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Prehistoric native copper production at Roua (Southern Alps, France) from the 4th millennium BCE

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Abstract: The native copper mines at Roua have yielded fire-setting workings and stone tools, evidence of ancient copper mining dating back to Prehistory. Located on a cliff, these works were partially damaged by black-powder workings conducted until the 19th century. An archaeological study conducted in the 1990s and 2000s already unscored the site's importance for prehistoric copper mining southern Alps. However, a comprehensive analysis was still needed to reconstruct the extent of the ancient works, date them and assess copper production in prehistoric times.

Two field campaigns (2019–2020) enabled systematic surveys to be carried out, revealing new galleries and identifying collapsed areas that were inaccessible due to the topography. The combination of several dating methods (radiocarbon, OSL, archaeomagnetism) applied to different sections of the cliff shows that native copper veins were mined as early as prehistoric times across all mining groups. Ancient copper production, estimated on the basis of dated galleries, reached several tonnes of copper during Prehistory.

Production at the Roua mines took place during the same period as that at Libiola and Monte Loreto in Italy (mid-4th–early 3rd millennium BCE), contributing to the spread of metallurgy from the Balkans. However, the specific nature of native copper mineralisation raises the question of how reduction techniques were acquired in the southern Alps, which have so far only been attested in Saint-Véran from the second half of the 3rd millennium BC. In any case, the native copper from Roua may have been used to manufacture small objects, such as those found in various contexts from the Late Neolithic period, particularly within Alpine and Chasséen cultures, possibly as early as the first half of the 4th millennium BCE.

Keywords: Neolithic, southern Alps, native copper, archaeomagnetic analyses

Résumé : Les mines de cuivre natif de Roua, situées dans les gorges de Daluis (Alpes-Maritimes, France), ont conduit à l'exploitation d'une minéralisation encaissée dans des formations permiennes très dures, sous forme de filons subverticaux millimétriques à gangue carbonatée. Le minerai est dominé par le cuivre natif, parfois associé à la cuprite, à des carbonates de cuivre ou encore, à de l'argent natif ; certains filons livrent des teneurs notables en arsenic. Ce type de minéralisation avec du cuivre natif abondant est rare en Europe. Il a suscité un intérêt dès la Préhistoire, le cuivre natif pouvant être extrait et mis en forme sans recourir à des procédés pyrométallurgiques. Des galeries creusées par le feu et des outils en pierre ont été rapportés dans les années 1990-2000, attestant d'une exploitation ancienne. Toutefois, l'absence de datations directes et d'études archéologiques approfondies ne permettait ni de dater ces travaux, ni d'estimer la production de cuivre aux périodes anciennes. Cet article, fruit d'un travail mené dans le cadre d'une thèse de doctorat (Bussone, 2023), vise à préciser l'extension des chantiers préhistoriques, à établir leur chronologie et à quantifier la production de cuivre aux périodes anciennes. Deux campagnes de terrain (2019–2020) ont permis d'établir des plans géoréférencés et de documenter les remplissages, l'état des parois, les traces d'outils et la morphologie des galeries. Ces observations ont permis de distinguer les creusements anciens, majoritairement réalisés par abattage par le feu, des reprises modernes et contemporaines, et d'identifier les secteurs propices aux datations.

La documentation d'un réseau de galeries jusqu'alors inexploré, le sous-groupe « Sud B » (S23-S28) a révélé des vestiges d'une activité préhistorique inédite, tant pour sa chronologie que pour la quantité de cuivre potentiellement extraite. Le réseau de galeries S24-S28 totalise environ 70 m de développement, 25 m de profondeur maximale et un volume d'environ 110 m³ documenté par photogrammétrie. Il conserve des indices nets d'une activité ancienne (fronts de taille liés à l'abattage au feu, remplissages cendreux, traces de suie) ainsi que 18 outils en pierre (17 maillets en roche encaissante et un outil en silex) attestant d'une activité préhistorique. Ces outils portent des stigmates compatibles avec l'extraction ou le dégagement du cuivre natif de la gangue ; un exemplaire présente des indices possibles d'emmanchement. Des microcharbons ont été identifiés dans des sédiments cendreux, vestiges d'anciens foyers d'abattage.

La chronologie des travaux a été établie par une approche croisée mobilisant radiocarbone, luminescence optiquement stimulée (OSL) et archéomagnétisme. Des charbons de petites branches prélevés dans les remplissages cendreux dans les parties profondes du réseau Sud B placent l'exploitation entre 3510 et 2900 (calBCE), soit du milieu du IVe au début du IIIe millénaire BCE. Des mesures OSL sur un bloc du même secteur fournissent un âge compatible avec des visites néolithiques (3165–2114 BCE à 95%, resserré à 2911–2379 BCE à 68%), le phénomène physique à l'origine de cet enregistrement doit être mieux compris (éclairage ancien ou chauffe). L'archéomagnétisme, appliqué à des prélèvements de parois chauffées dans d'autres secteurs, a livré des résultats qui convergent également vers le IVe millénaire BCE. Cette méthode permet aussi, pour certains travaux (groupes Sud A, Nord), de proposer des attributions à d'autres périodes protohistoriques, notamment l'âge du Bronze. Ainsi, à Roua, l'ensemble des groupes miniers livre des indices d'exploitation préhistorique compatibles avec le IVe millénaire et le début du IIIe millénaire BCE, sans exclure la possibilité de reprises plus tardives.
L'estimation de la production de cuivre repose sur plusieurs simulations, rendues incertaines par le manque de données sur la teneur en métal et la variabilité de la minéralisation (épaisseur, continuité). Malgré une large fourchette, ces approches permettent de proposer un ordre de grandeur pour la production métallique. À partir du volume des travaux, les galeries datées du IVe au début du IIIe millénaire BCE auraient produit entre une et deux tonnes de cuivre. Pour l'ensemble des creusements attribués à l'abattage au feu, la limite haute n'excéderait pas cinq à dix tonnes. Bien que modestes comparées aux grandes exploitations alpines de l'âge du Bronze, ces quantités demeurent significatives au regard des premiers objets en cuivre, généralement de faible masse et peu nombreux, identifiés dans la région.
Roua se place ainsi parmi les plus anciens sites de production de cuivre d'Europe occidentale, contemporains des mines ligures (Libiola, Monte Loreto). Le site s'inscrit dans la dynamique de diffusion des premières métallurgies, tout en présentant une spécificité liée à l'exploitation du cuivre natif. Cette dernière interroge sur la place de ce site dans l'acquisition des techniques de production du cuivre dans le sud de la France, les autres sites de production néolithiques ayant impliqué l'utilisation de procédés pyrométallurgiques. Ces résultats soulignent également le décalage entre une production potentiellement non négligeable de petits objets en cuivre dès le IVe millénaire BCE et leur faible représentation dans les découvertes néolithiques de la région, décalage qui pourrait s'expliquer par des problèmes de conservation du cuivre dans les sols, par des difficultés d'identification, et, très probablement dès cette période ancienne, par des pratiques de recyclage.

Mots clés : Néolithique, Alpes du sud, cuivre natif, analyses archéomagnétiques

The Southern Alps are rich in copper deposits (Rossi and Gasquet, 2014) that represent significant prehistoric mining potential. Although these deposits have been marginally exploited during historical periods (Ancel, 2010), some reveal limited evidence of prehistoric mining (Barge, 2006; see here fig. 1). To date, only the Saint-Véran mines have provided evidence of copper mining before the Bronze Age, supported by radiocarbon dating that places its beginning in the mid-3rd millennium BCE (Barge, 2003; Carozza et al., 2011).

The Roua native copper mines, located 70 km further south, had previously yielded evidence of prehistoric mining (Rostan and Mari, 2005). However, there was no chronometric data or quantification of the copper production to support this mining phase. This study, as part of a doctoral thesis (Bussone, 2023), aimed to fill these gaps and re-evaluate the significance of these deposits in prehistoric copper production within the Southern Alps.

A long-standing contrast exists between knowledge of early mines and the distribution of copper-based artefacts. Recent archaeological studies have confirmed the production of copper alloy objects specific to the Southern Alps and nearby areas such as Provence and northern Italy during the Metal Ages (e.g., Rubat Borel, 2009; Campolo, 2020; Girard, 2021; Mercurin and Lachenal, 2023). Although no prehistoric mines post-dating the Early Bronze Age have been documented locally, lead isotope analyses of some artefacts suggest compatibility with ores from the Southern Alps (Artioli et al., 2009; Bussone, 2023), hinting at possible regional mining.

The exploitation of regional mines during the early Late Neolithic is a hypothesis inferred from weapons engraved on rock art sites in the Southern Alps (Mohen and Eluère, 1990). Some of these engravings are morphologically like the daggers that were common in the Chalcolithic culture of Remedello (Müller et al., 2004; Morin et al., 2005; Bianchi, 2013a; Lumley, 2024; see here fig. 2). N. Bianchi has identified engravings, attributed to the even older Rinaldone culture, in the Vallée des Merveilles (Bianchi, 2013b). As a result, the study of Alpine engraved metal weapons attests to the circulation of copper objects in the Southern Alps between the first half of the 4th millennium BCE and the middle of the 3rd millennium BCE (Bianchi, 2013a; Huet, 2017), which potentially spurred regional copper mining.

Finally, as in other Alpine regions, copper objects and ore fragments from Late *Chasséen* settlements (Daurelle, Vernègues, Giribaldi, Arene Candide, Alba) attest to the circulation of copper production in the Southern Alps during the late Middle Neolithic and Late Neolithic (fig. 2). Indeed, awls or azurite fragments have been found at several of these sites, providing evidence of metal circulation from this early period (Giribaldi, Daurelle, Vernègues: Binder, 2004; Thiercelin et al., 2013; Moreau, 2017; Venturino et al., 2020). These discoveries, along with contemporary artefacts identified in northern Italy, Arene Candide, Alba (Maggi, 1997; Iaia and Dolfini, 2021), point to an early regional metallurgical development dedicated to the production of small copper artefacts (Van Willigen, 2017). The production of these objects predates known mining activities in the Southern Alps. However, they may be contemporary with the copper mines of Liguria (Maggi and Pearce, 2005). In fact, radiocarbon dating of the Libolia mines provides calibrated ages that fit with the first half of the 4th millennium BCE (Maggi et al., 2011). No contemporary mines had been identified in the Southern Alps prior to this study.

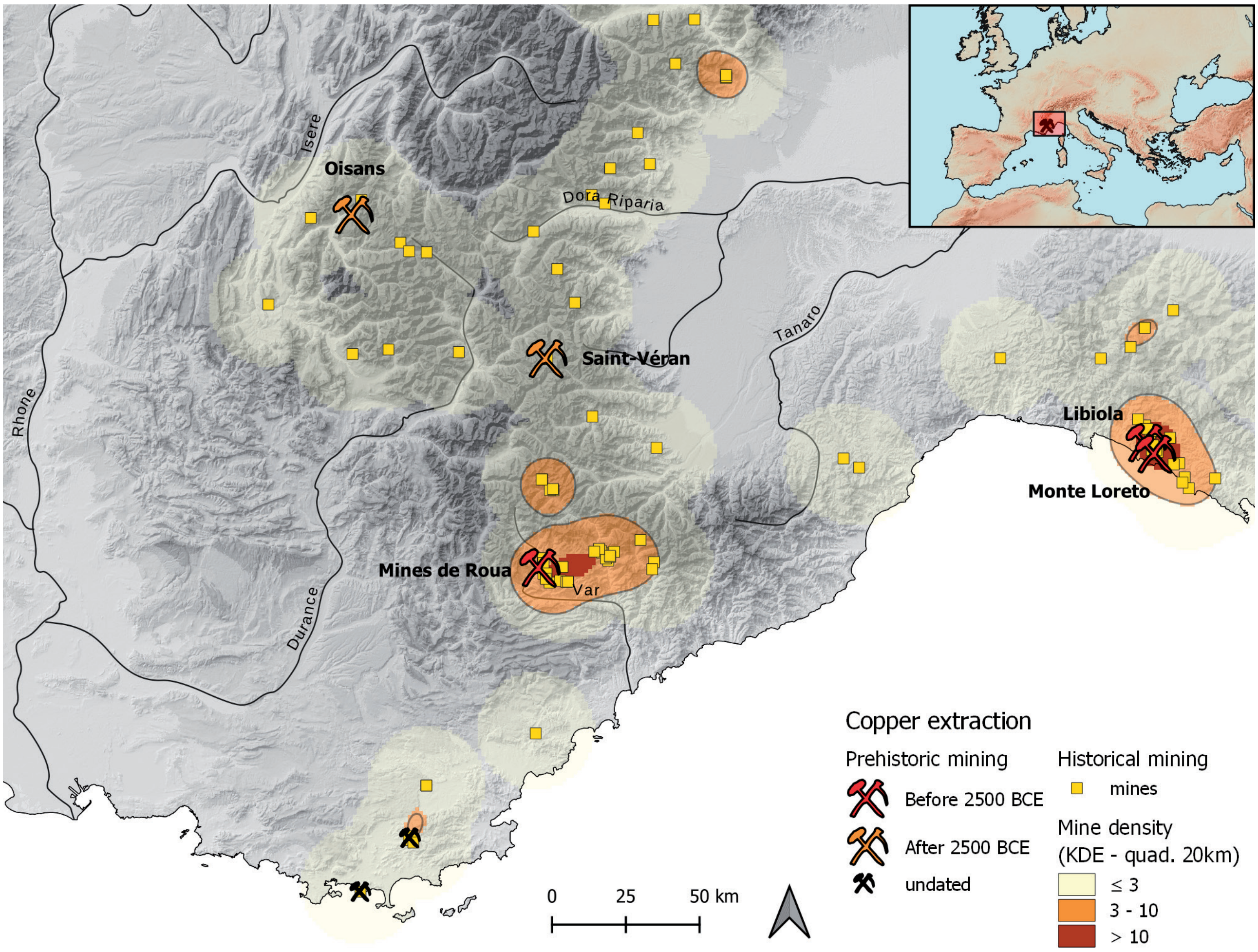

Fig. 1 – Copper deposits in the Southern Alps and prehistoric mining.

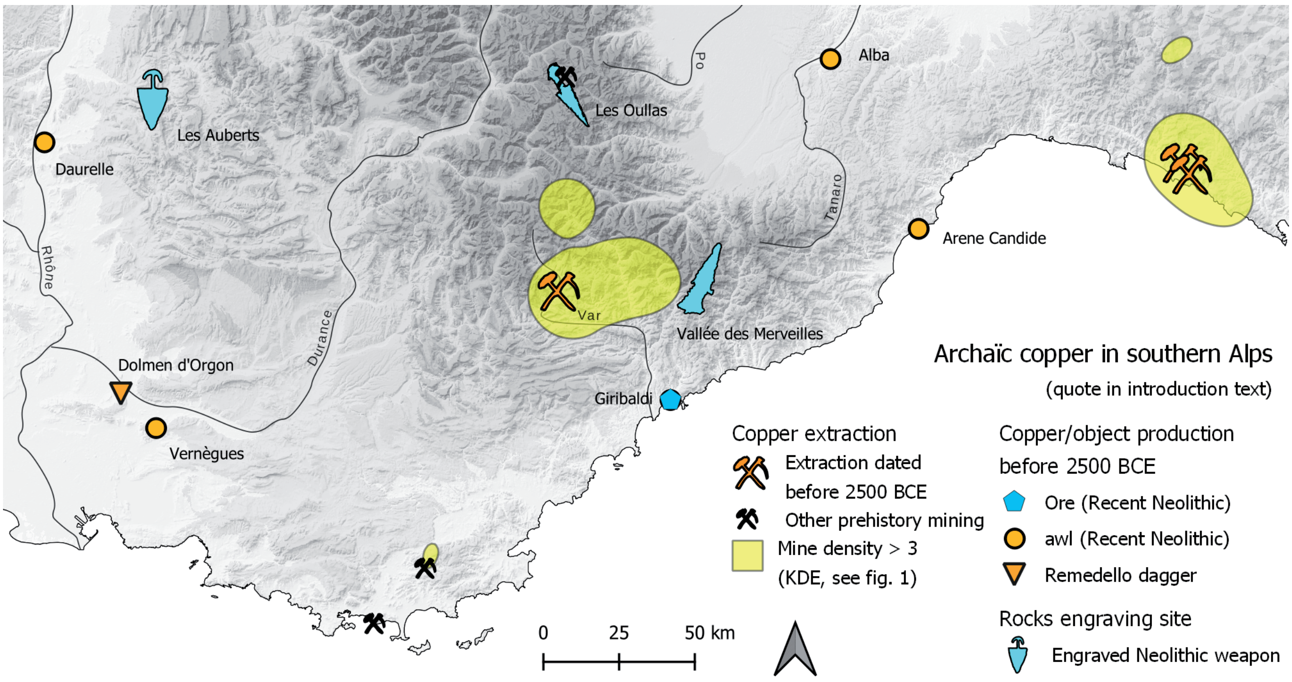

Fig. 2 – Copper mines and the location of copper artefacts dated to 4500 to 2500 BCE.

This paper presents the results of two archaeological survey campaigns at the Roua mine, incorporating chronometric analyses, material and artefact studies, and comprehensive mine surveys that enabled the 3D modelling of the mining volumes. The discovery of previously unknown galleries in 2020 has been a significant step forward for the study of prehistoric mining activities. Unlike other galleries that were damaged by more recent mining activities (17th-19th centuries), these newly discovered galleries are well-preserved and offer significant sections of prehistoric exploitation. They contained stone tools, fire-set workings, and backfill rich in ash and charcoal. These ecofacts, remnants of dismantled fire-setting pyres, allowed for the first reliable radiocarbon dating of Neolithic extraction activities through the analysis of charcoal from small branches. Additionally, we conducted Optically Stimulated Luminescence dating (OSL), which provided an age consistent with the prehistoric exploitation.

In galleries most affected by modern mining activities, the backfill remnants of pre-industrial fire-set mining were destroyed, making radiocarbon dating impossible. It was thus necessary to develop a specific methodology to date these ancient workings. Successful archaeomagnetic dating was carried out on several fire-set rocks. The study of mining remains from all periods enabled the reconstruction of the extent of the old galleries and the identification of sections most suitable for archaeomagnetic analysis. The dates obtained, combined with radiocarbon and OSL analyses, provide robust documentation of the prehistoric exploitation of native copper at Roua.

The 3D survey also facilitated the estimation of mining activity volumes and the quantification of copper production during prehistory. The results show that several tonnes of copper were produced at the Roua mines during the 4th millennium BCE, confirming the site's significant role in Neolithic metallurgy.

The dating and quantitative significance of this production prompt a reconsideration of the role of the Southern Alps in Neolithic copper production. Additionally, the importance of copper in the 4th millennium BCE in this region, as well as the question of its use in the production of regional artefacts, must be re-evaluated.

GEOLOGICAL AND HISTORICAL CONTEXT

Geology and Mineralogy

The Roua mines are in the heart of the geological Dôme de Barrot formation, within the Daluis gorges (Alpes-Maritimes, France). The mineralisation is hosted in Permian sedimentary rocks. Accessing the deposit is challenging, requiring a descent down a cliff that rises more than 300 m above the Var River. A layer of sandstone and carbonate-rich pelites outcrops on both sides of the gorges, 50 to 150 m below the summit ridge of the escarpment. The copper-bearing veins are controlled by this specific geological level, which has a maximum thickness of 5 m in the mining areas and consists of particularly hard rocks (Rostan and Mari, 2005). Although mineralisation outcrops on the western bank (e.g., observed in a road tunnel), ancient mine workings have only been identified on the eastern escarpment (fig. 3).

The mineralisation is trapped within subvertical veins, oriented between 60°N and 90°N, with thicknesses ranging from millimetres to centimetres. These veins rarely exceed two metres in height and are typically only recognised a few metres from the gallery entrances. Transverse faults observed in the field may have limited the depth extension of the mineralisation.

The veins are composed of a carbonate gangue (dolomite, aragonite) containing copper mineralisation. Two main types of veins have been identified: those hosted in pelite or sandstone, containing native copper with small amounts of cuprite and copper carbonates, and those hosted in sandstone, which contain more cuprite, along with native copper, millimetric geodes of arsenates, and copper carbonates. The latter vein has been the subject of mineralogical descriptions (Picot et al., 1966) and targeted for specific searches for micro-minerals near the geodes. Observations in the micro-geodes associated with cuprite have led to the description of nine new mineral types (Mari, 2023). The mineralogical composition of the veins is highly

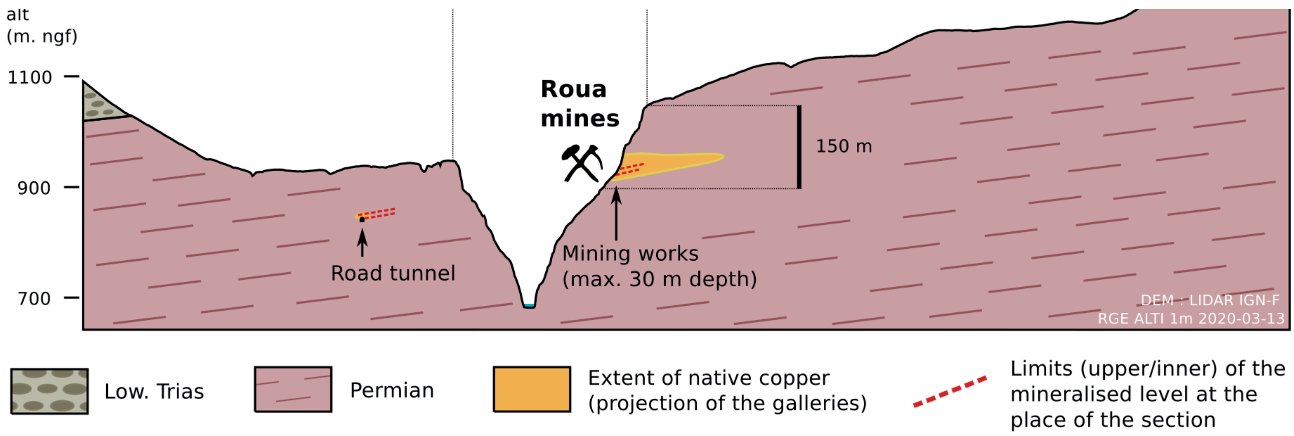

Fig. 3 – Topographic location of the Gorges de Daluis and the Roua native copper mines.

variable, with some veins lacking sulphides or arsenic, while others contain notable trace amounts. Native silver is present in several veins, and it appears to have been a significant component of the mineralisation in Gallery 1 of the Southern Roua group (Rostan and Mari, 2005).

Nonetheless, cuprite and native silver mineralisations are far less abundant than native copper (Mari, 2023), the primary ore extracted from this mine. It occurs as massive nodules or sheets a few millimetres thick within the carbonate gangue (fig. 4) and sometimes directly as small nodules in the Permian rock. The ore consists of nearly pure copper, making it usable by prehistoric societies without the need for pyrometallurgical processes.

Currently, the Roua deposit is exhausted. This makes it difficult to obtain mineralisation samples for geochemical analysis (lead and copper isotopes), which require only a few milligrams of ore at most.

Historical Mining (Industrial and Artisan)

The first mentions of ancient activities are found in contemporary archives of black-powder workings conducted between the 17th and 19th centuries CE (late 17th century; mid-18th century; 1863; 1883). In 1863, engineer Francfort documented the presence of ancient galleries filled with charcoal residues and human bones discovered during the clearing of the old underground workings (Francfort reports, cited in Mari and Mari, 2009). This ancient backfill, likely prehistoric, was discarded below the mines into the Var River. Between these exploration phases, small-scale black-powder artisanal mining was conducted in ancient mine workings around the 1840s (Juge, 1844). These artisanal workings, rediscovered in 2020 (Mari, 2021), had a lesser impact on prehistoric galleries and backfill.

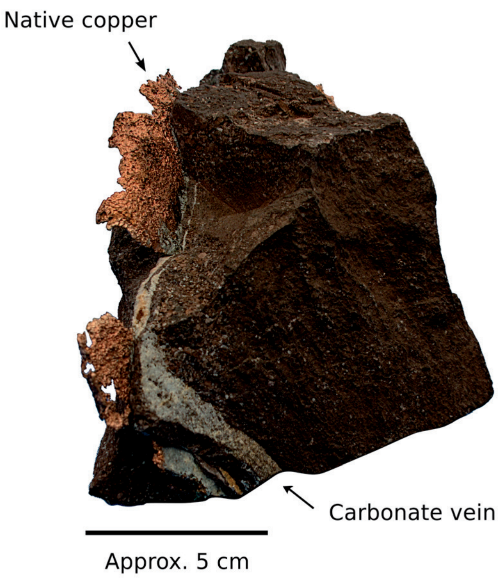

Fig. 4 – Roua native copper mineralisation (G. Mari collection).

First Archaeological Documentation: Evidence of Prehistoric Exploitations

The Roua mines have been the subject of archaeological studies to characterise the ore chemically (trace elements) and document the mining activities. Various extraction techniques were inventoried, and some of the remains were mapped (Rostan and Mari, 2005). The mine workings are divided into two geographical clusters, southern (S) and northern (N), numbered sequentially from south to north within each group. Several small or preliminary workings, too minor to be individually categorised, were sometimes included in the plan surveys (Rostan and Mari, 2005, fig. 2, 3 and 4). This initial study identified small-scale underground workings, rarely exceeding 5 m in depth. Most of these workings contain traces of later black-powder mining activities. The S1, S3, and N4 galleries revealed the most significant operations, conducted with powder, reaching depths of 30 m. Despite the extensive black-powder mining activities, remains of fire-set surfaces were observed near the gallery entrances in nearly all these mine workings. These remains indicate the existence of ancient exploitation phases that may have occurred from prehistory to modern periods. Stone hammers found in the northern group are the only evidence confirming a prehistoric mining phase.

First Steps in Tracing Prehistoric Metal Origins

Analyses of trace element concentration were conducted on native copper from Roua (Barge, 1995; Barge et al., 1998; Rostan and Mari, 2005) as the first step in studying the provenance of prehistoric metals. These analyses, performed on ore samples and experimental smelts (table 1), revealed mostly pure copper. However, it sometimes contained arsenic, in amounts of several percent by weight, and about 0.1 wt%. of silver. Arsenic content in the ore exceeded 10 wt%., while experimental productions yielded maximum concentrations of 2–3 wt%. Lead, antimony, nickel, iron, and zinc were present in low concentrations (less than 0.1 wt%.) in the ores and remained only as traces (less than 0.005 wt%.) in the experimental smelts. Other trace elements were found in very low concentrations in the ore, with some reaching up to 50–100 ppm (Hg, Mg, Bi) and others below 30 ppm (Au, Mn, Co, W, Te, Ti). Arsenic and silver are the main impurities likely to be present at low levels (approximately 2.5 wt% for arsenic and 0.1 wt%. for silver) in objects made from Roua's native copper.

The chemical composition of Roua's native copper, ranging from nearly pure to arsenical varieties, falls within the variability observed in prehistoric copper artefacts in Western Europe (Labaune, 2016). This does not imply direct evidence of native copper use, but rather shows that Roua ores are consistent with established compositional classes of prehistoric copper (e.g. arsenical and pure copper from the Stuttgart classification, Junghans et al., 1968). However, these observations

Summary of native copper analyses from Roua

Ore \ wt %.	Cu	Sn	Pb	As	Sb	Ag	Ni	Fe	Zn	Si
min	91.3	-	-	0.101	0.00011	0.013	0.00014	0.0021	-	0.1
max	99.9	0.04	0.098	12	0.0014	0.35	0.0038	0.0093	0.0032	0.4

Objects and experimental castings based on native copper from Roua (Barge *et al.*, 1998)

Obj. \ wt %.	Cu	Sn	Pb	As	Sb	Ag	Ni	Fe	Zn	Si
GLE	96.95	-	-	0.25	-	0.15	-	-	-	0.3
PA1	97.6	-	-	2.3	-	0.1	-	-	-	-
PA2	97.4	-	-	2.5	-	0.1	-	-	-	-
PA3	97.6	-	-	2.3	-	0.08	-	-	-	0.02
PRE	96.7	tr	0.005	3	-	0.15	tr	-	-	-

Summary of native copper analyses from Roua (next)

Ore \ ppm	Co	Au	Bi	Hg	Mg	Mn	Ti	V	W	Te
min	-	-	-	14	-	-	12	-	21	-
max	-	0.4	50	110	100	10	16	1.4	28	0.001

Objects and experimental castings based on native copper from Roua (next)

Obj. \ ppm	Co	Au	Bi	Hg	Mg	Mn	Ti	V	W	Te
GLE, PA1, PA2, PA3, PRE	-	*NA*	-	*NA*	*NA*	-	*NA*	*NA*	*NA*	*NA*

Table 1 – Summary of elemental analyses for Roua ore and experimental smelting products. Experimental smelts were not subjected to trace-level elemental characterisation. Data from C2RMF (1990s), Univ. Rennes (1990s), CINaM (SEM-EDX, 2010s), and DBM Bochum (before 2005) as reported in Rostan and Mari, 2005 and Mari, 2023. Ppm data reported for the C.2R.M.F series. Where not stated in the sources, analytical methods and instruments are unspecified. At Univ. Rennes: Cu by electrolytic determination, SiO_2 by gravimetry, impurities by spectrometry (Barge et al., 1998). Symbols: "–" undetected; "NA" not analysed; "tr" trace.

alone are not enough to determine the origin of copper in archaeological objects. Lead isotope analysis is needed to determine the geochemical fingerprint of Roua's copper ore. To date, some results have been obtained through doctoral research (Cattin, 2008; Bussone, 2023).

Characterising Prehistoric Exploitation: Chronology and Copper Production Quantification

The native copper from Roua constitutes a valuable resource for prehistoric societies. Fire-set workings are observable in many galleries of this mine. However, assessing the extent of prehistoric mining required the acquisition of chronological data on the exploitation. Finally, between 10 and 20 tonnes of metallic copper were extracted from the most extensive black-powder operations (Rostan and Mari, 2005). The prehistoric copper production also required estimation based on the ancient mine workings.

METHODOLOGY

We conducted two field campaigns in 2019 and 2020 to establish the chronology and quantify the volume of mining activities. Georeferenced surveys and plans were essential to determine the extent of the mining activities and to locate those attributed to different phases. This analysis included the study of mining techniques and the spatial distribution of archaeological artefacts to distinguish between different chronological phases. From these observations, fire-set surfaces were targeted for archaeomagnetic and OSL dating. Additionally, the few identified ecofacts were selected to obtain reliable radiocarbon dates for prehistoric activity.

Survey, Plan and Volume

The mine workings were surveyed by measuring azimuth, distance, and slopes between different stations using a DistoX. Topographic data and plans were produced using Therion software and a GIS. Georeferencing involved multiple stages: GPS point acquisition at select stations, targeting notable points from both banks, and finally controlling the position of the surveys using a high-precision (X-Y 1 metre) LiDAR model (IGN-F, 2020). The volume of mine workings was calculated from survey measurements by modelling simplified geometric shapes. Only the galleries in the South B group received complete photogrammetric coverage, allowing the generation of a high-resolution 3D model to estimate the volume of these underground workings. The volume and size of mine workings are used in the results section to estimate copper production during different phases of mining activities.

Chronological Phasing

Field observations allowed for the mapping of mining extraction methods, which were then recorded on plans to deduce the minimum extent of ancient mine workings. Relative chronological sequencing was determined based on the identification of mining techniques and signs of abandonment within the mine workings. The mining techniques were identified by the morphology of the gallery walls: thermal fracturing impacts and rounded profiles indicate fire-setting digging methods, while drill holes and blast damage are evidence of powder use. Tool marks (from metal tools) and scraped walls and heavy picking in very localised areas to reach the mineralised vein on the working face also serve as indicators of the most recent phases. The backfill within galleries sometimes reveals the digging method used. The presence of tiny rock fragments and ashy or charcoal-rich sediment indicates an ancient phase of fire-setting activity. Archaeological artefacts are also linked to different phases of mining activities. Stone tools are linked to an ancient (prehistoric) phase, wood fragments to more recent phases, and bones may correspond to various phases of mining or periods of abandonment.

Abandonment markers also provide clues about the age of the workings. Various geomorphological phenomena were observed, such as gallery roof collapses, the filling of mine workings, or walls covered with carbonate deposits. These observations, combined with the identification of mining techniques, revealed the existence of ancient fire-set workings that have since collapsed and are now inaccessible or destroyed.

Dating

Archaeomagnetic, TL/OSL and radiocarbon analyses were obtained to date the ancient mining phase (see Bussone et al., 2026 for further details). The archaeomagnetic method, successfully applied to the fire-set rocks of the mine, relies on the ability of ferromagnetic (sensu lato) minerals to record elements of the Earth's magnetic field (declination D, inclination I, intensity F) after heating. Analysis of orientated samples from fire-set rocks in galleries N4, N12, N14, S2, and S9 through thermal demagnetisation revealed two components of magnetisations for each sampled wall, with directional data (D and I) in opposite directions. The first (retrieved from laboratory thermal treatment up to 500–650°C) corresponds to the archaeological magnetisation (due to the fire-setting), while the second (retrieved from the highest laboratory temperatures) is the natural remanent magnetisation of the Permian bedrock.

The dating of the mining activity is based on the comparison of the archaeological magnetisation directions with a regional curve for the late prehistoric Alpine region, constructed specifically for the Roua area during the Neolithic (Roua-6KBCE; Bussone et al., 2026), and for antiquity and historical periods with the French local curves (Hervé and Lanos, 2018; Gallet et al., 2002). This was achieved using archaeomagnetic data and high-resolution sedimentary data within a 1000 km radius around the mines. The correlation between calibrated solutions for inclination and declination may provide one or more age proposals for the fire-setting activities. We select the most probable chronological intervals that coincide with dates obtained from other dating methods and with the exploitation phases documented by archaeology and archival records (Prehistory, and possibly the modern period).

Two TL/OSL datings were tested on a Permian block from the South B network (junction S26-28), chosen for its calcite encrustation, which may have preserved the surface of recent lighting, increasing the chances of dating the fire-setting phase. Finally, the charcoal remains from the South B network, selected for radiocarbon analysis based on anatomical and taxonomic criteria, provided a reliable age for the prehistoric exploitation. However, bones were not included in these analyses due to uncertainty regarding their antiquity: they come from the surface of a backfill that has not yet been archaeologically excavated.

RESULTS

Survey of Prehistoric Workings

Most of the mining activities at the Roua site were documented during field campaigns (fig. 5). Some galleries mentioned in Rostan and Mari (2005) were not found. This is likely due to cliff collapses that affected galleries S11–12 and possibly S17-19. Small fire-set workings near known mine remains have been identified at N14 and S22. Previously undocumented workings were also recorded, including the partially collapsed gallery N15, and especially galleries S23-28. The geographic location and extent of these newly documented workings resulted in the creation of the 'South B' subgroup. Each of the North, South A, and South B groups requires a specific access path from the top of the cliff, as was likely the case during prehistoric periods. Moving between these groups along the cliff face is perilous today.

The galleries in the South B group (S23–28) and the North group (N12–15; N4) exhibit some of the most extensive fire-set workings. Archaeological artefacts associated with these mine workings indicate their prehistoric exploitation.

South B Group Workings

The galleries in the South B group represent the only mining network documented at Roua so far (fig. 6). The network, which comprises galleries S24 to S28, totals 70 m of underground workings with a maximum depth of 25 m and an approximate volume of 110 m³. Nearby is the smaller S23 gallery, which is 6 m deep and likely dug during the same phase. The study of these interconnected galleries was facilitated by a high-resolution 3D digital model acquired by photogrammetry. Preliminary investigations revealed the extent of fire-set workings. These were identifiable by the characteristic gallery profiles, soot marks, and the spread of ashy and charcoal-rich backfill. Archaeological artefacts found during field surveys indicate multiple phases of mining activity, one of which dates to prehistory.

Artefacts from the South B Galleries

The discovery of seventeen stone hammers (fig. 7) provides evidence of prehistoric activity within these

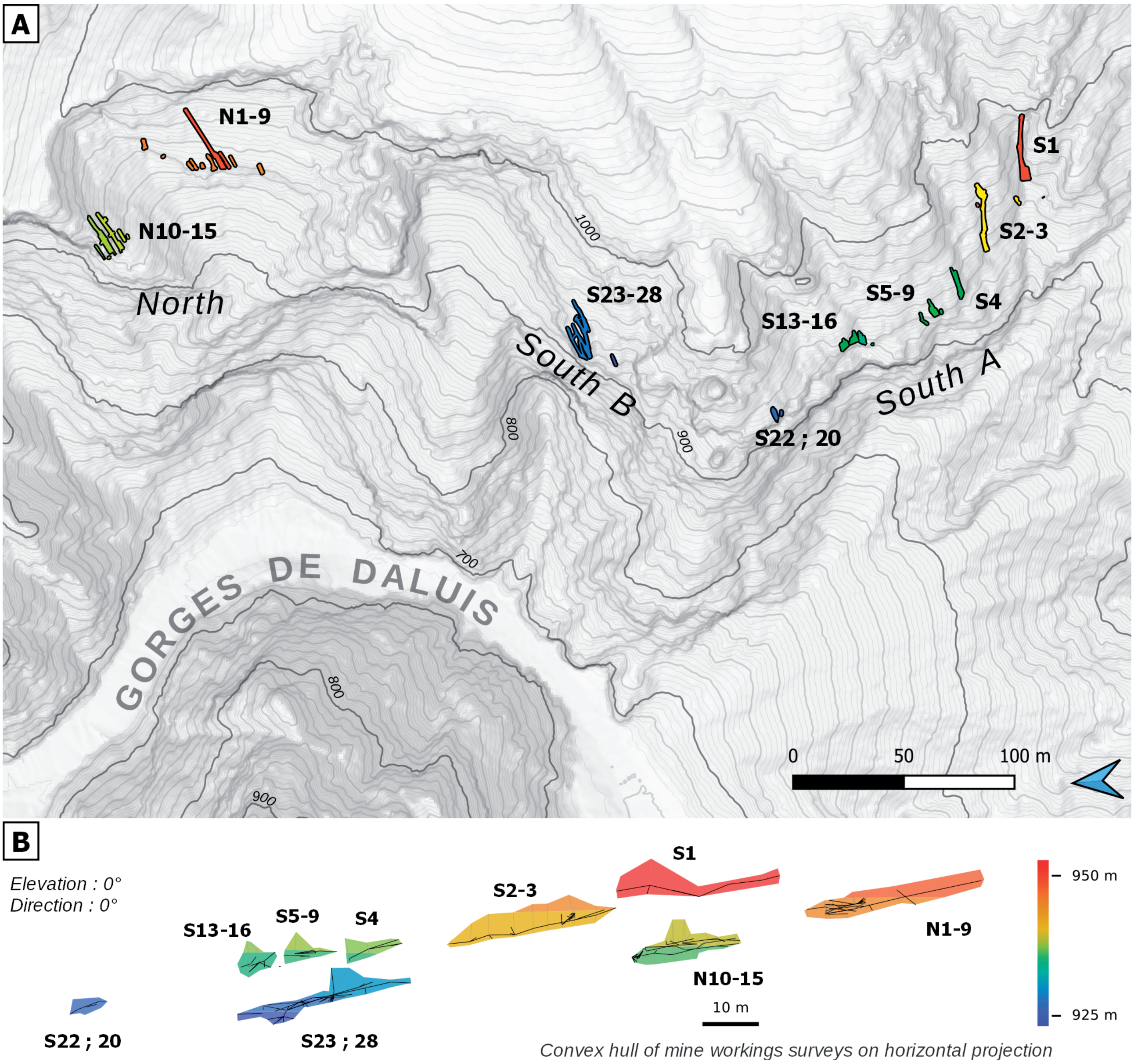

Fig. 5 – Plan (A) and section (B) surveys of the Roua mines. A: location of mining works in Gorges de Daluis; the colour indicates their average NGF altitude; B: projection of sections of all topographic surveys (underground workings are enclosed in a convex hull to distinguish them) with elevation and azimuth parameters sets at 0°.

workings. These artefacts were found on the ground at the southern entrance, within the stone blockages filling S26–28, and in the ashy sediment near the working face of S26. Crafted from the Permian host rock of the mine, these hammers vary in shape, from spherical to quadrangular, with weights ranging from approximately 400 to 960 g and diameters between 70 and 100 mm. Some show clear fractures and evidence of previous use (e.g. fig. 7, no. 11, no. 13). Only one hammer exhibits remnants of a possible hafting groove (fig. 7, no. 2). During preliminary observation, inclusions of native copper or secondary copper minerals were identified on two of the stone hammers recovered from Roua fig. 7, no. 11 and one found near N12 by G. Mari in the 2000s). One inclusion was located at a spall removal scar on maul no. 11 (fig. 7), well away from the striking surfaces observed for this tool, suggesting that it was initially used as a percussive implement and subsequently repurposed as an anvil. Most of the tools fit in the hand and could correspond to crushing tools; more rarely, the heavy ones and the one with remains of hafting (no. 2) possibly indicate a use for digging; Further examination would confirm these initial trends.

Additionally, a flint nodule with most of its surface still covered by cortex (fig. 7, no. 18) was found at the entrance of S23. It was used as a percussion tool, as indicated by erratic flake removals and the absence of cortex on one end.

Charcoal remains embedded in ashy sediment in galleries S24 and S26 testify to fire-setting activities. Prelim-

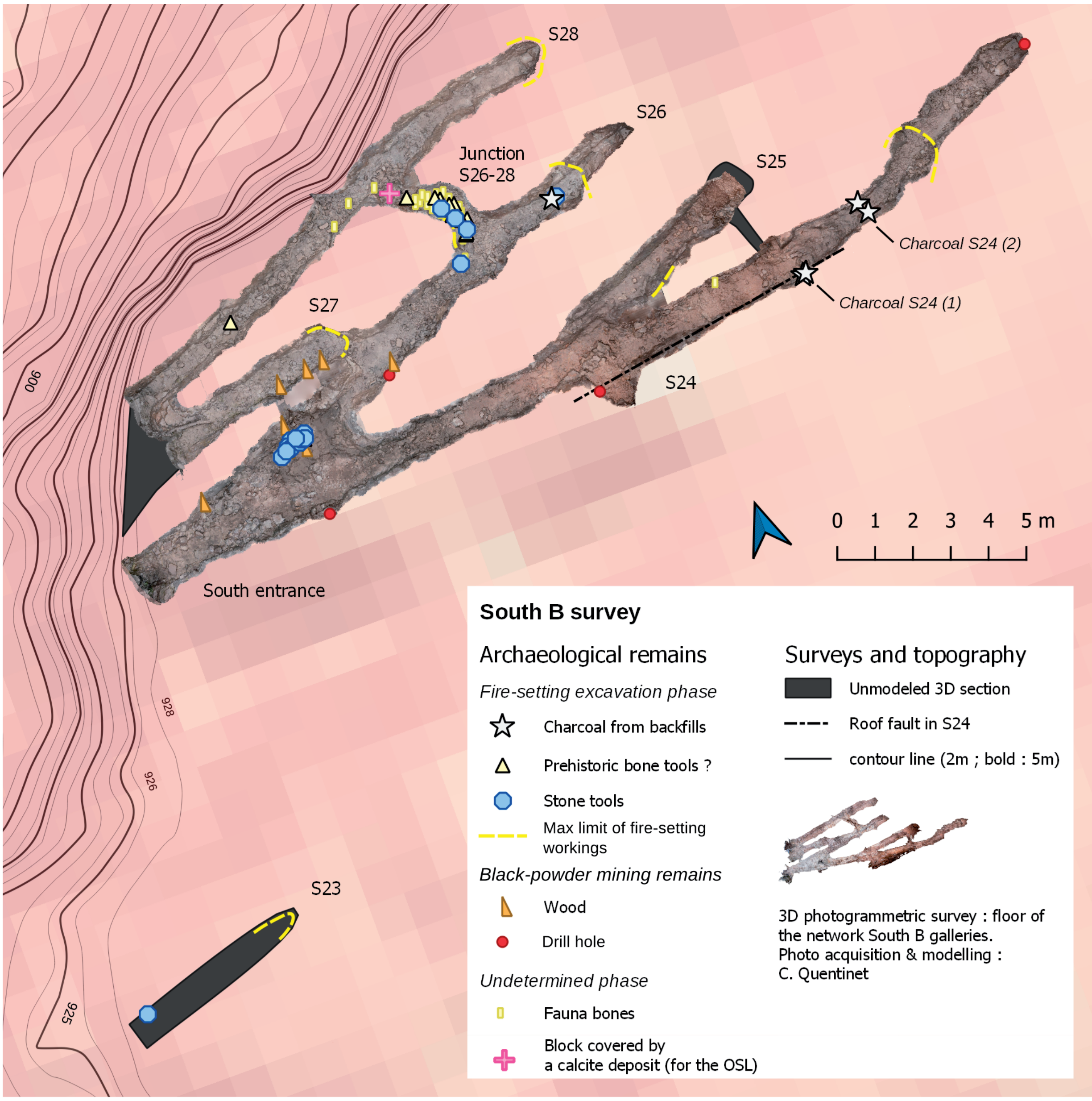

Fig. 6 – Fire-setting workings and prehistoric remains identified on the South B gallery surveys.

inary anthracological analysis identified wood remains of various sizes, including pine and oak logs, as well as small branches (Rosaceae, Ericaceae, Prunus, Acer, and juniper). These could have been used for the fire-setting process.

The bones were collected from the surface during the field campaign. A preliminary study was conducted to verify whether they were human bones, as identified by Francfort in the 19th century in old backfills of Roua mines (Mari and Mari, 2009). All those observed (NR = 35) are fauna remains, found dispersed across various sections of the network, although most (NR = 28) are concentrated in the S26–28 junction backfill. Among them, several bones exhibit characteristics that are incompatible with either recent mining remains or scavenger activities. This includes lower limb bones from a horse (one metacarpal) and cattle (one distal phalanx), which could date back to prehistoric times, possibly linked to the manufacture of miners' tools from long bones. Other bones belonging to ovicaprids (NR = 10) and a flat bone (scapula) of an ovino-caprine could also correspond to prehistoric tools. However, the antiquity of these remains is not guaranteed. Further studies, including excavation of the backfill, detailed archaeozoological analysis with use-wear traces examination and radiocarbon dating, are required to accurately identify the prehistoric faunal remains.

Finally, wooden remains were found near the entrances of the South B network. Torches stuck into the walls, burnt fragments on the ground, as well as unburned boards and tool handles, resulted from more recent visits. These items, including a long rosebush stick found near a drill hole at the entrance of S26, date to the black-powder workings phase, likely from the second half of the 19th century CE.

Fig. 7 – Stone tools found in the South B galleries.

The Extent of Prehistoric Workings

The fills and extraction marks on the walls of the South B group galleries reveal a complex mining history. Small-scale black-powder workings were located at the southern entrance, in the first few metres of S26, and inside S24, where these activities were most significant. The continued digging of S24 to a depth of 3–4 m, the clearing of a roof fault, and the installation of a platform midway through the gallery testify to this activity. Despite these modern interventions, prehistoric backfill remains have persisted. These remains, consisting of ashy/charcoal-rich sediments and tiny rock fragments, are found on the ground and in wall niches up to 20 cm above the current floor level. Coarser sediments cover these ancient fills in some areas, resulting from a partial roof collapse in S24 and S25, caused by the fault (the working face of S25 is nowadays still inaccessible). Traces of this collapse remain under the gallery roofs, suggesting that the original workings were cleared during later black-powder workings. This sequence of events is a highly significant indicator of the antiquity of the first diggings. While other galleries in the network show no signs of collapse, a calcite deposit covering the fire-set workings further indicates the antiquity of these mine workings.

The South B network was shaped by fire-setting. The working face of S28 retains the complete, characteristic smooth shape, while S27 has only preserved part of it. In galleries S24 and S26, remnants of the original working face are observed at 1 and 4 metres from the current face, respectively. In S25, the impact of fire-setting is visible at least in the first half of the gallery, and in the S26-28 junction, it is identifiable in the first half extending from S26.

The direction of diggings in different sections of the network also indicates relative chronology. The working face of S27 was dug before the opening of S26, the S26-28 junction was dug from S26 toward S28, and galleries S25 and S24 were once a single gallery before S24 was extended with a new section. Thus, S27 and the southern entrance are likely the oldest mine workings in the South B network.

The North Group Workings

The North group provided the first evidence of prehistoric activity with the discovery of stone hammers and four-

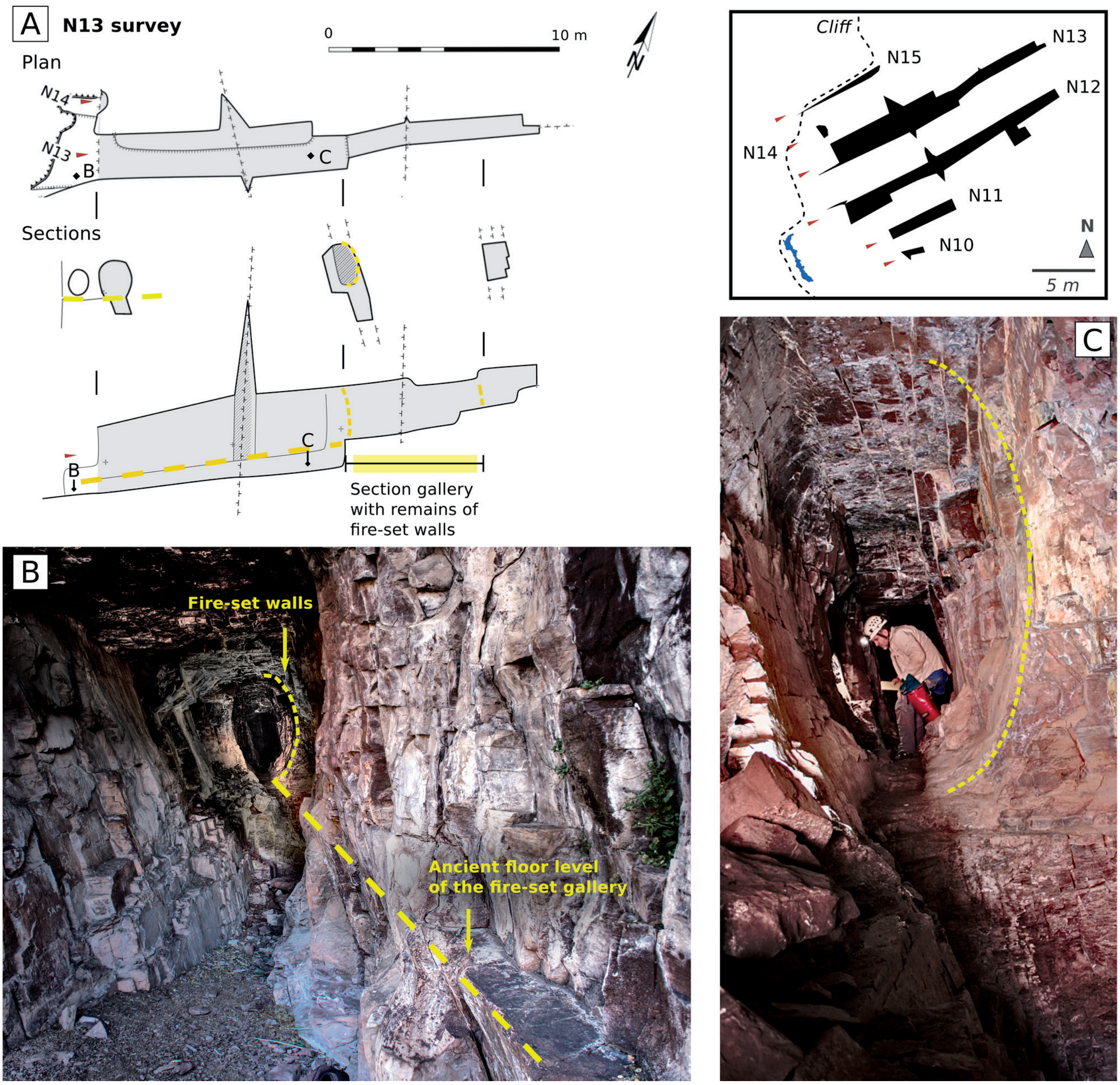

Fig. 8 – Plan and cross-section surveys (A) of the fire-setting evidence in N13. Photos of the entrance (B) and the mid-gallery (C) showing the scale of the ancient fire-setting workings (highlighted in yellow dotted lines).

teen native copper sheets (Rostan and Mari, 2005; Mari and Mari, 2009). These were located near the entrance of gallery N12. The extent of fire-set workings in galleries N12–15 and N4 was reassessed based on geomorphological observations and identifying the minimum extent of ancient workings.

Reassessment of fire-set workings (N12–15)

Galleries N12 to N15 have undergone significant destruction due to later mining activities and natural collapses. In N13, black-powder activities nearly obliterated the original fire-set galleries, leaving only a 5-metre section, partially destroyed by a trench dug from the cliff to the middle of the underground workings (fig. 8). Despite this, remnants of the original gallery level can still be seen on the right wall, up to approximately 4 metres from the current entrance, indicating that part of the original gallery entrance has disappeared (fig. 8; fig. 9; N13).

Observations of the surrounding mine workings lead to the conclusion that the original entrances of galleries N12, N14, and N15 were further out on the cliff face (fig. 9). The south wall of gallery N15, visible only from the west Gorges de Daluis bank, shows a typical fire-set gallery profile that contrasts sharply with the steep edges of the cliff (fig. 9; N15). The working face of this gallery is marked by a white deposit, likely calcium carbonates. These remains, which show no indication of black-powder reworking, likely collapsed during an ancient phase. The floor limits of this gallery can be observed at the base

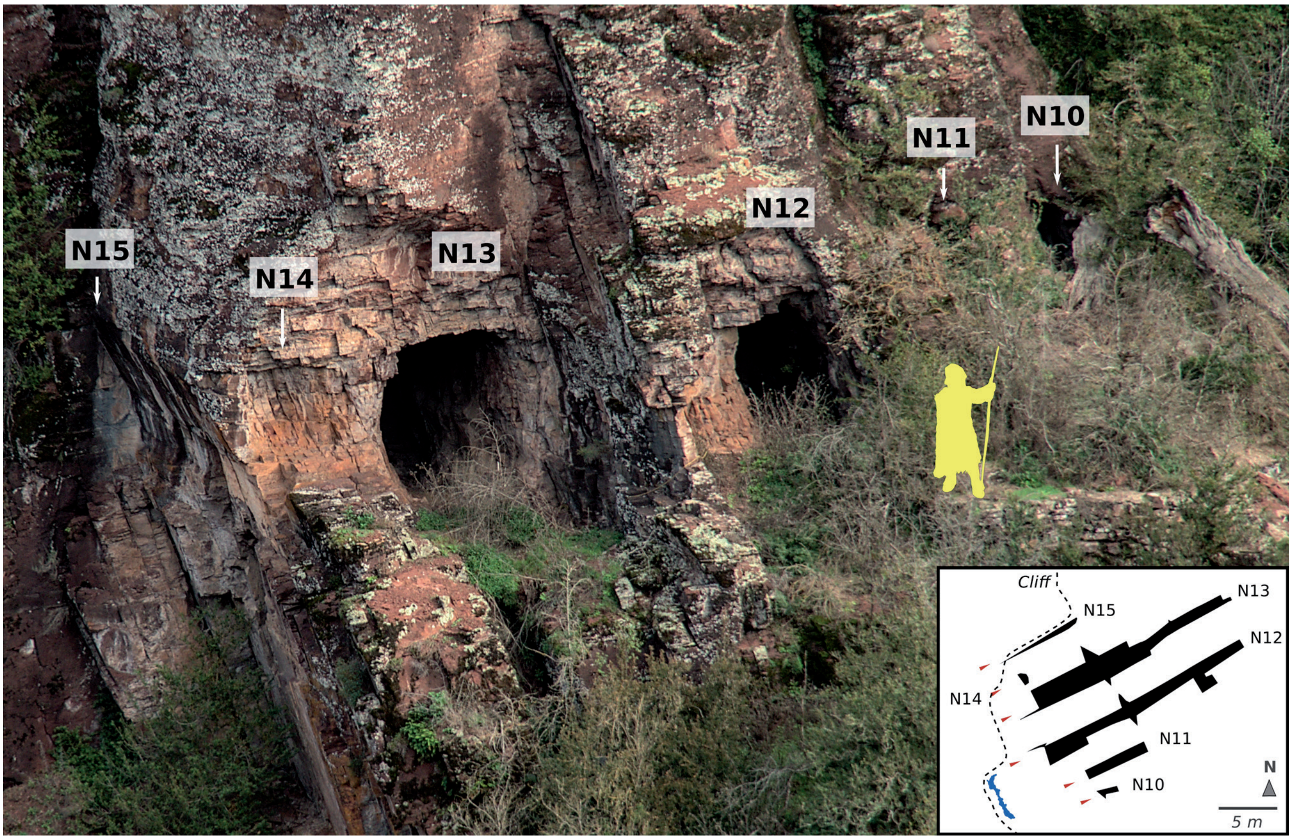

Fig. 9 – Photo of galleries N15–12, showing the collapse of the entrances to the old galleries.

of the right wall and might extend a few metres above the remains of N14. These observations led to a reassessment of the nature of the workings in N14. What initially appeared to be a small fire-set working is now understood to be the working face of a small gallery a few metres deep, now collapsed (fig. 9; N14).

Near the entrance of N12, magnetic susceptibility surveys revealed the presence of a heated wall, confirmed by archaeomagnetic analysis (Bussone et al., 2026). From the west bank, the limits of these workings are visible at the junction between N13 and N12 (fig. 9; N12). This too is a small gallery section, potentially connected to N12, which collapsed in ancient times.

Extent of fire-set workings

The estimation of the extent of collapsed fire-set sections represents a minimum for these workings. The depth of N15 was estimated at 9 m based on surveys of N13 (helped by the location of a transverse fault opening onto the cliff) and LiDAR data.

The minimum extent of fire-set surfaces in galleries N13, N12, and N4 was determined by observing profile interruptions. The combined extent of fire-set workings in N12-15 and N4 totals approximately 60 m.

Across the entire North mines, the cumulative depth of ancient workings reaches 93 m, making it the group with the most extensive fire-set workings. In comparison, the South B group reaches 76 m, and the South A group, heavily affected by destructive power-blast workings, totals 43 m.

Chronological Phasing and Dating

Four main phases of activity have been documented (fig. 10). The first phase corresponds to the initial fire-set workings. The second phase is characterised by the abandonment and deterioration (collapses) of these remains. The third phase involves powder-blast workings, while the fourth phase is marked by more recent abandonment and further collapses.

Evidence of the third phase includes numerous drill holes, the sub-rectangular profile of the workings, pick marks on the older working faces, surveyor inscriptions, and work platforms that facilitated mining operations between the 17th and 19th centuries CE.

Simultaneously, remnants from the first phase are still visible in most galleries. These include rounded sections of the workings and artefacts associated with earlier periods. Among these are stone hammers found in the North and South B groups, which attest to prehistoric activity. A grinding stone (see Rostan and Mari, 2005, fig. 5) found in the South A group might also be linked to this early phase of exploitation.

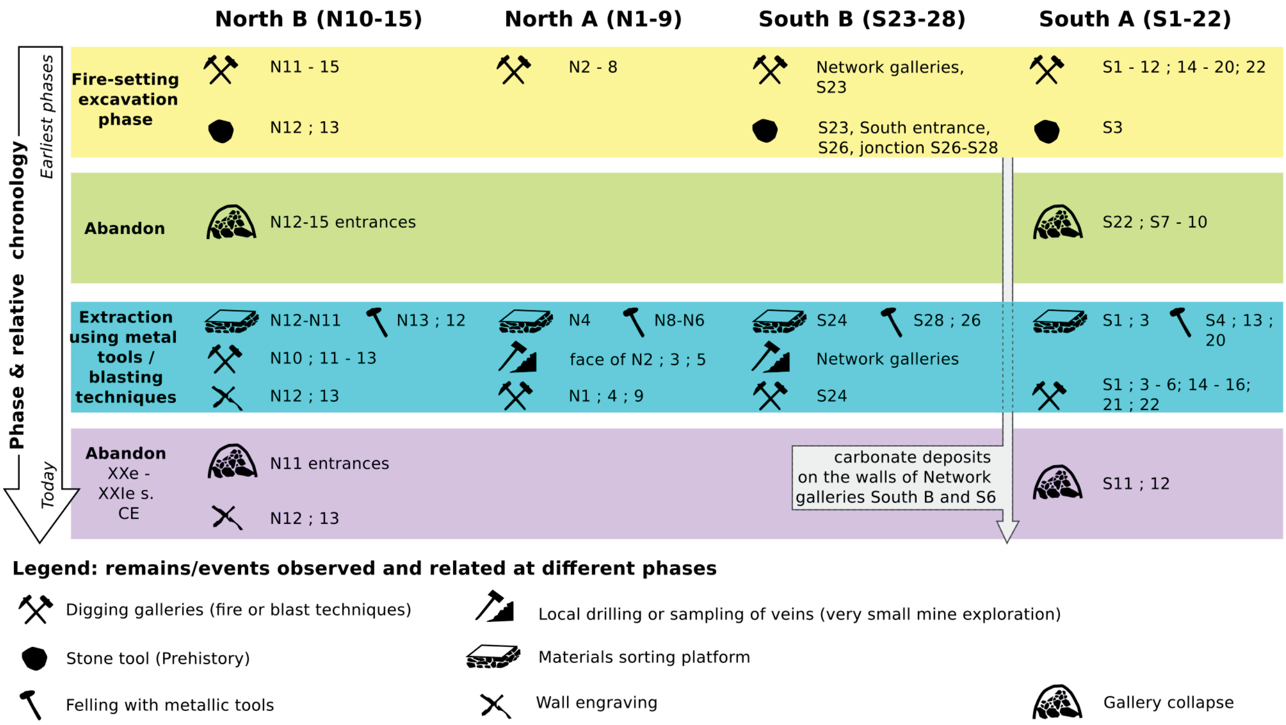

Fig. 10 – Relative chronology by mining techniques: main phases for Roua copper exploitation.

The first-phase workings have been dated by means of chronometric analyses (fig. 11, table 2). Radiocarbon dating was performed on charcoal samples extracted from ashy backfill layers located in the deepest parts of the South B network (S24 and S26). These radiocarbon ages, with a negligible old wood effect, were calibrated with the IntCal20 curve (Reimer et al., 2020). The exploitation of the South B network is thus situated between the mid-4th millennium and the early 3rd millennium BCE (3510–2900 cal. BCE).

Two OSL analyses from a block taken at the section between junction S26-28 and S28 provided an age range of 3165–2114 BCE (95 %), narrowing to 2911–2379 BCE at a 68 % confidence interval. The origin of the recorded signal (light from lighting or fire-setting) is unknown. This age confirms that different parts of the southern network were visited during the Neolithic period. Future in situ dosimetry measurements and analysis of the Permian rock mineralogy (to distinguish quartz from feldspar) will further refine the OSL analysis.

Archaeomagnetic calibration over a wide working range (4500 BCE–1950 CE) can yield multimodal HPD intervals for a single direction (D, I) due to secular variation. The Roua-6KBCE regional calibration curves, while less constrained for older periods because of the lack of archaeomagnetic data, perform better than global models (Bussone et al., 2026). The interpretation for age in this paper privileges posterior modes and the largest parts of the probability mass. Where independent constraints exist (^{14}C/OSL, stratigraphy, archives), they are used to arbitrate among competing modes. Finally, we assume that intervals recurring across independently sampled directions are more probable. Under these rules, the fire-set rocks analysed converge on the 4th millennium BCE. N12 reduces to two credible windows, late 5th or late 4th millennium, with a clearly dominant 4th millennium solution (3254–2999 cal BCE; 89 % of the probability mass). S9 yields a solution in the second half of the 4th millennium (e.g., 3286–3040 cal BCE, 12 % of the probability mass; while a large share of its mass and posterior modes lies in the later 5th millennium, that mode is not supported by regional context). N4 retains several credible intervals, most in the 4th millennium and together 48 % of its probability mass and S2 admits an early 4th millennium solution (3958–3528 BCE; 17 %). It should be noted that N4 and S2 also deliver regions compatible with the end of the Neolithic period (2326–2039 12 % and 2309–2129 BCE 5 % respectively) or with the Bronze Age (1796–1598 10 % and 1733–1153 BCE 23 % respectively). Finally, S2 yield HPD regions between 500 BCE and 500 CE (one corresponding to its posterior mode), but these calibrated ages do not overlap and are less consistent with archaeomagnetism, ^{14}C, and OSL elsewhere on the site. N14 is atypical: a Late Bronze Age interval (1219–1001 cal BCE; 34 %) is plausible, whereas a 16th century CE alternative is unlikely given the historical record.

Chronometric data from the three mining groups (North: N1–15, South B: S23–28, South A: S1–22) indicates a main phase in the 4th and early 3rd millennia BCE (fig. 11: ^{14}C and OSL data and N12/S9 archaeomagne-

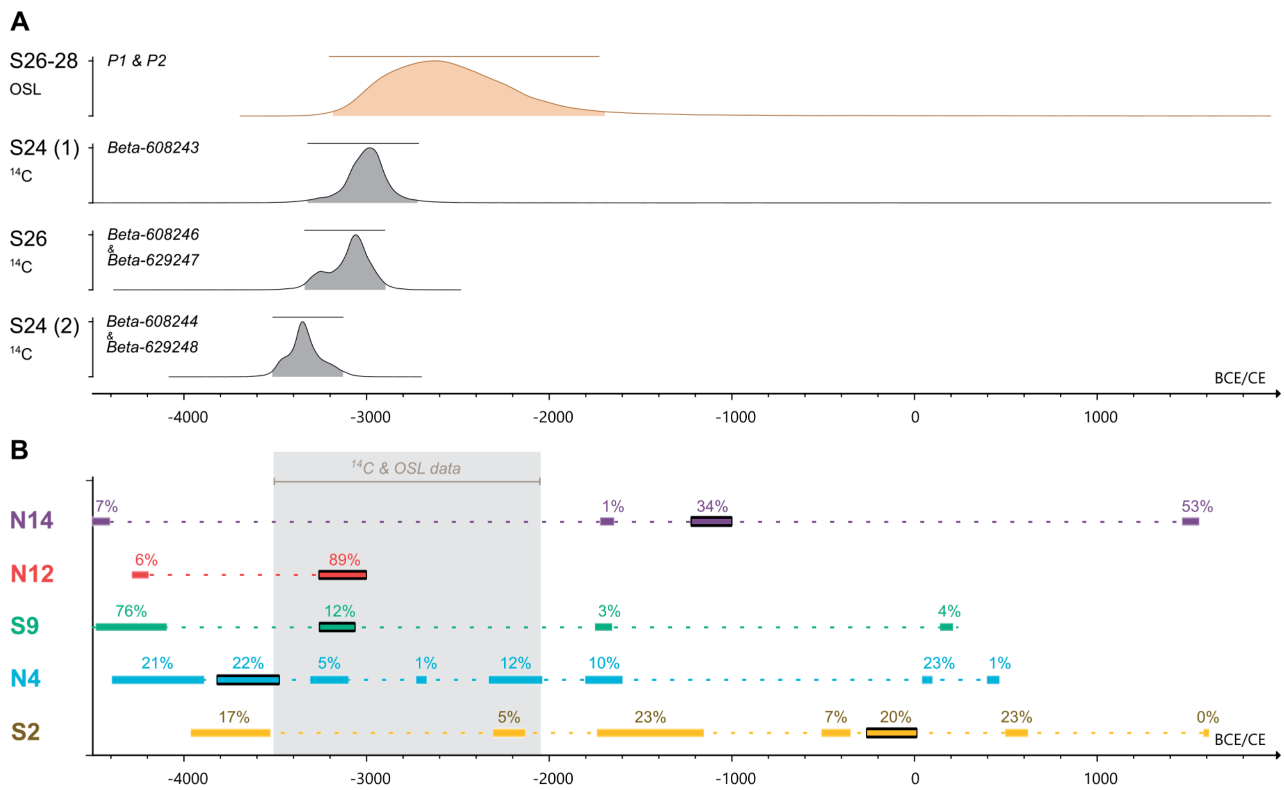

Fig. 11 – Chronology of the fire-settings (^{14}C and archaeomagnetism) and of ancient lightings (OSL) in the Roua mines (4500–1950 CE). A: bayesian a posteriori age (95 % of the HPD is represented, table 2 for raw data) for location S26–28, S24 (1), S24 (2), and S26 (see fig. 12) ordered from most recent to oldest (ChronoModel 3.2.9; Lanos and Dufresne, 2024; calibration curve: IntCal20; Event modelling); B: scatter plot of archaeomagnetic dating (see fig. 12 for sample location), credible intervals (95 %) obtained by combined inclination and declination calibrated data. Percentages indicate probability mass within each HPD. Black-outlined region indicates the posterior mode of the HPD (the region of highest posterior density) for prehistoric times post 4000 BCE. Grey square in the background delineates the prior time range defined by ^{14}C and OSL data (ChronoModel 3.2.9; calibration curves: Roua-6KBCE and French local curves post 300 BCE; Hervé and Lanos, 2018; Gallet et al., 2002).

Feuille1

Sample location*	Method	Remain	More details	Lab. Code	Lab. Data		Calibration curves	Age BCE** 95 % HPD
S24 (1)	14C	Charcoal	Verification of taxa and anatomical criteria on charcoal to date those without old wood effects; palaeotemperature and sedimentary context (ash) to avoid lighting remains	Beta-608243	4390 ± 30	BP (1950)	IntCal20	3093–2914
S24 (2)				Beta-608246	4620 ± 30			3511–3347
				Beta-629247	4510 ± 30			3354–3098
S26				Beta-608244	4420 ± 30			3319–2920
				Beta-629248	4440 ± 30			3330–2929
26-28	OSL	Permian rock	Sampled under a post-mining calcium carbonate deposit	P1-OSL	4480 ± 380	BP (2020)		3165–2114
				P2-OSL	4830 ± 360			
N4	ArchMag	Permian rock	Sampled on archaeological identified fire-set walls and field magnetic susceptibility	N4	D: -2.9°; I: 59.7°; α95: 0.5°		Roua-6KBCE	4000–1596
N12				N12	D: -9.9°; I: 41.4°; α95: 2.3°			3237–3019
N14				N14	D: 7.9°; I: 59.0°; α95: 2.1°			3642–997
S2				S2	D: 1.9°; I: 63.7°; α95: 1.4°			3958–1
S9				S9	D: 0.8°; I: 54.3°; α95: 0.9°			3686–1626

Table 2 – Chronometric data obtained for the fire-setting phases (^{14}C and archaeomagnetism) and ancient lightings (OSL). See Bussone et al., 2026, for more details on the methodology and data relating to the selected remains, analysed to obtain an age, as well as their interpretation. *The column refers to a specific location and not to the entire gallery (see fig. 6 or fig. 12 for sampling location). ** TPQ and TAQ are 95 % HPD computed between 4000 and 1 BCE. Credibility intervals for archaeomagnetic ages between 4500 BCE and 1950 CE are detailed in fig. 11.

tism). However, the possibility of later mining during prehistory or antiquity cannot be ruled out, particularly for the Late Neolithic or Early Bronze Age for N4 and S2, and especially for the Late Bronze Age with N14.

Radiocarbon ages from the deepest South B galleries imply that the earliest openings (e.g., South entrance, S27) predate these dates, likely falling within the 4th millennium BCE. The N4 and S2 calibrations also provide solutions for the first half of the 4th millennium BCE that we cannot exclude, despite later alternatives.

The frequency of ancient workings remains unknown. However, fire-setting is known to have been a slow and demanding process. These mining operations sometimes required numerous fires, particularly when dealing with hard rock. Larger pyres were necessary in such cases (Weisgerber and Willies, 2000). For instance, according to experiments by Py et al., 2012, approximately 200 fires were needed to dig a 2 m gallery in Triassic quartzite (Fournel, French Alps). The small size of the ancient galleries at Roua, combined with the site's topography (steep cliffs), highlights the considerable effort required for fire-setting on Permian rock. This rock is one of the hardest encountered in prehistoric mines in southern France, according to mechanical resistance analyses (Rostan and Mari, 2005).

PREHISTORIC COPPER PRODUCTION, THE QUESTION ABOUT THE AMOUNT OF METAL EXTRACTED

The absence of direct data on the grade and continuity of the veins makes any attempt to assess the quantity of copper extracted difficult, both in prehistoric times and in the modern period. The volume of the galleries does provide an estimate of the amount of material removed, but the proportion of copper in relation to the host rock remains unknown. This can vary greatly, with the thickness of native copper ranging from a few millimetres to more than three centimetres, as indicated by millimetric veinlets, now exhausted, still visible in the galleries which contrast with the very rich specimens preserved in private collections.

Three independent calculation methods (M1, M2, M3) are applied to estimate production from the mined volume, each defined by a set of parameters. To reflect uncertainty, we treat parameters and gallery volumes as variable and generate many plausible realisations via Monte-Carlo sampling. This yields distributions of copper production (rather than single figures) for each method and mining context, from which we report central estimates and uncertainty ranges; we also verified that results are stable at the chosen iteration count (30,000 iterations were run). The first approach (M1), based on the void volume, evaluates the mass of host rock using its density (2,400–2,650 $kg \cdot m^{-3}$), the fraction of ore within that volume (0,1–2 %), the copper grade (90–97 %), the proportion of ore gathered (85–95 %), and a dilution factor capturing gangue inclusion for ore gathered (1.03–1.07). The second approach (M2) models the mineralised portions of the veins directly, assigning each gallery a thickness (0.001–0.02 m) and assuming that a substantial share of this volume corresponds to metallic copper extracted (30–80 %). Finally, a third estimate (M3) generalises the results obtained for the most productive galleries (N13, N12, N4, S3), following P. Rostan's evaluation, about 10–20 t (Rostan and Mari, 2005), although the details of that calculation are not documented. These models are produced for distinct parts of the mine: the volume of the present underground workings (approx. 1.061 m^3); the sections attributed to fire-setting (including estimates for parts collapsed or destroyed by blasting; approx. 331 m^3); and, lastly, the segments upstream of dated sampling points (location in fig. 12; approx. 118 m^3), in order to assess prehistoric production (N14: 2 m; N12: 4 m; N4: 4 m; S9: 2 m; S2: 2 m; and the South B network, except parts of S24, S25, S28, and S26–28). 80 % of the volume corresponds to sections dated to the second half of the 4th millennium BCE (N12, S9, parts of the South B network). For all three mining contexts considered (table 3), M1 systematically yields the lowest estimates, whereas M3 provides the highest. M2 displays the greatest dispersion (largest standard deviation), while M3 is the most tightly constrained. Although the three models differ, their results remain within the same order of magnitude for any given volumetric context.

Aggregated over all periods, total copper production does not exceed a few tens of tonnes (table 3), with an upper bound of 37.9 t under M3; fire-set workings account for several tonnes, peaking at 9.7 t under M2; lower bounds for M1 and M2 are on the order of a few hundred kilograms. For the prehistoric segments upstream of the dated points, production amounts to a few tonnes overall (approximately 1–3 t), with a maximum of 4.8 t under M2 and minima between 200 and 300 kg under M1 and M2. The credible upper limit for extraction in prehistoric times is given by the tonnage obtained from fire-based mining, i.e., between 5 and 10 t of copper at most. All things considered, we can deduce that production in the galleries dating from the 4th millennium BCE produced around one or two tonnes of copper.

Also, at the end of prehistoric exploitation and for the fire-setting exploitation phase, the Roua deposit remained rich in copper resources, as evidenced by specimens extracted during modern and contemporary black-powder workings (Mari and Mari, 2009). The abandonment of mining during prehistory may have been more related to social or economic factors than to resource depletion.

Finally, compared to the 1400 tonnes of copper produced at Saint-Véran between 2400 and 1600 BCE (Carozza et al., 2011), the Roua mines are considered small. However, this production may have played an important role in the spread of metallurgy beyond the Southern Alps.

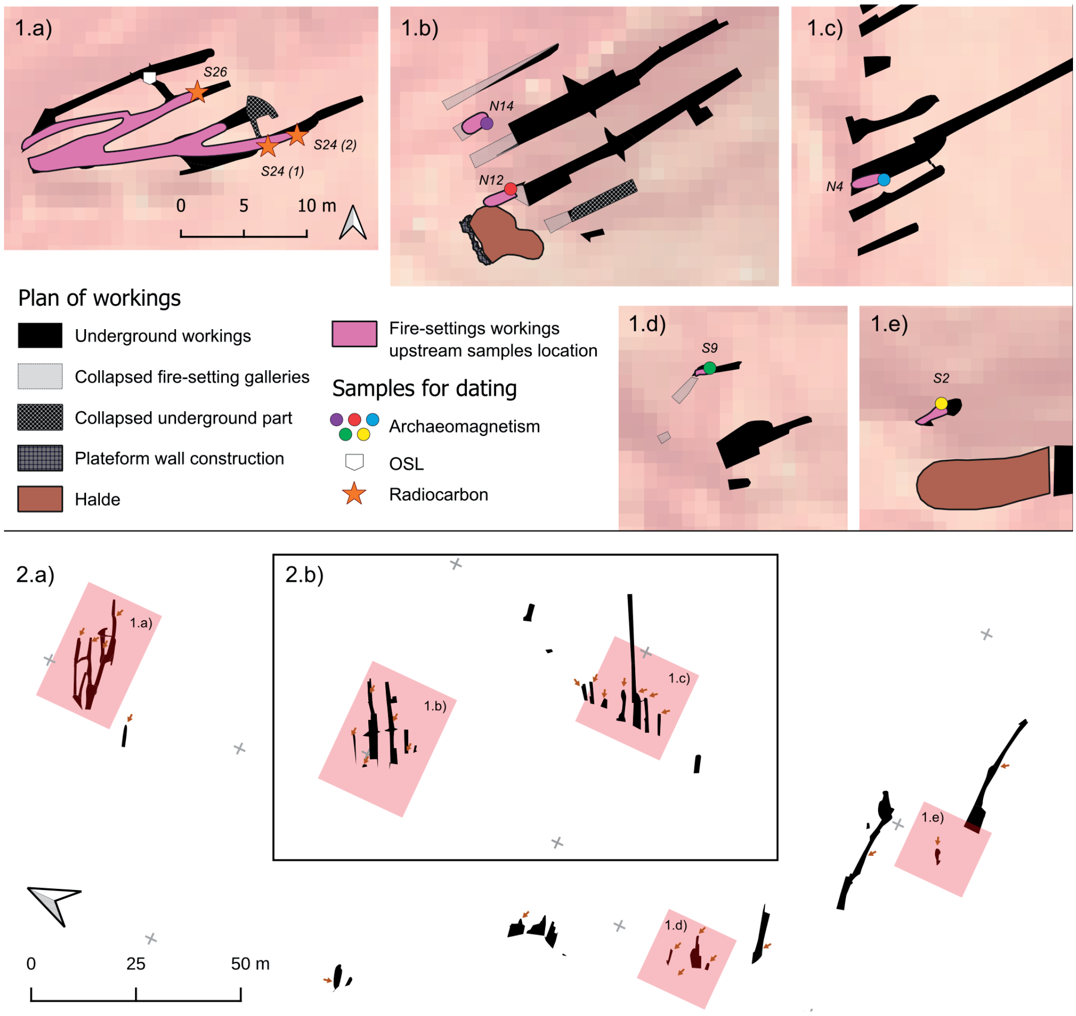

Fig 12 – Locations of sampling points and of fire-setting workings upstream of the dated samples, used for tonnage estimation. 1: maps of sampling locations, all at the same orientation and scale, with the parts of the dated works used for tonnage estimation coloured in pink; 1a: OSL and radiocarbon sampling (South B); 1b-1e: archaeomagnetic sampling at N14 (violet circle) and N12 (red circle), N4 (blue circle), S9 (green circle) and S2 (yellow circle), respectively. 2: maps situating the locations in (1) within the survey of the mine workings, at the same orientation and scale; 2a: South A and South B groups; 2b: North group. Little brown arrows indicate the deepest fire-setting workings observed. See fig. 5 for the position of these different groups in the local topographical and geographical environment.

		Quantity of copper metal extracted (tonnes)		
Methode		All underground work preserved	Prehistoric mines	Firesetting
M1	mean ± sd	**11.8** ± 6.6	**1.2** ± 0.7	**2.2** ± 1.2
	min – max (HDI 95 %)	*[2.2–24.6]*	*[0.2–2.4]*	*[0.4–4.6]*
M2	mean ± sd	**17.4** ± 10.4	**2.2** ± 1.3	**4.5** ± 2.7
	min – max (HDI 95 %)	*[2.6–37.6]*	*[0.3–4.8]*	*[0.7–9.7]*
M3	mean ± sd	**29.4** ± 4.39	**2.9** ± 0.4	**5.5** ± 0.8
	min – max (HDI 95 %)	*[21.2–37.9]*	*[2.1–3.8]*	*[4–7.1]*

M1 — Void-volume model: Estimates copper from excavated void, combining host-rock density, ore fraction, copper grade, gathered ores, and dilution (part of gangue in collected ore).

M2 — Vein-thickness model: Models mineralised vein volume per gallery (thickness/width) and converts it to copper via metal fraction and copper density.

M3 — Reference-scaling model: Scales Rostan and Mari's 10–20 t estimate from key galleries to the whole mine in proportion to gallery volumes.

Table 3 – Copper metal produced (t) by method (M1–M3, see text) and mining context (all galleries preserved, prehistoric mines, fire-setting work). Values are Monte-Carlo summaries (mean ± sd; 95 % Highest Density Interval min–max).

DISCUSSION

The renewed documentation of the Roua mines and the successful application of archaeomagnetism to fire-set rocks provide concrete insights for the study of early metallurgy in Western Europe. The ages obtained for fire-set workings, through various chronometric tools (radiocarbon, archaeomagnetism, OSL), indicate that mining took place during the 4th millennium and into the early part of the 3rd millennium BCE. Up to a few tonnes of copper were produced from Roua in prehistoric times. Although the rhythm of mining is unknown, this production stands out in comparison to the quantity of artefacts identified in the region for the period.

Pioneering Copper Production Sites in Europe: 6th–4th millennium BCE

The chronology of prehistoric exploitation at Roua places these mines among the earliest copper production sites in Europe (fig. 13). The Balkans provide the earliest evidence of mining activities, along with sites like Ai Bunar in Bulgaria, Rudna Glava, and Jarmovac in Serbia (Radivojević et al., 2021). Copper pyrometallurgy activity is also documented at Akladi Cheiri in Bulgaria (Rehren et al., 2016), dating from the second half of the 6th millennium BCE to the first half of the 5th millennium BCE. In Spain, evidence of contemporary copper production was found at the Cerro Virtud settlement (Montero-Ruiz, 2005). A crucible fragment containing copper residues was dated between 4900 and 4460 BCE (Ruiz-Taboada and Montero-Ruiz, 1999).

In Western Europe, the earliest known mine workings are found in the Southern Alps, in Liguria and in Spain. Mining activities are confirmed at Roua, Monte Loreto, and Libiola for the 4th millennium BCE, where copper production likely began during the early stages of this millennium (this study; Maggi et al., 2011). By the end of the 4th millennium BCE, other mining sites in Europe emerged, such as Spanie Pole in Slovakia (Tocík and Žebrák, 1989) and Mocissos in Spain (Goldenberg et al., 2021), whereas copper from Alpine mines was only widely used from the middle of the 3rd millennium BCE in the production of Central Mediterranean artefacts (Artioli et al., 2020). Other archaeological sites provide evidence of copper production around the Alps in the 4th millennium BCE. Copper reduction sites from this period include Mariahilfberg in the Austrian Alps (3950–3650 BCE; Bartelheim et al., 2002), where the ore

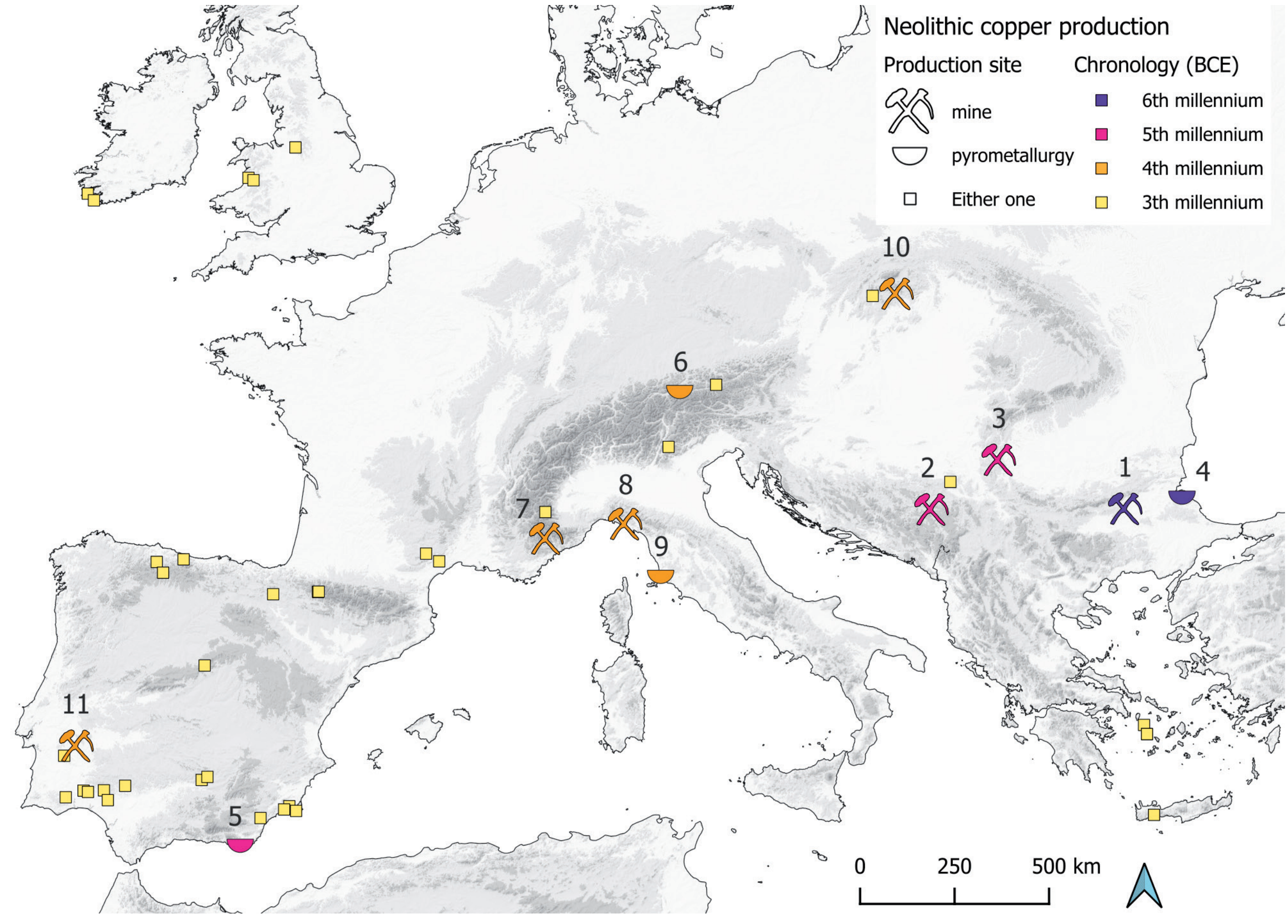

Fig 13 – Europe's earliest copper production sites, mines and pyrometallurgical workshops (6th–3rd c. BCE). 1: Ai Bunar; 2: Jarmovac; 3: Rudna Glava; 4: Akladi Cheiri; 5: Cerro Virtud; 6: Mariahilfberg; 7: Roua; 8: Libiola – Monte Loreto; 9: Cava Solvay di San Carlo; 10: Spanie Pole; 11: Mocissos.

may have been imported (Höppner et al., 2005), and Cava Solvay di San Carlo in central Italy (Fedeli and Galiberti, 2016), a production site processing ore that is probably the source of the copper used in Otzi's axe (Artioli et al., 2017), one of the rare demonstrations of artefact production based on Italian ores for these ages.

The dating of mining activities at Roua (and, by extension, in Liguria) during the 4th millennium BCE does not contradict existing hypotheses about the diffusion of metallurgy from the Balkans to Western Europe. In the Central Mediterranean Basin, exchanges of objects and copper with the Balkans are well-documented through typological studies (Van Willigen, 2017; Iaia and Dolfini, 2021) and geochemical analyses using lead isotope analyses (Artioli et al., 2020). These studies indicate the importation of Balkan objects and probably copper raw materials from this region. Nonetheless, the results of our study provide an indication that the temporal gap between the introduction of copper artefacts and the exploitation of local mines may be smaller than previously assumed. However, the use of copper from Southern Alpine mines is rarely confirmed by isotopic tracers (Artioli et al., 2020; Dolfini et al., 2020) in artefacts dated to the 5th–4th millennia BCE. Few objects from this period have been analysed to date. Consequently, the impact of local copper ore exploitation and the production of metal objects in these regions require further in-depth investigation.

Regarding copper production volumes, Roua's output before the beginning of the 3rd millennium BCE, estimated at 1–2 t, appears modest compared to other pioneering mines, such as Ai Bunar in Bulgaria (6th–5th millennium BCE) and Monte Loreto in Italy (4th–3rd millennium BCE), which have been estimated to have produced several hundred tonnes of copper (approximately 725–800 t, and 454–500 t respectively; Pearce, 2009; Chernykh, 1998). Although these early estimates should be treated with caution, as they rely on limited and sometimes uncertain data, they nonetheless suggest that the Roua mines were considerably less productive than these other European copper sources throughout prehistory. If the total Roua production is considered over several centuries of continuous activity, it would represent only a few kilograms of copper extracted per year during the second half of the 4th millennium BCE. Even if this low annual output appears modest in absolute terms, it remains remarkable in the broader context of early metallurgy, when the first copper artefacts in Western Europe, mainly small beads and awls, rarely exceeded a few tens of grams each. The quantities potentially extracted at Roua could therefore account for the production of a considerable number of such small objects. This observation strengthens the hypothesis that copper mined in the Southern Alps may have supplied local or regional copper object production (as suggested by Van Willigen, 2017). Although most of these early artefacts currently escape archaeological discovery, this discrepancy suggests that the amount of circulating copper during these periods is likely to have been significantly underestimated (Pearce, 2009).

More broadly, the production of copper objects in Eastern France during the transition from the 5th to the 4th millennium BCE is highly likely, as evidenced by recent discoveries in the Paris Basin and Alsace (Lefranc et al., 2012; B. Milles in Cottiaux et al., 2014). These early objects are comparable to Swiss Alpine and Central European artefact production. In the vicinity of the Western Alps, some artefacts may also originate from regional production (Van Willigen, 2017). The local manufacture of objects raises questions about the origin of the copper used. Based on current evidence, we can hypothesise that small-scale copper mining in Alpine deposits was probably already practised at the beginning of the 4th millennium BCE.

Copper Objects Contemporary with Roua's Copper Production West of the Alps

Copper artefacts in the vicinity of the Western Alps, dating to the later 5th and first part of the 4th millennium BCE, may have been produced using regional copper. This includes several copper awls found in *Chasséen* contexts, particularly in Provence: at Daurelle in Montélimar, Drôme, France (Thiercelin-Ferber, 2013) and Cazan Clos du Moulin in Vernègue, Bouches-du-Rhône, France (Moreau et al., 2017). In northwestern Italy, similar artefacts have been unearthed from *Chasséen* levels in the Arene Candide cave in Finale Ligure, Liguria, Italy (Maggi, 1997) and at a *Chasséen* settlement excavated at the 'G. Rodari' primary school in Alba, Piedmont, Italy (Venturino et al., 2020). Lead isotope analyses of the awl from Alba revealed compatibility with copper from the Balkans, like contemporary artefacts and ores from that region (Artioli et al., 2020). Technical and elemental analyses of that from Arene Candide indicate that it was made from pure copper, probably native copper (Campana et al., 1997). Unlike the few objects from the 4th millennium in Italy that match Balkan ores, the Arene Candide value (Campana et al., 1996 for the isotopic analyses) lies outside the Balkan fields. G. Artioli notes that this old analysis was obtained with a TIMS instrument on a Pb poor artefact, so lead isotopes ratios calculated on ^{204}Pb are uncertain. In his review (Artioli et al., 2020) the value does not fit the Balkan ores, except perhaps in areas absent from the reference sources, and has only a weak affinity with Catalonia. The western regions of the Alps remain plausible, but in the absence of precision on the isotopic ratios calculated for ^{204}Pb for the awl, it is difficult to compare them with a specific deposit in these regions, especially since most of the mine coppers are absent from the references. Therefore, a regional native copper source such as Roua remains a plausible hypothesis. Additionally, two azurite fragments from the same period were found at the *Chasséen* site of Villa de Giribaldi in Nice, Alpes-Maritimes, France (Binder, 2004). These finds indicate active prospection of copper-bearing materials at the 5th–4th millennium BCE transition and suggest that regional deposits likely supplied copper, for pigments, and plausibly for early copper objects (Pradeau, 2015, p. 114, p. 250; Van Willigen, 2017).

Other copper objects discovered earlier in Provence could also be contemporary with Roua's prehistoric exploitation and might incorporate copper produced from regional mines. However, the chronological and cultural attribution of Neolithic metallic objects presents a significant challenge due to poor discovery contexts (see, for example, the case of ones attributed to the Bell Beaker culture in eastern Provence and Southern Alps: Lemercier, 2004; or more generally for Western Europe: Labaune, 2016). When the chrono-cultural context is lacking, the dating of these objects primarily relies on typological comparisons, which can lead to divergent chronological interpretations. A notable example for the Southern Alps is the double-spiral copper pendant found in Grotte de la Sarrée (also known as Magagnosc) in the Alpes-Maritimes. Proposals for dating this object range from the late 5th millennium BCE to the Early Bronze Age (Mercurin, 2017, p. 582–585). Some authors suggest a connection with examples found in Pfyn cultural contexts (Strahm, 1994; Binder et al., 2008). Quantitative elemental analyses revealed nickel (0.03 wt%) and bismuth (0.022 wt%) levels too high to correspond to copper directly produced from Roua's mines (Courtin, 1974, analyses by S. Junghans at the Stuttgart Laboratory).

In Provence, rolled sheet metal beads have been inventoried (Barge, 1995). These objects could be among the earliest copper items produced in the Southern Alps, as well as in other regions of eastern France and the Northern Alps. In these areas, some have been dated to the late Middle Neolithic and Recent Neolithic (Ottaway and Strahm, 1975; Lefranc et al., 2012; B. Cottiaux et al., 2014). However, in Provence, the age of most of these objects is uncertain due to early, clandestine excavations or the disturbed nature of their burial contexts from ancient reoccupations (multiple burials, natural cavities). Sometimes, the mere presence of a copper bead has led archaeologists to date a site to the end of the Late Neolithic. These contexts should be re-examined, considering the possibility of an earlier date for these copper artefacts.

Flat axes can also be counted among the oldest copper objects in Europe, with examples found in Italy in contexts dating from the second half of the 5th and 4th millennium BCE (Van Willigen, 2017; Iaia and Dolfini, 2021). Between the Southern Alps and the western Rhône Valley, several flat axes, either whole or fragmentary, have been inventoried, all found out of context: on the La Gaude plateau, Alpes-Maritimes (Barge, 1995), in the Grotte de Déboussadou, Bouches-du-Rhône; Courtin, 1978), in the Grotte des Conchettes, or Déroc, Ardèche (Montjardin, 1991), at Puyméras and Brémonde, Vaucluse (Lermercier et al., 2004), as well as a fragment preserved in the Saint-Jurson museum collection, Alpes-de-Haute-Provence (Barge, 1995). According to the classification used by Iaia and Dolfini (2021), the example of La Gaude is of the trapezoidal type with a plain biconvex side profile, and is therefore similar to axes found in peninsular Italy and central Europe, dated to the 4th millennium BCE, or even the 5th millennium BCE.

The Orgon dagger of the Remedello type can be compared to Italian examples dated to the first half of the 3rd millennium BCE. Although belonging to an Italic culture, this object may have incorporated copper produced in the Southern Alps, Provence, or Liguria. However, the use of copper directly produced from Roua's mines is excluded due to impurities in bismuth (0.2 wt%., analyses by J.-R. Bourhis, CNRS, Laboratory of Prehistoric Anthropology, Rennes, according to Courtin and Sauzade, 1975).

Fragments of copper (rods, sheets, wires, broken objects, or unidentified fragments) from throughout the Neolithic have been unearthed from sites in Provence or the Lower and Middle Rhône Valley. These metallic remains, sometimes only briefly mentioned, indicate the circulation of raw metallic copper materials that could have been used locally to manufacture objects. Some of them are dated from the early Late Neolithic, like the two copper sheets from the Abri Sanguinouse, Roque-sur-Pernes, Vaucluse (Lemercier et al., 2004), and the origin of the metal in this type of object could be regional. It is noteworthy that a very small number of Neolithic sites in the Southern Alps also yield raw copper ore (e.g. Giribaldi, Dolmen des Arboins, Alpes-Maritimes, France: Binder, 2004; Mercurin, 2017) and, more rarely, remnants related to evidence of practices of local metallurgy. These observations do not seem to concern the direct use of native copper (with the possible exception of the piece of copper found at the Dolmen des Arboins; Mercurin, 2017, vol. II.1, p. 440–441, unfortunately now lost) and indicate the use of other types of copper ore (azurite for Giribaldi, assuming that it is indeed the original mineral collected in prehistoric times and not a neo-formed oxidation). Other remains provide direct evidence of Neolithic pyrometallurgical activities in Provence; the Late Neolithic site of Fortin du Saut, Bouches-du-Rhône, yielded a stone crushing tool made from a Permian material similar to the host rock of the Roua mines (which could also correspond to several Provençal copper mines) and casting waste (Furestier et al., 2007; Labaune, 2016), which probably dates from between 2550 and 2350 BCE according to the pottery. This leads us to believe that the metallurgy at Fortin du Saut may have relied on regional ore exploitations, now confirmed in the Southern Alps for the 4th and 3rd millennia BCE (Roua, Saint-Véran).

CONCLUSION

The copper deposits of the Southern Alps and Provence, despite only modest historical exploitation, reveal significant prehistoric mining potential. Up to several tonnes of copper were produced during prehistoric times from Roua mines. The scarcity of prehistoric mining data is mainly due to the destruction of ancient remains during historical mining activities. Using archaeomagnetism to date fire-set surfaces is a novel approach with the potential to uncover the earliest mining activities.

The chronology established for the exploitation of the Roua mines challenges traditionally accepted timelines for the spread of metallurgy in Western Europe, particularly in southern France. While the influence of Balkan metallurgy in the spread of Neolithic copper artefacts remains unquestioned, especially in Italy, in terms of both cultural context and material provenance, this study demonstrates that by at least the mid-4th millennium BCE, the copper deposits of the Southern Alps were sought after. The dates obtained for Roua's fire-setting extraction method are contemporary with those of Ligurian mines. It is plausible that other copper deposits, notably those in Permian host rock from Provence, may also have been exploited during this period, although there are currently no dates available for these mines. Recent awl finds from late Middle Neolithic contexts in the Southern Alps may point to early regional use of copper, as for other Alpine culture (Pfyn or Cortaillod). Accordingly, the production of local copper artefacts, potentially based on regional mining as early as the transition between the 5th and 4th millennium BCE, should be considered plausible but remains to be demonstrated pending further geochemical (Pb isotopes) and ancient mining investigations.

Copper production at Roua during prehistory is estimated at several tonnes, which may seem modest compared to other European Neolithic mines. However, the exploitation of these small copper mines likely played a crucial role in the spread of metallurgy across Europe. The copper mined at Roua was a valuable resource for the Neolithic societies of the Southern Alps. This production far exceeds the mass of copper artefacts found in the region and dated to the 4th and 3rd millennium BCE. This indicates a period when metal was more abundant than previously thought. The current scarcity of copper objects attributed to the Recent Neolithic is largely due to recycling practices. It is important to note that in the Southern Alps, the chronology of Neolithic copper artefacts is often uncertain due to the nature of the archaeological documentation and site contexts. This uncertainty may have led to the overlooking of chronological hypotheses predating the end of the Late Neolithic.

Given the nature of the ore (native copper), copper production at Roua did not require pyrometallurgical treatment. To date, the earliest evidence of ore processing areas in the Western Alps is for those at Saint-Véran, dated to the mid-3rd millennium BCE. These observations raise questions when considering the Balkan metallurgy, which was based on the exploitation of copper oxides and sulphides. Integrating Roua's mining activities into the diffusionist model of Balkan metallurgy, particularly in terms of technical transfers and the adoption of pyrometallurgical practices in the Southern Alps, needs further investigation.

Finally, the geographical location of the Roua mines, at the crossroads between the Alps and the Mediterranean and at the junction of Piedmont, Provence, and the Rhône corridor, suggests new avenues for investigating potential connections with early metallurgies observed in Switzerland, northeastern France, and the western Mediterranean Basin. A re-evaluation of the role of smaller regional mining areas in the development of prehistoric metallurgy in Western Europe is necessary.

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