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1 **A contribution to the synsedimentary versus epigenic origin of the Cu**
2 **mineralizations hosted by terminal Neoproterozoic to Cambrian formations**
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4 **deposit (Anti Atlas, Morocco).**

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21

22 **Abstract**

23 The Neoproterozoic to Cambrian formations that compose the cover of the Bou Azzer-El
24 Graara inlier, host a great number of Copper occurrence whose origin is largely discussed. To bring
25 some light to this debate, structural, petrographic and geochemical observations were performed on
26 the copper deposit of Jbel Laassel. This deposit, located at the extreme ESE of the Bou Azzer –El
27 Graara inlier, is mined since 2012. At the district scale, the ore bodies localize in a folding band that
28 extends along a NE-SW direction. At macroscopic, microscopic and scanning electron microscope
29 scales the mineralization appears as banding veins, with locally cockade breccia and comb quartz
30 textures. From the macroscopic scale to the scale of the scanning electron microscope, all these
31 mineralized textures are connected there between forming a stockwork with an auto-similar structure
32 in the range of used scales of observation. At the district scale, this stockwork is preferentially located
33 in the anticlinal hinges of the folding band. Principal component analyses of geochemical database
34 enable to distinguish several groups of chemical elements, each of these groups corresponding to the
35 different lithologies and to the copper mineralization. This last group doesn't show any correlation
36 with the distinguished lithological groups. All these observations bring new arguments to an
37 epigenetic origin for the copper mineralization of the Jbel Laassel deposit, with a formation
38 contemporary or posterior with the folding band development attributed to Variscan deformation.

39

40 **Keywords:** Anti-Atlas, Cu-mineralization, folding band, stockwork, epigenetic.41 **1. Introduction**

42 More than 200 Copper mineralizations are known over a large part of the Neoproterozoic to
43 Cambrian cover in the Anti-Atlas (fig. 1A) (Bouchta et al., 1977). They are localized at different
44 stratigraphic levels within the cover and present different characteristics. Their origin remains in most

45 cases currently poorly understood and there is no general model for this copper mineralization. Several
46 genetic interpretations have been proposed on specific deposits: (i) based on textural and petrological
47 observations, Leblanc (1986) suggests that Alous mineralization crystallized during the cooling of an
48 ignimbrite; (ii) For the Cu-occurrences of Tizert, Talat N'Ouamane, Tizirt and Amadou, Pouit
49 (1966), Bouchta & al (1977) and Skacel (1993) consider these mineralizations generated through a
50 synsedimentary process arguing of a strong paleogeographic control of the ores. Moreover, the Cu-
51 mineralizations hosted in the Neoproterozoic to Cambrian cover in the Anti-Atlas can be differentiate
52 by their morphologies as veins, dissemination or stratiform bodies, without relationship have been
53 established between these morphologies yet (Pouit, 1966; Skacel, 1993). As the result, the syngenetic
54 or epigenetic nature of that mineralization remains still undetermined (Pouit, 1966). New data and
55 evidences are then necessary. The Jbel Laassel deposit is one of these numerous cover-hosted copper
56 occurrences known in the Anti-Atlas terminal Neoproterozoic to Cambrian cover, often called
57 Adoudounian cover (Pouit, 1966; Bouchta et al., 1977; Benssaou & Hamouni, 1999). Since the 60's,
58 various genetic models were proposed by several geologists hired by Managem Goup for the copper
59 mineralization at Jbel Laassel site. Maacha et al. (2011) resumed these different models: in 1964 the
60 mineralization was attributed to a porphyry copper type, in 1967 it was interpreted as a stratiform
61 synsedimentary deposit, with a re-concentration stage associated to a Jurassic doleritic intrusion, in
62 1978 an epigenetic origin was proposed for this mineralization with a mainly vein-shaped texture and
63 a close association with barite. Some authors evoked a synsedimentary genesis for the Jbel Laassel
64 deposit, where mineralization is controlled by the basement paleogeography and were locally
65 remobilized by a tectonic event (Pouit, 1966; Bouchta et al., 1977). According to Skacel (1993),
66 copper should be synchronous with sedimentation; its precipitation being regulated by the redox
67 conditions, themselves under the control on the deposition environment.

68 In 1984, the MANAGEM Group discovered the potential of the Jbel Laassel Cu-
69 mineralizations. Different preliminary estimations were performed until 2006 (Maacha et al., 2011). In
70 2010 Managem decided to lead a core drill campaign to estimate the feasibility of this deposit. This
71 work resulted in an estimation of 7.5 million tons at 1% Cu (Maacha et al., 2011) and the exploitation

72 began in 2012 with SOMIFER as operator. In this article, based on MANAGEM Group pre-
73 exploitation targeting, we report the main results of an original study performed on Jbel Laassel Cu-
74 mineralization. This work consists of: (i) a structural analysis of ore bodies, (ii) a mineralogical study
75 of samples collected both on outcrops and drill cores and (iii) a statistical analysis of the first chemical
76 analyses carried out in this deposit. These new data bring out new insights on the debated, epigenic
77 versus syngenetic origin of the Jbel Laassel deposit.

78 **2. Geological setting**

79 **2.1. The Bou Azzer El Graara inlier**

80 The Bou Azzer El Graara inlier is one of a series of Proterozoic windows oriented NW-SE that
81 expose Panafrican formations in the central part of the Anti-Atlas (Choubert, 1947). The Proterozoic
82 basement is mainly composed by a dismembered ophiolitic sequence and arc fragments (Leblanc,
83 1975; Saquaque et al., 1989) (fig. 1B). These formations are unconformably overlain by a thick
84 Neoproterozoic to Cambrian volcano-sedimentary cover (Soulaimani et al., 2014). This cover can be
85 divided into three formations from bottom to top: (1) The Tiddiline Formation (~750 to 650 Ma)
86 attributed to the “Saghro Group” (Thomas et al. 2004), composed of clastic, volcanoclastic and
87 volcanic series, rests mainly unconformably on the Panafrican substratum; (2) The Ouarzazate Group
88 (~610 to 550 Ma), composed of a volcano sedimentary complex, rests in angular unconformity on the
89 Tidiline Formation; (3) Terminal Neoproterozoic to Cambrian Formations consisting of detrital and
90 carbonated series (Soulaimani et al., 2013). These Terminal Neoproterozoic to Cambrian Formations,
91 varying in age from terminal Neoproterozoic to the middle Cambrian, are associated with a major
92 marine transgression toward the Southeast and can be subdivide into two groups: the Taroudannt
93 Group and the Tata Group (fig. 2). During the Late Paleozoic compressional event, the Panafrican
94 structures of the basement were reactivated along the inlier’s borders. This results in box-shaped folds
95 distributed throughout the Bou Azzer-El Graara area and by large open synclines of Cambrian rocks
96 (Soulaimani & Burkhard, 2008). Upright detachment folds, from meters to decameters in scale, are

97 frequent in the lower Cambrian rocks and they exhibit a dominant NW-SE trend with subordinate NE-
98 SW structures (Soulaimani & Burkhard, 2008).

99

100 **2.2. Lithostratigraphy of the Jbel Laassel Cu-deposit**

101 The Jbel Laassel deposit is hosted in the Lower Cambrian part of the Neoproterozoic to
102 Cambrian volcano-sedimentary cover, at the extreme ESE part of the Bou Azzer-El Graara inlier, 30
103 kilometers NE of the Bleida mine (fig. 1B). The whole of this cover is often call Adoudounian cover,
104 it is a local appellation, and on the other hand the term Adoudou correspond to the name of a precise
105 stratigraphic formation (Soulaimani et al, 2013). The Lower Cambrian is represented in the studied
106 site by the Adoudou and Tikirt Formations, both belonging to the Taroudann Group, whereas the
107 Igoudine, Amouslek, Issafene and Tazlaft Formations correspond to the Tata Group (fig. 2)
108 (Soulaimani et al., 2013). All these formations are interlayered locally with volcanic flows dated at
109 534 ± 10 Ma (U/Pb on zircon by Ducrot & Lancelot, 1977) related to the Jbel Boho-type volcanism
110 (Alvaro et al., 2006) (fig. 1 and 2).

111 **2.2.1 The Taroudannt Group**

112 The Adoudou Formation (Choubert, 1952) is represented in the area study by a basal
113 sedimentary breccia with a thickness of 5 to 100 meter and by an alternation of dolostones and red or
114 white clay's siltstones with a total thickness varying from 150 to 250 meters. Dolostones frequently
115 present an intensive secondary silicification (Soulaimani et al., 2013). The Tikirt Formation (250 to
116 300 meters thick) rests in conformity on the Adoudou Formation; it is composed essentially by
117 sandstones frequently interlayered by centimetric clayed siltstones. The age of this formation is
118 unknown; but the Taliwine Formation, a westward stratigraphic equivalent level has been dated by
119 U/Pb on zircon from Early Cambrian volcanic horizons at 521 ± 7 Ma and 522 ± 2 Ma (Compston et
120 al., 1992; Landing, 1998; Maloof et al., 2005). On the Jbel Laassel site and at regional scale, Tikirt
121 sandstones end with a continuous level of red claystones 8 to 15 meters thick (fig. 2).

122 2.2.2 The Tata Group

123 This Group includes, from oldest to youngest, the formations of Igoudine, Amouslek, Issafène
124 and Tazlaft. The age of the Tata Group varies from the Tomotien (in the lower Cambrian) at its base,
125 to the Middle Cambrian at its top. (Soulaimani et al., 2013). The Igoudine Formation (50 to 60 meters
126 thick) is made up of dolostones with microbialite interlayered with clayed siltstones or siltstones. The
127 Amouslek Formation appears as an alternation of stromatolitic dolostones with heterolitic facies of
128 clayed siltstones, for a total thickness of 150 to 180 meters. The Issafene Formation is composed by
129 red claystones and thin beds of sandstones, and it is 30 to 40 m thick (Soulaimani et al., 2013). The
130 Tazlaft Formation, 90 to 100 meters thick, is composed of sandstones with oblique cross bedding and
131 mega-ripples marks (Soulaimani et al., 2013).

132 3. Methodology and Analytical procedure

133 In order to decipher the complex pattern of geometries and structures, a structural study has
134 been performed in the field coupled with high density drill control. As a result, well constrained and
135 high resolution maps and cross-sections have been constructed (fig. 3 to 5).

136 During the field work, 10 samples have been collected from outcrops and 55 samples have
137 been collected on 9 core drills. 60 polished thin sections were prepared from these samples. They have
138 been first observed using a Leica DMRX petrographic microscope (transmitted and reflected light
139 modes). Complementary observations and analyses were carried out using JSM-6400 JEOL Scanning
140 Electron Microscope (SEM) at ISTO. Polished thin-sections have been first coated by a thin carbon
141 layer. Acceleration voltage and beam current were 20 kV and 8 nA, respectively. IdFix Software
142 package was used for data processing. Back-scattered electrons (BSE) imaging mode was used to
143 reveal the composition variations at microscopic scale, whereas the texture of clayey material was
144 examined with secondary electrons (SE) imaging mode. The SEM system is coupled to an Energy-
145 Dispersive X-ray spectrometer (EDS) to make qualitative determinations of the mineral composition.

146 The Managem Group performed analyses on 23 Reverse Circulation drilling's samples
147 collected at different depths for the following elements: Cu, CuOx, SiO₂, Al₂O₃, Fe₂O₃, CaO, MgO,
148 K₂O, MnO, TiO₂, P₂O₅, As, B, Ba, Be, Bi, Cd, Co, Cr, Ge, Li, Mo, Nb, Ni, Pb, Sb, Se, Sn, Sr, W, Y,
149 Zn, Ag and loss on ignition (LOI). "Cu" corresponds to the total copper content and CuOx
150 corresponds to the non-sulphide copper content. For the major elements analysis, 0.5 g of the sample
151 is crushed at less than 100µm and it is dissolved by fusion at 500°C during 45 minutes with 2.5 g of
152 sodium peroxide in a zirconium crucible. The melt mixing is dissolve with 100 ml of hydrochloric
153 acid (28% HCl) and the solution is analyzed using an ICP-AES ULTIMA 2C using the Jobin Yvon-
154 HORIBA device. For the other elements, 0.25 g of the sample is dissolved by acid attack (50%HCl
155 and 50% HNO₃) microwave-assisted during 45 minutes at 220°C. The solution is then analyzed by
156 ICP-MS Thermo X'Serie 2.

157 **4. Results**

158 **4.1. Structural study**

159 The whole sequence undergoes at least one deformation stage. Two types of folds are present.
160 The first family corresponds to upright folds characterized by sub-horizontal to slightly NW dipping
161 axes with a NW-SE to NNW-SSE orientation (fig. 3b). They are marked by an axial planar cleavage
162 particularly developed in the fold hinge zone. Those NW-trending folds are concentrated in a band,
163 named herebelow "folding band", which displays a width of 150 to 200 meters and is oriented N145°
164 (fig. 3 and 4). This "folding band" is developed along a N150E-trending vertical fault, folds being
165 localized in both sides of the fault. The second fold family shows moderately inclined fold's axes to
166 the NE, oriented NE-SW (fig. 3). The orientation of NE-trending folds is parallel to the direction
167 (around N30°) of a SE-vergent thrust that outcrops through the entire area (fig. 3). Therefore, at large
168 scale, the Jbel Laassel area and its ore body appears to be located within a large NE-trending synclinal
169 developed in the thrust footwall (figure 3). The relations between the two types of folds could not be
170 observed in the field. In the thrust hanging wall, a similar vertical fault is found northeastward (fig. 3)
171 with sub-parallel folds and mineralizations along the northwestern prolongation (out of fig. 3).

172 Consequently, we infer that both hanging- and footwall vertical fault segments are part of the same
173 vertical fault offset by the late thrust. As the fault is vertical, the thrust might have right lateral oblique
174 slip component of about 300 meters.

175

176 **4.2. Jbel Laassel ore bodies**

177 **4.2.1. Geometries and orientation**

178 The vertical and lateral extent of ore bodies was delimited by surface cartography and drills.
179 Part of the outcrops are covered by superficial alteration formations and mining waste. Ore bodies
180 extend 150 to 250 meters in width (fig. 4), with a maximal longitudinal extension of 400 meters (fig.
181 3) for an average thickness of around 100 meters (fig. 4 and 6). Mineralization is hosted in Igoudine
182 and Amouslek Formations and more especially in dolostones and siltstones beds, rarely in lavas or
183 claystones beds. It is noteworthy that ore bodies are distributed within and along the “folding band”
184 with an orientation NE-SW i.e., they show the same preferential orientation as that of the folds (fig. 3).
185 Moreover, on a NE-SW cross section (fig. 4), the ore bodies show thickness variation: in the hinge of
186 anticlinal the thickness is maximal whereas in the hinge of synclinal the thickness is minimal (fig. 4).
187 Similarly, the vertical fault strongly controls the ore bodies distribution with a nearly barren
188 southwestern compartment contrasting with a rich folded northeastern one (fig. 4). On a NW-SE cross
189 section, the thickness of the ore bodies is constant and does not show significant variation (fig. 5).

190 **4.2.2 Mineralogical composition and paragenetic succession**

191 Without distinction between primary and secondary origin, the copper mineralization is
192 composed of chalcocite, bornite, chalcopyrite, covellite, digenite, malachite, chrysocolla, tenorite,
193 native copper and cuprite, associated with quartz, dolomite and calcite as gangue mineral. These
194 gangue minerals in veinlets or voids systematically show, a banding texture. The observed growth
195 direction indicates a centripetal quartz, dolomite and finally calcite (fig. 6A). This gangue chronology

196 is a good landmark to determine the copper mineral succession. Bornite appears as minute grains (less
197 than 20 μm) in the quartz and dolomite ribbons, equally distributed between these two minerals.
198 Frequently, lamella exsolutions of chalcopyrite are observed in bornite grains. Chalcocite occurs in
199 ribbon between the bands of dolomite and calcite. Chalcocite grains mostly appear with an anhedral
200 shape without internal structure. Sometimes this mineral displays a hexagonal cleavage (fig. 6B and
201 6C), suggesting, in this case, a primary origin at above 103°C (Ramdhor, 1969). This generation of
202 chalcocite is named CC1. Beside, chalcocite exists in association with covellite, digenite and
203 chalcopyrite, in replacement around the bornite, in this case chalcocite, covellite and digenite can be
204 interpreted as cementation assemblage. This chalcocite is named CC2. Malachite replaces chalcocite
205 and dolomite and may be replaced by chrysocolla. Malachite also replaces cuprite but sometimes the
206 opposite situation is observed. Veinlet fills only by malachite are been observed, they cut all the other
207 rock components and structures except chrysocolla.

208 All these relations between minerals allow to discriminate a primary origin represented by:
209 quartz, bornite, chalcopyrite, dolomite, chalcocite (CC1) and calcite, and a secondary origin
210 represented by: covellite, digenite, chalcocite (CC2), malachite, chrysocolla, tenorite, native copper
211 and cuprite (fig. 7). Based on intersections relations between the different mineral phases, several
212 episodes of fissuring have been observed (fig. 7).

213 **4.2.3 Multiscale observations of the ore texture**

214 At macroscopic scale, on core samples, two textural types of mineralization have been
215 distinguished. The most frequent is a stockwork with veins/veinlets parallel or oblique to the
216 stratification plane (fig. 8). Parallel-bedding veins are still connected to cross-bedding veins (fig. 8C).
217 The second type corresponds to disseminations within the rock ground mass. Locally it is spatially
218 related to the stockwork (fig. 8D). When it is well develop, veins of the stockwork can show breccia
219 texture with angular fragments and in situ fragmentation texture without significant rotation of the
220 fragment that is characteristic of fluid-assisted brecciation (Jébrak, 1997) (fig. 8A). At the microscopic
221 scale, both types of mineralization appear composed by the same ore and gangue minerals. Textural

222 and chronological relationships being also similar, both mineralization types have the same
223 paragenetic sequence (fig. 6, 7 and 8). Veins can also locally show a cockade breccia and quartz with
224 comb texture (fig. 6F and 6G). At this scale, disseminated grains of copper-bearing minerals, down to
225 50 micrometers in size, are still observable (fig. 6E). Noteworthy, they frequently show a close spatial
226 relationship with the veinlet of the stockwork (fig. 6E). At the scanning electron microscope scale, the
227 disseminated mineralization appears as micro-voids or geodes that display the same mineralogical
228 content and the same paragenetic succession as that observed at higher observation scales (i.e. with
229 quartz or dolomite at the wallrock and chalcocite at the center) (fig. 9).

230 **4.2.4 Mineralogical distribution at the deposit scale**

231 Using the data collected on 9 core drills and on surface mapping, the Cu-bearing mineral
232 abundance is plotted in cross-sections (fig. 4 and 5). The mineralogical abundances are displayed in
233 the form of spider diagram, with, at the top, the secondary Cu-bearing "oxydized" minerals (malachite,
234 chrysocolla and cuprite) and at the bottom the primary or cementation Cu-bearing minerals
235 (chalcocite, bornite and chalcopyrite). The mineralogical abundances are evaluated through
236 microscopic observations of polished thin sections of mineralized cores. The content of each mineral
237 is evaluated visually using an abundance chart (Dutro et al., 1989). Results are expressed in the
238 corresponding axis of the spider diagram in a scale of 0 to 100% with steps of 20%.

239 Chalcocite and malachite are the most abundant minerals in the Jbel Laassel deposit (fig. 4 and
240 5). According to our observations, no obvious zonation appears between primary sulfides and
241 "oxidized" mineralization.

242

243 **4.3. Principal Component Analysis (PCA) of chemical data**

244 Two multi-element databases were available for PCA: the larger one, does not include Cu
245 analyses, while the second one includes Cu analyses for a smaller number of samples. PCA analysis
246 was performed on both sets separately using varimax criteria.

247 4.3.1. Dataset without copper measurements

248 The first results on database without copper measurements (228 analyses) show that two
249 factors F1 and F2 explain 42.06 % of the total variability (fig. 10A). Three groups of elements
250 discriminated in the F1-F2 plane represented by the CaO, MgO and MnO cluster (group 1)
251 discriminates the carbonate matrix, the second SiO₂, Al₂O₃, K₂O and B clusters represents the clay
252 sedimentary component (group 2) whereas the last Co, P₂O₅, Fe₂O₃, TiO₂ and Pb cluster (group 3)
253 probably marks the lava component (fig. 10B). Thus, referring to the F1 F2 chemical space (fig. 10C),
254 the analyzed dolostones consists of alternation of siltstones and dolostone layers, with interstratified
255 lavas in both of them. It appears that the three groups of variables can be interpreted in terms of
256 lithology: the groups 1, 2 and 3, corresponding respectively to dolostones, siltstones and lava
257 formations (fig. 10C).

258 4.3.2 Dataset including copper measurements

259 This data set comprises 72 analyses. For the Cu-mineralized data set (Cu % and CuOx %), the
260 four first factors account for 80% of the total variance. Beyond factor 4 the explained variance
261 decreases sharply. The plane F1-F2 represents 48.29% of the total variance (28.27% for F1 and 20.01
262 for F2). The three petrographic groups previously identified in the F1-F2 plane are well discriminated
263 by the same element clusters (fig. 10D). This representation of the variables suggests that copper (total
264 or oxidized) is not linked to any of the three types of lithology. Indeed, copper is independent of
265 sedimentary dolostones and siltstones, and it is anticorrelated with the lavas (fig. 10D). Moreover, an
266 examination of the F1-F2 plane, suggests that copper could be associated with barium, but the
267 correlation coefficient between total copper and barium is -0.05 and that of barium with oxidized
268 copper is 0.03. This is due to the fact that the total copper, oxidized copper and barium are badly
269 represented in the plane F1 - F2, as shown in the diagram in figure 10D and by the values of the
270 weighting coefficients between the original variables and factors. For total copper, oxidized copper
271 and barium, these values are -0.19, -0.23 and -0.16 with respect to F1 and -0.30, -0.38 and -0.38
272 relative to F2. The factors where copper (total and oxidized) is best represented are F3 and F6. The

273 weighting coefficients between the copper, the oxidized copper and the factors are 0.54 and 0.42 with
274 respect to F3 and 0.59 and 0.63 relative to F6, respectively. The variables representation in the plane
275 F3-F6 (17.37% of the total variance, 12.55% for F3 and 4.82% for F6) shows that the variations of the
276 total copper and of the oxidized copper are not associated with changes in the others variables values
277 (fig. 10E). Therefore, the PCA highlights the independence of copper (total and oxidized) relative to
278 the others variables present in the available database, especially that corresponding to lithology.

279 5. Discussion

280 In the Jbel Laassel copper deposit, at a macroscopic scale, the mineralization is present as a
281 stockwork and disseminations. The stockwork is composed by veins filled with a primary paragenesis
282 composed by: quartz, bornite, chalcopyrite, dolomite, chalcocite, calcite and a secondary paragenesis
283 composed by: covellite, digenite, malachite, chrysocolla, tenorite, cuprite and native copper. The veins
284 of this stockwork crosscut the stratification plane or are parallel to it. Both vein families always
285 present the same mineralogy, texture and paragenetic evolution. These observations suggest that, with
286 respect to the primary sulfide paragenesis, all the stockwork veins are coeval and formed during the
287 same mineralizing event. SEM observations reveal that disseminations correspond to microcracks and
288 cavities filled with the same mineralogical content and the same textural characteristics that of
289 stockwork veins; moreover the disseminated Cu-bearing mineral grains are directly “connected” to the
290 stockwork veins. Thus, all the primary mineralization, from the macroscopic scale to the scanning
291 electron microscope scale, is related to the stockwork and deposited during a unique hydrothermal
292 event of fluid assisted fracturation of the host sedimentary rocks. All these observations favor an
293 epigenetic origin of the Jbel Laassel mineralization. In addition, the principal component analysis
294 shows that copper does not have affinities with any of the lithological groups present in the area. This
295 result is also consistent with an epigenetic origin of the mineralization. The limits of the ore body
296 correspond to the limits of the “folding band” (fig. 3). In the cross-section perpendicular to the main
297 extension of the folding band (fig. 4), the ore body is concentrated in the anticline hinges and his
298 thickness decreases in syncline hinges; whereas in cross section parallel to the main extension of the
299 folding axis, the ore body is continuous and does not show noticeable thickness variations (fig. 5).

300 Consequently the mineralized stockwork is clearly controlled by hectometric folds, which are, with the
301 Igoudine and Amouslek Formations, the trap of the mineralization. Available structural and fault
302 analysis data do not allow us to decipher clearly the control exerted by the vertical faults on NW-
303 trending mineralized folds. However, the structural pattern associated with the "folding band" suggest
304 folding developed within the cover above fault involving basement through drap folding and/or
305 flower structure mechanisms (Sylvester, 1988; Fossen et al., 2013).

306 Soulaïmani & Burkhard (2008) describes variscan kink bands with a rough cleavage in the
307 vicinity of Panafrican structures in the basement of the Bou Azzer El Graara inlier. These authors
308 interpret these folds in terms of the reactivation of Panafrican structures during the late Paleozoic
309 compression. In the terminal Neoproterozoic to Cambrian's cover, folds are currently attributed to this
310 Paleozoic compression, controlled by the movement of inherited basement structures (Leblanc, 1972;
311 Soulaïmani, 1997; Faïk et al, 2002; Soulaïmani & Burkhard, 2008). It results in Bou Azzer-El Graara
312 inlier, metric to decametric folds, have NW-SE trending axes exhibit with a subordinate NE-SW
313 orientation (Soulaïmani & Burkhard, 2008). The folds in the "folding band" of Jbel Laassel display the
314 same characteristics as the ones given by Soulaïmani & Burkhard (2008), for the Variscan folds, i.e.
315 metric to decametric folds and NW-SE trending axes with a subordinate NE-SW orientation. In such
316 conditions, the age of the mineralizing event could probably be contemporary to the deformation or
317 younger. It could be possible that the intersection between the "folding band" and the NE-SW
318 synclinal took a role in the trap of mineralization formation. This "folding band" is associated with a
319 major NW-SE fault with a kilometers extension. This fault probably acted as a drain for fluids that
320 formed the mineralization of the "folding band" in the Jbel Laassel area. Anticlinal hinges of the
321 "folding band" could be a trap for hydrothermal discharges with a fluid-assisted fracturing focused in
322 these hinges. The major NW-SE fault could be in direct relation with the basement, as reported by
323 Soulaïmani & Burkhard (2008) for the others Variscan faults in the terminal Neoproterozoic to
324 Cambrian cover. This fault could thus emphasize a basement influence at the origin of the Cu
325 mineralization of Jbel Laassel. We propose that Cu mineralization hosted in the terminal
326 Neoproterozoic to Cambrian cover are linked to Variscan reactivation of inherited basement structures

327 and Variscan faults that drained fluids which precipitated its copper content in the anticlinal hinge of
328 the Jbel Laassel "folding band".

329 **9. Conclusion**

330 The copper mineralization in Jbel Laassel area is epigenetic and is controlled and coeval with
331 decametric folding, whose axes exhibit a NW-SE trend in the Igoudine and Amouslek Formations.
332 These folds are concentrated in a 150 to 200 m wide band, probably formed during the Variscan
333 compression. Consequently the mineralizing event took place during this period or later. The
334 mineralization appears as a stockwork, displaying the same characteristics (texture and mineral
335 composition) from the macroscopic scale to the scale of the scanning electron microscope, i.e. it shows
336 a textural autosimilarity regardless the scale. The proposed interpretations therefore should not be
337 extended to the others mineralization hosted in the Neoproterozoic to Cambrian's cover of the Bou
338 Azzer El Graara inlier without any further study. On the other hand, for academic but also applied
339 purposes, this work highlights the necessity to perform more detailed studies of the Cu-occurrences
340 hosted in the cover of the Bou Azzer El Graara inlier to reevaluate the factors controlling these
341 mineralizations.

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415 **Figures:**

416 **Figure 1: A:** Schematic geologic map of the Anti-Atlas with occurrences of copper mineralizations
417 modified from Bouchta et al. (1977). Inliers abbreviations : If, Ifni; Kr, Kerdous; Ir, Igherm; TA,
418 Tagragra d' Akka; TT, Tagragra Tata; AM, Agadir Melloul; Ze, Zenaga; Sr, Sirwa; Bz, Bou Azzer-El
419 Graara; Sg, Saghro; Og, Ougnat. **B:** Geological and structural map of the Bou Azzer-El Graara area
420 with occurrences of copper mineralizations, modified from Leblanc (1975).

421 **Figure 2 :** Lithostratigraphic column for the Jbel Laassel area modified from Soulimani et al. (2013).

422 **Figure 3: (a)** Geological and structural map of the Jbel Laassel area, modified from Kersit (1984); **(b)**
423 Stereogram (Wulff stereonet, lower hemisphere) of bedding (S_0) and fold axes (n, number of
424 measures).

425 **Figure 4:** Geological cross-section (section location A-A' in the map) with ore body limits and
426 mineralogical abundance of the copper mineralization which are represented in a spider diagram.
427 Results are expressed in the corresponding axis of the spider diagram in a scale of 0 to 100% with
428 steps of 20%. Abbreviations: Mal, malachite; Ccl, chrysocolla; Cup, cuprite; Dg, digenite; Bn, bornite;
429 Ccp, chalcopyrite; Cc, chalcocite.

430 **Figure 5:** Geological cross-section (section location B-B' in the map) with ore body limits and
431 mineralogical abundance of the copper mineralization which are represented in a spider diagram.
432 Results are expressed in the corresponding axis of the spider diagram in a scale of 0 to 100% with
433 steps of 20%.. Same abbreviations than fig.5.

434 **Figure 6:** Microphotographs of the Jbel Laassel Cu ore. **A:** Vein showing banding gangue texture
435 with quartz on wall, next dolomite and calcite at center (TL nic. +). **B:** Chalcocite in ribbon between

436 bands of dolomite and calcite (RL, nic. //). **C:** Chalcocite in vein with hexagonal cleavage (RL, nic. //).
437 **D:** Quartz and chalcocite veinlet link to a vein forming a stockwork (TL, nic. //). **E.1:** Quartz vein
438 cutting bedding (S0) of siltstone and silicification of the siltstones bedding (TL, nic.//). **E.2:** Same
439 photography as E.1 but in RL (nic. //), chalcocite in vein and in dissemination in silicified bedding,
440 these disseminations were observed at SEM scale (see fig.9). **F:** Quartz, dolomite and chalcocite vein
441 showing micro-cockade breccia texture (TL, nic. //). **G:** Quartz in vein with comb texture and
442 malachite veinlets cutting other rock components and structures (TL, nic. +). Abbreviations: Cc1,
443 primary chalcocite; Dol, dolomite; Mal, Malachite; Qtz, quartz. TL, transmitted light; RL, reflected
444 light; nic. //, parallel nicols; nic. +, crossed nicols; S0, bedding of rock.

445 **Figure 7:** Paragenetic succession.

446 **Figure 8:** Photographs of core drill samples. **A:** Stockwork with gangue minerals, chalcocite,
447 chrysocolla and malachite, and a fluid assisted breccia texture. **B:** Chalcocite stockwork. **C:**
448 Chalcocite stockwork with vein secant and parallel to the dolostone bedding. **D:** Veins of chalcocite
449 cutting the dolostone bedding and chalcocite in dissemination in dolostone but linking to the vein, these
450 disseminations were observed at SEM scale (see fig.9). Abbreviations are given in figure 7.

451 **figure 9:** SEM photographs of disseminated copper mineralization (see figures 6E and 7D). **A:** BSE
452 image of a micro-vein (100 μm width) composed by quartz, dolomite and chalcocite. **B:** BSE image of
453 a micro-vein (25 μm width) composed by quartz, dolomite and chalcocite.

454 **Figure 10:** Results of PCA analyses of the data base without copper (A, B and C) and of the data base
455 with copper (D and E). **A:** Eigenvalues and cumulative variance function of factors. **B:** Variables
456 projection in the F1-F2 plane (data set without copper: 228 analysis). **C:** samples lithology project in
457 F1-F2 plane (data set without copper: 228 analysis) and Variables projection in the F1-F2 plane
458 without legends. **D:** Variables projection in the F1-F2 plane (data set including copper: 72 analysis).
459 **E:** Variables projection in the F3-F6 plane (data set including copper: 72 analysis).

460

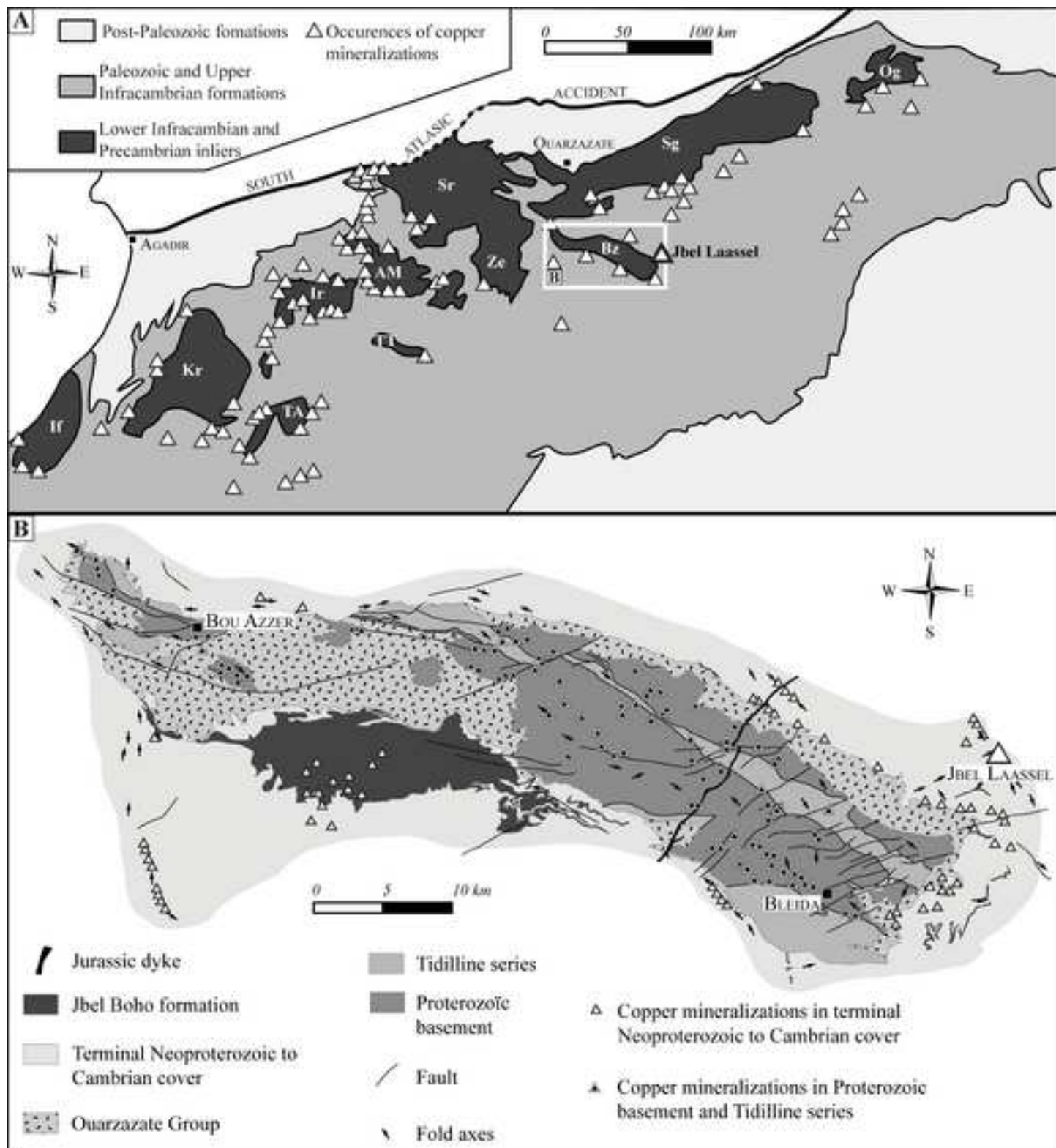


Figure 2

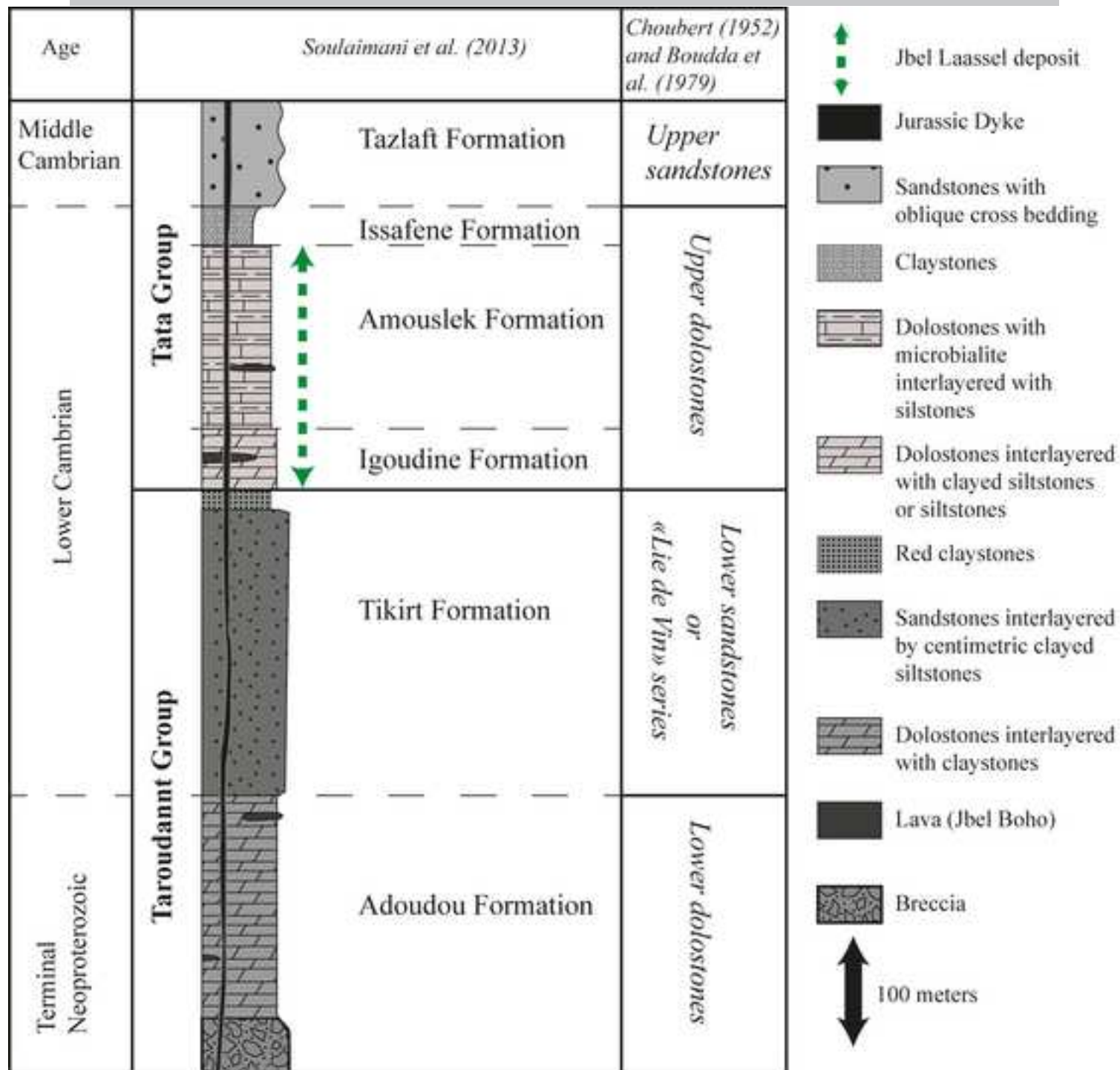


Figure 3

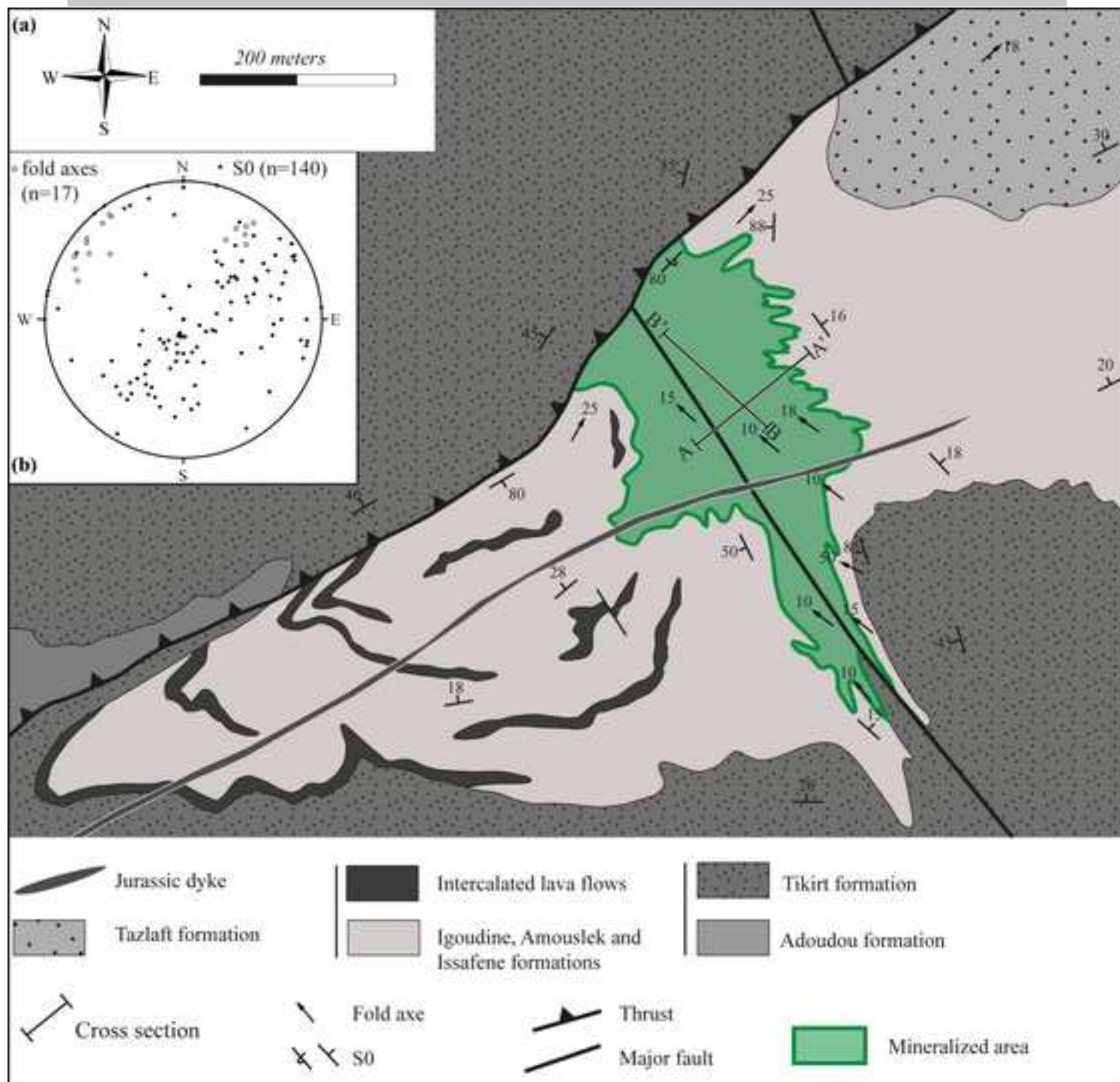


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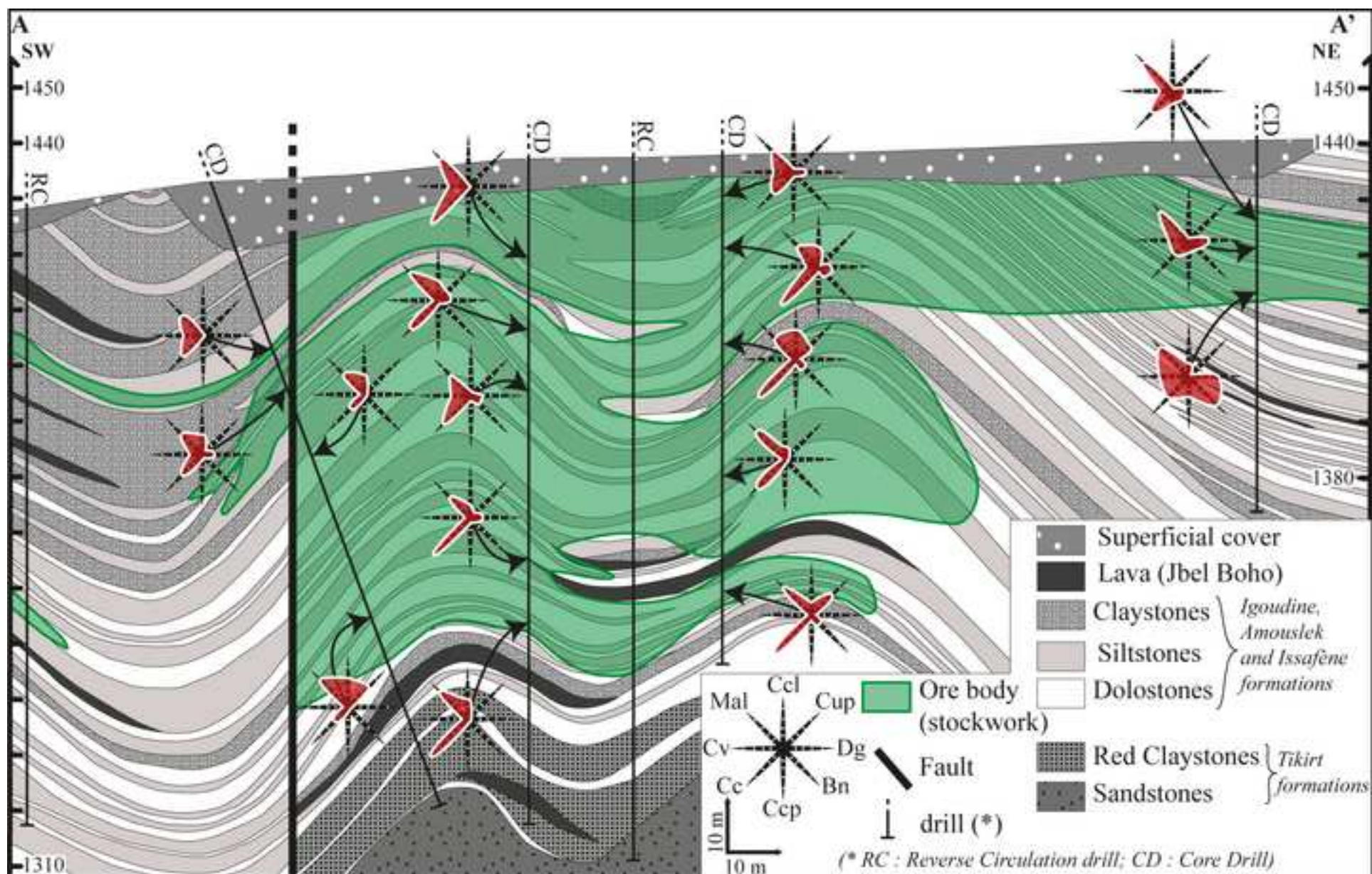
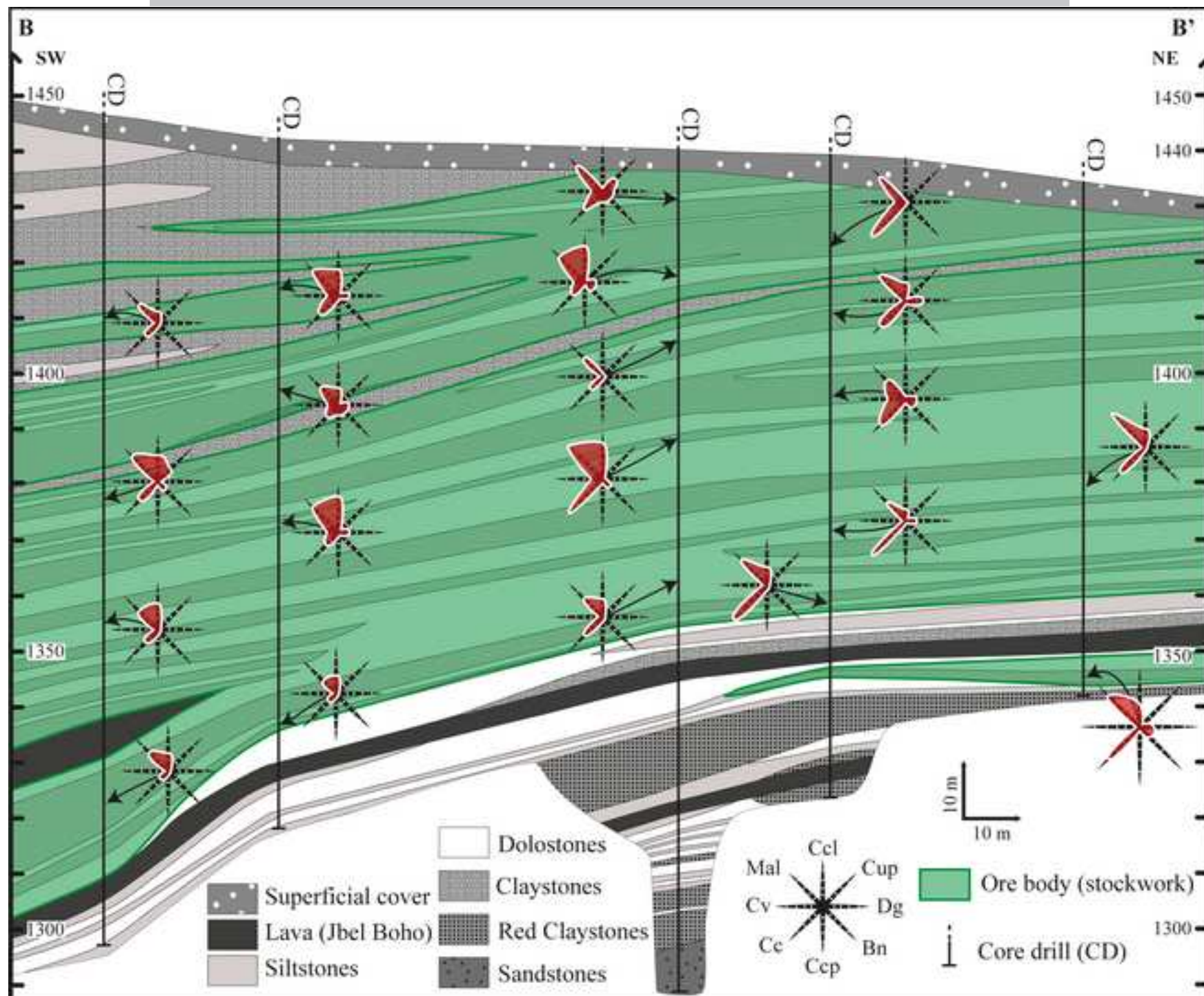
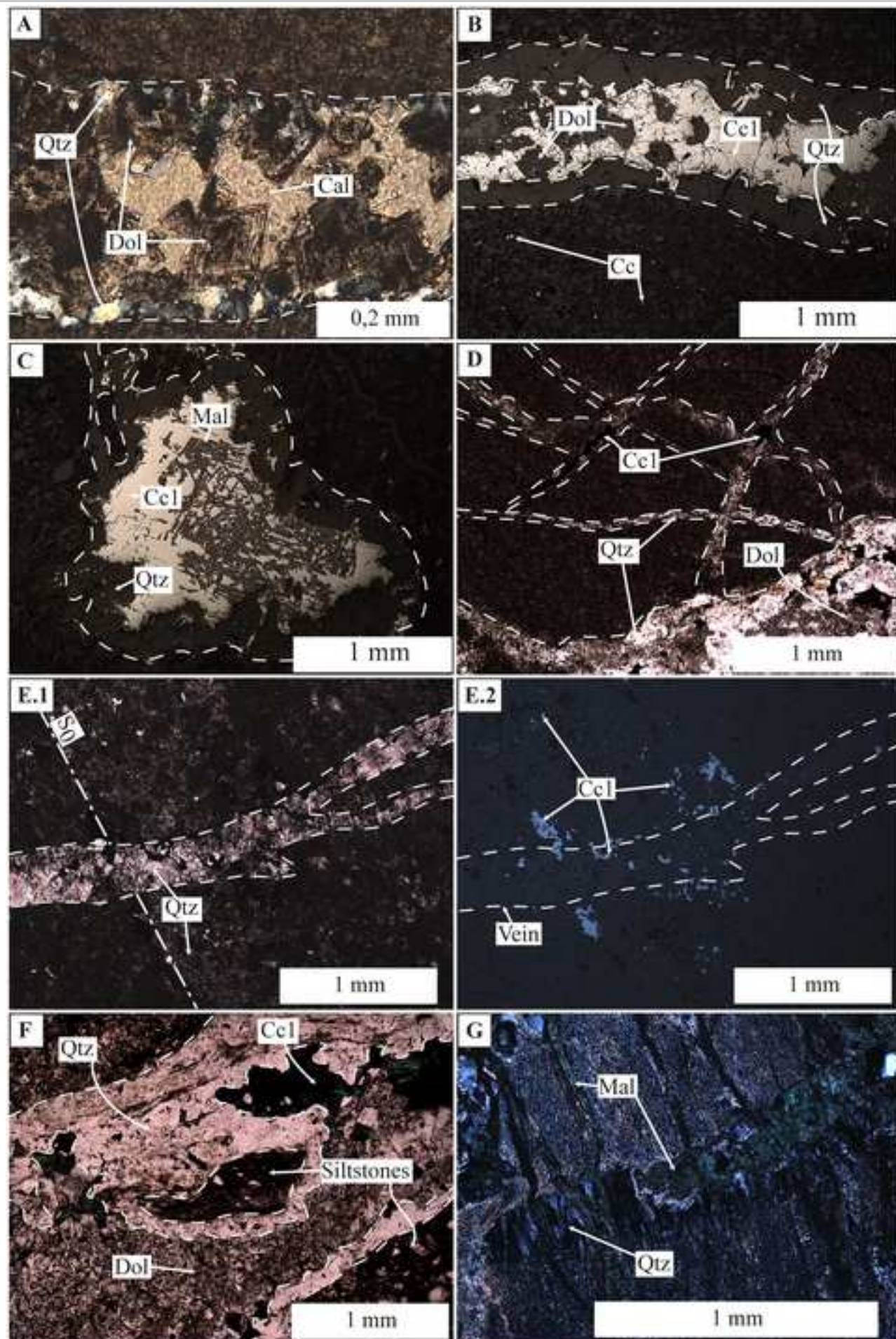
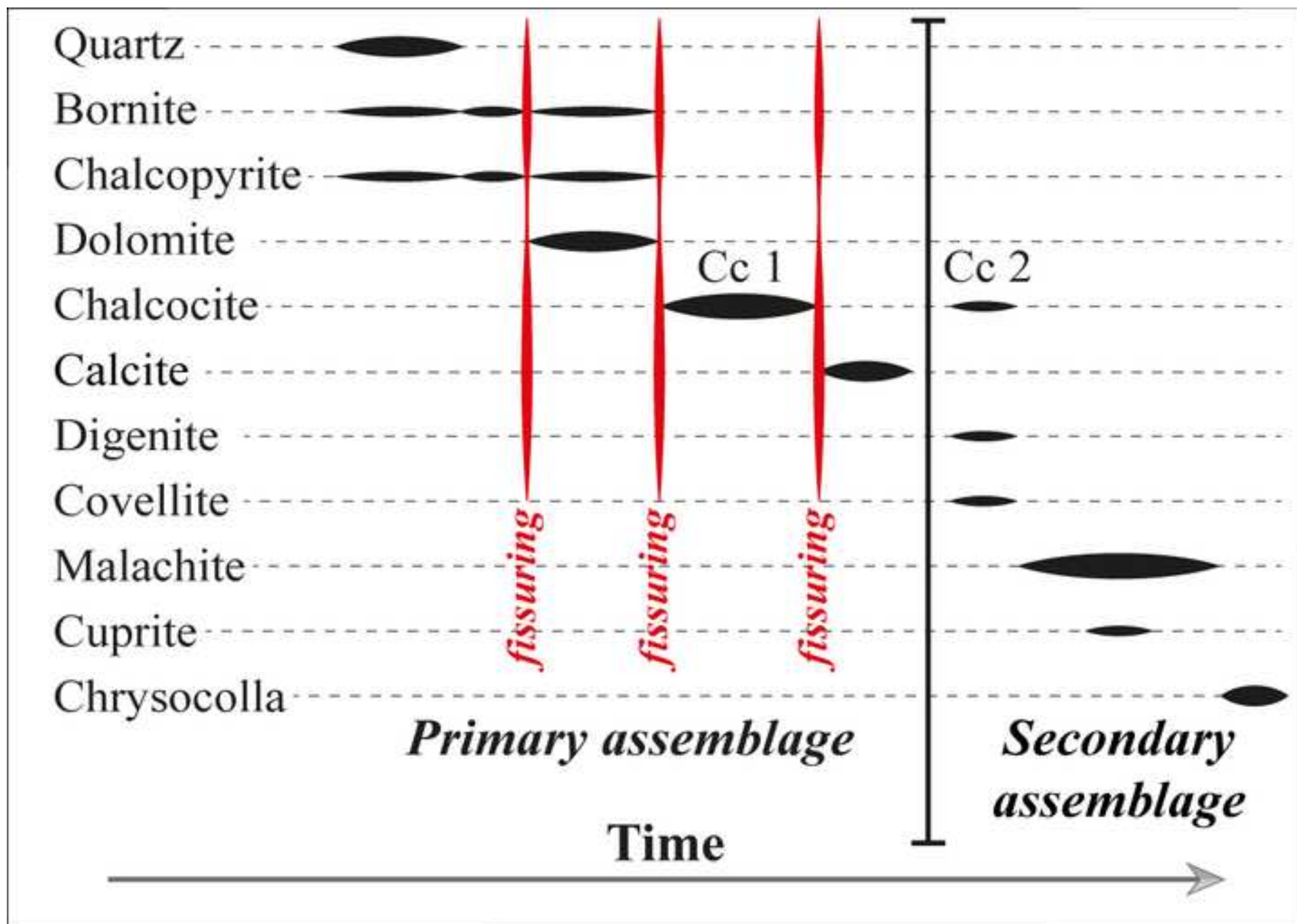
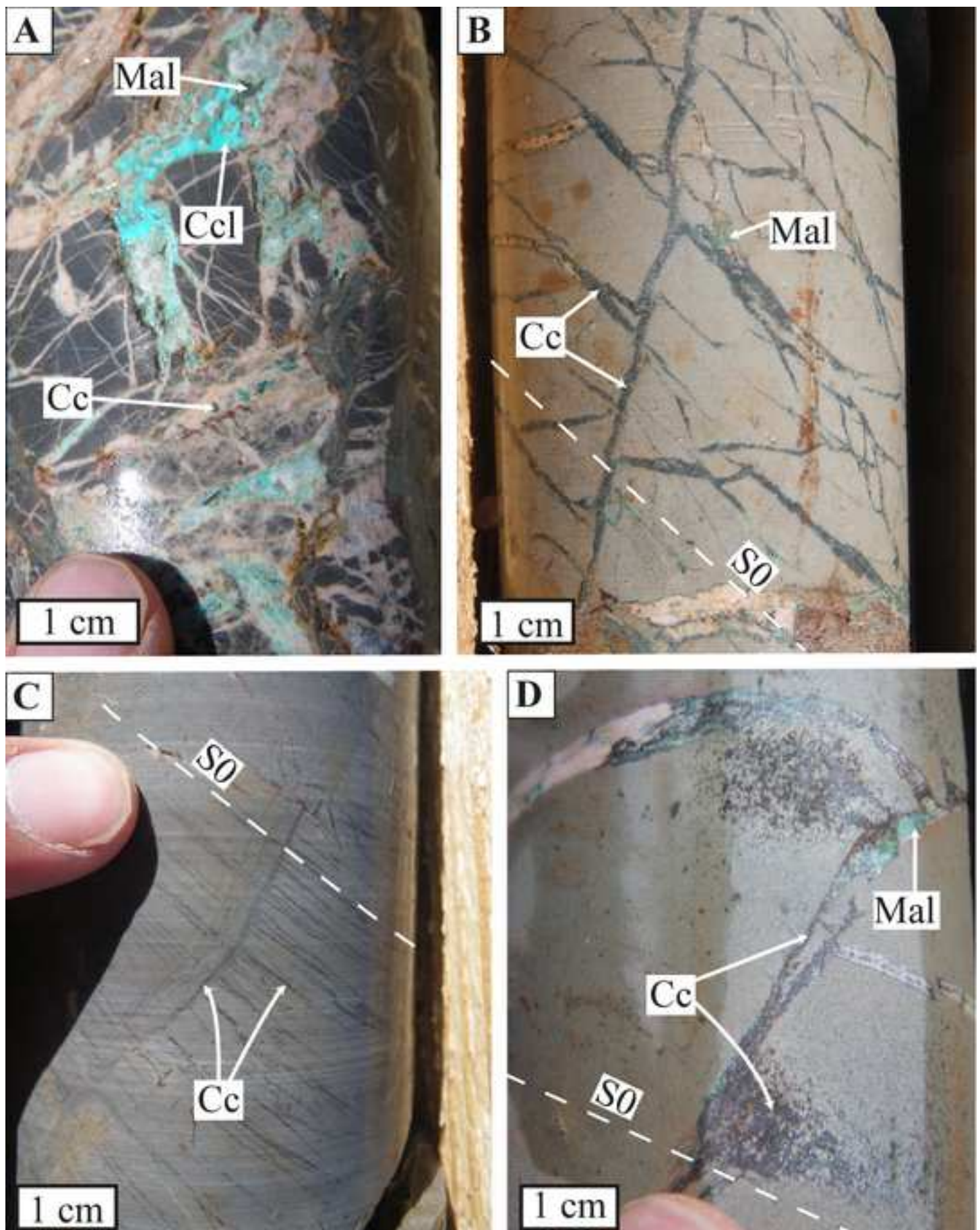


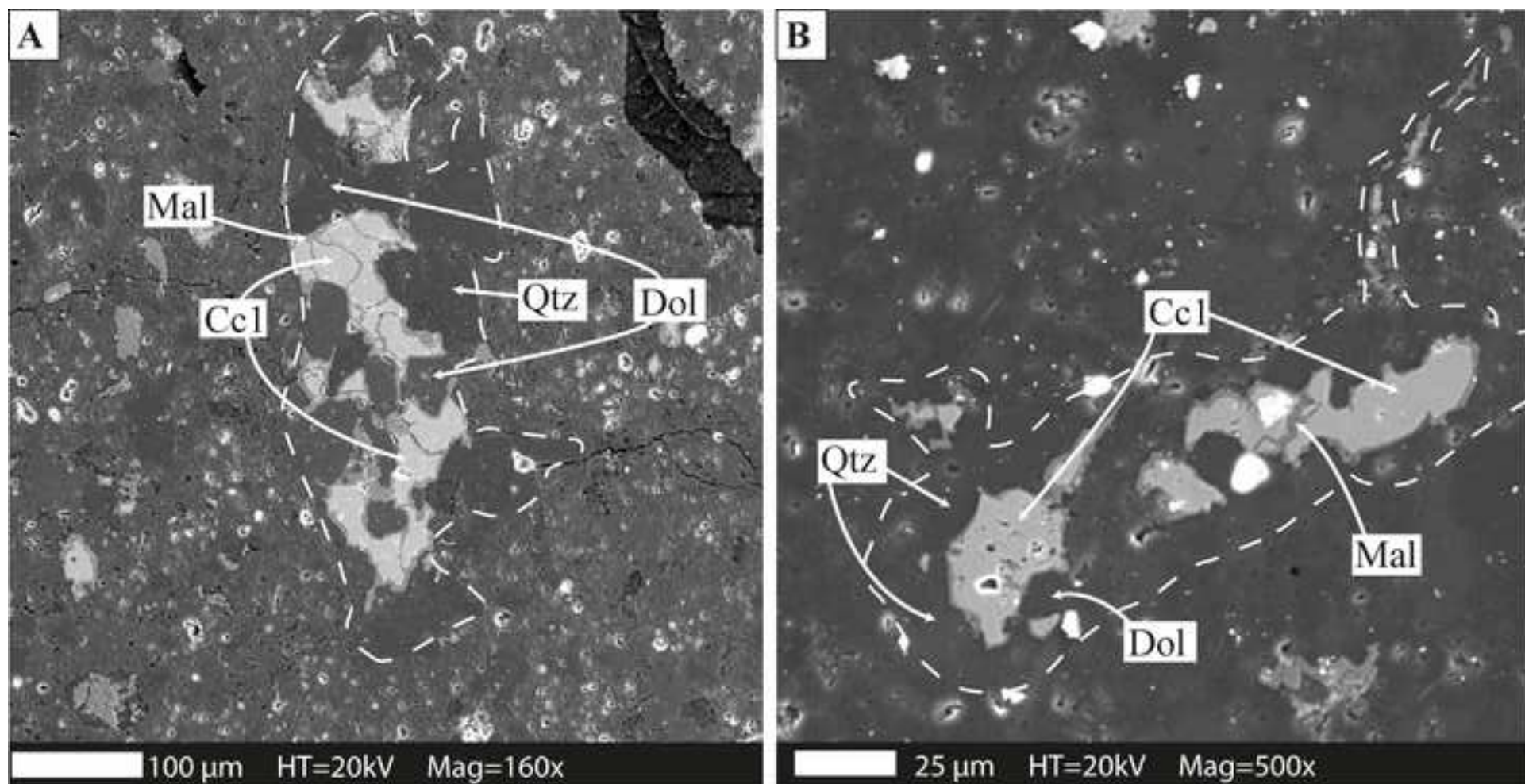
Figure 5

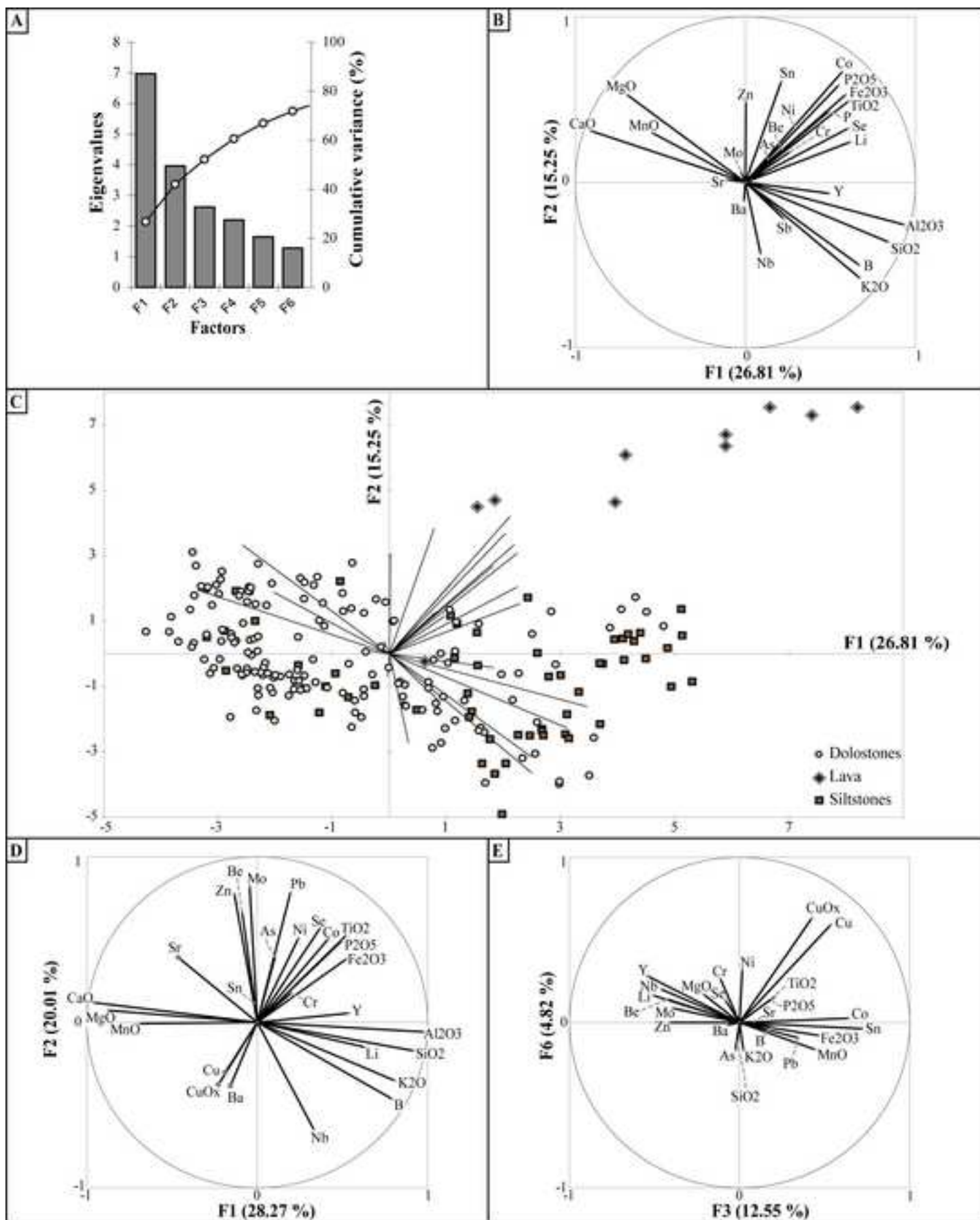












461

462

463 Highlights:

464

- 465 • Copper mineralization occurs in a Variscan folding band in Cambrian cover.
- 466 • The mineralization appears as a stockwork with autosimilar texture.
- 467 • Results from component principal analyses don't show relation with lithology.
- 468 • The Cu-mineralization is epigenetic, controlled by fold axis.

469

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