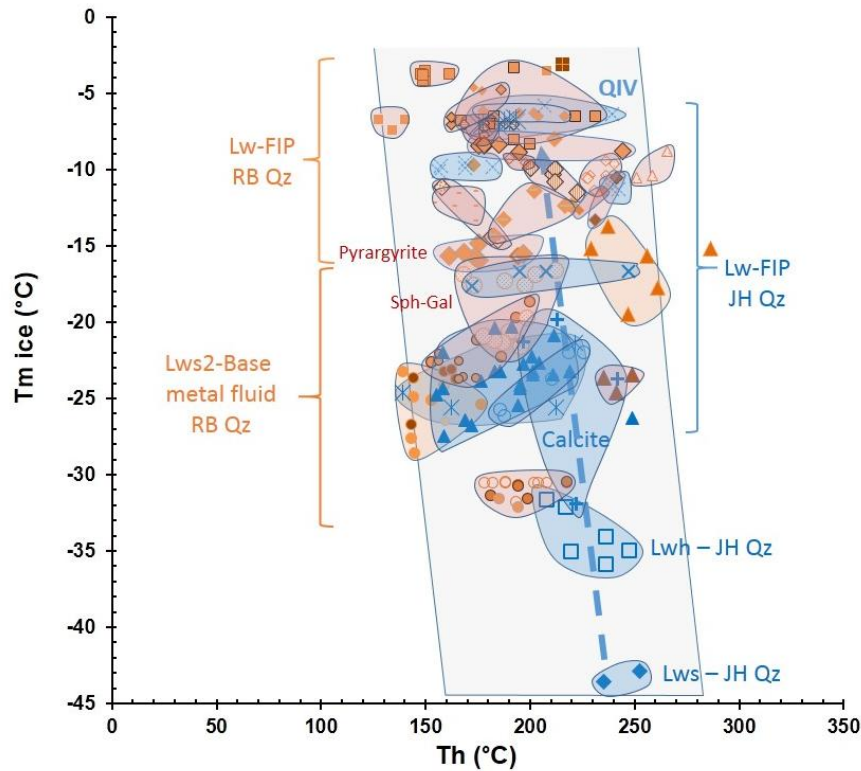
998  
 999 **Fig. 9.** CO<sub>2</sub>-CH<sub>4</sub>-N<sub>2</sub> ternary diagram presenting Raman data for FIs from Jbel Haïmer compared  
 1000 with data from vapour fluid inclusions from the Roc Blanc and the Koudia El Hamra silver  
 1001 deposits and a quartz vein (Bastoul, 1992) crosscutting the Sarhlef schist in central Jebilet.  
 1002 Arrows indicate the evolution of fluid inclusion composition over time.



1003

1004 **Fig. 10.** Fluid inclusions from the late stages at Jbel Haïmer. **a** Lws FIs in recrystallised QII  
 1005 quartz (Rec-QII). **b** Lws FIPs in QIII. **c** Lws FI showing halite cube and 3 solids. **d** Lwh FI. **e**  
 1006 Lwh FIs crosscutting one phase carbonic FIP in QIII. **f** recrystallised cloudy quartz QI around  
 1007 chalcopyrite crystal (fluid inclusion poor), scarce Lw FIs. **g** Aqueous FIP (Lw) crosscutting  
 1008 Lwh FI assemblage in QIV. **h** Perpendicular FIP sets crosscutting QI quartz vein.

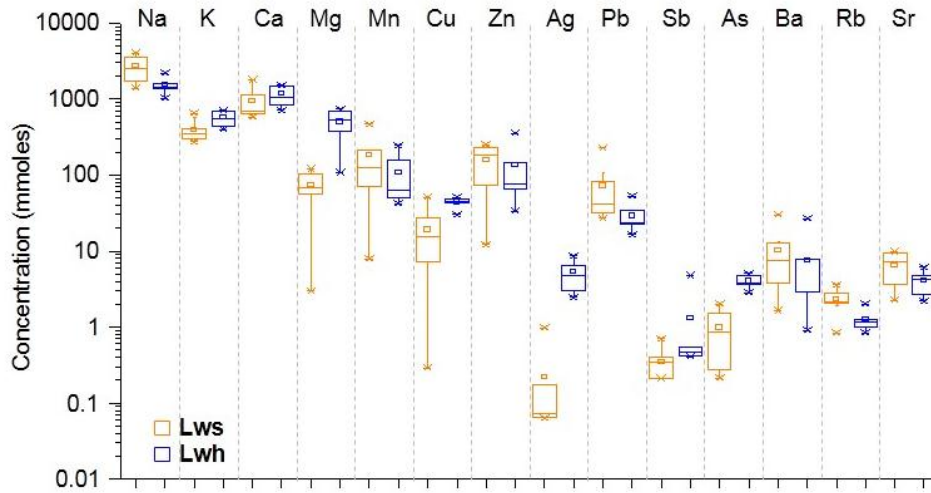




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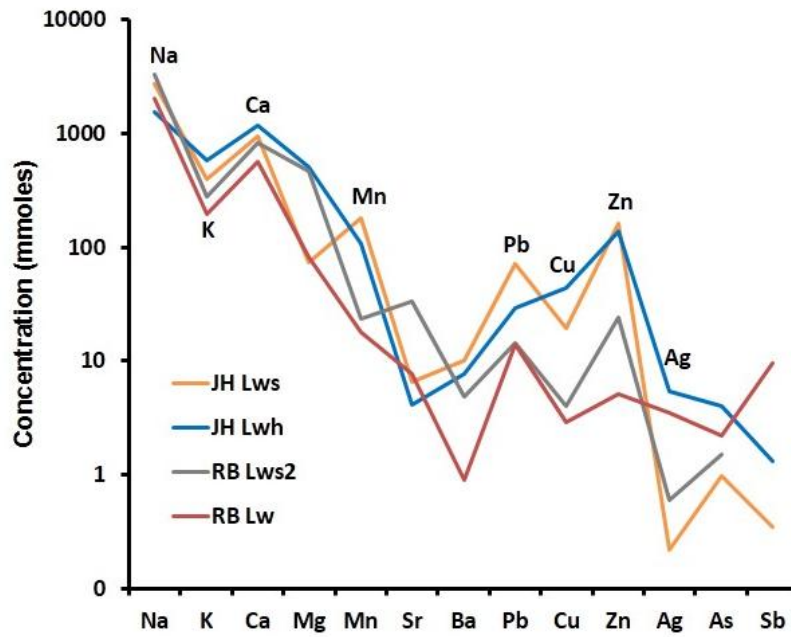
1010 **Fig. 11.** Tm ice vs Th for aqueous fluid inclusions from Jbel Haïmer (in blue). For comparison,  
 1011 data for aqueous fluid inclusions from the Roc Blanc deposit are presented (in orange) (from  
 1012 Essarraj et al., 2017a). Different symbols correspond to different FIPs. Arrow represents the  
 1013 mixing trend described in the text. JH Qz: FIs in quartz from Jbel Haïmer, RB Qz: FIs in quartz  
 1014 from Roc Blanc, calcite domain: FIs in calcite from Jbel Haïmer. Sph-Gal and pyrrargyrite: FIs  
 1015 associated respectively to sphalerite – galena and pyrrargyrite from Roc Blanc (Essarraj et al.,  
 1016 2017a). See text for fluid inclusions types and comments.

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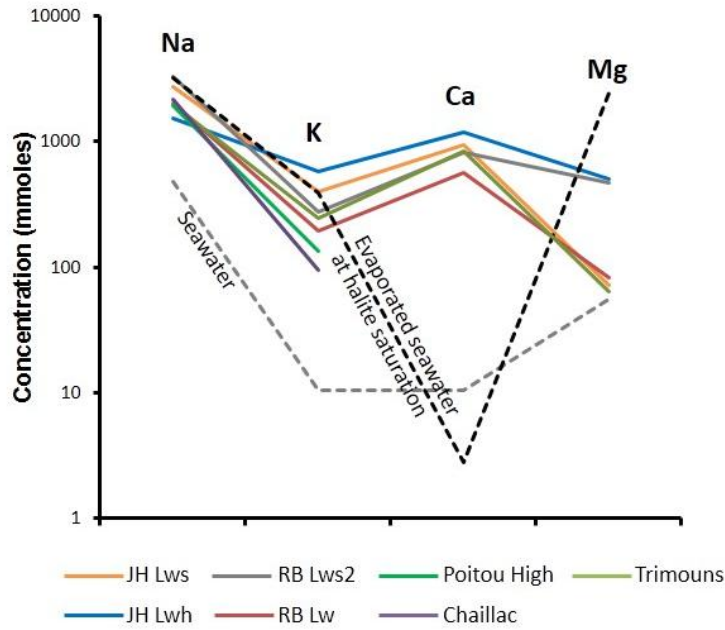


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 1019 **Fig. 12.** Range of the major, minor, and trace element compositions (in mmol/kg of solution)  
 1020 of the Lws and Lwh brines from Jbel Haïmer, analysed by LA-ICP-MS.

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 1023 **Fig. 13.** Comparison of the Jbel Haïmer brine compositions (JH Lws and JH Lwh brines)  
 1024 with the compositions of brines from the Roc Blanc silver deposit (RB Lws2 and RB Lw brines,  
 1025 from Essarraj et al., 2017a).

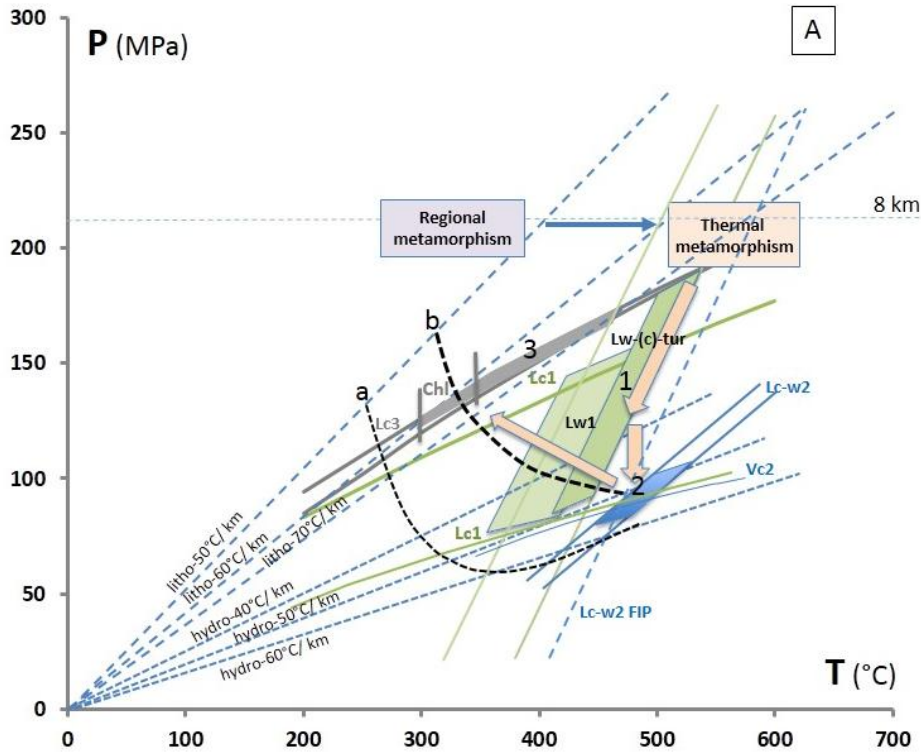


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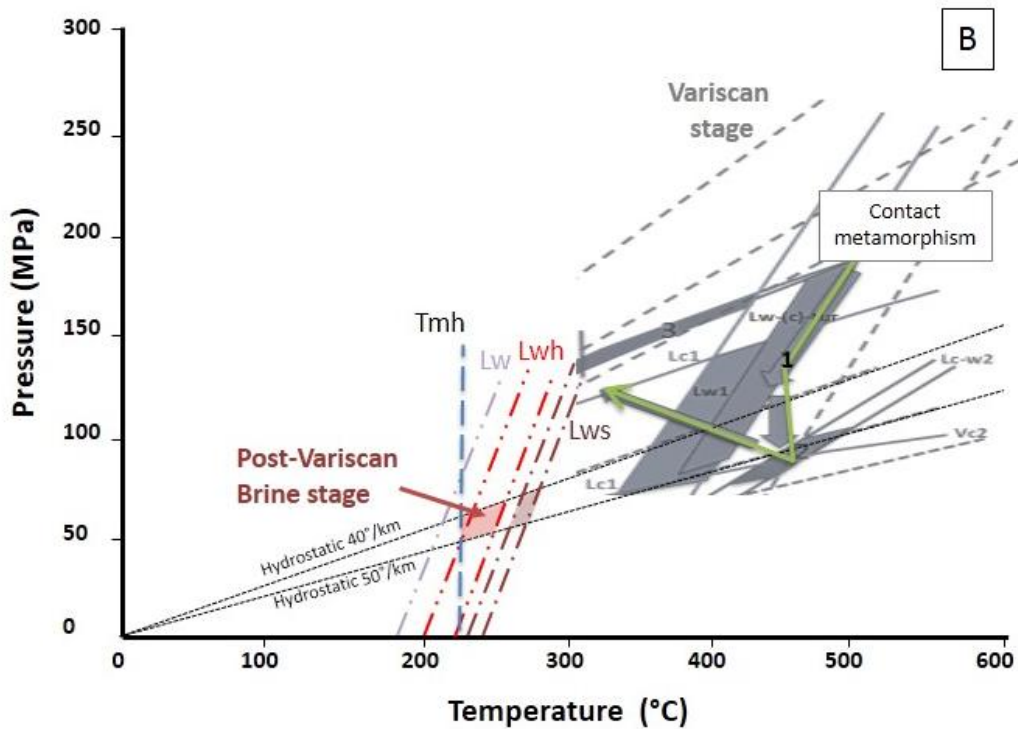
1027 **Fig. 14.** Average Na, K, Ca and Mg concentrations in fluids from Jbel Haïmer (JH Lws and JH  
 1028 Lwh brines, this study) and Roc Blanc (RB Lws2 and RB Lw brines, Essarraj et al, 2017a). For  
 1029 comparison, chemical composition of brines from literature are plotted: Poitou High and  
 1030 Chaillac (Boiron et al., 2002), Trimouns (Leisen et al., 2012b) as well seawater and evaporated  
 1031 seawater after halite saturation (Fontes and Matray, 1993).

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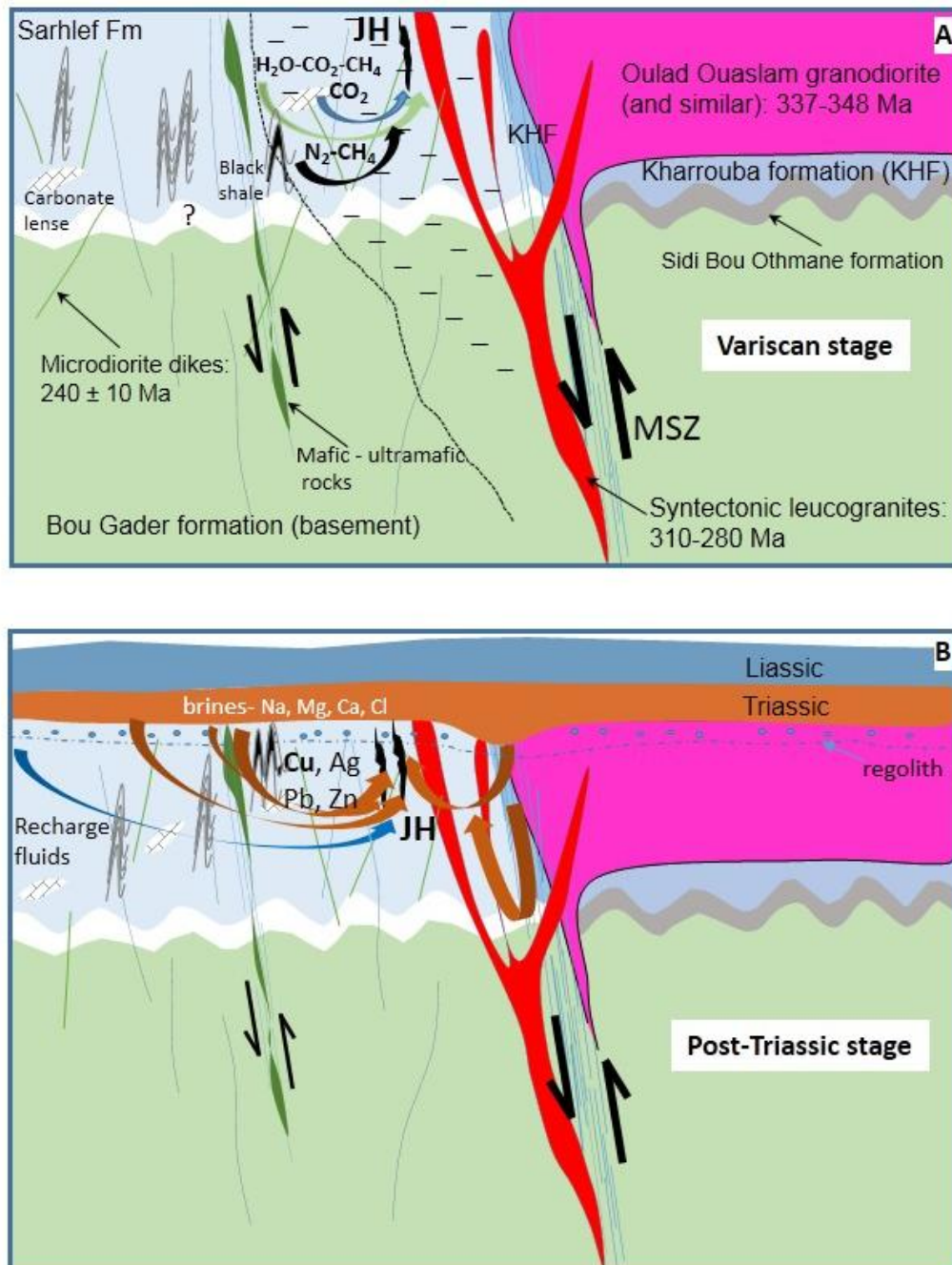
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1036 **Fig. 15.** P-T diagram for the two main stages at Jbel Haïmer with typical inclusions of each  
 1037 fluid inclusion type, distinguished by their colours: **A** Variscan stages; **B** Post-Variscan Cu-  
 1038 base metal ore stage. Thermal gradients for the lithostatic and hydrostatic pressures are  
 1039 reported, as well as isopleths from Weisbrod (1984) for two compositions: (a) 10 % CO<sub>2</sub> and 6

1040 % NaCl and (b) 20 % CO<sub>2</sub> and 6 % NaCl. The thermal metamorphism box for the Central  
 1041 Jebilet is from Bastoul (1992). Chl: Roc Blanc chlorite temperature domain from Essarraj et al.  
 1042 (2017a). Arrows represent the evolution P-T trend. In Fig. 15B, the Variscan domain is shown  
 1043 in grey.  
 1044



1045  
 1046 **Fig. 16.** A two-stage model of fluid circulation in the Jbel Haïmer area (JH) Jebilet: **A** Variscan  
 1047 stage: the intrusion of late leucogranites, the thermal metamorphism M2a lead to the genesis of  
 1048 CO<sub>2</sub>, CH<sub>4</sub>-N<sub>2</sub> and H<sub>2</sub>O-CH<sub>4</sub>-CO<sub>2</sub> fluids which mix, and form, in pre-existing discontinuities,

1049 the early quartz assemblages with the Fe-As-Sn-(Bi) association. See text for references on the  
 1050 granodiorite, granite and microdiorite ages. MSZ: Marrakesh Sear Zone. **B** Mesozoic brine  
 1051 stage: after peneplanation and deposition of Triassic/Early Jurassic formations, circulation of  
 1052 brines coming from Triassic evaporite formation within the regolith, and several types of  
 1053 lithologies including black shales, basic intrusions and schists, yield to the extraction of metals,  
 1054 the transport and the formation of Cu-polymetallic ores in the Jbel Haïmer area. Triassic and  
 1055 Liassic covering rocks in the Jebilet are from Saddiqi et al. (2009). Figures (A) and (B) are not  
 1056 to scale.

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1059 **Table 1.** Paragenetic sequence for the Jbel Haïmer occurrences.

1060

Stages	Pre ore stages			Ore stages		
	Sn-Bi stage	Fe-As-Co-Ni stage	Fe stage	Cu-Ag-(Au)- base metals stages	Supergene	
Quartz I (QI)	█		Brecciation			
Biotite (chloritized: chlorite 1)	█					
Turmaline	—					
Muscovite	↕					
Cassiterite	—					
Bi-minerals	—					
Quartz (QII)		█				
Pyrite		█				
Arsenopyrite		█				
Co-pyrite		█				
Co-Fe-Ni-sulfarsenide		█				
Quartz III (QIII)			█			
Pyrrhotite			█			
Chlorite 2			█			
Feathery quartz				—		
Carbonates				█		
QIV				—		
Fe-Sphalerite				?		
Chalcopyrite				█		
Stannite				—		
Bi-Te-Se sulphide				—		
Galena				█		
Natives : Ag-Au alloy				—		
Malachite					█	
Covellite					—	
Fe-Oxides/hydroxides					█	
Cerussite					—	
Native metals (Pb, Zn, Ag, Cu, Bi, Se)					—	
<b>Fluid circulations</b>	N <sub>2</sub> -CH <sub>4</sub> -CO <sub>2</sub> -H <sub>2</sub> O metamorphic fluids - Variscan			Basinal brines (aqueous) - Triassic +	Meteoric Fluids	

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1063 **Table 2.** Description of fluid inclusion types from Jbel Haïmer using nomenclature from Boiron  
 1064 et al. (1992) completed. L: liquid, V: vapour; (\*): fluid inclusions homogenising to an aqueous  
 1065 liquid.

Fluid inclusion type	Fluid inclusion description
Lc	One-phase liquid N <sub>2</sub> -CH <sub>4</sub> -CO <sub>2</sub> (carbonic: c)
Vc	One-phase vapor N <sub>2</sub> -CH <sub>4</sub> -CO <sub>2</sub> (carbonic: c)
Lc-w *	Two-phase aqueous (w) carbonic (c), liquid water dominated + V
Lw-(c) *	Two-phase liquid water dominated + V, with traces of gas (clathrates)
Lws *	Multi-phase aqueous (w) L+V + unidentified solids + halite
Lwh *	Multi-phase aqueous (w) L+V + one solid + halite
Lw *	Two-phase liquid water dominated + V

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1068 **Table 3.** Summary of microthermometry data of fluid inclusions from the Jbel Haïmer ores.  
 1069 T<sub>m</sub> CO<sub>2</sub>: melting temperature of volatile phase, T<sub>h</sub> CO<sub>2</sub>: homogenisation temperature of  
 1070 volatile phase to the liquid (L) or vapour (V), T<sub>m</sub> cl: melting temperature of clathrate, T<sub>e</sub>:  
 1071 eutectic temperature, T<sub>m</sub> ice: melting temperature of ice, T<sub>h</sub>: homogenisation temperature to  
 1072 the liquid (L) or vapour phase (V), T<sub>m</sub> hh: melting temperature of hydrohalite, T<sub>m</sub> h: melting  
 1073 temperature of halite. All values are in °C, mode: bold font in brackets

Fluid inclusion types	Microthermometry data					
<i>Early stages - Fe-Sn-As-Bi-Co-Ni</i>	T <sub>m</sub> CO <sub>2</sub> (°C)	T <sub>h</sub> CO <sub>2</sub> (°C)	T <sub>m</sub> cl (°C)	T <sub>e</sub> (°C)	T <sub>m</sub> ice (°C)	T <sub>h</sub> (°C)
<b>Aqueous dominated FI in quartzite</b>						
Lw-(c)-tur - Scattered in tourmaline (< 10 µm, 60-70% liq. H <sub>2</sub> O; 3 FIs)			~ -0.6 / 0	-52 / -50	-25.7 / -22.3	> 380 ± 10 L
Lw-(c)1 - Secondary in quartz (< 10 µm 60-70 % liq. H <sub>2</sub> O; 11 FIs)			-1 / 0	-51 / -49	-12.6 / -11.7	286 to > 386 L
<b>Fluid inclusions in QI</b>						
Lw1 - Random (10 µm, 60-70% liq. H <sub>2</sub> O; 5 FIs)			T <sub>m</sub> hh: ~ -13	-50 / -49	-25 / -16.5	296 to > 357 L
Lc1 - Random (< 15 µm; 20 FIs)	-78.4 / -67.9 L (-71)	-70.2 / -13.7 L (-32)				
FIP Lw2 - (< 10 µm, 70-90% liq. H <sub>2</sub> O; 25 FIs)				-50 / -44	-11.8 / -8.1 (-10)	261 - 317 (290)
<b>Fluid inclusions in QII (&lt; 20 µm): Vc2 and Lc-w2</b>						
Scattered: Vc2 (0 to 10% H <sub>2</sub> O) and Lc-w2 (up to 70% liq. H <sub>2</sub> O; 15 FIs)	-102.8 / -68.5	-71.6 / -60.5 V	-4.2 / 1 (-3)		-8.4 / -3.8 (-4)	> 460 L; D > 350
FIP: Vc2 (0 % visible H <sub>2</sub> O) and Lc-w2 (up to 70% H <sub>2</sub> O; 11 FIs)	~ -102	~ -97 V	6.2 / 9.1		-10 / -9	414 - 453 L (425)
<b>Fluid inclusions in QIII</b>						
Lc3 - Scattered to pseudo-secondary (65 FIs) (< 20 µm)	-65 / -57.6 (-59)	-46.9 / +18.6 (L, V)				
<b>Ore stages - Cu-Zn-Pb-Ag-(Au) - Aqueous fluids</b>						
		T <sub>m</sub> h (°C)	T <sub>m</sub> hh (°C)	T <sub>e</sub> (°C)	T <sub>m</sub> ice (°C)	T <sub>h</sub> L-V (°C)
Lws (< 20 µm; 20 - 30 % vap; 6 FIs)		209 to > D ~ 230	-28 / -15.9	-65 / -50	-43.6 / -39	174 to 252 - D ~ 230 ° and >
Lwh (< 15 µm, 10% vap; 43 FIs)		155 / 262 (220)	~ -12 / -13	-65 / -50	-35.9 / -31.6	179 / 264 L (220); D ~ 270
Lw / Feathery quartz - calcite (scattered and FIP; 9 FIs)					-32 / -20	186 - 242 L
Lw FIP/QI, QII, QIII (< 15 µm, 10% vap; ~ 50 FIs)			~ -11.9 / -6.5	-60 / -45	-29.6 / -7.1	139 - 249 L (200)
Lw FIP/QIV (10 µm, 10% vap; 10 FIs)				~ -49	-11.3 / -5.8	156 / 242 L

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1082 **Table 4.** Microthermometric and Raman data for carbonic and aqueous-carbonic fluid  
 1083 inclusions from Jbel Haïmer and the neighbouring Roc Blanc deposit (\*Essarraj et al., 2017a).  
 1084 Concentrations of the volatile phase components are given in mole %. Vc1 and Vc2 are  
 1085 respectively early and late carbonic vapour fluid inclusions from Roc Blanc. (FIs: Fluid  
 1086 inclusion, nm: not measured)

Deposit/Fluid inclusion type	FI reference	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub>	Tf CO <sub>2</sub>	Th CO <sub>2</sub>
<b>Jbel Haïmer</b>						
Vc2 scattered/QII	L6-2A-P2-8	7.7	22.5	69.8	-102.8	(nm) V
Vc2 ( ~10% H <sub>2</sub> O) scattered/QII	L6-2C-IF4	17.7	22.1	60.2	-73.6	~ -70
Vc2 scattered/QII	L6-2C-IF5	18.6	23.8	57.6	-82.1	(nm) V
Vc2 scattered/QII	L6-2A-P2-9	9.1	51.5	39.4	-95.6	(nm) V
Lc-w2 scattered/recrystallised QII	L6-2A-P1-1	30.7	64.5	4.8	~ -102	-96.7 V
Lc-w2 scattered/recrystallised QII	L6-2A-P1-2	23.8	70	6.2	(nm)	(nm) V
Lc3 scattered QIII	JH4-1-IF19	58.5	12.2	29.3	-59.6	-13.5 L
Lc3 pseudo-secondary QIII	JH4-1-IF1	88	1.7	10.3	-59.5	-15.9 L
Lc3 pseudosecondary QIII	JH4-1-IF5	83.7	4	12.3	-58.2	+1.6 L
<b>Roc Blanc *</b>						
Vc1	RB19/2	22.5	67.3	10.2	(nm)	(nm) V
Vc1	RB22/1-1	15.9	36.9	47.3	-81.1	(nm) V
Vc1	RB22/1-2	14.2	39.6	46.2	-79.1	-106.8 V
Vc1	RB22/1-6	14.8	39.6	45.5	-80.6	(nm) V
Vc2	RB22/1-3	50.2	22.5	27.3	-68.7	-51.8 V
Vc2	RB22/1-4	48.9	22	29.1	-69	-51.3 V
Vc2	RB19B-1	58.2	19.1	22.8	-60.8	-23.6 V
Vc2	RB19B-3	54	17.5	28.5	-60.7	-24.7 V
Vc2	RB19B-5	51.2	17.7	31.1	-59.2	(nm) V

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1102 **Table 5.** Representative LA-ICP-MS data obtained on Lws and Lwh fluid inclusions from the  
 1103 Cu- stage (Jbel Haïmer). Absolute element concentrations are in mmol/kg of solution in the  
 1104 first line, and ppm (second line, italic font).

FI type	FI number	Na	K	Ca	Mg	Mn	Cu	Zn	Ag	Pb	Sb	As	Ba	Rb	Sr
<b>Lws</b>	JH3-6-1-IF1	2971	277	860	61	146	13.9	251.2	0.1	68.6	0.7	1.1	12.2	3.6	9.8
		<i>68332</i>	<i>10814</i>	<i>34405</i>	<i>1452</i>	<i>8027</i>	<i>878</i>	<i>16577</i>	<i>7</i>	<i>14194</i>	<i>85</i>	<i>79</i>	<i>1698</i>	<i>310</i>	<i>861</i>
	JH3-6-1-IF3	2284	649	601	97	183	4.9	244.9	0.2	228	0.3	0.9	4.5	3.1	4.3
		<i>52539</i>	<i>25300</i>	<i>24034</i>	<i>2330</i>	<i>10072</i>	<i>311</i>	<i>16163</i>	<i>19</i>	<i>47196</i>	<i>42</i>	<i>64</i>	<i>623</i>	<i>265</i>	<i>377</i>
	JH3-6-2-IF2	2542	415	1304	56	98	15.4	72.8	nd	32.2	0.2	2.0	3.7	0.8	3.7
		<i>58473</i>	<i>16182</i>	<i>52148</i>	<i>1354</i>	<i>5401</i>	<i>973</i>	<i>4807</i>	<i>nd</i>	<i>6658</i>	<i>26</i>	<i>149</i>	<i>519</i>	<i>72</i>	<i>322</i>
	JH3-6-3-IF1	1753	388	1079	76	431	50.6	226.8	0.1	81.5	0.4	0.3	12.2	2.1	8.1
		<i>40317</i>	<i>15126</i>	<i>43163</i>	<i>1817</i>	<i>23704</i>	<i>3185</i>	<i>14968</i>	<i>7</i>	<i>16870</i>	<i>50</i>	<i>21</i>	<i>1701</i>	<i>175</i>	<i>707</i>
	JH3-6-4-IF4	3977	328	580	30	66	31.2	147.3	0.1	39.1	0.2	0.2	7.5	2.1	3.4
		<i>91475</i>	<i>12806</i>	<i>23199</i>	<i>730</i>	<i>3655</i>	<i>1965</i>	<i>9720</i>	<i>14</i>	<i>8083</i>	<i>26</i>	<i>16</i>	<i>1042</i>	<i>182</i>	<i>299</i>
	JH3-6-4-IF5	3539	354	706	3	125	0.3	213.0	nd	41	0.2	nd	12.5	2.8	7.3
		<i>81400</i>	<i>13791</i>	<i>28238</i>	<i>71</i>	<i>6858</i>	<i>18</i>	<i>14058</i>	<i>nd</i>	<i>8489</i>	<i>26</i>	<i>nd</i>	<i>1742</i>	<i>238</i>	<i>637</i>
	JH3-6-7-IF1	1621	304	1139	69	471	17.4	212.5	1.0	108.0	0.4	0.7	29.8	1.9	9.3
		<i>37291</i>	<i>11875</i>	<i>45570</i>	<i>1660</i>	<i>25912</i>	<i>1099</i>	<i>14028</i>	<i>103</i>	<i>22349</i>	<i>54</i>	<i>55</i>	<i>4145</i>	<i>163</i>	<i>812</i>
	JH3-6-7-IF4	3245	376	632	121	212	7.3	180.2	0.1	68.3	0.4	0.3	13.2	2.6	7.4
		<i>74646</i>	<i>14652</i>	<i>25284</i>	<i>2893</i>	<i>11674</i>	<i>462</i>	<i>11896</i>	<i>8</i>	<i>14143</i>	<i>53</i>	<i>19</i>	<i>1828</i>	<i>218</i>	<i>648</i>
	JH3-6-8-IF1	1379	577	1803	109	71	21.7	29.8	0.1	27.1	0.2	1.5	3.1	2.0	9.3
		<i>31724</i>	<i>22505</i>	<i>72103</i>	<i>2619</i>	<i>3923</i>	<i>1367</i>	<i>1969</i>	<i>7</i>	<i>5600</i>	<i>26</i>	<i>113</i>	<i>432</i>	<i>175</i>	<i>811</i>
	JH3-6-8-IF3	4040	305	703	104	8	27.7	12.1	nd	28.3	nd	2.0	1.6	nd	2.3
		<i>92916</i>	<i>11879</i>	<i>28120</i>	<i>2497</i>	<i>432</i>	<i>1748</i>	<i>801</i>	<i>nd</i>	<i>5860</i>	<i>nd</i>	<i>146</i>	<i>228</i>	<i>nd</i>	<i>198</i>
<b>Lwh</b>	JH3-1-IF2	2201	686	826	559	51	45.1	66.6	6.6	52.4	nd	nd	7.7	nd	4.8
		<i>50631</i>	<i>26761</i>	<i>33043</i>	<i>13418</i>	<i>2821</i>	<i>2839</i>	<i>4394</i>	<i>701</i>	<i>10854</i>	<i>nd</i>	<i>nd</i>	<i>1074</i>	<i>nd</i>	<i>425</i>
	JH3-2-IF3	1482	439	1519	380	63	43.2	75.9	3.0	16.7	0.4	3.8	4.4	0.8	2.7
		<i>34086</i>	<i>17112</i>	<i>60749</i>	<i>9110</i>	<i>3473</i>	<i>2723</i>	<i>5007</i>	<i>322</i>	<i>3452</i>	<i>51</i>	<i>281</i>	<i>618</i>	<i>71</i>	<i>237</i>
	JH3-2-IF5	1633	688	1429	108	155	51.3	146.3	4.7	24.1	0.5	4.7	2.9	1.2	4.3
		<i>37558</i>	<i>26840</i>	<i>57164</i>	<i>2580</i>	<i>8502</i>	<i>3231</i>	<i>9656</i>	<i>506</i>	<i>4996</i>	<i>58</i>	<i>354</i>	<i>402</i>	<i>101</i>	<i>373</i>
	JH3-4-IF1	1389	562	1047	682	84	45.5	146.4	2.5	34.1	0.5	5.1	2.9	1.3	2.2
		<i>31956</i>	<i>21929</i>	<i>41878</i>	<i>16362</i>	<i>4620</i>	<i>2865</i>	<i>9664</i>	<i>267</i>	<i>7054</i>	<i>67</i>	<i>382</i>	<i>404</i>	<i>109</i>	<i>192</i>
	JH3-4-IF4	1034	710	1507	532	42	30.5	33.1	6.5	22.6	0.4	2.8	0.9	2.0	4.3
		<i>23778</i>	<i>27675</i>	<i>60279</i>	<i>12764</i>	<i>2319</i>	<i>1921</i>	<i>2186</i>	<i>691</i>	<i>4682</i>	<i>49</i>	<i>213</i>	<i>126</i>	<i>173</i>	<i>373</i>
	JH3-5-IF1	1451	394	717	744	248	48.0	352.2	8.7	23.1	4.7	3.7	26.6	1.0	6.1
		<i>33367</i>	<i>15385</i>	<i>28681</i>	<i>17853</i>	<i>13621</i>	<i>3023</i>	<i>23248</i>	<i>929</i>	<i>4785</i>	<i>578</i>	<i>279</i>	<i>3691</i>	<i>87</i>	<i>535</i>

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 1108 **Table 6.** Comparison of LA-ICP-MS data obtained on brines from Jbel Haïmer and Ag-base  
 1109 metal brines from Roc Blanc (data from Essarraj et al., 2017a). Concentrations are in mmol/kg  
 1110 of solution in the first line, and ppm (second line, italic font).

FI Type	Na	Mg	K	Ca	Mn	Sr	Ag	Ba	Pb	Cu	Zn	As	Sb
<b>Lws Jbel Haïmer</b>	2735	73	397	941	181	6.5	0.2	10	72.2	19.1	159.1	1	0.4
	<i>62877</i>	<i>1774</i>	<i>15522</i>	<i>37713</i>	<i>9944</i>	<i>570</i>	<i>22</i>	<i>1373</i>	<i>14960</i>	<i>1214</i>	<i>10402</i>	<i>75</i>	<i>49</i>
<b>Lwh Jbel Haïmer</b>	1532	501	580	1174	107	4.1	5.3	7.6	28.8	43.9	136.8	4	1.3
	<i>35220</i>	<i>12177</i>	<i>22677</i>	<i>47052</i>	<i>5878</i>	<i>359</i>	<i>572</i>	<i>1044</i>	<i>5967</i>	<i>2790</i>	<i>8944</i>	<i>300</i>	<i>158</i>
<b>Lws2 Roc Blanc</b>	3303	470	274	819	24	33.2	0.6	4.8	14.3	4	24.1	1.5	nd
	<i>75924</i>	<i>11417</i>	<i>10730</i>	<i>32814</i>	<i>1301</i>	<i>2909</i>	<i>65</i>	<i>659</i>	<i>2963</i>	<i>254</i>	<i>1576</i>	<i>112</i>	<i>nd</i>
<b>Lw Roc blanc</b>	2047	82	196	564	18	7.7	3.5	0.9	14	2.9	5.1	2.2	9.6
	<i>47060</i>	<i>1993</i>	<i>7663</i>	<i>22604</i>	<i>989</i>	<i>675</i>	<i>378</i>	<i>124</i>	<i>2901</i>	<i>184</i>	<i>333</i>	<i>165</i>	<i>1169</i>

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