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# Of Fire and Water Microarchaeological Evidence of Mining, Rituals and Floods in North Tyrol's Kropfsberg Mine (Austria)

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## ABSTRACT

Kropfsberg, located near Reith im Alpbachtal, in North Tyrol (Austria), has been exploited for its copper ores for centuries, since at least the Early Iron Age. Excavations conducted in 2020 by the University of Innsbruck exposed the detailed stratigraphic sequence of the mine, leading to a surprising discovery: what was initially believed to be only a site for mineral extraction showed clear indications of ritual use during the Roman period and Late Antiquity. These cultic layers are characterised by abundant charcoals, animal bones and almost 200 votive coins, and suggest that the mine served during this period as a Mithraeum. Using micromorphology and µXRF, along with macroscopic, hydro- and geomorphological information about the mine and its surroundings, we reconstructed the processes that led to the deposition of sediments within this artificial cave. Our analyses indicate that remains of ceremonial fires and offerings were deposited within a cultic pit, rather than being spread over the floor. Also, evidence suggests that the cultic use of the mine likely ceased before the area surrounding the mine was flooded, potentially due to the damming of the Inn River caused by a significant rock fall during the Roman period. We also traced the phases following the inundation, including the cave's reopening after a period of abandonment, and identified a sequence of mining backfills that provide evidence of the site's subsequent secular use. Ultimately, the study sheds new light on the cultural and geomorphological dynamics of the Inn Valley during the Roman Period and the Late Antiquity, while underscoring the importance of integrating microarchaeological approaches to disentangle the complex interaction of cultural and environmental influences, even in historical (artificial) cave contexts.

## 1 | Caves and "Artificial Caves"

Research on caves has traditionally focused on early human habitation of natural caves (Bergsvik and Dowd 2018). The natural shelter offered by these cavities has attracted humans—among other animal species—who made these spaces their residence since the Palaeolithic, for more than 2 million years (Mallol and Goldberg 2017). As Bergsvik and Dowd (2018, 1) note: 'Not surprisingly, therefore, cave archaeology has become synonymous with the Palaeolithic'. Natural caves are primarily found within limestone formations, which are known as karstic environments. The chemical composition of the surrounding rock, the sheltered underground environment and the thermal stability of enclosed spaces (Salesse et al. 2014) favour the survival of archaeologically significant materials, such as bones, teeth, plant phytoliths, charcoal and ash. Indeed, caves have been described as highly efficient sediment traps, where accumulation characteristically excels over erosion, and as sources of continuous sedimentological records that are absent in open-air sites (Collcutt 1979; Sherwood and Goldberg 2001; Straus 1990). However, other factors, such as the decomposition of bat guano and local hydrology, affect the preservation of these materials, by promoting chemical reactions, diagenesis and authigenic mineral formations (Karkanas et al. 2000; Shahack-Gross et al. 2004).

In sum, caves represent rich yet complex archaeological archives. A variety of geo- and bioarchaeological approaches, including ancient DNA analysis (aDNA), Fourier-transform infrared spectroscopy (FTIR), proteomics, micromorphology, scanning electron microscopy with energy-dispersive X-ray analysis (SEM/EDS), X-ray fluorescence (XRF), X-ray diffraction analysis (XRD), biomarkers and stable isotopes, have been used to extract valuable information. These methods aid in reconstructing not only the diagenetic and paleoenvironmental characteristics of these environments but also the biological, technological, economic and social characteristics of the early human groups inhabiting them (Cabanes and Albert 2011; Cremaschi, Nicosia, and Favero 2022; Fernández-Palacios et al. 2024; Inglis et al. 2018; Moyo et al. 2016; Roldán et al. 2018; Vanwezer et al. 2021; Vernot et al. 2021).

In recent years, there has been a growing recognition of the importance of not only natural caves but also artificial ones as multi-period sites with evidence of human use spanning up to the modern era (Bergsvik and Dowd 2018). Artificial 'caves' from later prehistoric and historic periods refer to man-made, rock-cut subterranean chambers that resemble natural caves. Some of these artificial caves may have started as natural caverns that were modified and enlarged beyond recognition, such as certain cave churches or catacombs (Bergsvik and Dowd 2018). These structures have served various purposes, including sacred places, animal shelters, dwellings and workshops (Bonsall 1997). Additionally, some cavities have resulted from mineral resource exploitation (Goldenberg 2021; Staudt et al. 2019). Despite their distinct and widespread presence as geomorphic forms, research on mines and artificial cavities remains underpublished compared with studies on natural caves (Schuchová and Lenart 2020).

Our article contributes to this growing research field by presenting the case study of the Kropfsberg mine in North Tyrol, Austria. The peculiarity of this site lies not only in its intermittent use as a mine from prehistory to the Modern Era but also in its role as a venue for cultic practices and performances during Late Antiquity. While microarchaeological methods have been applied to a handful of cultic underground sites (see Lo Russo et al. 2022; Müller-Scheeßel et al. 2020), studies using these approaches in underground mining settings are even scarcer. To our knowledge, only one study has focused on the Bronze Age layers of the salt exploitation centre of Hallstatt in Upper Austria (Schneidhofer 2011). This is notable, given the abundance of sedimentary traces left behind by these practices, which are well suited for such analyses. This work highlights the critical importance of microarchaeological approaches in unravelling the complex stratigraphy of similar sites. By examining the nature and depositional pathways of refuse mounds—whether they are of cultic or secular significance—microarchaeology provides deeper insights into their formation and evolution. Mines have played a pivotal role in human history, particularly in mountainous regions such as the Alps. A detailed investigation of the creation, use and transformation of these artificial landscapes is therefore crucial for reconstructing their economic and socio-cultural implications.

## 2 | Kropfsberg, From Prehistory to Nowadays

The Kropfsberg hill is situated in the Tyrolean Lower Inn Valley, south of the Inn and at the entrance to the Ziller Valley (Figure 1). Geomorphologically, Kropfsberg is classified as an inselberg (*Härtling* in German), an isolated rock hill that rises out of a more or less flat plain, composed of Schwaz dolomite. The dolomite is a carbonate rock, which mainly consists of the mineral dolomite CaMg(CO3)2. In this devonian rock formation (geological era Lower Devonian, about 420–390 million years ago), which extends south of the Inn Valley between Schwaz in the west and Radfeld in the east over a length of approx. 25 km, the so-called 'fahlores' occur. These complex sulphide minerals form a mixed series between $Cu_{12}Sb_4S_{13}$ (tetraedrite) and $Cu_{12}As_4S_{13}$ (tennantite). On top of the hill, which reaches a maximum elevation of approx. 560 m above sea level, rests a castle dating back to the Middle Ages (Vogl-Fernheim 2019). Most sections of the castle originate from the 13th century CE, with additional structures incorporated into the complex up until the 17th century CE (Franzen et al. 2005).

The hill shows impressively well-preserved traces of prehistoric underground mining (Goldenberg et al. in press). A notable characteristic of prehistoric copper mining in the Lower Inn Valley is the use of the fire-setting technique, where the fire was utilised to loosen or blast rock, aiding mining operations. This method resulted in distinctive dome-shaped cavities within the Schwaz dolomite (Figure 2). Extensive copper mining also occurred on the steep dolomite massif of the Reither Kogel, situated directly south of Kropfsberg (Staudt et al. 2019, 122–129).

Initial evidence of a prehistoric settlement on top of the mound was uncovered in the 1970s (Bitschnau 1972). Recent investigations have confirmed these findings, revealing broad settlement features and evidence of fahlore copper production on the terraced hill (Staudt and Trebsche 2022, 2024, in press). These discoveries, alongside the mining remnants on the Reither Kogel, mainly belong to the Hallstatt period (Early Iron Age, 8th–7th century BCE).

The easily accessible entrance to the mine (at 522 m above sea level) is located just a few metres above the current level of the Inn River, at the northern base of the hill. The inner space boasts a lateral extension of up to 10 m and it extends approximately 30 m in a south-western direction into the dolomite rock (Figure 3). The central dome of the mine reaches a maximum height of 8 m and features a ventilation shaft that was constructed to expel smoke generated during the mining activities. A smaller cavity, slightly elevated, was created by fire-setting in the northern part of the mine, leading to a second mouth hole sealed with coarse dolomite blocks and mortar. Also in the entrance area, the remains of a mortared wall made of dolomite blocks were discovered in front of the mouth hole

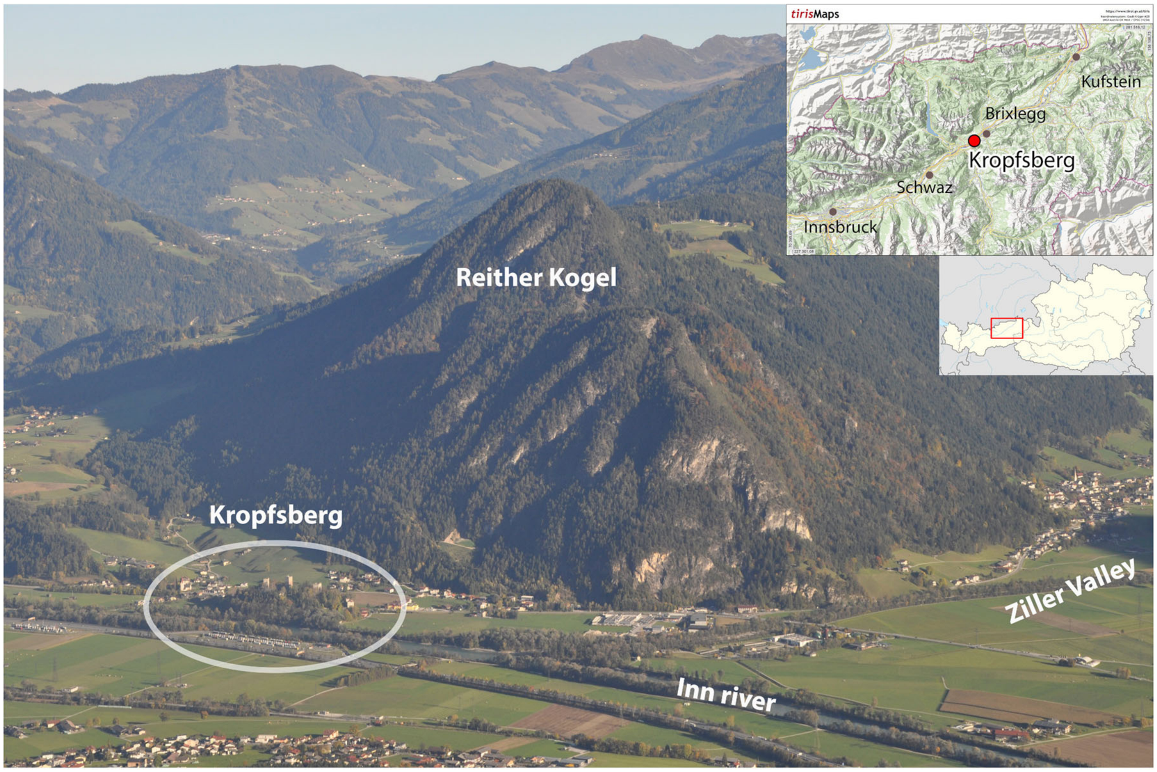


**FIGURE 1** | The Kropfsberg castle hill (framed in white) at the foot of the Reither Kogel mining district, almost at the entrance to the Ziller Valley. Picture: M. Staudt.

**FIGURE 2** | View of the spacious Kropfsberg mine, characterised by its distinctive dome-shaped form, a result of prehistoric fire-setting activities. View to the southwest. Picture: G. Goldenberg.

(inside the cave), while dry Buntsandstein sandstone walls were found inside the mine itself. A precise dating of these structures is still lacking.

A 3-week excavation campaign, conducted by the research center HiMAT of the University of Innsbruck in summer 2020, aimed primarily to gather evidence of these mining activities and to establish their chronology (Staudt and Goldenberg 2022). A secondary objective was to document and to date its possible non-mining-related uses (e.g., storage room, dungeon, torture chamber, shelter during the Second World War or party cellar). Four trenches were opened in different parts of the mine to document these activities. Trench 1 (Figure 4) showed the thickest and most detailed stratigraphy. Below the modern surface (SE 1), deposits (SE 2a +b, 3) comprised mining backfill characterised by large angular dolomite fragments and reached a maximum thickness of 40 cm. Layer 2a displays a sloping orientation, while layers 2b and 3 are mainly horizontal in the northern part of the profile, gradually inclining towards the south. The recovery of drill pipes (SE 2a), still bearing traces of the gunpowder used for detonation, allowed to date these deposits to the 17th–18th century CE, which coincides with the last (written) documented mining operations within the mine. Additionally, modern glazed ceramic fragments and a few late medieval pottery shards (SE 2b), including a fragment of a 'Schwaz lamp'—a typical mining lamp from the 15th-16th century CE—were unearthed in these layers. Of particular interest was the discovery of a fragment of Roman oil lamp (SE 1), adorned with a partially preserved depiction of a ram's head. The presence of this Late Antique fragment in later deposits is likely a result of mining activities. Such activities involved periodic 'clearing' operations within the mine, occasionally mixing materials from different periods.

Below the backfill layers, a horizontal deposit of ashy material (SE 4a), a few centimetres thick and seemingly truncated towards the south, marks a sharp discontinuity within the stratigraphy. This layer is followed by a dark brown/black deposit rich in charcoal, approximately 25 cm thick (SE 4b), which appeared to partially overlay older layers while also cutting through them. In addition to the already mentioned charcoals, this deposit contained almost 200 Roman coins (Figure 5), fragments of Roman oil lamps and numerous

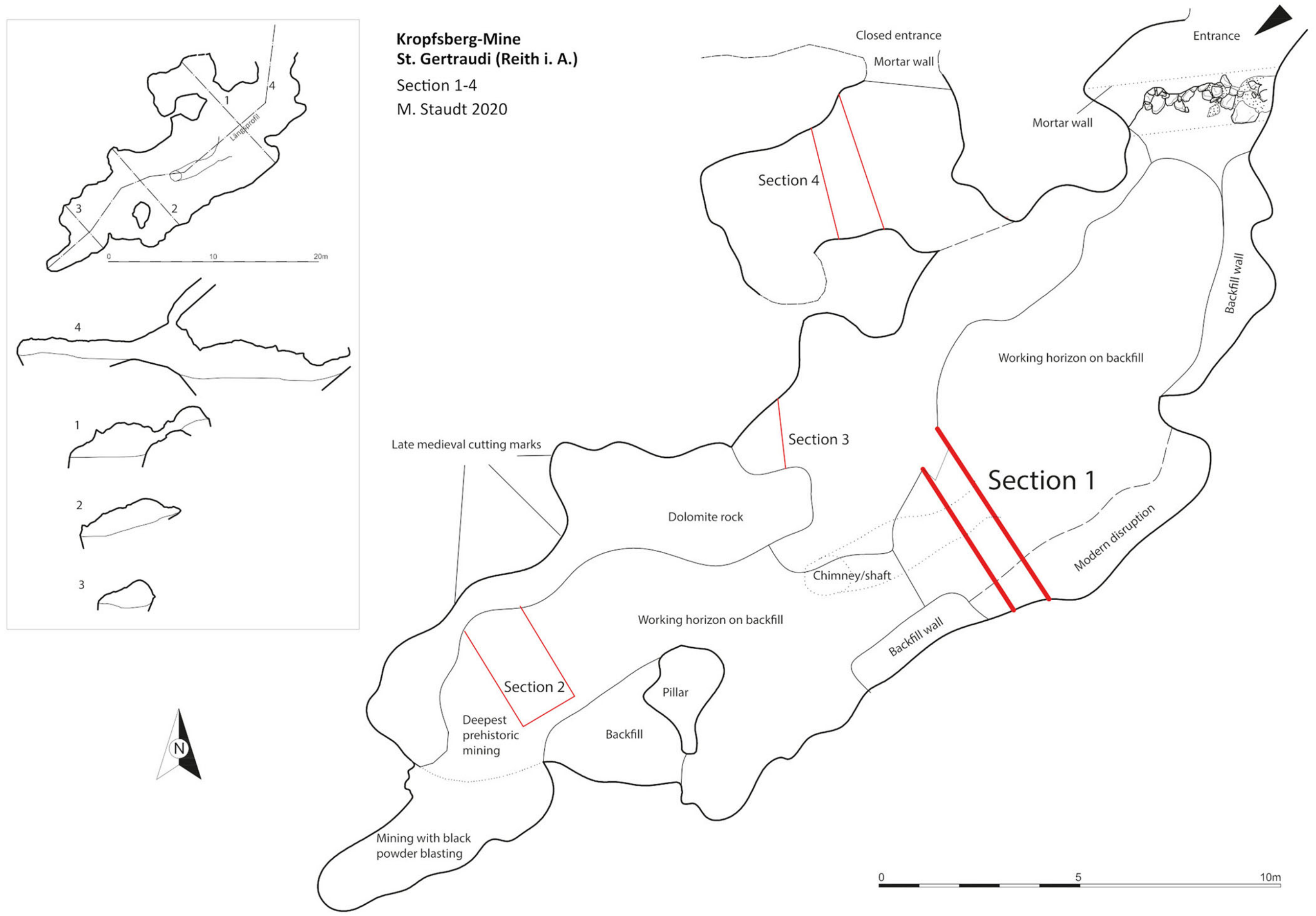


**FIGURE 3** | Plan of the Kropfsberg mine. The areas outlined by the red lines represent the four trenches excavated during the 2020 campaign. At the two entrances of the mine, situated in the northern and northeastern sections, mortar walls were discovered. Presently, the northern wall still seals the entrance, whereas the northeastern wall remains preserved only in one or two rows. The plan also highlights various activity areas and periods of use of the mine, revealing its complex history and enduring chronological significance. Picture: M. Staudt.

animal bones, with a significant proportion belonging to bird (poultry) specimens (Goldenberg et al. in press). Based on the content of layers 4a and 4b, these were interpreted as cultic deposits within the mine, likely dating back to the Late Antique period. The dating is supported by the presence of coins spanning from the early 2nd century CE to the late 4th century CE, with a notable increase in quantity from the second half of the 3rd century onwards, peaking in the second half of the 4th century CE and ending with coins minted in 392 CE (Goldenberg et al. in press). The mine, located alongside the Inn River and near a long-presumed 'Roman road' (Heitmeier 2005; Mayer 1927), could have been an ideal site for a sanctuary. Although it cannot be definitively determined whether Mithras or another oriental deity was worshipped here due to a lack of corresponding iconographic or epigraphic evidence, parallels with Mithraic sites within, north and south of the Alps suggest this as a plausible option (Bricault, Veymiers, and Amoroso Boelcke 2021; David 2023; Ebnöther et al. 2021; Gleirscher 2022; Hinker 2022; Stacul 1976).

Finally, the remnants of prehistoric copper mining activities were detected below (and partly cut by) the Late Antique deposits. Based on a limited number of pottery fragments (Hallstatt C types) and one $^{14}C$ charcoal date, the earliest layers in this trench were assigned to the Early Iron Age, between the 8th and 6th centuries BCE, although a certain degree of uncertainty remains due to the limitations of radiocarbon dating during the so-called 'Hallstatt plateau' (Goldenberg et al. in press).

## 3 | Methods and Results

To study the nature and formation processes of both the cultic layers and the secular deposits in the cave, three undisturbed and oriented earthen samples were collected from the western profile in Trench 1. An attempt was made to collect a fourth block to sample the prehistoric backfill deposits, but no intact sample could be extracted. The three collected blocks were then hardened with resin and ground into six 30 µm-thin sections, ensuring complete coverage of the sequence with overlapping between the blocks (see Table 1). We conducted two sets of analyses on these six thin sections: micromorphology and micro-XRF (µXRF). These methods present the advantage of being able to be conducted directly on the same set of thin sections, thus providing the opportunity for direct results' correlations.

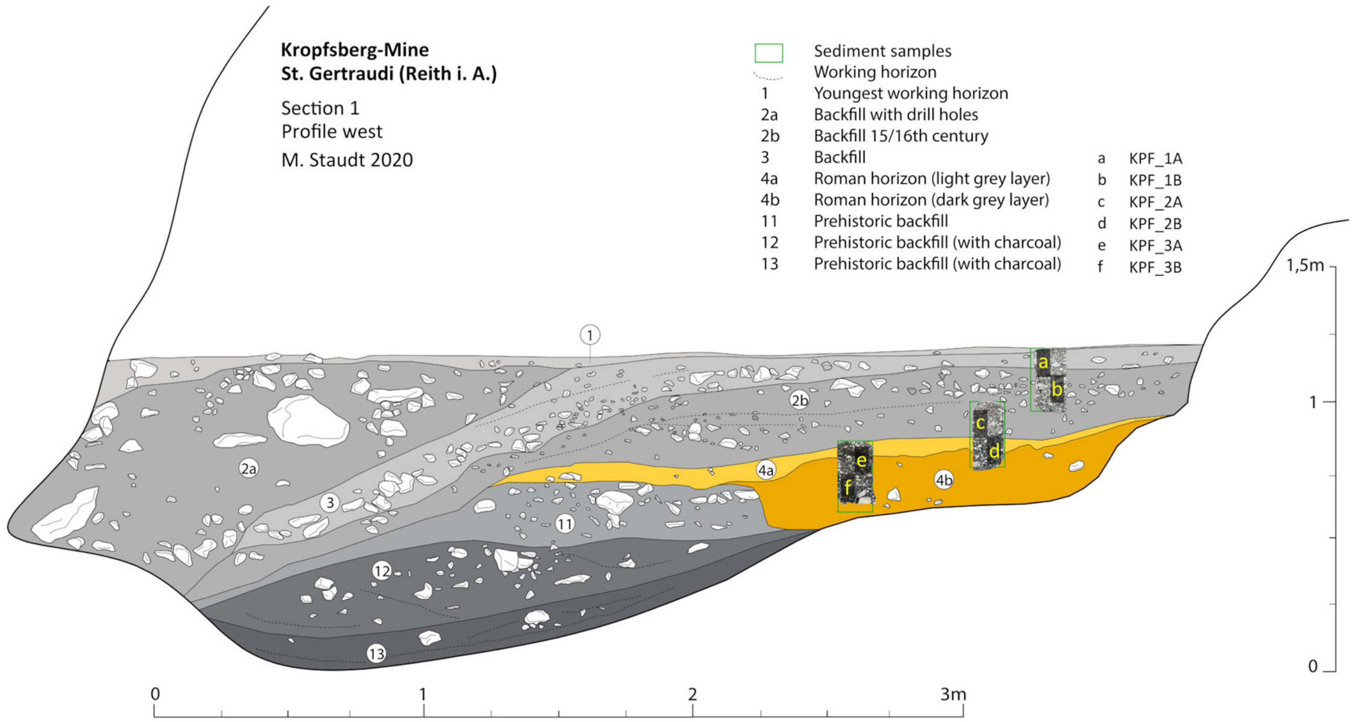


**FIGURE 4** | West profile in Trench 1 with modern and prehistoric backfill and intercalated Late Antique cultural layers. Layer 3 was initially interpreted as a thin lens beneath layers 2a and 2b. However, during excavation, it became clear that SE 3 actually separates these two units, as shown in this profile. The dotted lines represent potential unconformities that could not be further differentiated macroscopically. The sediment blocks, highlighted by green rectangles on the right side of the drawing, show the carved sections, with the overlaying slide positions indicated within each block. Picture: M. Staudt and S. Cereda.

### 3.1 | Micromorphology

This technique involves the examination of soil/sediment components under a petrographic microscope, to analyse their nature, geometry and spatial arrangement. This method helps in understanding the processes contributing to the formation of the investigated contexts (Courty, Goldberg, and Macphail 1989; Goldberg and Macphail 2006; Stoops 2003, 2021). Detailed microstratigraphic data are crucial for interpreting micro-contextual and taphonomic information, facilitating correlation with archaeological and geochemical proxies. All thin sections were studied at the Microarchaeological Laboratory of the University of Innsbruck using a Leica DM2700 P polarising microscope, at magnifications ranging from 12.5× to 400×, under plane polarised (PPL), cross polarised (XPL) and oblique incident light (OIL). The standard micromorphological guidelines and manuals were used for description and interpretation (Karkanas and Goldberg 2019; Nicosia & Stoops, 2017; Stoops 2003, 2021; Verrecchia and Trombino 2021). The analysis allowed us to identify 11 microlayers (ML) in the three sediment blocks (Figure 6). A brief description of the main micromorphological characteristics of each ML is provided in Table 2.

MLs 1–9 correspond to layers SE 1, 2b and 3, which have been dated from the Middle Ages (12th century) to the present based on archaeological finds. These layers are categorised into coarse ones (ML 2–5, 7–8) and others rich in finer material, where sheet silicates and siliceous sands are observed (ML 1, 6, 9). The finer layers are also rich in dispersed amorphous organic mass, incorporating partially preserved plant remains, which likely represents allochthonous humic input—possibly entering through the ventilation shaft or the mouth hole. The organic material may be mixed with bat guano from within the cave; although no bats or guano accumulations were observed during excavation, and guano was not clearly identified under the microscope, occasional phosphatic rims on some coarse rock fragments might indicate degraded guano presence. However, these features are rare, suggesting that guano did not constitute the bulk of the fine mass of the deposit. Additional biogenic remains include small charcoals, occasional bone splinters, fungal spores, spherulites interspersed in the groundmass and rare submillimetre phosphatic fragments (possibly carnivore coprolites or nodules from guano degradation?).

The organic-rich layers differ from the coarse ones in microstructure and porosity, with ML 1 and 6 (respectively, SE 1 and SE 2b) showing mostly massive structures, while ML 9 (also SE 2b) shows a banded platy structure and well-developed parallel planar voids. The main coarse geogenic component of all these layers is the dolomite rock forming the mound itself. Larger fragments are predominantly angular, with finer gravel having subangular edges and continuous coatings, referred to as 'rolling pedofeatures' (see Angelucci and Zilhão 2009). Evidence of extractive activities includes opaque particles, interpreted as possible ore fragments, and rock fragments exposed to fire. The micro-debris, apart from mining backfill, includes only a few splinters of cryptocrystalline quartz (flints from fire strikers?). ML 8 (SE 2b) is distinctive from previous deposits due to its composition of predominantly siliciclastic sand particles,


**FIGURE 5** | Selection of the unearthed Roman coins (after restoration), sorted by minting period (2nd to 4th century CE). Picture: G. Goldenberg.

which are generally rounded or subrounded. The sands are poorly sorted and interspersed with abundant dolomite fragments; they lack sedimentary structures and show very irregular boundaries with the upper and lower deposits. Notably, rare particles with distinctive optical properties are present at the interface with the underlying ML 9 (Figure 7). Under cross-polarised light, these particles display a fine cryptocrystalline carbonate groundmass with bluish birefringence, and in plane-polarised light, they show wavy internal rims, indicative of a plastic state before crystallisation. These features are consistent with descriptions in the literature and strongly suggest that the particles belong to fired lime binder (Stoops, Canti, and Kapur 2017).

MLs 10 and 11, which correspond to excavation units SE 4a and SE 4b, represent the deposits formed during the cultic phase of the mine. ML 10 consists of a minerogenic fine-grained groundmass embedded with abundant rock fragments in a bi-modal sorting. This deposit is particularly notable for its banded appearance, characterised by a series of stacked laminations. At least six laminations were observed, each a few hundred micrometres thick, displaying an undulating distribution and horizontal orientation (see Figure 8h). These laminations show no evidence of a drying phase, such as desiccation cracks or sediment intermixing from different origins (whether allochthonous or autochthonous but not deposited by water action). The indistinct boundaries between these lenses suggest that they formed in a plastic and wet state. The transition between ML 10 and the overlying ML 9 is gradual, marked by an increase in silt and sand-sized particles and aggregates towards the top. Conversely, the lower boundary with ML 11 is sharp and digitated, with fine sediment from ML 10 extending downwards approximately 1 cm and filling voids between coarse components in ML 11. Inclusions within these laminations, aside from dolomite fragments, primarily consist of small-sized charcoal fragments. These charcoals show signs of rotation, horizontal-wavy orientation and a parallel distribution. The porosity is very low, with the few voids present appearing as either vesicles or channels. Occasional bioturbation is noted, with roots (still partly identifiable) cutting through the laminations (Figure 8e,g). Under crossed polarised light (XPL), the laminations show various interference colours and textures, with some composed of a clayey groundmass and others composed predominantly of sericite (Figure 8g). No ash grains, whether intact, recrystallised or phosphatised, were observed in this layer.

The lowest ML encountered in the sequence is ML 11. In comparison to ML 10, this deposit is once again very coarse, but its distinctive feature is that charcoal represents the main

**TABLE 1** | Overview of the sampled sediment blocks, the resulting thin sections and the corresponding archaeological layers (SE), as described in Section 2.

| Sample | Thin section | SE |
|---|---|---|
| KPF1 | KPF 1a | 1, 3, 2b |
| | KPF 1b | 2b |
| KPF2 | KPF 2a | 2b |
| | KPF 2b | 2b, 4a, 4b |
| KPF 3 | KPF 3a | 4a, 4b |
| | KPF 3b | 4b |

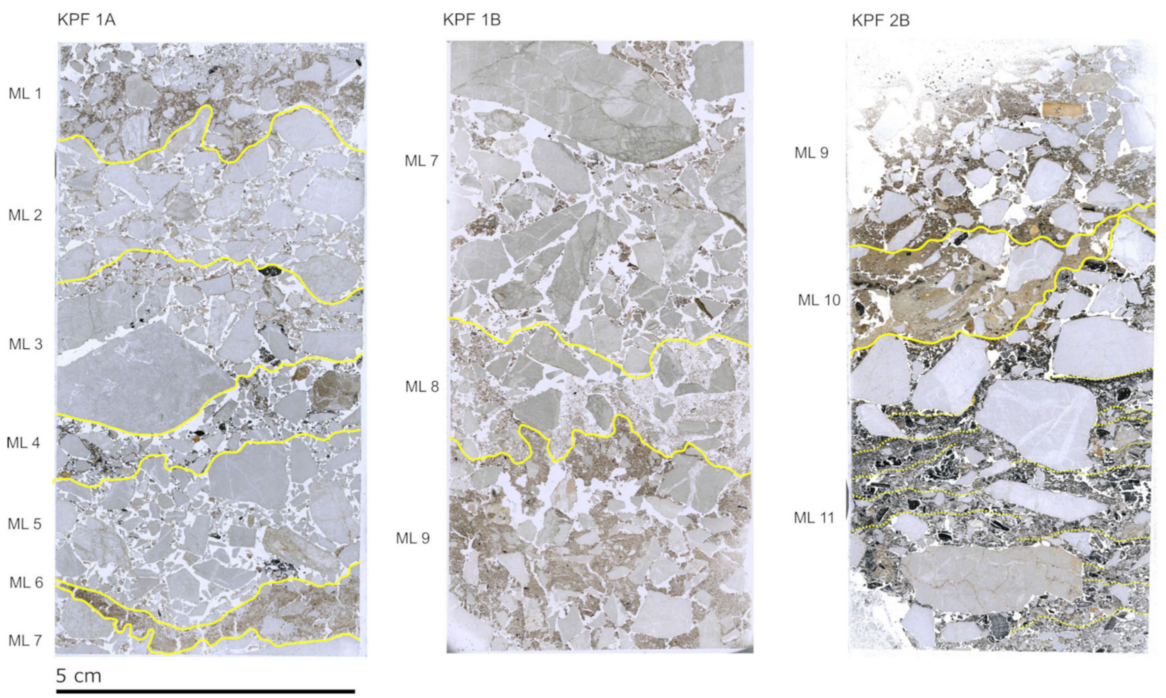


**FIGURE 6** | Scan of three (KPF 1 A, 1B and 2B) of the six thin sections from the Kropfsberg mine. The three slides illustrate the complete sequence of microlayers (ML) excavated in Trench 1. The boundary between each ML is highlighted by a full yellow line; the dotted lines indicate instead the sub-horizontal lenses observed in ML 11. Picture: S. Cereda.

**TABLE 2** | Summary of the different ML distinguished in the thin sections, together with the description of their main features and their interpretation.

| Microlayer (ML) | Stratigraphic unit (SE) | Sample | Description | Interpretation |
|---|---|---|---|---|
| 1 | 1 | KPF_1A | Silty gravel deposit with a massive structure and low porosity. Moderately sorted, dominated by subangular and angular dolomite rock fragments. Moderate quantities of charcoal and bone splinters. Organic-rich micromass. | Trampled surface |
| 2 | 3 | KPF_1A | Coarse layer of poorly sorted angular and subangular dolomite. Occasional fragments of cryptocrystalline quartz. Fine groundmass occurs only in small aggregates or coatings around the rock fragments. Rare biogenic remains. | Mining backfill |
| 3 | 3 | KPF_1A | Unsorted layer with some very coarse dolomite angular and subangular fragments, organised according to a moderate normal grading. Slightly higher amounts of fine material than ML 2. Possible ore fragments observed. | Slightly trampled mining backfill |
| 4 | 2b | KPF_1A | Thin layer of moderately sorted angular and subangular dolomite of medium coarseness (~1 cm). Small phosphatic particles (coprolite?) rarely observed. Very dark organic fine material is interspersed in aggregates between coarse rock fragments. They almost confirm the deposit of a massive structure. Occasional burnt rock fragments can be observed as well. | Slightly trampled mining backfill |
| 5 | 2b | KPF_1A | Coarse layer of unsorted angular and subangular dolomite. Occasional burnt rocks and an ore fragment occur as well. Monic c/f related distribution. Besides a large, broken charcoal fragment, no anthropogenic/biogenic remain is present. | Mining backfill |
| 6 | 2b | KPF_1A | Thin gravelly silt layer with an organic-rich micromass. Spores, minute charcoals and occasional spherulites (bat guano?) constitute the main non-geogenic components. Massive structure with low porosity and concave profile. Very sharp upper and lower boundaries. | Well-trampled surface |
| 7 | 2b | KPF_1A; KPF_1B | Similar to ML 5. Unsorted deposit showing moderate oblique orientation of rock fragments (fallen/dumped?). Aggregates of fine amorphous organic material are occasionally found between larger rock fragments. Few larger remains (1 cm) of plant tissue can be observed. | Slightly trampled mining backfill |

(Continues)

**TABLE 2** | (Continued)

| Microlayer (ML) | Stratigraphic unit (SE) | Sample | Description | Interpretation |
|---|---|---|---|---|
| 8 | 2b | KPF_1B | Poorly sorted deposit characterised by very irregular and digitated boundaries. The layer is composed in large part of sandstone fragments, mixed with dolomite ones. The coarse sands and fine gravel are mostly 'clean', but they occasionally contain areas with silty-sized aggregates of amorphous organic mass. The porosity is well developed; orientation and distribution are random. Fragments of lime binder observed. | Mortar remains/ construction material |
| 9 | 2b | KPF_1B; KPF_2A; KPF_2B | Thick deposit of rock fragments embedded in a massive silty sand mass. The micromass is organic-rich and it embeds fine charcoals, sclerotia and spherulites. Gravel and sand particles (both silica-rich and carbonatic) are abundant. The coarse material is moderately sorted, and the porosity is moderately developed. The distribution is random and the orientation is moderately horizontal. The structure is mostly planar and characterised by abundant horizontal planes. | Accretion of the surface through natural processes |
| 10 | 4a | KPF_2B; KPF_3A | Layer composed of six stacked laminations of silty clay and sandy silt embedding dolomite rock fragments and charcoals (mostly fine). Both laminations and embedded particles show strong orientation and rotation features, suggesting the direction of flow. The upper boundary is gradual and diffuse, while the lower one is sharp, though wavy. | Water-lain lenses |
| 11 | 4b | KPF_2B; KPF_3A; KPF_3B | Thick unsorted layer composed of discontinuous and poorly developed overlapping lenses. Moderate porosity. The upper boundary is very sharp. The main components are charcoals (~40%), moderately burnt bones (~5%), ashes (~5%), dolomite fragments (~35%) and clay aggregates (~15%). Particles show moderate to strong horizontal orientation. | Dumped and compacted fire-related debris |

Abbreviation: ML, multilayer.

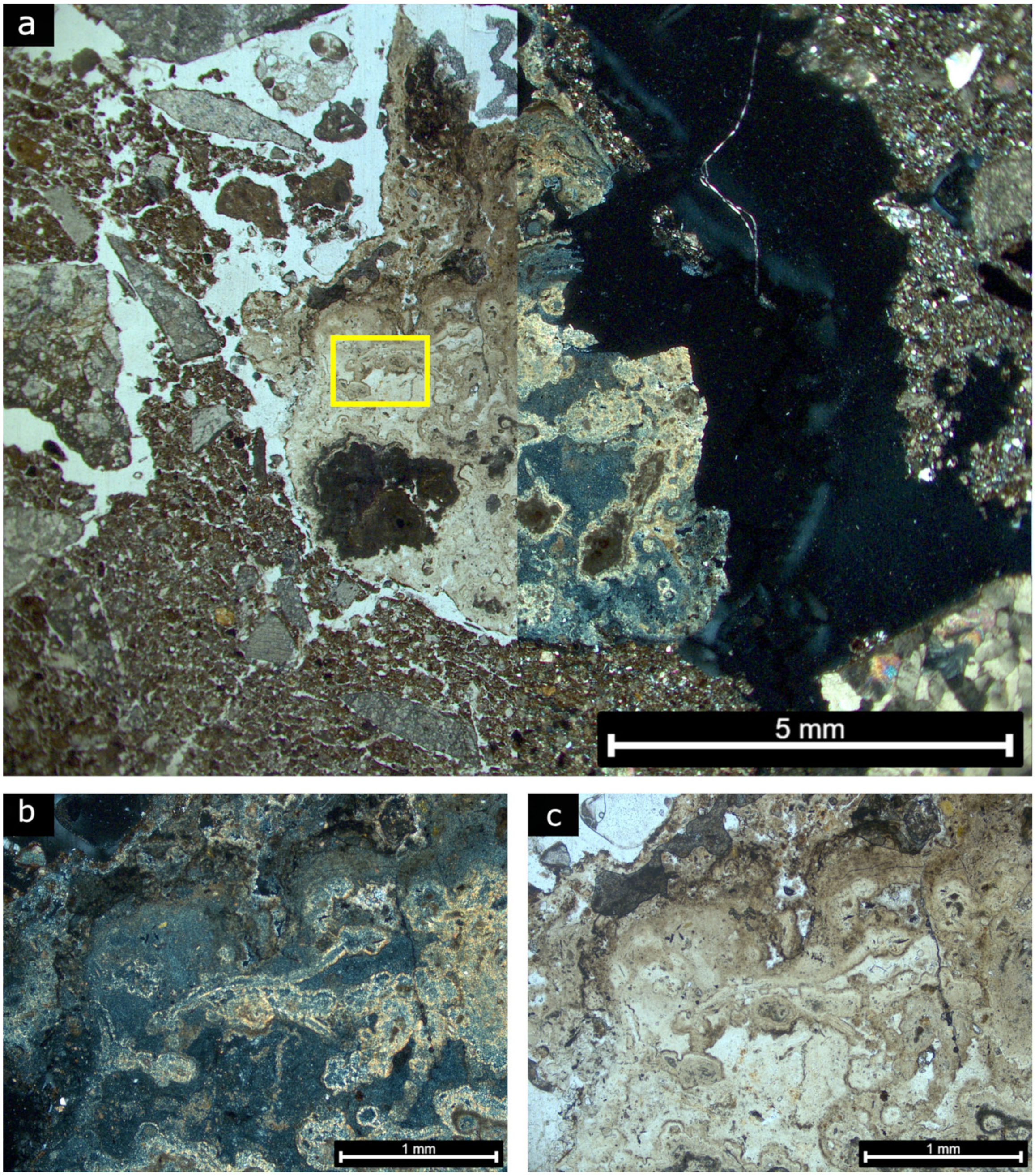


**FIGURE 7** | The image shows a lump of amorphous material interpreted as a remnant of lime-based binder (a), possibly used in connection with the sandstone walls or other fixtures built within the mine. The picture on the left was taken in PPL and the one on the right was taken in XPL. Images (b) and (c) show close-ups of the area marked by the yellow rectangle, detailing the micromass of the lump. This micromass consists of a beige-brown cryptocrystalline carbonatic material. Under cross-polarisation, the micromass shows a bluish hue and features wavy reaction rims. Picture: S. Cereda.

component beside the omnipresent dolomite fragments (Figure 8c). No indications of fuels other than wood were found, and there was no indication of char produced by burnt fats. While rock fragments are still abundant, they are less so than in the previously described layers, and there is a higher concentration of bones compared with later deposits. The cell structure of charcoals is often preserved, although they are highly fragmented, rarely exceeding 1 cm in size, making them unsuitable for further morphological identification. Bones too, with one exception, are found as splinters no larger than 1 cm. Bone particles show signs of fire exposure—such as dark coloration and poor birefringence in XPL—indicating varying degrees of burning, though calcination was not observed (Figure 8a). Beside the remains already found also at macroscale, no particles of other origin (such as eggshells or pottery) were found.

### 3.2 | μXRF

X-ray Fluorescence provides high-resolution semi-quantitative and qualitative elemental data with minimal sample preparation. This technique utilises X-rays to excite and displace electrons in

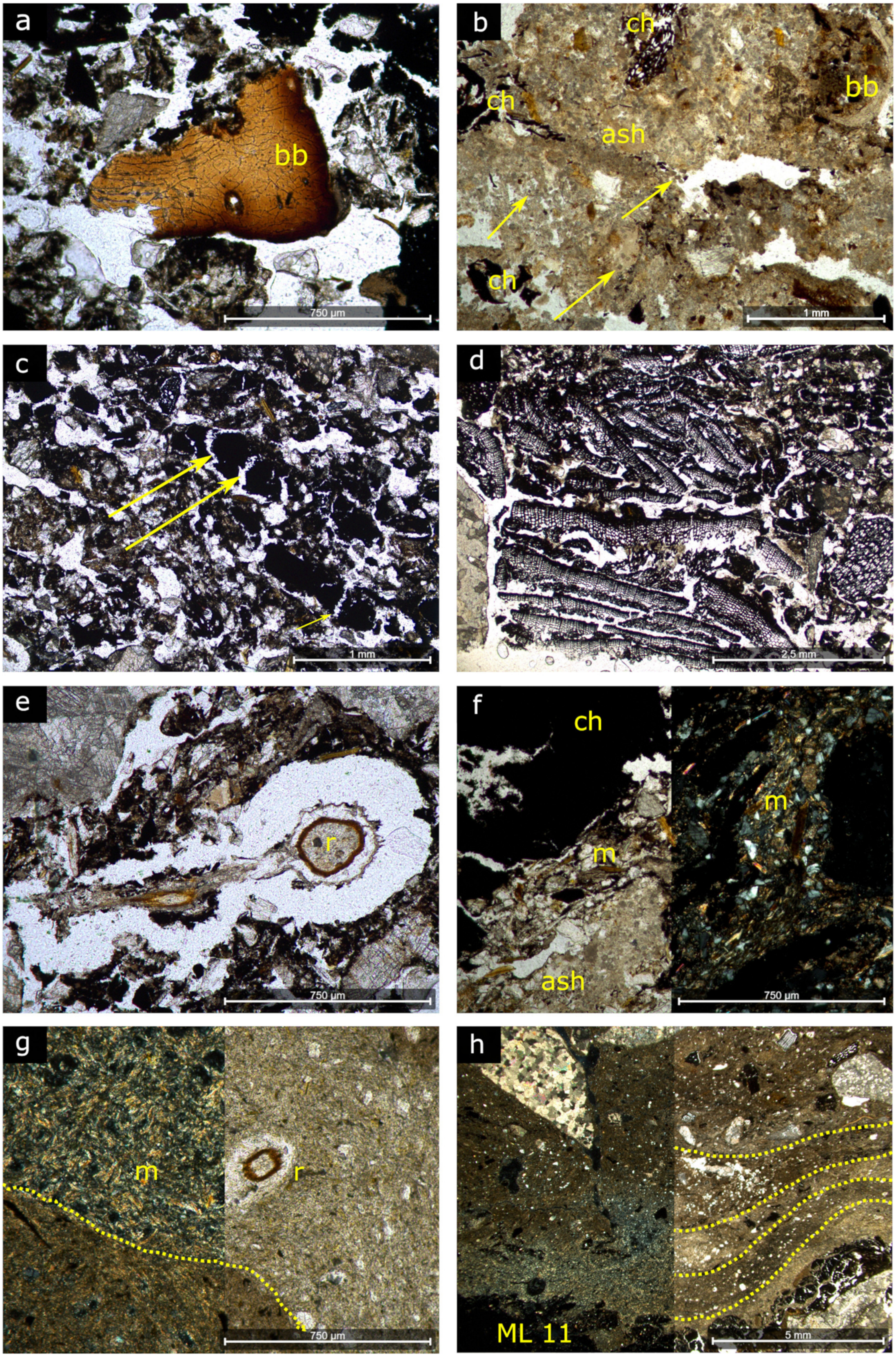


**FIGURE 8** | Legend on next page.

the inner shell of atoms. Subsequently, electrons from the outer shell fill the void, emitting X-ray photons that can be quantified to identify the elements present in the sediment sample. Benchtop μXRF yields notably superior and more detailed results compared with conventional XRF, offering a rapid and continuous elemental record at a high spatial resolution of 20 μm (e.g., Mentzer 2017; Wouters et al. 2017).

Non-destructive μXRF analyses were carried out using a Bruker M4 Tornado at the Institute of Mineralogy and Petrography of the University of Innsbruck. For elemental mapping, the Bruker M4 Tornado, which uses a single rhodium target X-ray tube with up to 50 kV and 600 μA power and is equipped with a Be window, focusses the beam with polycapillary optics down to a spot size of ~20 μm. The dwell time per pixel is 15 ms. Because of the large-size samples, the step size for the measurements was fixed at 50 μm. For imaging purposes, a so-called F1 image was created. This image is defined by a so-called 'free region' (a certain energy range of ca. 3–19 keV in the X-ray spectrum) in Bruker software and integrates all intensities over this energy range. Therefore, phases with higher mean atomic numbers (e.g., containing more heavy elements) appear brighter in the images. This 'free region' can then be used to produce something like a backscatter electron image. This microanalytical instrument provides element mapping of the entire sample via the x–y–z moving stage. Combining chemical elements together and attributing them to certain mineral phases aid in gaining a general overview of the mineral distribution throughout the sample, which is supported by the mineral identification in thin sections.

Overall, the upper sequence (ML 1–ML 9, corresponding to SE 1, 2b and 3) shows clasts with clear concentrations of Ca and Mg and no Si, consistent with the dolomite backfill of the mine. Additionally, fahlore fragments were detected throughout the deposits, indicated by their enrichment in Cu, As, Sb, Zn, S, Ag and Hg (Figure 9). The combination of these elements reflects the ore mineral assemblage found in the Schwaz–Brixlegg district, characterised predominantly by tetrahedrite-tennantite (Krismer et al. 2011). While these particles were observed in the micromorphological analysis, they could not be definitively identified as fahlores using this method alone. Deposit ML 8 (SE 2b), identified in thin section as a layer of coarse sands and gravel, notably differs from the surrounding predominant dolomite background and displays concentrations of Al, K and Si, suggesting the presence of feldspar minerals (K-feldspar) or sheet silicate minerals such as micas (muscovite). In addition to the concentrations found in the fahlore fragments, Cu is ubiquitous throughout the fine matrix of the upper deposits, with particularly high concentrations in ML 9 and, to a lesser extent, in ML 7 (both corresponding to SE 2b). P is also uniformly detected in these deposits, with higher concentrations corresponding to occasional bone and possible coprolite fragments identified under the microscope.

Interestingly, the particle in ML 8, identified under the microscope as a potential lime binder, shows a pronounced Ca signal but lacks Mg entirely. This suggests that the binder material was not derived from the available dolomite rock. Regarding the two cultic layers, they also contain a matrix with dolomite fragments, as indicated by the concentrations of Ca and Mg (respectively, depicted in blue and light green in Figure 10). ML 10 (SE 4a) stands out distinctly from the upper and lower deposits due to its high concentrations of Si, Al and K (depicted in purple, green and pink in Figure 10), as well as Fe. This suggests an increase in silicate minerals, supporting the identification of micas (muscovite, biotite) in the micromorphological analysis. Interestingly, the phosphorus signal is completely absent in ML 10, while it clearly highlights fine bone splinters and altered ash pockets in ML 11 (SE 4b). Also notable is the stronger enrichment in Cu (depicted in orange in Figure 10) at the interface of ML 10 and ML 11.

## 4 | Discussion of the Results

### 4.1 | The Cultic Layers

Following our microarchaeological analyses, the layer initially interpreted as a deposit of altered ashes (SE 4a/ML 10) covering

**FIGURE 8** | Sequence of photomicrographs from thin section KPF 3 A, illustrating the main features of the Mithraic layers: (a) Fragment of burnt bone (bb) interspersed in the groundmass. Note the net of fine cracks running across the surface of the piece and its darkened rim, indicative of fire exposure. Since the darkened rim is not continuous around the bone fragment, it can be inferred that the fragmentation occurred after burning. PPL; (b) Detail of a lump of slightly phosphatised ashes (note the amorphous pale yellowish micromass in which they are embedded). Although most of the weathered ashes have lost their original structure, some rhombohedral pseudomorphs (yellow arrows) can still be observed. In the ashes, other burnt inclusions were found, such as a fragment of burnt bone [bb] and some small charcoals [ch]. PPL; (c) Overview of the groundmass in ML 11, which is predominantly composed of fine charcoals, whose further identification is not possible because of the small dimension of the particles. Note the vertical cracks (yellow arrows) across some of the fragments, presumably resulting from a certain degree of compaction. PPL; (d) Detail of ML 11 where elongated charcoal fragments, corresponding to individual year rings of the same piece, are deposited in close proximity. This suggests that the charcoal, although being dumped, did not travel far, and did not completely lose its original anatomical connection. PPL; (e) A partly preserved (iron precipitation?) root [r] can be occasionally seen within the channel that they bore through ML 11 as well as ML 10. PPL; (f) Aggregate in ML 11. Together with charcoals [ch], and pockets of ashes [ash], lumps of siliciclastic silty sands are scattered throughout layer. Medium to fine sand mica crystals [m] are visible in the terrigenous aggregate. Left in PPL and right in XPL; (g) Detail of two laminations, separated by the dotted yellow line, in ML 10. Despite both being much finer than any other deposit found in the sequence, note the difference in grain size between the two lenses. While the lower one is a very fine silty clay, the upper one is a sandy silt mostly composed of bundled mica crystals [m]. A root remnant [r] can be observed in the upper lamination. Left in XPL and right in PPL; (h) Overview of deposit ML 10. Distinct laminations (separated by the dotted yellow lines) are only partly well defined, while in other areas of the deposit, their boundaries cannot be followed clearly. Nonetheless, a general difference based on colour and grain size can be recognised. Note the sharp boundary with the underlying ML 11, and that part of the fine terrigenous material occupies the space between charcoal fragments. Coarser particles (mostly geogenic) begin to appear towards the upper part of the picture. Left in XPL and right in PPL. Picture: S. Cereda.

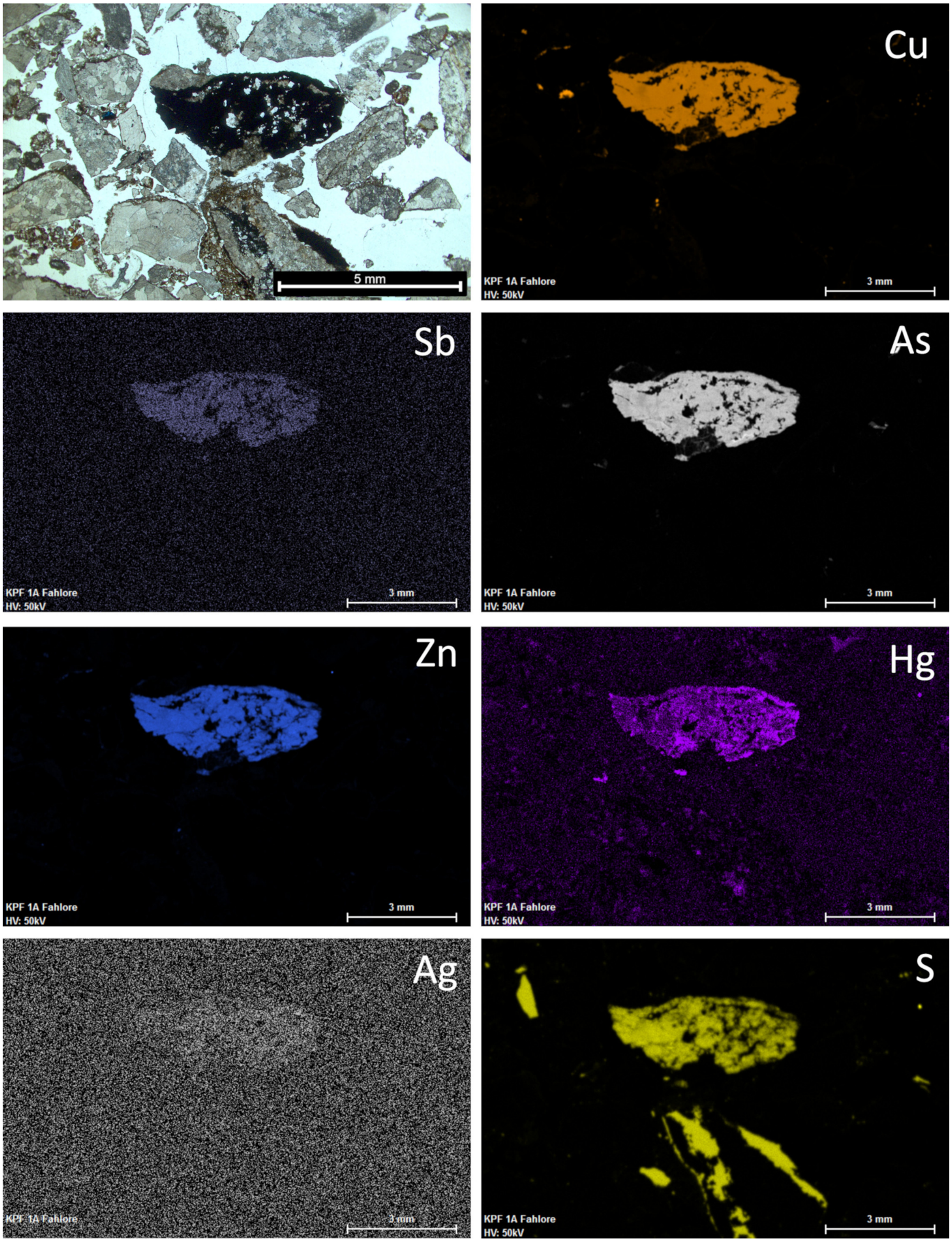


**FIGURE 9** | Detailed element mapping of a fahlore fragment in sample KPF_1A. The first image shows a microphotograph of the same particle under PPL light. In this illumination, fahlore appears opaque and cannot be clearly identified. The application of instrumental analytical chemistry is, in this case, crucial for accurate determination. Picture: S. Wagner. and S. Cereda.

the charred remains (SE 4b/ML 11) was found to be composed of fine silts and clays. Elemental mapping confirmed that these lenses belong to the silicates group, showing high concentrations of Al, Fe, K and Si. This discovery raised two important questions: (a) Where did this fine material originate? (b) What event or process led to its deposition within the mine? Concerning its source, the fine texture of the lenses compared to the coarse mining backfill, together with their siliceous composition, suggests that they likely did not originate from within the mine, but rather from outside.

One hypothesis for how they became deposited inside the mine is that these fine clays were intentionally collected and spread over the surfaces of the ceremonial space with the

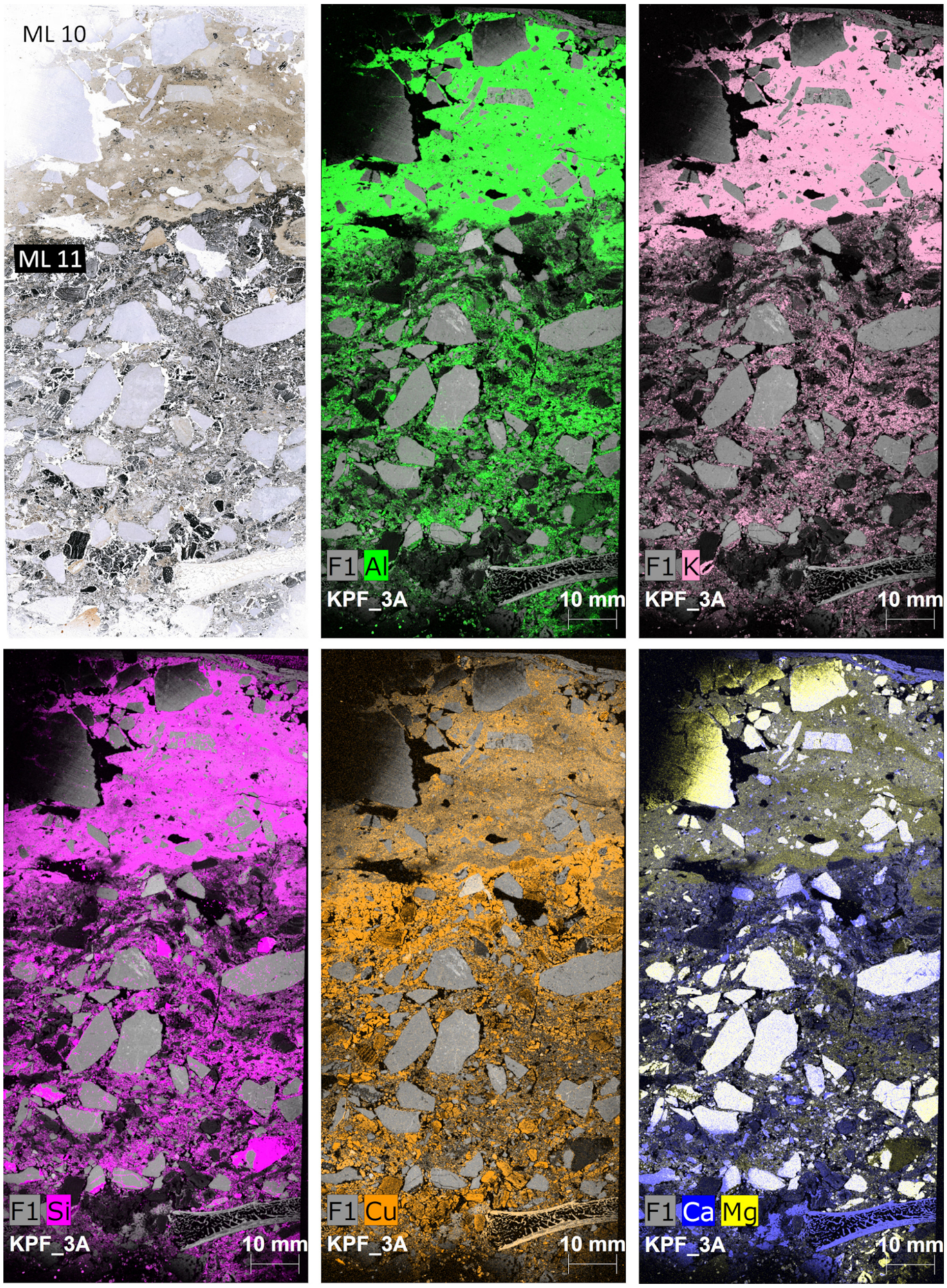


**FIGURE 10** | Selection of the most representative element mappings of sample KPF_3A. The spatial distribution of the elements is overlain over a so-called F1 image (see text for F1 description). Al, Si and K differentiate very well the silty–clayey laminations in ML 10 from the underlying cultic deposit ML 11. Ca and Mg highlight the distribution of dolomite fragments. Cu evidences the existence of a 'crust' at the interface between ML 10 and ML 11, and possibly of a second one further down in the profile of ML 11. Picture: P. Tropper.

intent to 'obliterate' the ritual practices carried out in Late Antiquity. The destruction of Mithraea was indeed a cultural practice that widely occurred amidst the turmoil of the fifth century (Schuddeboom 2017; Prijatelj 2018). However, the structure of the deposit, together with the presence of distinct fabric features, suggests that it did not form due to anthropic intervention. Its bi-modal sorting (silty clays and gravel clasts) and laminated appearance, as well as the occurrence of rotation features and the horizontal, undulating orientation of elongated particles collectively suggest ductile deformation and a lateral flow direction of the deposit. These characteristics indicate that the mud was deposited by waters carrying a high sediment load (Friesem et al. 2014; Karkanas and Goldberg 2019) and that the flow even mobilised some of the dolomite clasts. That the lenses were deposited in a viscous state is further supported by their downwards 'seeping' appearance, filling the space between charcoal fragments at the boundary with ML 11. Finer distinctions between the individual lenses were not detected via µXRF and further analyses are necessary to refine our understanding of their mineralogy. However, the presence of different lenses with slight textural and colour differences could be detected optically and suggests that multiple flow episodes occurred. These events probably occurred in a very short time span, too brief for clay crusts to desiccate or for other sediment to be deposited between the lenses.

As mentioned in Section 2, a major body of water flows just a few metres away from Kropfsberg and its mine: the Inn River. A look at the hydrogeomorphology of this waterway is crucial for understanding the deposition of allochthonous clays inside the mine. Modern maps of inundation risks for this area show that even today, the Inn is capable of flooding the entire surroundings of Kropfsberg (see Figure 11). Historical and environmental records further indicate abrupt and significant increases in water levels in the past. The major events documented in this area are the catastrophic multi-phase rock avalanches of the Pletzachkogel (Kramsach), which occurred a few kilometres downstream on the Northern Limestone Alps side of the valley, some of which had far-reaching consequences for the historical, cultural and political development of the region (Patzelt 2012). By mobilising substantial volumes of rock mass that accumulated at the valley bottom, the failed slopes led to the damming of the Inn River and the formation of fluvio-lacustrine backwater sediments. One of the lakes, which formed during the period when the Mithraeum existed, reached an elevation of 522 m above sea level, matching the height of the cultic entrance (Patzelt 2012, 31).

Under these conditions, even slight fluctuations in water levels could have resulted in water flowing into the mine. Organic material found at the interface between the Inn alluvial deposits and the base of the rock avalanche was radiocarbon-dated, yielding results ranging between the 2nd and 3rd century CE (Patzelt 2012). This indicates that the lake would have formed by the time the cultic cave was in use. However, the chronological evidence recovered from the cultic layers suggests a much later terminus post quem for the inundation of the mine, with the most recent coins dating back to the late 4th century CE (refer to Section 2). While it is possible for coins to remain in circulation for extended periods—depending on their usage and function beyond their financial value—in such cases, they typically show noticeable signs of wear, like weathering and flattening of minted designs due to continuous handling, or the presence of holes for hanging as ornaments or amulets. However, such signs are conspicuously absent in this case. It seems more plausible that the deposition of the Kropfsberg coins did not significantly deviate from their minting and circulation period. If the inundation within the mine and the Pletzachkogel rock avalanche are connected, these findings suggest that the catastrophic event may have occurred much later than previously believed.

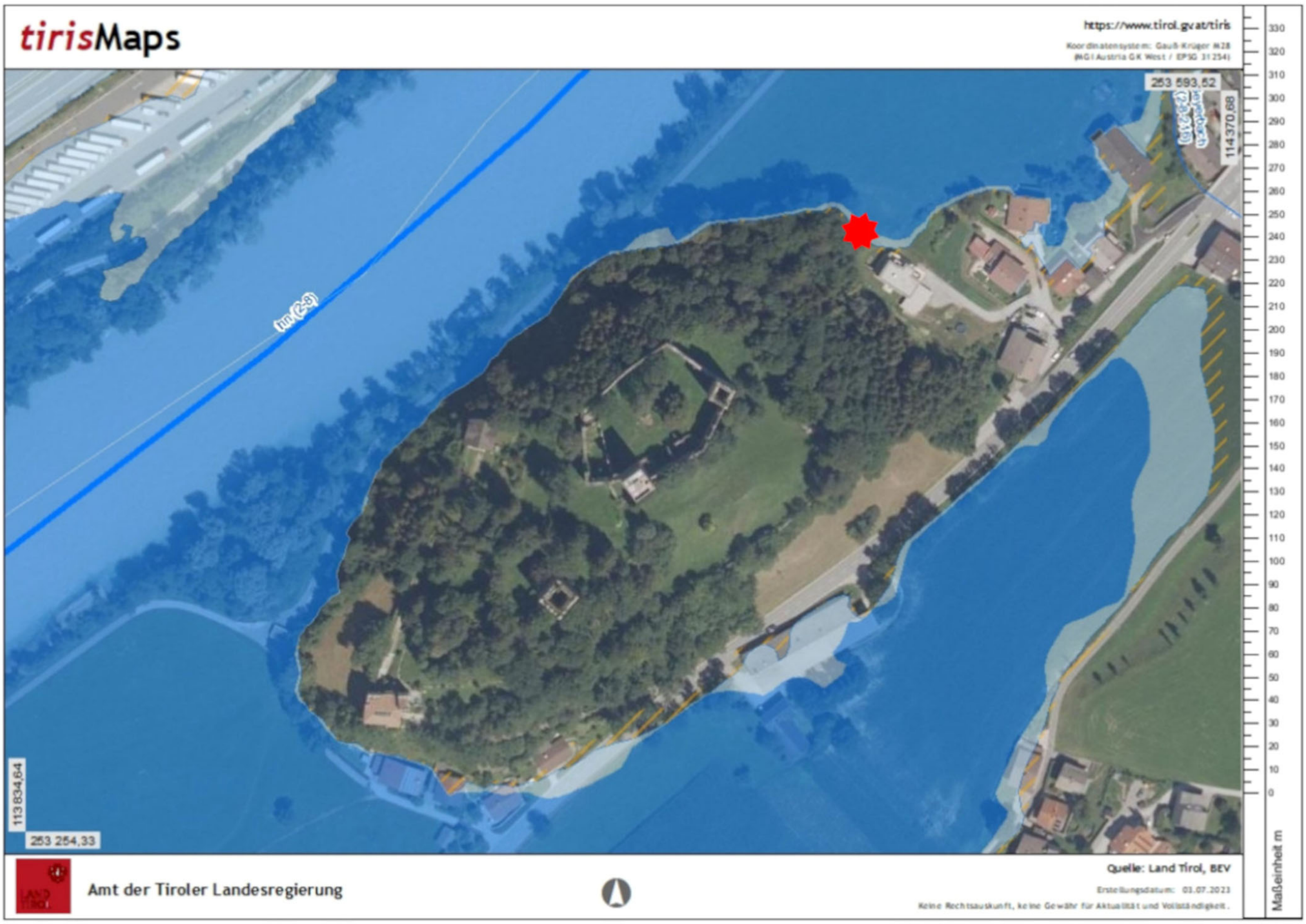


**FIGURE 11** | Map from the Online GIS tool of the Federal State of Tyrol, depicting the high-water risk (updated to 2017) around Kropfsberg. Various shades of blue represent different levels of inundation risk (darker shades indicating higher risk than lighter ones). The red dot to the northeast of the mound shows the location of the entrance to the mine. Picture modified from: tirisMaps (accessed on March 7, 2024).

If the sealing of the cultic layers was not a result of human activity, another question arises: was the hypothesised Mithraeum intentionally destroyed or abandoned? The burnt deposits in ML 11, directly beneath the washed-in clays, could point towards a destruction episode; however, the morphology and structure of these layers argue against this interpretation. The deposit comprises multiple thin and diffuse bands of partly compacted material with occasional vertical cracks, interspersed with sediment clods of allochthonous mud. The high degree of charcoal fragmentation, their lack of anatomical connections, random distribution and the lack of burning signs in the surrounding substrate indicate that these layers are not the result of in situ fires. Rather than being the result of sudden destruction, these features suggest that the burnt layers (possibly the result of ceremonial fires) were deliberately removed and placed here. Similar discoveries, with thin layers predominantly composed of charcoal and finely fragmented, non-calcined bones, were recorded by Lo Russo (2021) and Lo Russo et al. (2022) in the Mithraea of Biesheim (FR) and Kempraten (CH), as well as in the cultic cave of Zillis (CH). According to the authors, artefacts such as fire shovels, or their depictions, have been unearthed in various Mithraea (Lo Russo et al. 2022, 46), further supporting the idea that the scattering of combustion debris likely held high ritualistic significance. Despite traces of compression, the remains at Kropfsberg were not substantially trampled, indicating that they probably do not represent floor renewals. Indeed, even though the charred particles seem fragmented, some anatomical features and structural characteristics remain identifiable, and the deposit as a whole shows moderate porosity. Additionally, when looking at the excavated profile, it becomes clear that deposit ML 11 is primarily concentrated in the northern part of the area, enclosed by older layers and the bedrock (see Figure 4). This concentration suggests that the layers were deposited within a small depression in the ground, probably a pit.

Pits containing coins and charcoals are a common feature found in various Mithraea. The ritual associated with these pits seems to have involved a performative act in which worshippers '[…] dined with the god, consuming special foods like chicken, and then commemorated the occasion by collecting remains from the meal and burying them in a specially-made box in the nave of the mithraeum while it was still under construction' (McCarty, Egri, and Rustoiu 2019). However, not all deposits discovered can definitively be attributed to similar foundation rites. For instance, in the nearby Mithraeum of Pons Aeni (Pfaffenhofen am Inn, Germany), approximately one hundred coins dating between the late 3rd and early 5th centuries CE were unearthed in an underground structure (Garbsch 1985). According to the excavator, these deposits were not sealed, and while the specific positions of the coins within the pits were not documented, they do not seem to have been part of foundation boxes (McCarty, Egri, and Rustoiu 2019). Another well-known form of interaction, albeit violent in this case, with Mithraic sites is the scattering of liturgical furnishings and objects, such as cult images and coin deposits (Luciani 2018; Schuddeboom 2017; Walsh 2019, 2023). To address the question of the significance of the coins discovered in the Kropfsberg mine—whether they represent a cultic offering or the deliberate closure and secularisation of the space—it is thus essential to understand their depositional context. Unfortunately, none of the coins were examined in thin sections. However, based on excavation reports, it appears that they were recovered in equal amounts from both stratigraphic units SE 4a and 4b. While the coins found in the pit can be most probably considered votive objects, the presence of other coins above the burnt pit deposits may indicate that at least a few of them were not found as ceremonial offerings. These upper may have been scattered on the floor and later covered by the intrusive mud that embedded them, filling every empty space, as observed in thin sections.

When did the cultic phase end, and when did the inundation occur? We have previously noted that inundation lenses may have formed sometime after the end of the 4th century CE. Regarding the interval between the cessation of cultic activities and the inundations, although we cannot precisely quantify the time passed, both micromorphological and µXRF data suggest the presence of a non-depositional interval between ML 11 and ML 10. This phenomenon can be hypothesised based on the Cu distribution map of these deposits (see Figure 10), which displays a thicker 'crust' at the interface of the two MLs. Such an enrichment could reflect the general tendency of charcoals to adsorb elements from the groundwater and/or sediment moisture. At the same time, other charcoal-rich areas within the same layer do not show the same pronounced copper signal, suggesting that the surface may have experienced a more prolonged exposure. The enrichment may have been caused either by waters enriched with copper from the ores or it may be related to the presence of degraded bat guano, which is known to induce an increase in Cu and other element levels in cave sediments (Massilani et al. 2022; Queffelec et al. 2018; Wurster et al. 2015). The presence of root channels (see Figure 8g), penetrating the deposit during a phase of stasis, also suggests a gap in deposition, at least at the interface between ML 11 and ML 10, and potentially between ML 10 and ML 9.

## 4.2 | The Secular Deposits

The cultic use of the artificial cavity eventually ceased, with its remains (ML 11/SE 4b) buried by inundation deposits (ML 10/SE 4a). Two mortared stone walls at the mine entrances possibly signify the deliberate end of its cultic function. However, the absence of absolute dating for these features leaves this interpretation open. The cultic pit layers are followed by ML 9, a relatively thick deposit (approximately 20 cm) characterised by well-developed planar fissures with unconforming boundaries that delimit platy ped structure. This deposit likely formed through colluvial processes involving the mixing of fine sandy silt and organic material with dolomite clasts. This deposit, overlooked during excavation, marks a transition phase where accretion occurred independently of human activity. Therefore, the absence of archaeological evidence in the mine before the Middle Ages is likely due to historical developments rather than the loss of stratigraphy, such as the truncation of older deposits through mining activities.

The presence of a thin layer (ML 8) rich in sandstone fragments and traces of lime binder may record the actual reopening of the mine, with the removal of the walls blocking the north-eastern entrance, or of previous cultic installations that were probably built inside the mine. That ore extraction was the only activity carried out at the site is confirmed by the composition of these layers, constituted almost exclusively by sharp angular dolomite debris and by the occasional identification of fahlores, too small to be collected by the miners. The stratigraphy of mine backfills is in general complex, characterised by numerous overlapping lenses, with wedge-like shapes and thinning edges that make them sometimes difficult to follow across larger exposures. Interestingly, the microstratigraphic analysis of these backfills reveals numerous thin layers (ML 1–7) that were indistinguishable during excavation (see Figure 4). Overall, their sedimentary structures, with chaotic, unsorted and unstratified clast fabric, indicate formation through natural mass wasting processes, without water involvement (Karkanas et al. 2012; Selby 1993). To facilitate access and movement within the cave, mining debris was likely cleared periodically. The effects of this activity are evidenced by the presence of a thin silty clay film that adhered to the surface of coarse clasts during their transport. The mining debris was then spread over older surfaces, creating layers that occasionally display moderate normal grading (see ML 3), a feature typically associated with downslope particle movement (Karkanas et al. 2012). Besides episodes of dumping and levelling, the sequence also includes periods when these activities cease, allowing fine organic material (humic and/or coprolitic) to accumulate on the walking surface, and being subsequently trampled. Characteristic trampling features of these surfaces include the massive, compacted structure of the groundmass, together with the presence of horizontal planes and vertical cracks forming a network of voids (Rentzel et al. 2017). Two main surfaces can be identified: one corresponding to the final cessation of cave use (ML 1) and another lower in the profile (ML 6). The latter may indicate a temporal gap in mining activities (and the use of this space for other, non-documented purposes) or a shift in the centre of extraction to other areas of the mine.

Despite the centuries-long use of the site and the significant amount of debris generated, the thickness of the investigated sequence is relatively limited. This may be due to maintenance operations that involved periodically removing older backfill, perhaps when new veins were followed and new areas of the mine were excavated. Truncation episodes have been associated with abrupt changes in grain size, porosity and compaction, either alone or in combination (Karkanas et al. 2012). However, in the sequence of this mine, truncation episodes are not easily identifiable, and distinguishing between a truncation and changes in deposit structure caused simply by subsequent dumping and levelling events, without sediment removal, is challenging. Additionally, the coarse nature of the backfill deposits obscures sharp boundaries between layers, complicating the identification of intentional removal. Our reconstruction is limited to the sampled area and may differ in the left part of the profile in Trench 1, which slopes southward. Confirmation is currently not possible due to the lack of necessary sedimentological samples.

## 5 | Conclusions and Future Perspectives

Caves act as sediment traps, enclosed or partially enclosed environments that can preserve a wealth of information in their sedimentary layers, shedding light on both human activities and the natural environment. This phenomenon holds true not only for natural caves and prehistory but also, as demonstrated in this study, for historical periods and in artificial cavities that mimic natural caves in structure and characteristics. Despite being based on a limited number of samples from a single profile, this study significantly advances our understanding of the site's mining function over time.

Analyses of backfill layers revealed distinct episodes of dumping, levelling of mining waste and interruptions in extractive activities (or their relocation to other parts of the cave). Following a period of abandonment and natural deposition, the site reverted to its original function. Mining activities resumed during the Middle Ages, specifically from the 12th century CE, continuing until the 18th century CE, with no other apparent use identified during this period. Evidence of renewed activity at the site is observed in a stratigraphic layer (ML 8), which contains remnants of construction materials, such as mortar or plaster. These materials likely originated from walls blocking the entrance or fixtures related to the site's religious function (for which direct evidence is lacking). The presence of these remains suggests that structural elements were removed to restore access to the interior of the mine.

Regarding the cultic layers, the presence of burnt deposits does not indicate in situ fires. However, the displacement of these debris within a pit-like feature suggests the presence of an altar nearby. This pit contained multiple lenses of charcoal and finely fragmented, non-calcined bones, interspersed with aggregates of fine minerogenic material. It remains uncertain whether these remains were deposited during different ceremonial events or represent the aftermath of a single ceremony. The identified cultic objects, primarily coins, appear to have been partly scattered across the floor and partly deliberately placed in the pit. This distribution, along with the presence of walls blocking the entrances (which remain unfortunately undated), suggests that specific measures were taken to desacralise the space at the conclusion of the rituals performed in the cave. Eventually, thin layers of allochthonous clayey silts from the nearby Inn River washed over the surface of the already abandoned cultic cave, covering these religious deposits. The potential correlation of this flooding with the Pletzachkogel rock fall, currently dated to the 2nd–3rd centuries CE, but possibly occurring sometime after the 4th century CE, could have significant repercussions on local and regional historical narratives.

From a methodological point of view, the chosen techniques complement each other well, and the same thin sections can be used for both optical and chemical analyses of specific features or whole deposits. In situ chemical identification enabled by $\mu$XRF can strengthen micromorphological interpretation or reveal additional details that are not morphologically recognisable, such as the copper enrichment over the surface of charred deposits, the presence of fahlore fragments or the non-dolomitic nature of a lime binder. Conversely, the identification of different lenses in the water-laid clayey silts and backfill deposits proved more effective through micromorphology than elemental mapping. Also, the identification of the many backfill layers collectively labelled SE 2b during excavation was primarily achieved through micromorphology alone.

This underscores how indispensable microstratigraphic observations are for reconstructing complex formation processes, even in historical caves and mines, ensuring that interpretations of these contexts account for different possible depositional paths.

To further elaborate on these initial findings, additional analyses are underway to determine whether the presumed Mithraeum was simply abandoned or intentionally desacralised. These analyses use both microarchaeological methods, including CT and μCT analyses of micromorphological blocks and dating of mortar samples, and macroarchaeological methods, such as examining the spatial location of individual coins within the microstratigraphic sequence. Future research will extend beyond the cave to explore its geomorphological and hydrological surroundings in detail. This aims to provide new insights into the natural environment during the Roman period and Late Antiquity and to examine the role of Kropfsberg—both as a cult cave and as a mine—within the networks and circulation systems of the Inn Valley.

## Author Contributions

**Susanna Cereda:** conceptualisation, methodology, investigation, visualisation, writing–original draft, writing–review and editing. **Gert Goldenberg:** funding acquisition, writing–review and editing, investigation, project administration. **Markus Staudt:** investigation, visualisation, writing–original draft, writing–review and editing. **Peter Tropper:** methodology, visualisation, writing–original draft, investigation, writing–review and editing.


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## Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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