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Early Bronze Age copper extraction(s) in the Grandes Rousses Massif (Isère and Savoy departments, France)

ABSTRACT: *Field work between 2007 and 2012 led to the discovery and investigation of a large-scale Early Bronze Age mining field at the Grandes Rousses Massif (Dauphiné and Savoy parts). Mining archaeological and geological work resulted in a detailed description of the ore-geology that included a description of the structure and the composition of the mostly hydrothermal veins. Two major vein systems coexist: mesothermal sulfurised mineralisations of the "BPGC" type (= including sphalerite – i.e. blende in french – pyrite, galena, chalcopyrite), with supergene mineralisations (malachite, azurite, iron hydroxides) in the oxidation caps, and Alpine-type fissure mineralisations. Several small test-excavations allowed sampling of charcoal for radiocarbon dating and enabled also sampling for an ongoing palynological investigation. Already the old datings of the workings came as a surprise and ascertained the chronological span between the beginning of the 2nd millenium and the 17th century BCE. Fire-setting is attested as the main exploitation mode of the mining field. Fire-setting is used for test-excavations on the surface of the veins, and for digging the hard rocks (shafts, trenches, galleries). The article presents the current state of knowledge and concludes with the necessary further steps of investigation at this Bronze Age mining field.*

KEYWORDS: BRONZE AGE MINING, EARLY BRONZE AGE, ORE GEOLOGY, BPGC ORE TYPE, SULFURIZED MINERALISATION, FIRE-SETTING

Introduction

The survey, carried out in the Grandes Rousses Massif by a team directed by M.-C. Bailly-Maître with the aim of documenting ancient mines around the medieval site of Brandes, led to the discovery of the large-scale exploitation of copper ore at high altitude. Ad hoc trial trenches dug in the mine dumps, followed by radiocarbon measurements carried out on charcoals, provided an additional surprise: the dating to the Early Bronze Age (Bailly-Maître & Gonon, 2008). Subsequently, six campaigns of surface prospecting and palynological sampling took place between 2007 and 2012 with the aim of documenting the whole extraction field and of identifying remains related to ore processing (Moulin et al., 2012). In this article we briefly assess the geological and mineralogical setting of the site and the extraction features that were identified. The above-mentioned publications include a detailed presentation of the history of the research, of the workings that were identified and of the economic and social issues related to the Alpine area at the beginning of the Bronze Age.

The Grandes Rousses Massif, located in the heart of the internal French Western Alps (Fig. 1), forms a long north-south-trending ridge spanning over 17 km astride the departments of Savoy and Isère (Fig. 2). This high massif dominates the Bourg d'Oisans plain and the Romanche valley in the south, the Arves valley in the north and the Eau d'Olle valley in the west. The summit of the range culminates at 3,464 m at Pic de l'Étendard, which is ice-covered and clearly separates the two slopes.

The areas exploited during the Bronze Age are located between 2,410 and 2,650 m on a large apron planed by glaciers which reaches down to the Croix de Fer pass in the north (Savoy department) and between 2,200 and 2,700 m on the central bench terrace in the west (Isère department) sloping northwards from the Dôme des Petites Rousses up to the Couard pass. It is no exaggeration to say that the climatic conditions prevailing during the periods of ancient exploitation were mountainous: high snowfall and even freeze-up depending on the altitude, rugged slopes and rock faces, etc. Nonetheless it is possible to reach the exploited sectors in many places from the south, the west and the north.

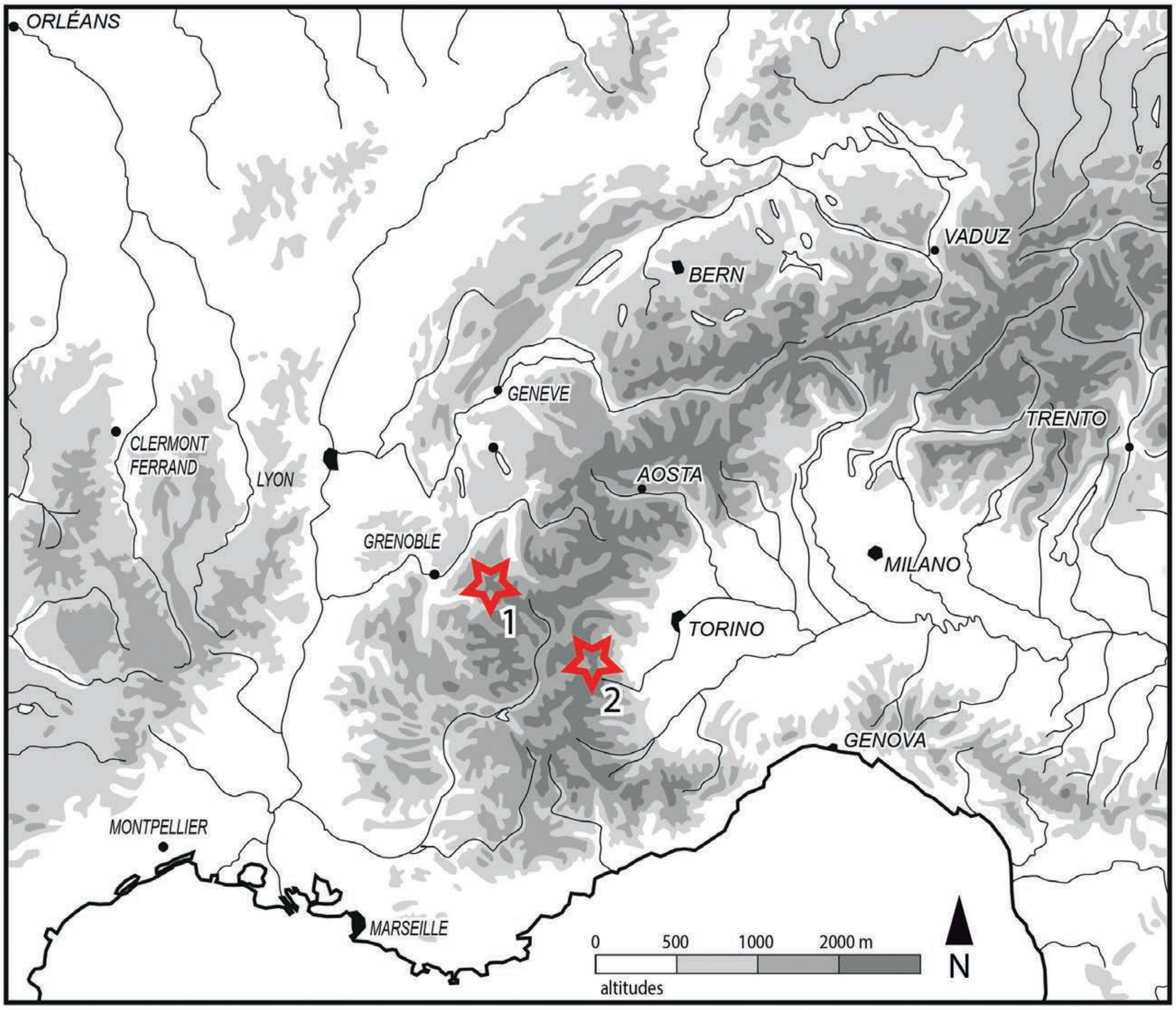

Fig. 1: Location of the Grandes Rousses Massif (1) and the sector of Saint-Véran/Molines (2) where the mines exploited during the Early Bronze Age were identified.

However, it is impossible to ensure efficient control of all these accesses.

Geological setting and mineralogical composition of the veins

Prior to any technological study of the mining activity, it is important to define the type of working, which, by definition, was completely or partially destroyed. It was therefore necessary in the field to characterise the remaining vein structures, to define the nature and the distribution of the ores and to characterise the gangues. This programme was carried out by one of the authors (BM). Each point of mineralization has been sampled (sulphides, supergene mineralisations, gangue, minerals of alpine-type fissures) during the survey. Characterisation of minerals of each point was made with stereomicroscope for the mean minerals (chalcopyrite, pyrite, galena, sphalerite, tetrahedrite, malachite, azurite) by optical and physical characters: hardness, colour, streak, cleavage, etc. (Fischesser, 1977).

The local geological setting

The Grandes Rousses Massif belongs to the external crystalline Western Alps. This massif hosts magmatic and crystallophyllian formations (granites, gneiss, micaschistes, etc.) predating the Carboniferous. The formations of the crystalline basement and the pinched synclinal fold of Le Houiller des Grandes Rousses are disconformably overlaid by a not very thick Triassic sedimentary cover (Barbier et al., 1976; Bartéfy et al., 1972; 1977; 2000). In the surroundings of the massif the Jurassic sedimentary cover is heavily expanded (half-graben of Ferrand in the east and half-graben of Bourg-d'Oisans

Fig. 2: View from above of the central sector of the Prehistoric workings in the Isère department (Plan des Cavales and La Jasse). Photograph taken in August 2008 in a south-western direction. In the background the Romanche valley.

– Ornon – Col du Sabot in the west; Fig. 3). In structural terms two aspects can be highlighted: the significance of large north-south-trending longitudinal faults which transformed the pre-Triassic peneplain into a series of impressing terraces from the east to the west and the presence of up warding of the centre of the massif along its north-south axis, culminating at the height of Pic de l'Étendard (3,464 m).

Structural geology and vein systems

The relationship between brittle tectonics and vein mineralisation is an established fact and mining geologists became interested very early in rock fracturing processes because these are privileged access ways for mineralised fluids. The faults in the strike-slip and shatter zones, and first and foremost the tension cracks, which are open faults, are likely to be mineralised and thus will form the veins. The configuration of the vein fields therefore is strongly dependent on the history of local and regional tectonics.

Quite a large number of compass measurements (725 values) were taken as regards the direction and dip of the vein planes of the Grandes Rousses Massif. All the direction measurements were transferred onto a rose diagram with radial sections of 10° (Fig. 4a). As a result, almost all the measurements are grouped together in the NW and SE quadrant of the diagram revealing three preferential directions which are the following: N 160°E – N 170°E, N 110°E - N 120°E and N 140°E – N 150°E and significant difference of the direction between the western vein field (Fig. 4b) and the northern vein field (Fig. 4c). With regard to the proper characteristics of the veins, a fairly large array can be observed ranging from straight and regular veins with parallel sides, between several decimetres and several metres thick (Col de Montfroid, Croix de Picheu, Plan des Cavales, Balme Rousse), and veins presenting a series of swells and pinchouts or digitations, with veins presenting "horsetail" structures. The fillings (gangues and sulfurised mineralisations) affect both the associated tension cracks and the main fractures.

Two major vein systems coexist (Fig. 3): hydrothermal sulfurised mineralisations of the "BPGC" type (= including sphalerite – i.e. blende in french – pyrite, galena, chalcopyrite) and Alpine-type fissure mineralisations.

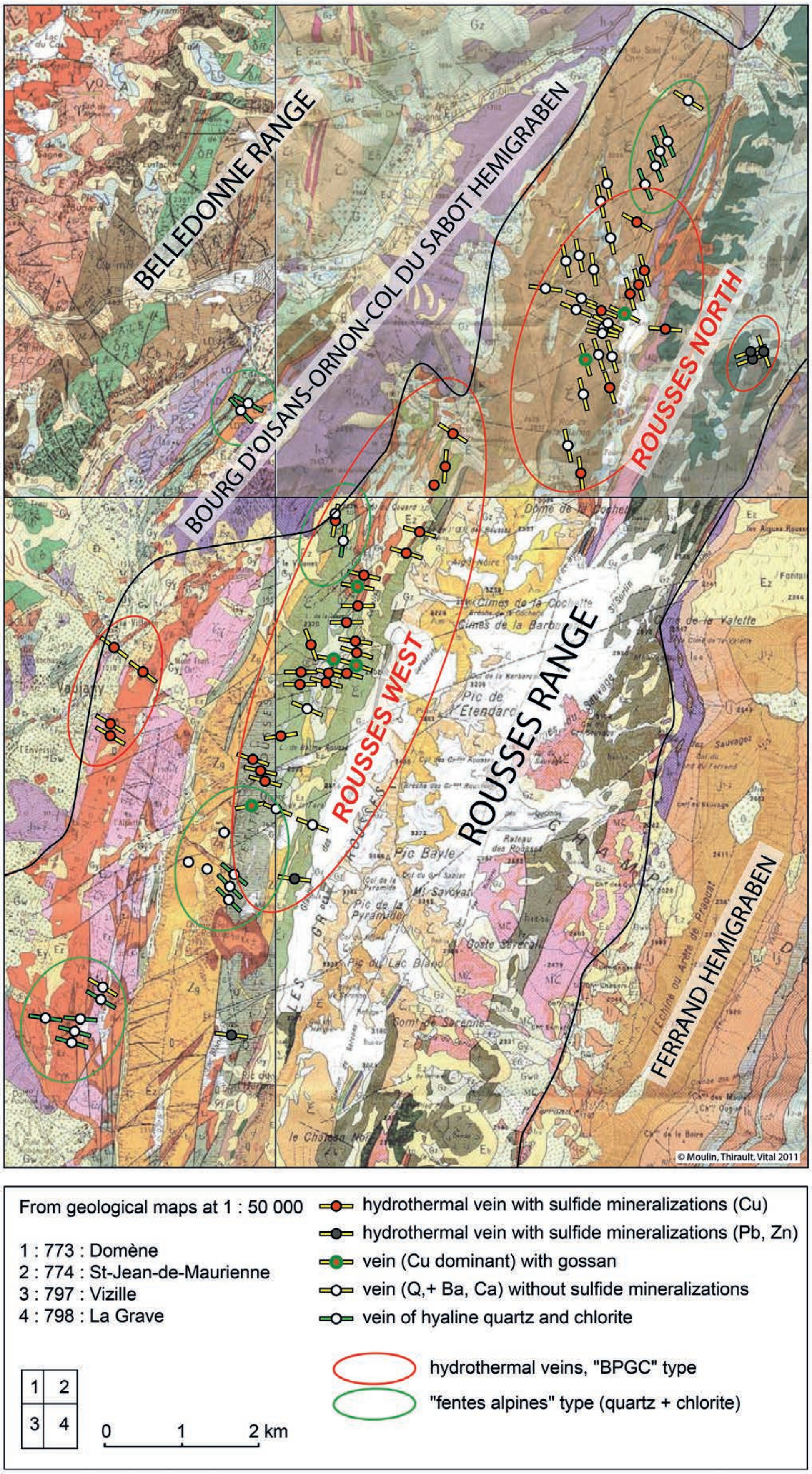

Fig. 3: Location and specification of the veins and main mineralogical and metalliferous indicators identified in the Grandes Rousses Massif during the survey (map base: assembling of the 1:50,000 scale geological maps after Barbier et al., 1976; Bartéfy et al., 1972; 1977; 2000).

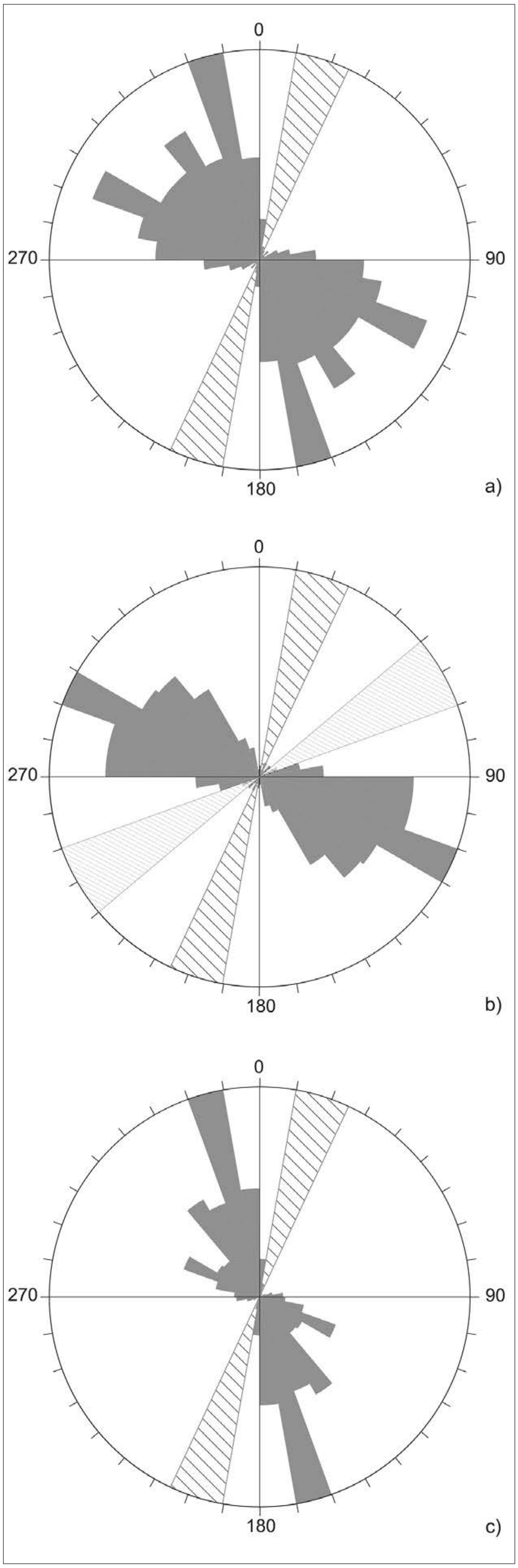

Fig. 4: Grandes Rousses Massif, rose diagrams of the directions of the vein planes; compass measurements presented from 10° to 10°; a) total of the measurements carried out in the massif (725 measurements, grey-shaded plot) and the direction of the large longitudinal accidents (10°-25°E); b) total of the measurements carried out in the Western Grandes Rousses, from the Dôme des Rousses to the Col du Sabot (301 measurements, grey-shaded plot) and direction of the longitudinal (10°-25°E) and transversal accidents (50°-70°E); c) total of the measurements carried out in the Northern Grandes Rousses, from the Aiguille de Laisse to the Rochers de la Curiaz (424 measurements, grey-shaded plot) and direction of the major longitudinal accidents (10°-25°E).

The "BPGC" type veins

The vein systems that formed at medium temperatures of the "BPGC" [= Blende (=sphalerite), Pyrite, Galena, Chalcopyrite] type of the Grandes Rousses Massif include the following sulphides, in order of frequency: chalcopyrite, tetrahedrite, pyrite, galena and sphalerite, within a gangue formed by milky quartz, barite and calcite. This vein system can be subdivided geographically into two large vein fields: the Western Grandes Rousses vein field (municipalities of Vaujany, Oz and Huez; Isère department) and the Northern Grandes Rousses vein field (municipality of Saint-Sorlin-d'Arves; Savoy department).

The vein field of the Western Grandes Rousses (area of Isère department) stretches from the Source des Demoiselles in the north to the Lac du Milieu in the south (Fig. 3). The veins cut the basement and sometimes intersect the Triassic dolomite cover in the northern part. The predominating direction (N 110°E to N 120°E), in the centre of a cluster of values comprised between 90°E and 150°E (Fig. 4b), is slightly orthogonal to the main direction of the main tectonic accidents of the massif (N 10°E to N 25°E). The directions of the veins formed by sulfurized mineralisations range between N 90°E and N 130°E, with a maximum of values comprised between N 120°E and N 130°E (Fig. 5a) corresponding to the "WNW-ESE transversal fractures" described by J.-C. Vathaire (Vathaire, 1965). The gangue is formed by quartz and barite; in some cases calcite is abundant and then forms the heart of the vein (Plan des Cavales 4). The gangue of the veins becomes enriched with barite in the eastern and south-western part of the vein field and even farther south of the surveyed sectors (Lac Blanc mine) and beyond (Brandes). The sulfurized mineralisations are unevenly distributed along the entire length of each vein but they present clusters such as "pockets", monomineral or plurimineral clusters in the centre of the vein or near the walls. As regards the mineral associations, chalcopyrite predominates while the presence of tetrahedrite and pyrite is more secondary, corresponding to mesothermal veins of the "(B)P(G)C type with predominating copper and subordinated Pb-Zn" (Routhier, 1963). Galena and sphalerite are indeed extremely rare in the central area (between La Fare and Cochette) and they

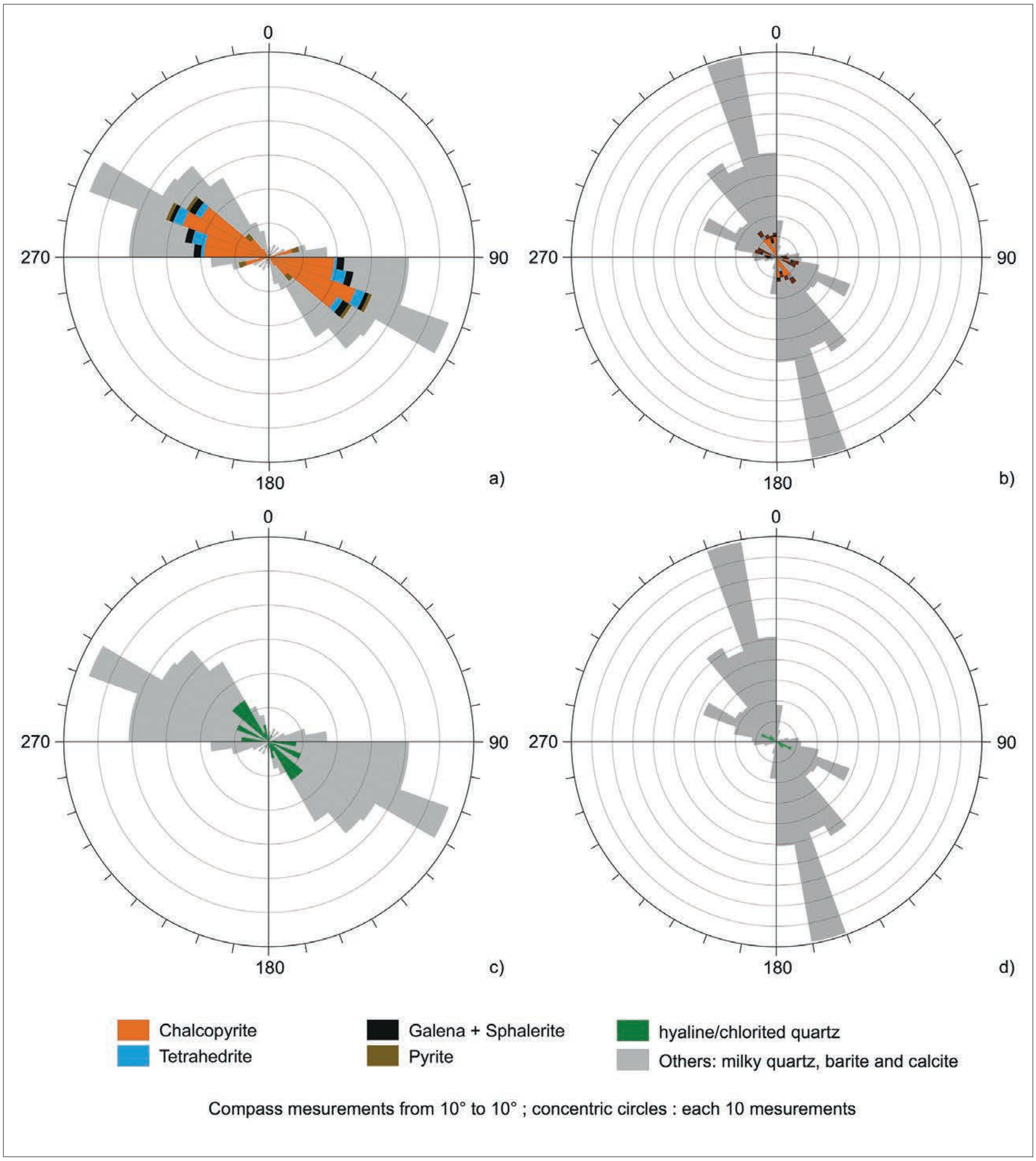

Figure 5: Grandes Rousses Massif, rose diagrams of the directions of the vein planes and the associated mineralisations; a) Western Grandes Rousses, sulfurised mineralisations of the "BPGC" type hydrothermal veins with milky quartz, barite and/or calcite gangue; b) Northern Grandes Rousses, sulfurised mineralisations of the "BPGC" type hydrothermal veins with milky quartz and calcite gangue; c) Western Grandes Rousses, Alpine-type fissure veins with hyaline quartz and chlorite; d) Northern Grandes Rousses, veins of the Alpine fissure-type with hyaline quartz and chlorite.

are predominating minerals only in the northern (source des Demoiselles) and southern areas (Lac du Milieu) of the vein field, then corresponding to the vein field of the "B(P)G(C) [= Blende, (Pyrite), Galena, (Chalcopyrite)] type including Zn-Pb-Ag with subordinated pyrite and chalcopyrite" (Routhier, 1963). In the southern part, farther up to Col du Lac Blanc (mining areas of several lakes: Lac Blanc, Lac de Brandes and Lac de l'Herpie), outside the prospected area, grey coppers and galena seem to be predominant, embedded in a barite gangue (Héricart de Thury, 1841; Vathaire, 1965).

The northern vein field of the Grandes Rousses (Fig. 3), located in the municipality of Saint-Sorlin-d'Arves (area of Savoy), extends from the western shores of the lakes (Lac Tournant, Lac Blanc de St-Sorlin and Lac Bramant) and continues northwards (Étendard mountain refuge, Rochers de la Curiaz). The largely predominant direction of the veins is N 160°-N 170°E, the two secondary directions being N 140°E - 150°E and N 110°E – N 120°E (Fig. 4c). Considering only the sulphide vein mineralisations, clearly less abundant than in the western vein field of the Grandes Rousses, a quite large bundle appears between N 140°E and N 180°E whereas a secondary group corresponds to N 100°E – N 120°E (Fig. 5b). Towards the west the veins are sterile; they become enriched with sulfurised mineralisations (chalcopyrite predominant, tetrahedrite, sometimes pyrite) on the western margins of Lac Tournant, Lac Blanc de St-Sorlin and especially Lac Bramant (veins of the "(B)P(G)C type with predominating copper and subordinated Pb Zn"). The evidence (Fig. 3) located east of the lakes is of a different kind: these are sulfurized veins with sphalerite and galena (galena predominating at Aiguille Rousse, sphalerite predominating in the mining areas of Rieu Blanc).

The veins formed in Alpine-type fissures

The vein system formed in Alpine-type fissures in the broader sense with a generally differing direction (Fig. 3), often including hyaline quartz, chlorite, oligist and more rarely siderite and albite. They are scattered in several distinct vein fields from the north (Rochers de la Curiaz) to the south (Lac Besson/Lac Noir; municipality of Oz). These veins, which are not discussed here, yielded massive chlorite and hyaline quartz, the latter being of potential interest for prehistoric people (Rostan & Thirault, 2016).

The mineralisations of the hydrothermal veins

The gangues

The gangues are formed, in order of frequency, of quartz, calcite and barite. Quartz is the main component of the sterile veins and the veins with sulfurized mineralisations. Generally, it has a milky aspect (Fig. 6g). The structure of the vein quartz can be massive or banded. Associations of quartz and barite and of quartz and calcite are frequent (Fig. 6h and 6i). Calcite occurs abundantly as a component of vein gangues, more particularly in the northern Grandes Rousses, as a filling of the veins with milky quartz walls. At the surface dissolution phenomena are frequent, mirroring the imprints of the original automorphous crystals. Distinct sections of the large mineralised veins such as Plan des Cavales 4 clearly had a median calcite filling that disappeared because of dissolution processes on the first few metres down from the surface. Barite occurs as various facies, from microcrystalline saccharide texture to the enlargement of large blades, including all the intermediate forms, either pure or associated with quartz (Fig. 6h).

The hypogene sulfurized mineralisations

The main sulphides and sulfosalts identified in the Grandes Rousses veins are the following in order of frequency: chalcopyrite, tetrahedrite, pyrite, sphalerite and galena (Moulin et al., 2012).

Chalcopyrite is an ubiquitous sulphide of the Grandes Rousses Massif. It is present in the form of pockets or monomineral clusters of varying sizes (Fig. 6a and 6i), sometimes reaching a weight of several hundred grams, in a milky quartz or barite, more rarely calcite gangue. It was identified in almost all the sulfurized veins (Fig. 3 and 5a-b).

Evidence of tetrahedrite was identified in 25 spots of the inventory (Fig. 3 and 5a-b), often associated with chalcopyrite and in distinct cases with galena (mining area of Lac du Milieu). Tetrahedrite appears as flecks or small masses included in quartz, barite or calcite veins, either in the bedrock or in the dolomitic bed. Small automorphous crystals (tetrahedrons) are sometimes present (Fig. 6b).

Pyrite occurs in veins with quartz and calcite or barite gangues, either isolated or associated with other sulphides in the "BPGC" veins as flecks or clusters. Pyrite also appears as diffuse impregnation in the enclosing rock. Given its unstable state, it frequently alters into limonite. Although pyrite is not an ore type exploited by prehistoric people, its importance as an associated ore in the "BPGC" veins in the primary sources is substantial because it can be considered as being the starting point of the chain of chemical reactions in the oxidation area producing ferric sulphate, a powerful oxidant (Routhier, 1963). These reactions will lead to copper ore enrichment in the area of cementation.

Sphalerite was only encountered in a few spots in the peripheral areas of the chalcopyrite vein fields (Fig. 3): in the north (Rieu Blanc mines as large monomineralic clusters of black sphalerite) and in the south (Lac du Milieu mine, brown sphalerite in association with galena). The polymetallic sulfurized veins rich in sphalerite of the Grandes Rousses Massif were probably exploited in protohistoric times for sulphides other than zinc sulphide the extraction of which is of a late date.

Galena was only identified in a very small number of find spots, at the periphery of chalcopyrite vein fields, included in barite more rarely quartz gangue, sometimes as monomineralic clusters (Fig. 6c) of several hundred grams (Lac du Milieu mine), or associated with sphalerite or tetrahedrite, pyrite and chalcopyrite (Demoiselles mine).

The main supergene mineralisations of the "BPGC" veins

The area of superficial alteration of the veins enables the formation of new minerals through oxidation and hydration on contact with atmospheric agents at the expense of primary sulphides. These are often strongly coloured and in ancient times they enabled the detection of underlying sulfurised veins. In particular cases, which are still difficult

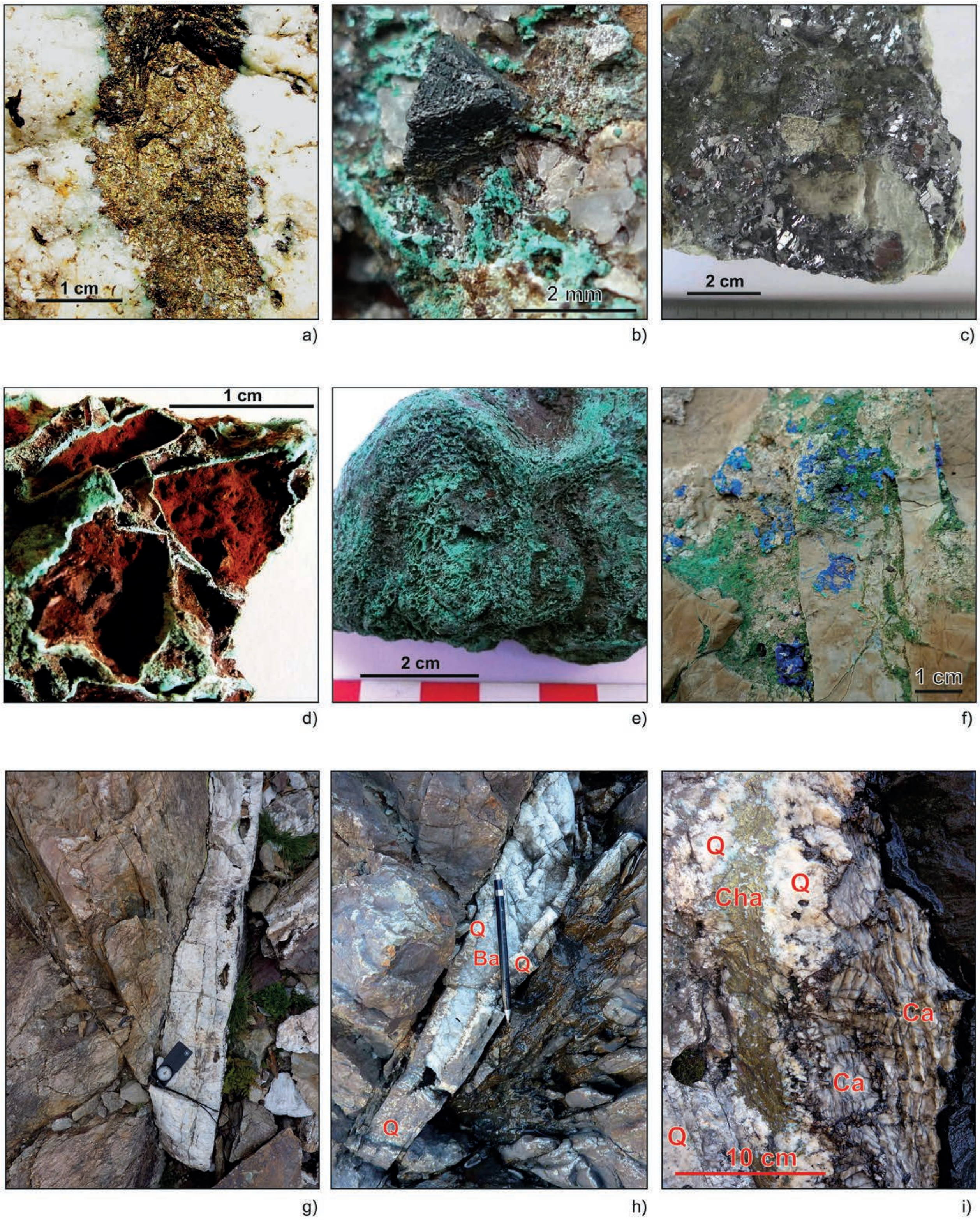

Figure 6: Grandes Rousses Massif, mineralisations and gangues of the hydrothermal veins; a) massive chalcopyrite embedded in milky quartz (Étendard); b) automorphous tetrahedrite (Demoiselles mine); c) massive galena (Lac du Milieu mine); d) box-work with a compartmented structure of brown limonite and malachite in perimorphosis (Cochette); e) massive concretioned malachite (Cochette); f) azurite and malachite on dolomite (Étendard Nord mountain refuge); g) massif and regular milky quartz vein (aiguille de Laisse); h) barite vein with milky quartz on the walls (La Fare); i) milky quartz vein (Q) with massive chalcopyrite (Cha) in the centre and calcite (Ca) on the walls (Étendard).

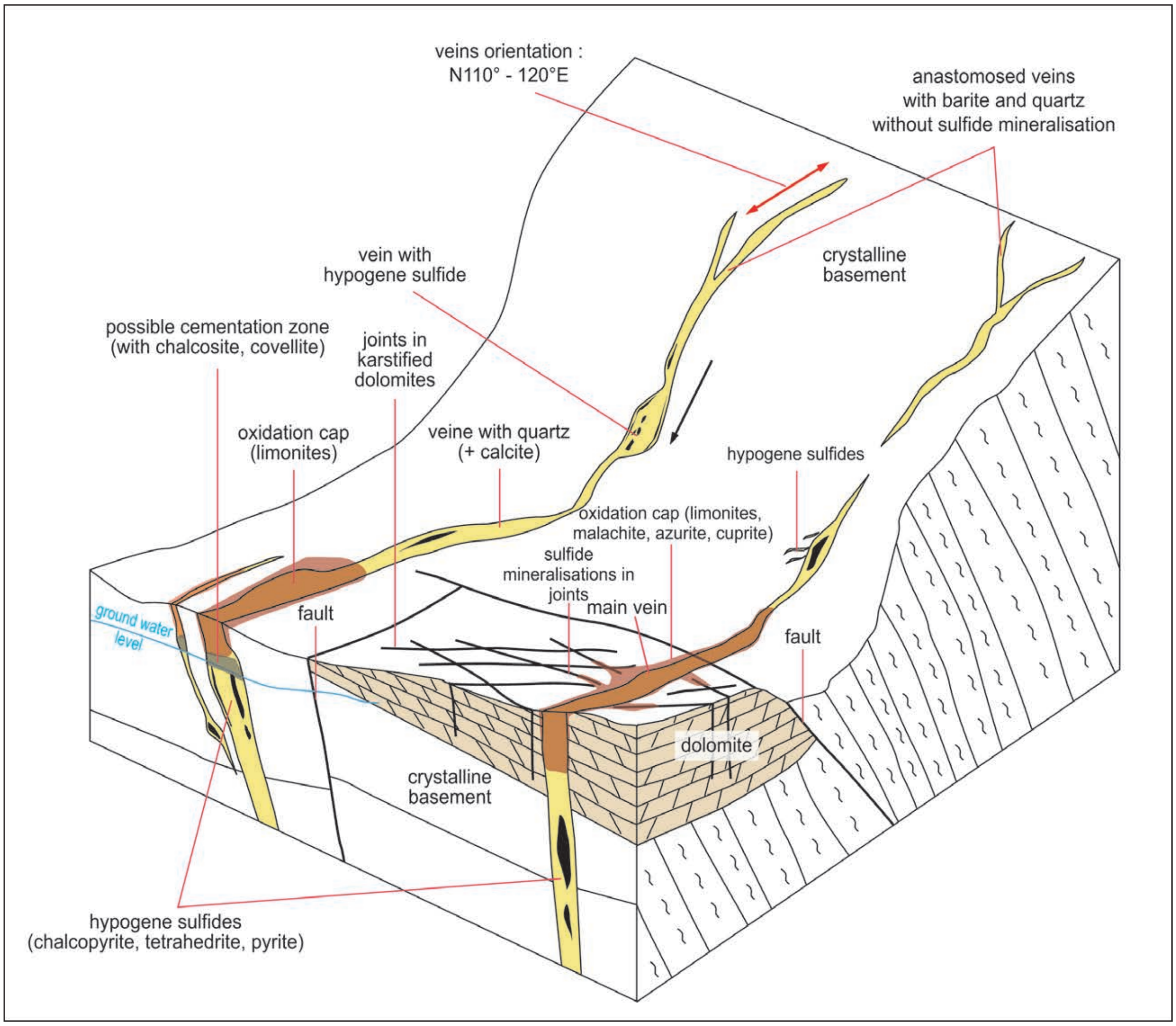

Fig. 7: Schematic block diagram showing the metallogenic context of the vein mineralisations and their alteration zones in the Western Grandes Rousses Massif.

to diagnose, phenomena of superficial enrichment may have created exploitable deposits (currently depleted) above distinct sulfurised veins.

Several types of limonites in the broader sense (iron hydroxides) were present in the oxidation caps. The earthy varieties are the most frequent; other more compact facies occur as box-work of primary sulphides, in the form of chalcopyrite, siderite and pyrite perimorphisms or pseudomorphisms (Fig. 6d).

Malachite is encountered frequently in the weathering zones of the sulfurised veins, more particularly when these latter cross the dolomitic cover or contain calcite in their gangue. Malachite occurs as green crustified clusters (Fig. 6e), as a coating (Fig. 6f) or as small needle-like or fibro-radiated crystals, also as perimorphism (Fig. 6d), often associated with the limonites of the oxidation caps. While malachite only appears as an accessory mineral in many spots, significant amounts of malachite were encountered in distinct sites (Cochette 9); the question whether it was extracted as copper ore remains open for the moment.

Azurite (Fig. 6f), which is more unstable than malachite, was more rarely identified than this latter. Generally, it is associated with the weathering zones of tetrahedrites, with antimony ochre. It occurs as small crystals or as a bright blue coating. Other weathering minerals of the oxidation and cementation zones were also mentioned (cuprite, chalcocite, covellite, tenorite, pyromorphite, cerussite; Vathaire, 1965).

Metallogeny of the oxidation zones of the veins

The oxidation caps correspond to the superficial part of the sites submitted to the oxidation of sulphides and their leaching (Fig. 7). In the contexts on which our study focused the development of these oxidised areas remains limited, about 2 to 3 m thick. The oxidation caps are characterised by the presence of often abundant

field reference	laboratory reference	object	result(BP)	deviance	calibration 68.2% probability	calibration 95.4% probability
Barbarate3	ARC-2430	fuelwood	3480	45	1879-1748	1914-1690
Barbarate3	ARC-2326	fuelwood	3395	70	1868-1608	1882-1527
Cochette4	ETH-31100	fuelwood	3480	55	1883-1744	1944-1666
Etendard1	ETH-31099	fuelwood	3515	55	1906-1756	2012-1692
PlandesCavales4	ETH-32540	fuelwood	3625	55	2119-1910	2193-1783
PlandesCavales4	ETH-34334	humidwood	3580	55	2025-1834	2126-1756
LacBramant	POZ-13993	vegetaldebris	3650	35	2121-1956	2137-1929

Fig. 8: Inventory of the radiocarbon dates available for the workings in the Grandes Rousses Massif. Calibration with OxCal software, version 4.1 (edition 2009). After Bailly-Maître & Gonon, 2008, completed.

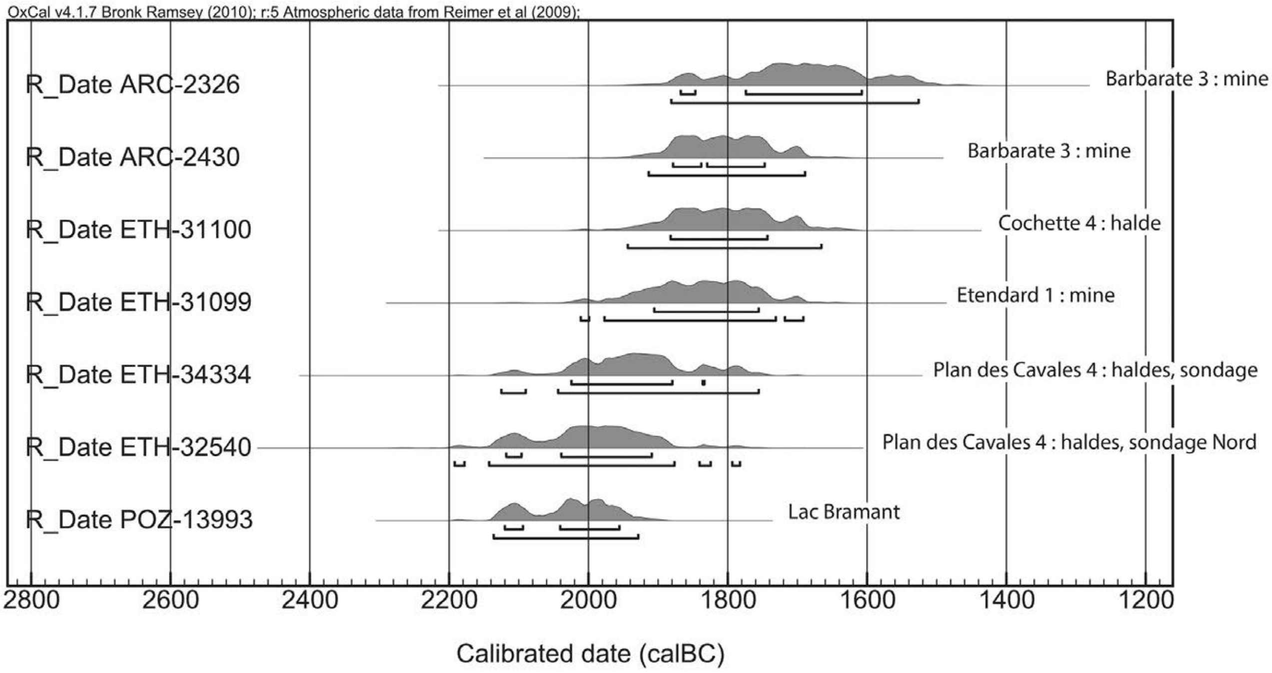

Fig. 9: Seriation of the radiocarbon dates for the workings in the Grandes Rousses Massif. Calibration with OxCal software, version 4.1 (edition 2009). The first line below the curve indicates the intervals at the 68.2% confidence level, the second at the 95.4% confidence level. For the data see figure 8.

limonites exhibiting various facies. When the sulphides were completely leached out, only the quartz skeleton remains, which then takes a spongy aspect. The oxidation caps present varying sizes at the surface of the inventoried vein deposits. As regards distinct sites with intense exploitation it is difficult to get a precise idea of the original size and quality of these superficial weathering zones as the initial aspect was strongly modified. This is also the case for the potential cementation zones that are precisely located below the oxidations caps in the zone of groundwater table fluctuation (Routhier, 1963). It should be noted, in this respect, that several galleries and trenches (Plan des Cavales 4, Lac Blanc de St-Sorlin 2, etc.) are currently flooded and thus lying in a favourable context for the formation of supergene sulphides (chalcocite, covellite) typical of the cementation zones, much richer in copper than chalcopyrite, a primary sulphide of the supergene deposit.

In addition to the hydrogeological context, whether linked to the presence of a groundwater table or not, other aspects should be taken into account: the supergene evolution of the veins depends on the presence or absence of pyrite associated with other sulphides on the one hand and on the nature of the enclosing rock and of the gangue on the other hand. The presence of pyrite favours the formation of sulfated solutions and, conversely, the presence of carbonated rocks inhibits the migration of distinct sulfated solutions. These then immediately react with copper sulphate to form copper carbonates (Routhier, 1963). This could be the case for distinct deposits of Cochette, close to the Triassic dolomite, where malachite occurs abundantly in the oxidation caps.

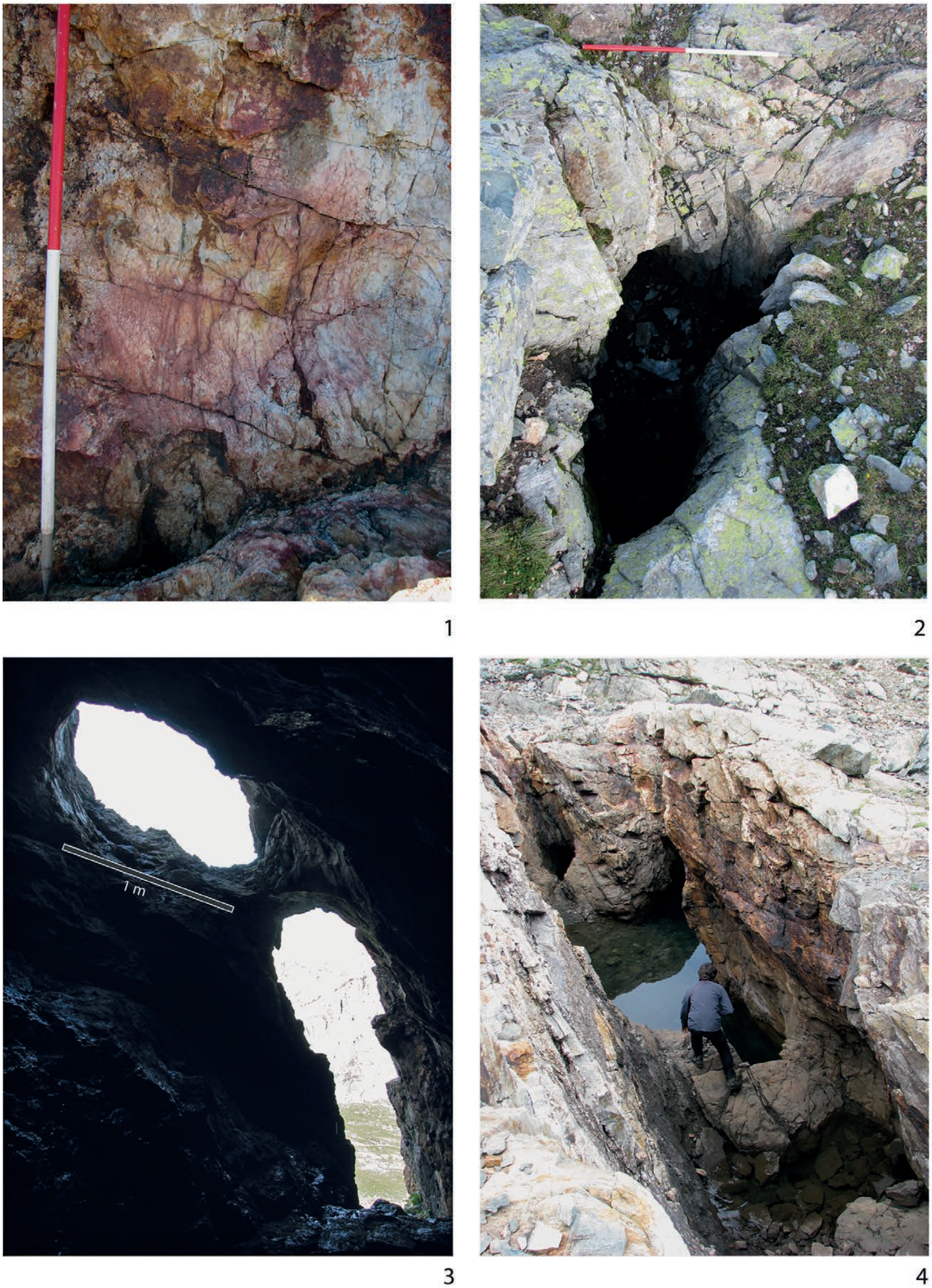

Fig. 10: Types of fire-settings. 1: working of a vein, notice the rubefaction of the quartz and its peel-like structure (Plan des Cavales); 2: vertical shaft on the vein (La Jasse 6); 3: gallery stemming from the connection of two workings, still marked by two accesses (Barbarate); 4: extraction trench produced by the coalescence of shafts and galleries (Plan des Cavales 4).

The dating of the workings

Two major extraction techniques are attested: galleries that were cut using explosives and metal tools and excavations of all sizes (ranging from the cupule to the gallery) achieved by thermic fracturing. The first are more or less precisely dated by written documents (Bailly-Maître, 2001) and are not very ancient, dated to one or two hundred years ago. The use of fire-setting is very common throughout all periods and is therefore not a precise dating criterion (Weisgerber & Willies, 2001; Ancel et al., 2012). At the end of the initial identification work six radiocarbon dates were made on charcoals stemming from the mine dumps, thanks to some test excavations realised under the responsibility of M.-C. Bailly-Maître (Bailly-Maître & Gonon, 2008; Figs. 8 and 9). The measurements range from the 21st to the 17th century BC, at the 68% confidence level. By analysing these dates in more detail, a succession can be identified: the two dates obtained for Plan des Cavales 4 can be attributed to the 21st and 20th century BC; clearly differing from the three dates stemming from Étendard 1, Cochette 4 and Barbarate 3, which can be assigned to the 19th and 18th century BC. An additional radiocarbon date obtained for the same gallery as the preceding one indicates an extension into the 17th century BC. Moreover, the drilling carried out in Lac Bramant, which yielded a copper and zinc pollution peak dated to the 21st-20th century BC, may indicate a working that was contemporaneous or slightly earlier in the Savoy area (Guyard et al., 2007).

We can only postulate that all the workings and fire-settings that could not be dated by radiocarbon analysis, also date to the Early Bronze Age. The heavy metals pollution peak in Lac Bramant provides an argument to support this hypothesis. The mining waste and the features located close to the workings (see below) were dated to the same period as they were presumed to be related to the extraction sites. We will present the "ancient" workings as a whole keeping in mind that only a few of these are precisely dated.

The use of fire in the workings: general organisation

In the field a distance of 4 km and the watershed crest separate the extraction sectors of the Dauphiné side of the Grandes Rousses Massif, oriented towards the west (municipalities of Huez, Oz and Vaujany), from those of the Savoy side, oriented towards the north-east (municipality of Saint-Sorlin-d'Arves). However, the typology of the extractions and the systematic use of fire-setting are similar and the radiocarbon dates make it possible to consider that these two areas form one mining district.

The mineralised veins outcrop at the surface, more particularly the supergene formations and the oxidation zones that are strongly coloured. It is therefore possible that the ancient miners looked for these indications in order to test the contents of the veins and then started their working. Four types of excavation carried out to search for copper ore could be identified (Fig. 10).

The fire-settings

We have registered 112 spots, a minimum number. Fire-setting aims at fracturing a vein by thermal shocks in various positions according to the slope and the structure of the vein: horizontally, vertically, following the vein axis, from the walls, etc. The setting of one or more fires makes it possible to break out a volume of quartz and ore that equals one cubic metre (Ancel & Marconnet, 2012). The result depends on the layout of the terrain: frequently these are cupules with very rounded shapes (forming a bathtub when developing horizontally) or a simple rounded notch. The erosion processes transform this initial stage to such an extent that it is sometimes impossible to determine whether these concavities were natural or made by humans. Most probably, these small fire-settings were tests aiming at evaluating the ore content of a vein identified at the surface. These tests are largely distributed across the mining field and they were encountered everywhere where workings were developed but also in areas without workings in which the ores are still visible today. These isolated tests are proof of a systematic survey of the mining area in prehistoric times.

The shafts and the trenches

Thirty shafts were identified. In this case, the vein was exploited through vertical digging, still using fire. This is a succession of thermal cupules, the processing of which is not easy to understand, but the result is clear: the excavation develops downwards following the mineralisation. We have inventoried 32 trenches. Invariably using fire-setting, the working followed the mineralised vein horizontally or obliquely. Nowadays the excavation is open, but it is difficult to determine, prior to any detailed study, whether the initial excavation was made in this way, for example by taking advantage of natural recesses identified for distinct veins through calcite dissolution (as is the case at Plan des Cavales 4), or whether these are galleries the roof of which had collapsed.

The galleries

Nineteen galleries were identified. These are fully underground workings that were carried out by following the mineralisations. One single cross-cut was identified at Cochette 7. All the other ancient galleries were workings. Some have direct access from the surface; others were carried out from a shaft. In many cases the galleries are

Fig. 11: Upper terrace of the Grandes Rousses, sector of Lac de La Fare (Isère): fire-settings and galleries for the extraction of copper ore. 1: no. 447, LF2, perched fire-setting on the right bank of a waterfall; 2: no. 448, LF2, two cupules stemming from fire-setting, currently flooded; 3: no. 454, LF1, refilled access to a gallery opened by fire-setting; 4: nos. 453 and 454, view of the three accesses of the gallery. The red and white stake measures 1 m in length.

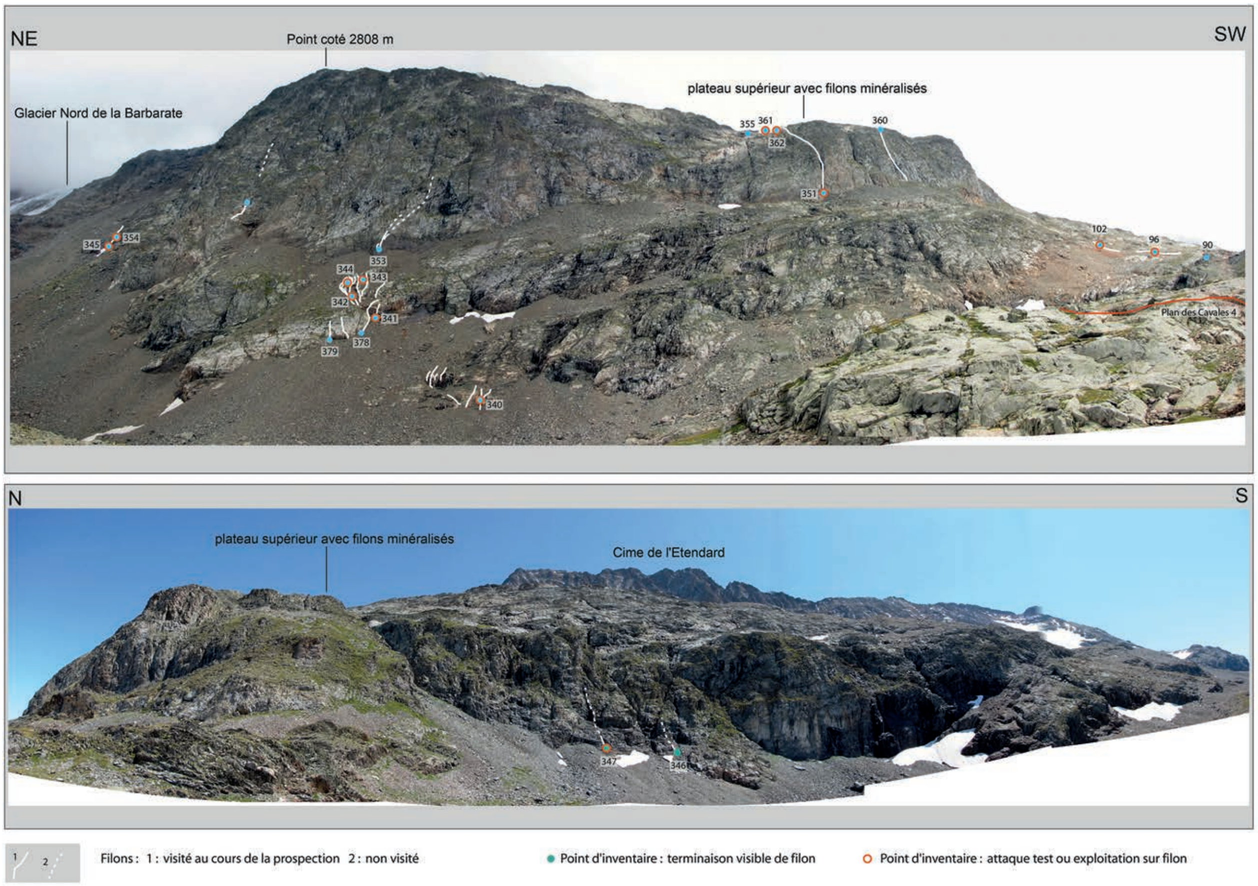

Fig. 12: Upper terrace of the Grandes Rousses, panoramic view to the eastern part of the Étendard sector (Isère department) with indication of the surveyed spots: "Étendard Nord" at the top, "Étendard Sud" at the bottom.

difficult, even impossible, to access because of collapses and obstructions. As a consequence, their real development is unknown and it remains impossible to define the size of the workings.

The trenches and associated galleries

It was possible to identify eleven diggings where open parts and subterranean parts are associated as regards the large workings.

Assessment

By adding a further 18 workings with unknown extraction techniques, 222 ancient extractions can be counted for the entire mining field of the Grandes Rousses Massif. The structure and the content of the mineralisations guided the workings of the miners. As this could be stated as early as the first discoveries, it is difficult to individualise an ancient mine because the diggings that are visible today result from the clustering of a more or less large number of fire-settings, carried out with varying sizes and modalities. Consequently, a detailed study of each digging is necessary in order to understand the project and its completion and to best define what corresponds to "one single" digging or "one single" working in the Grandes Rousses area.

In the current state of research the ancient extractions and their associated features are spatially distributed in two distinct groups. This partition also corresponds to different dispositions in the field, which warrant separate presentation.

The workings of the Dauphiné side

These workings develop along a length of 4 km on the upper terrace of the Grandes Rousses (alt.: 2,200-2,700 m), following mineralised veins on a strip that does not exceed 600 m in width (Fig. 11 and 12). The mining field is dense with peripheral extensions. It groups together all the working types described above. The fire-settings and all kinds of extractions (shafts, trenches, and galleries) are clustered in the same areas (Fig. 11). Within the exploited zone a distinct number of isolated fire tests can be identified, sometimes on veins other segments of which were subject to large workings (for example, Balme

Fig. 13: Plan des Cavales (Isère), altitude 2,500 m: two circular dry-stone features built at the edge of a cliff, immediately north-west of the extraction trench. Both features were erected on a ridge of unknown formation the visible surface of which is, however, rich in rubefied quartz fragments. The red and white stake measures 1 m. 1: overall view into a south-western direction (the Romanche valley is visible at top right); 2: detail of the southern circle (no. 62); 3: detail of the northern circle (no. 63).

Rousse 2 - BR2). This fact shows that all the mineralisations were identified and that the exploitations of veins presenting sufficient ore contents according to the criteria of that time were carried out systematically. According to the mineralogical observations, the boundaries of the mining field correspond more or less to the extent of the copper mineralisations. However, within the working area substantial mineralisations (according to our criteria) are still visible on the veins, whether in the workings or on the unexploited veins. In this way it is possible to measure

Fig. 14: Cochette sector (Isère), at an altitude of 2,330 – 2,340 m, small fire extractions were dug into the sedimentary cover (CO8). 1: no. 123, rock shelter (erratic block) with a semi-circular platform, clearly delimited in the northern part in close connection with the extractions; 2 and 3: no. 120, two adjacent fire-settings on the right bank of the torrent; 4: no. 124, extraction through a circular shaft of 1.5 m in diameter (in the background with stake), located on the right bank of the torrent (in the foreground). The red and white stake measures 1 m.

the mining value of this zone and the size of the workings and to intuitively evaluate the thresholds of the ore content that determined the mining.

The only exception to this statement is the eastern boundary of the extraction to the top. In this direction, the veins climb up the steep slope with large wall workings (Étendard and Barbarate sectors, altitudes 2,390 to 2,640 m; Fig. 12). Upwards, above the walls several isolated fire-settings on veins that are still highly mineralised today testify to their identification up to an altitude of approximately 2,700 m, but not farther. Is there a physical restriction (presence of *névés* or glaciers that masked the veins?) or a technical restriction (difficulty in bringing the wood for firing?) that forced the miners to give up any exploitation?

To conclude, it can be considered that the mineralisations of the Dauphiné side were entirely exploited if the technical and physical limitations and also the selection criteria of the Bronze Age miners are taken into account. We should keep in mind the possibly long duration of the workings and the possible resuming of ancient extractions. In any case, traces of workings carried out with explosives are almost inexistent in this mining field, apart from some tests in altitude (Étendard sector).

The largest workings group together all the extraction types. The most impressive are located on the terrace, at Plan des Cavales 4 and Balme Rousse 2, where the trenches and galleries follow each other on several hundreds of metres with probably large subterranean parts that are completely inaccessible without mechanical facilities. Smaller workings that also represent large excavations were carried out mainly at Plan des Cavales, La Jasse and Cochette, as well as at Barbarate and Étendard, through the digging of galleries into the walls. Some of these workings in addition yielded surface features the function and datation of which is not yet clearly established: areas in which the ore was crushed, stone circles, small retaining walls or heaps of stones removed from the field, canals (Fig. 13). These features are well distinguishable from the pastoralism features, wich are not numerous nearby the mines.

To get a complete picture, it should be noted that the extractions documented along the Cochette torrent (Cochette 8), at the northern boundary of the Dauphiné mining field, present a very different typology with small coalescing pits (Fig. 14). It will be important to determine whether these technical differences are linked to the site conditions (here the ore is embedded in carbonated sedimentary formations) or to temporal factors.

The workings of the Savoy side

On the Savoy side no ancient extraction was mentioned prior to our surveys. The geological mapping alone made it possible to advance the hypothesis that the copper mineralisations could be similar to those of the Dauphiné side and thus would have potentially interested the ancient miners.

After two survey campaigns (2009 and 2010) the boundaries of the copper mineralisations are well identified. It can be stated that the area delimited in this way was clearly prospected by the ancient miners because isolated fire-settings are attested across the entire mineralised area along a length of 3 km and up to an altitude of 2,650 m, and perhaps 2,700 m as regards two uncertain spots in the Lac de Tournant sector. However, in contrast to the Dauphiné side, only very few veins were mined. At La Curiaz 1 the vein was exploited in several points as attested by large thermic cupules but it is difficult to speak of a real working. On the other hand, four veins were subject to organised extraction:

- Above Lac Blanc de St-Sorlin (BS1), a succession of short galleries, shafts and thermic cupules with mine dump areas (Fig. 15).
- Above the preceding, a small working with a flooded gallery and mine dump (BS2).
- North of the Étendard mountain refuge, on the western decline of the crest, a small working (RE2) exceeded the stage of fire tests with a short removal and mine dumps. A stone feature built within the mine dump may be contemporaneous with the extractions.
- On the western shore of Lac Bramant, a working associates shafts and the beginning of a trench, with mine dumps (LB2: Fig. 15).

In addition, on the western shore of Lac Bramant isolated fire-settings were identified. The veins dip into the lake the current level of which currently exceeds its natural height, which makes it possible that additional extraction are flooded presently. In this lake a palaeoenvironmental drilling sample yielded a pollution peak of heavy metals interpreted by the authors as stemming from atmospheric pollution (Guyard et al., 2007). It is likely that this peak may be directly associated with the visible or flooded extractions if the drilling came through the thin deposits directly stemming from a working. In any case this is an important chronological marker to confirm that the Savoy side of the Grandes Rousses is indeed connected with the same mining complex as the Dauphiné side. As a conclusion, very large workings are not present on the Savoy side but the ancient miners prospected and tested the entire area and small extractions were made on well mineralised veins.

Concerns and prospects

Many aspects are still unknown. Here we mention five most important ones:

- The chronology of the workings is very unclear: the dates obtained make it possible to attribute distinct extractions, from the largest ones, to the Early Bronze Age. As regards the remainder, not a single dating element could be advanced. There is nothing to exclude the existence of workings dated to earlier or later periods.
- Although the surveyed area is already large, other sectors of the Grandes Rousses Massif (for example the eastern slope) remain completely unknown and it is possible that additional working areas are still to be discovered.
- Nothing is known about the processing of the ore after extraction; except for possible crushing areas next to the mine dumps there is no discovery related to ore roasting and to the production of the copper metal. The dating and the function of the sub-circular stone features identified near the large mines have to be documented.
- Knowing that there are opposed entities from a metallogenic and mineralogical perspective (hypogene mineralisations of the sulfurised veins / supergene oxidation mineralisations basement / carbonated cover, chalcopyrite veins / veins with grey copper ore) could it be possible to establish a chronology of the extraction and processing techniques according to these different types?

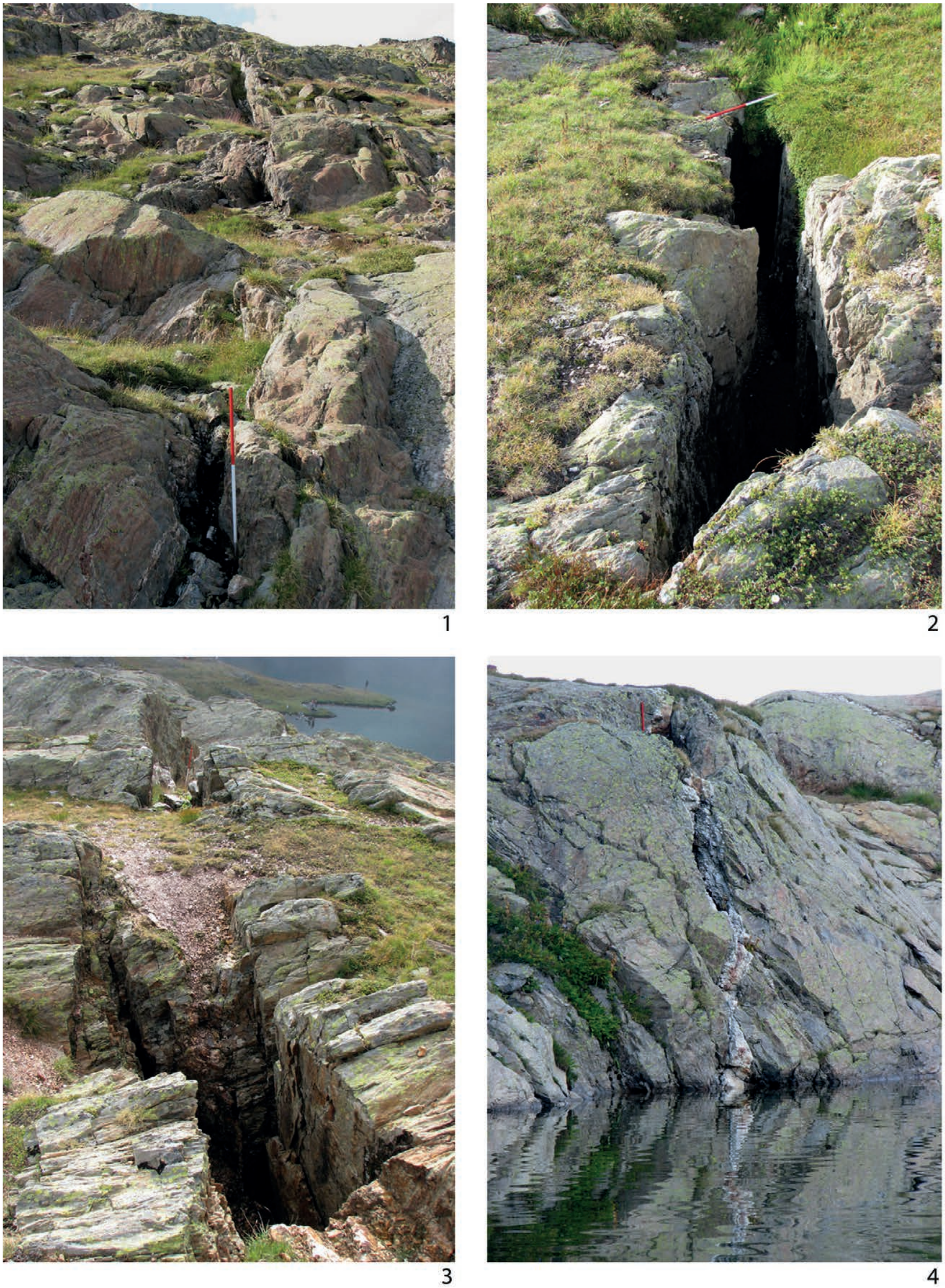

Fig. 15: Savoy sector, examples of copper ore mining. 1: no. 706, Lac Blanc de St-Sorlin, one part of the exploited BS1 vein, view to the north; 2: no. 709, BS1 working, filled trench; 3: no. 726-729, Lac Bramant, working LB2, overall view towards the south-east with the lake in the background; 4: Lac Bramant, fire tests at LB1 strung along a vein dipping into the lake, view to the north. The red and white stake measures 1 m.

- The social and cultural context of the workings remains enigmatic: no diagnostic vestigial remains, no settlement features have been identified so far.

The following achievements result from these survey operations:

- The inventory of the wet areas made it possible to launch several campaigns of palynological and paleoethnobotanical drilling (F. David) in the sectors located below the ancient workings. (1,800 - 2,100 m). Their potential is obvious as the dated sequences cover the last ten thousand years (ongoing study).
- The characterisation of the mineralisations exploited in the Grandes Rousses Massif on the basis of lead isotopic ratios is ongoing (F. Cattin). This would be a pre-conditional stage prior to any attempt to seek out connections between the exploited ores and the finished copper and bronze products.

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