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Evaporitic brines and copper- sulphide ore genesis at Jbel Haïmer (Central Jebilet, Morocco): A reply.

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Sir: Our article “Evaporitic brines and copper - sulphide ore genesis at Jbel Haïmer (Central Jebilet, Morocco)” is far from being « *a contribution to the greater understanding of the granite-related vein-type base and precious metal sulphide deposits* », as Bouabdellah et al. comments pointed out to us. The comments are based on indirect geochronological data, an unacceptable generalization, a wrongful extrapolation, and a paradigm. In what follows, we will show that the comments provided by Bouabdellah et al. are unwarranted because their arguments are poorly supported by data.

Our paper seeks to show that late-Variscan structures, which were originally the site of at least metamorphic if not strictly magmatic fluid transfers, can replay during later stages totally disconnected from the Variscan stages, notably during extensional tectonics related to the Atlantic Ocean opening. It is therefore this notion of telescoping between two distinct processes that is put forward.

It is obvious that the Variscan faults and shear zones carried fluids most often deeply equilibrated with the metamorphic host rocks, and set in motion around magmatic intrusions whose heat flow initiated the convective movements of fluids. Such processes are distinct from those occurring later with the involvement of basinal brines. There are many other examples where faults have been reactivated and comprise Paleozoic and Mesozoic mineralisation that present similar geological history and fluid evolution for “five-element”, fluorite-baryte and Pb-Zn-Cu vein ores such as in the French Massif Central (Cathelineau et al., 2012), Schwarzwald (Walter et al., 2016) and Erzgebirge (Haschke, et al., 2021).

Ages of the ore processes

Late Variscan magmatic Sn-W-Mo deposits and orogenic Au-deposits: Contrary to the comment, our paper does not examine at all the Au-deposits in Morocco, but is focused on base metal and silver veins. It is evident that Sn-W (Mo), Au-As deposits in ductile to brittle

structures are related to fluid movements associated to late Variscan exhumation and deformation, frequently driven by late magmatism in the whole Variscan belt including Portugal, Galicia, South-West England, French Massif Central, Bohemia (Sn-W: Harlaux et al., 2018, Burisch et al., 2019, Moscati and Neymark, 2020, Cathelineau et al., 2020; Au-As deposits: Boiron et al., 1996, 2001, 2003, Essarraj et al., 2001, Vallance et al. 2003).

Introduction of Ag in the systems: The main remarks of this comment are based essentially on data from the literature, often debatable or subject to opposing interpretations. It is recalled that the polemic on the Ag deposits of the Pan-African buttonholes from Morocco is not new and was initiated by Levresse et al., in 2017 on the example of our contribution to the paleofluids study from the Imiter deposit (Anti-Atlas) (see our reply for more details, Essarraj et al. 2017a). We looked carefully for the arguments that led these authors to put forward a purely magmatic-hydrothermal model for this type of Ag-deposit when it is clear that basin brines of evaporitic origin at least reworked if not contributed to the whole silver stock. The only argument found in the publications of Levresse et al. (2004) is disarming because it is based on the sole postulate that a deposit of this importance can only have been formed by or in the vicinity of a magmatic intrusion. Therefore, by applying this postulate, authors then date the intrusion to date the processes at the origin of the deposit. But the story of such deposits is not so simple. In a non-exhaustive list of statements:

- no direct dating on base metal-silver metal ores in Morocco have been carried out in all the works cited (herein) by comment's authors. In the absence of textural data that would validate the contemporaneity of the magmatic phases with the hydrothermal events responsible for ore deposition, they bet on attributing the age of the intrusions to the ore veins. As Levresse et al., (2016), comment's authors repeat the same bet.
- zircon ages for Jbel Aouam Pb-Zn and Zgounder Ag-deposits but also for Panafrican host rocks enclosing Imiter Ag-deposit: dating magmatism is easy and well done, whereas the temporal relationship between magmatism with the neighbouring ores is not established.
- muscovite from host rocks or early barren veins at the Zgounder silver deposit, which are not proven to be contemporary of Ag-ores.
- Cu – Pb – Zn ± Ag ± Au ore vein system clearly crosscuts granitoids at Bouskour deposit, according to Walsh et al. (2008). Although molybdenite Re/Os age slightly corresponds to the age for granitoids in this area, Bouabdellah et al., (2016) themselves admit that the Bouskour mineralisation is polyphase (three stages) where the third stage of *“base-metal ± Ag ± Au ± copper sulphide mineralization remains enigmatic and its emplacement is poorly constrained*

due to the lack of reliable geochemical data”, thus not coeval with molybdenite (i.e. second stage). In conclusion, it seems like line of arguments of Boudabdellah et al. is based on indirect age data and misunderstanding of the concept of polyphase mineralisation through attributing the same age to all the successive parageneses and their host rocks when distinct events with neither temporal nor genetic relationships may have been superimposed in the same place.

The second problem we would like to highlight is that this comment intentionally ignores and dismisses certain facts that challenge purely magmatic-hydrothermal models. The best example is the Imiter deposit where: (i) dating of adularia (non-magmatic) clearly preceding silver-base metal ores (as established by Essarraj et al., 2016, Tuduri et al., 2018), gave an Ar/Ar age about 254.7 Ma (Borisenko et al. 2014, Lebedev et al., 2016), (ii) halogen ratios (Cl-Br-I) clearly demonstrated that ore brines are sedimentary bitterns (Essarraj et al., 2016, 2017a) excluding any involvement of magmatic fluids in silver mineralisation. In the same way, Yajoui et al., (2019) described a “Imiter-type” silver-base metal mineralisation at Tassafte deposit (located about 20 km NE of the Imiter mine) constituted of ore veins clearly crosscutting Paleozoic rocks, thus much younger than Panafrican intrusions. All these arguments remove any ambiguity about the post-Permian age of most, if not all, silver-base metal mineralisation in the Eastern Anti-Atlas. This agrees with the genesis of similar deposits in Western and Central Europe - all related to the opening of the Northern Atlantic: F-Ba in Spain (Asturias, Sanchez et al., 2010), Pb-Zn (Ag) in the Poitou High and French Massif Central (Cathelineau et al., 2012, Boiron et al., 2010), Germany: (Markl et al., 2016; Burisch et al., 2016), Schwarzwald deposit, (Walter et al., 2016), Poland (Silesia, Heijlen et al., 2003).

Age of the microdiorite at Jebel Haïmer and relative timing with brines and Cu-ores

The Cu-mineralisation at Jbel Haïmer fills carbonate veins unambiguously crosscutting microdiorite dikes, and is therefore later. Absolute dating of dikes (Youbi et al. 2001; Dostal et al. 2005; Bouloton et al. 2019) are all concordant on an age of 240-255 Ma. Therefore, the age of brine circulation and Cu-deposit is younger than this age. The circulation of brines under hydrothermal-diagenetic conditions is related to the presence of Triassic evaporites that postdate the microdiorites. The setting in motion of these brines, and consequently the formation of copper mineralisation, is therefore related to the episodes of fracturing and heat flow produced by the most important subsequent events from a geodynamic point of view, which are linked to the opening of the Atlantic Ocean.

Magmatic versus evaporitic brines

Comment's authors affirm without argument: « *fluid inclusion compositions presented by Essarraj et al. are likely related to hydrothermal circulation of magmatic brines coincident with the emplacement of late Variscan granitoid* ».

More than 270 fluid inclusions (FIs) were studied at Jbel Haïmer:

- Granite intrusions and contact metamorphism (Paleozoic late granite stage): high temperature assemblages (quartz-tourmaline-biotite-cassiterite) are formed at more than 300°C, from relatively high salinity fluids which could be of magmatic origin. Such fluids are followed by C-H-O-N fluids produced in metamorphic series and at equilibrium with graphite, and which formed the As (Co-Ni) assemblages.
- The post-Triassic Cu-stage is characterised by sedimentary brine FIs (salinity 31 – 39 wt% NaCl) showing much lower homogenisation temperatures (Th of 180-250°C) compared with the Variscan FIs (see Table 3 in Essarraj et al., 2021 for more details). Brine fluid inclusions have been analysed by LA-ICP-MS (see Fig. 14 in Essarraj et al. 2021) and their composition strongly resembles most Triassic brines known in Western Europe, frequently implied in metasomatic processes and F-Ba-base metals ore deposits (Boiron et al., 2002, Leisen et al., 2012, Walter et al., 2016, Quesnel et al., 2019).

The concept of superimposed metallogenic events

Comment's authors did not perceive that we attributed early parageneses from Jbel Haïmer (tourmaline, Sn, Bi, Fe, As, ...), constituting the first stage of our model, to magmatic – metamorphic Variscan events and not to post-Permian events (see the first part of our discussion in the article and figure 15 which illustrates the two distinct metallogenic events).

If our paper is read carefully, there is no ambiguity on the attribution of mineral assemblages, isotopic and fluid inclusions data to two distinct stages:

- a late Variscan stage, with high temperature C-H-O-N fluids (> 300-350°C at less), Sn- tourmaline, and then As (Ni-Co) assemblages linked to convection of fluids in metamorphic rocks around late plutons. The Kettara deposit and Roc blanc – Jbel Haïmer share early fluids from metamorphic origin (O-H data in N'Diaye et al., 2016 and Essarraj et al. 2017b), similar to those described in the whole Central Jebilet (Bastoul, 1992) responsible for large swarms of early barren quartz veins at Kettara, Roc Blanc, Jbel Haïmer and at Koudia El Hamra (Nshimiyimana et al., 2018).
- a post-Permian, post-microdiorite (e.g. post-240 Ma) stage, consisting of pre-Atlasic carbonate vein swarms, characterized by evaporitic brines mixing with less saline fluids at

temperatures below 280°C, and Cu-Pb-Zn (Ag) assemblage. P-T estimates as well as geothermal gradients used are based on geodynamic and paleogeographic context taken from reliable literature data. Reasonable thermal gradients, even much higher ones, would not modify significantly the resulting P-T boxes, because isochores for aqueous fluids with non-volatile are steep, and cannot be intersected in domains of high temperature. These two stages are superimposed at the same place as early Variscan faults have replayed during later on extensional tectonics linked to Atlantic rifting stages.

In conclusion, we provide a robust line of arguments showing that the critical comments from Bouabdellah et al. are unjustified and based on a misinterpretation of geochronological data and paragenetic relationships. As we have shown in the original manuscript, we here present a model that involves reactivation of fractures in response to several mineralisation stages. Based on the contrasted fluid types, the Paleozoic C-H-O-N fluids and Post-Permian sedimentary brines, the post-Permian absolute age of microdiorite dikes which are undoubtedly crosscut by Cu-ore bearing carbonate veins, we conclude that the Cu - base metal mineralisation at Jbel Häïmer is Post-Triassic. It is related to the mixing of high salinity basinal brines of evaporitic origin with low salinity fluids under moderate temperature (200°C) and low pressure (50 MPa) corresponding to a depth of 4-5 km.

It should be noted that the various deposits for which the magmatic-hydrothermal model is adopted as a guide to prospecting frequently encounter serious problems in extending their exploitation areas, probably because of the inefficiency of the chosen model. This seems to be the case, for example, of the Imiter deposit, where the model used for prospecting in the Precambrian basement is one that associates the mineralisation with Pan-African magmatism, whereas recently, the same type of mineralisation has been discovered in the Paleozoic cover. Thus, our model could only widen the field of exploration for base-precious metal deposits, since it allows the inclusion of at least Permo-Triassic terrains in the target areas and especially since metal-bearing basin brines, as it is well known for example in the MVTs, can circulate and mineralise much wider domains than fluids emanating from magmatic bodies.

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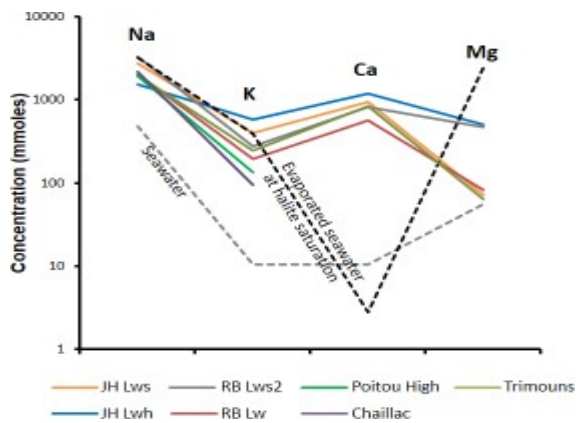


Fig. 14. Average Na, K, Ca and Mg concentrations in fluids from Jbel Haïmer (JH Lws and JH Lwh brines, this study) and Roc Blanc (RB Lws2 and RB Lw brines, Essarraj et al, 2017a). For comparison, chemical composition of brines from literature are plotted: Poitou High and Chaillac (Boiron et al., 2002),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

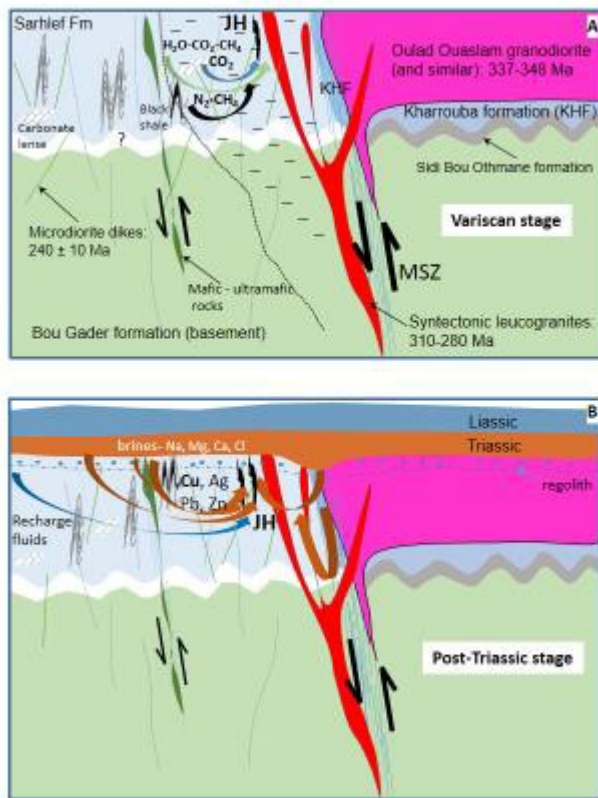


Fig. 16. A two-stage model of fluid circulation in the Jbel Haïmer area (JH) Jebilet: **A** Variscan stage: the intrusion of late leucogranites, the thermal metamorphism M2a lead to the genesis of CO₂, CH₄-N₂ and H₂O-CH₄-CO₂ fluids which mix, and form, in pre-existing discontinuities, the early quartz assemblages with the Fe-As-Sn-(Bi) association. See text for references on the granodiorite, granite and microdiorite ages. MSZ: Marrakesh Sear Zone. **B** Mesozoic brine stage: after peneplanation and deposition of Triassic/Early Jurassic formations, circulation of brines coming from Triassic evaporite formation within the regolith, and several types of lithologies including black shales, basic intrusions and schists, yield to the extraction of metals, the transport and the formation of Cu-polymetallic ores in the Jbel Haïmer area. Triassic and Liassic covering rocks in the Jebilet are from Saddiqi et al. (2009). Figures (A) and (B) are not to scale