Fuliginochronology
Reading Past Occupational Sequences in Carbonate Crusts

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One of the recurring questions in archaeology concerns the temporalities in the use, visitation and occupation of places by past human groups. How often did people do things at a place? How long did they stay there? How many times did they return to undertake particular activities, and how did those activities change through time? To what degree can we talk of 'continuity' and 'change' when dealing with a site's 'life story', and how do these concepts shift in meaning as we move from one temporal scale to another? Archaeological excavations, and the dating of materials (bone, charcoal, etc.) contained in their sediments, allow us to understand the antiquity of human occupation, when people first arrived and when they left, the duration of occupational phases, and temporary or permanent departures (as shown, for example, by the absence of artefacts). It is also sometimes possible to identify the seasonality of occupation through zooarchaeological data (e.g. Balasse et al. 2015; Fontana 2017; Julien et al. 2015; Naji et al. 2022; Roussel et al. 2021). Conventionally, archaeologists have usually approached such investigations through the accumulated deposits buried underground.

Beyond the floors, information on the antiquity, number, duration, frequency and seasonality of occupation can also be gathered from the walls of rockshelters and caves. These physical traces of the past can contain information about a site's hydro-climatic history (e.g. through the formation of speleothems, surface alterations, gelifraction, heat-related weathering, etc.) as well as information about when and how people used it. One particularly rewarding but under-studied avenue of enquiry are the soot deposits left on walls and ceilings as a result of the smoke from the fires that people made. Those soot deposits can become trapped in the micro-layers of mineral crust that grow over time. The high-resolution study of carbonate crusts on walls and ceilings offers a new avenue of enquiry into the human history of enclosed spaces, through the layers of soot captured in their layers. Once identified and analysed, these soot layers can then be cross-correlated with other kinds of archaeological and geomorphological evidence obtained from a site.

Carbonate crusts on rock walls sometimes contain alternating micritic (WPL) (secondary carbonates consisting of small crystals of calcite) and (micro)sparitic (DCL) (consisting of larger calcite crystals) laminae (Figure 1). The micrite/sparite alternation is generally the expression of a seasonal signal linked to water conditions. Depending on the climate regime, and therefore on the region, the number of annual WPL/DCL laminae may vary: one annual doublet can be expected in Mediterranean and subtropical environments (corresponding with the alternating dry/wet seasons); up to four laminae (DCL/WPL/DCL/WPL) can occur in temperate environments; while in some regions or contexts laminae will not be seasonal (Baker et al. 1993; Genty 1993; Perrette et al. 2008; Shen et al. 2013). To demonstrate that these crystalline fabric changes reflect annual rhythms, other seasonal signals that not only depend on water conditions have to be sought out. For example, variations in concentrations of minor or trace elements can reflect seasonal variations in their deposition on the rock surface (Desmarchelier 1999; Fairchild et al. 2001; Huang et al. 2001; Johnson et al. 2006; Nagra et al. 2017; Roberts et al. 1998; Stoll et al. 2012; Treble et al. 2003). Variations in the concentration of Sr in carbonate crusts at Mandrin Cave (actually a rockshelter, in the Department of Drôme in southeast France), for example, have thus made it possible to establish the annual deposition of alternating DCL/WPL laminae at this site (Vandevelde et al. 2021). Such detailed examination of laminated rock crusts sets the scene for working and thinking at seasonal temporal scales for the past, even through periods of climate change. The antiquity of crusts can also be determined by U-series or radiocarbon dating their carbonates or trapped organic matter. The thickness of the laminae and their variations over time make it possible to infer hydrological conditions (especially rainfall) for the site and for the region, something that is often difficult to determine for Pleistocene times.

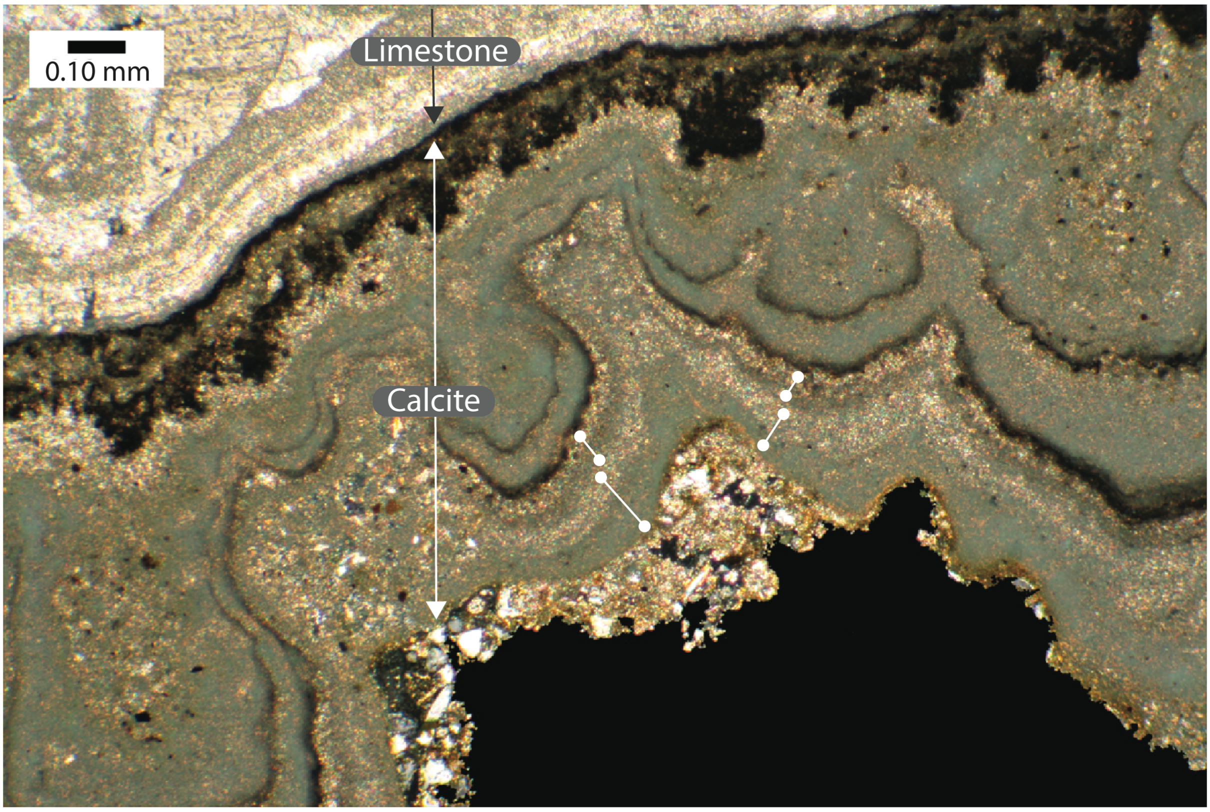

Figure 1. Thin section of crust sample C-MAN49a from Mandrin Cave, from sediment Layer C of the excavated deposit (photographed at ×50 magnification under crossed-polarized transmitted (XPL) and reflected (RL) light). All the crust samples discussed in this paper had fallen from the rockshelter's walls or ceiling in antiquity, becoming buried in on the palaeo-floor as soft sediments accumulated. A succession of paired calcite laminae ('doublets') of different sizes can be seen. The combination of cross-polarized transmitted light and reflected light improves the discrimination between the WPL (White Porous Laminae, appearing here as opaque micrite), DCL (Dark Compact Laminae, appearing here as translucent microsparite), and soot films (anthropogenic particles trapped as black micro-layers) in the carbonate crust. Each of the superimposed short white line with circular endings shown here spans a calcite doublet consisting of a micritic (WPL) and a sparitic (DCL) lamina (figure by Ségolène Vandevelde).

Information other than through their use as palaeoclimate proxies can also be extracted from carbonate crusts. Prominent among these are traces of soot trapped in carbonate laminae. In such cases, the soot stains the carbonates; the soot concentrations are very thin and tend not to form actual layers of their own. Rather the soot intermingles with the carbonate crystals of its contemporary wall or ceiling surface. A review of the global literature highlights that the presence of soot in carbonate crusts is not such a rare occurrence, and would warrant much more attention than it currently receives (Vandevelde et al. 2018). Thin carbonate crusts on the walls of Mandrin Cave, travertine formations at Orgnac III (France), stalagmites at Cueva de Nerja (Spain), and flowstone at La Mouthe (France), for example, all contain micro-layers of trapped soot (studies in progress; see also Vandevelde et al. 2018 and references there-in; see Vandevelde et al. 2020 for other examples). This soot can have been caused by hearths on the floor or by grease or oil lamps or torches close to the walls (Ferrier et al. 2017; Medina-Alcaide et al. 2021; Pons-Branchu et al. 2022; Vandevelde et al. 2017). These observations have led to the development of a new method for reading and analysing rock walls at archaeological sites: 'fuliginochronology'. The method aims to chronicle episodes of occupation based on the study of soot traces found in carbonate accretions. The term 'fuliginochronology' comes from the fusion of two words, the Latin *fuligo* or *fuliginosus* meaning 'soot' or 'sooty', and the Greek '*χρονολογία*' meaning 'chronology'. It is built on the same logic as 'dendrochronology', in homage to the technical similarities and analogous temporal resolutions produced by the two methods (Vandevelde et al. 2017, 2018). Indeed, layers of soot trapped in carbonate accretions can reach annual and even seasonal microstratigraphic resolutions, thanks to the seasonal carbonate laminae, again comparable with tree rings (e.g. Baker et al. 2008). In cases where hydro-climatic conditions are favourable, long sequences of alternating laminae sometimes trapping soot deposits can be obtained. In such instances, the sooty (fuliginous) carbonate accretions become valuable archives for both archaeological and paleoenvironmental research. When studied together with other lines of archaeological evidence from a site, such as adjacent floor deposits, a richer (hi)story of the site's occupation and its contemporary environmental conditions can be reached.

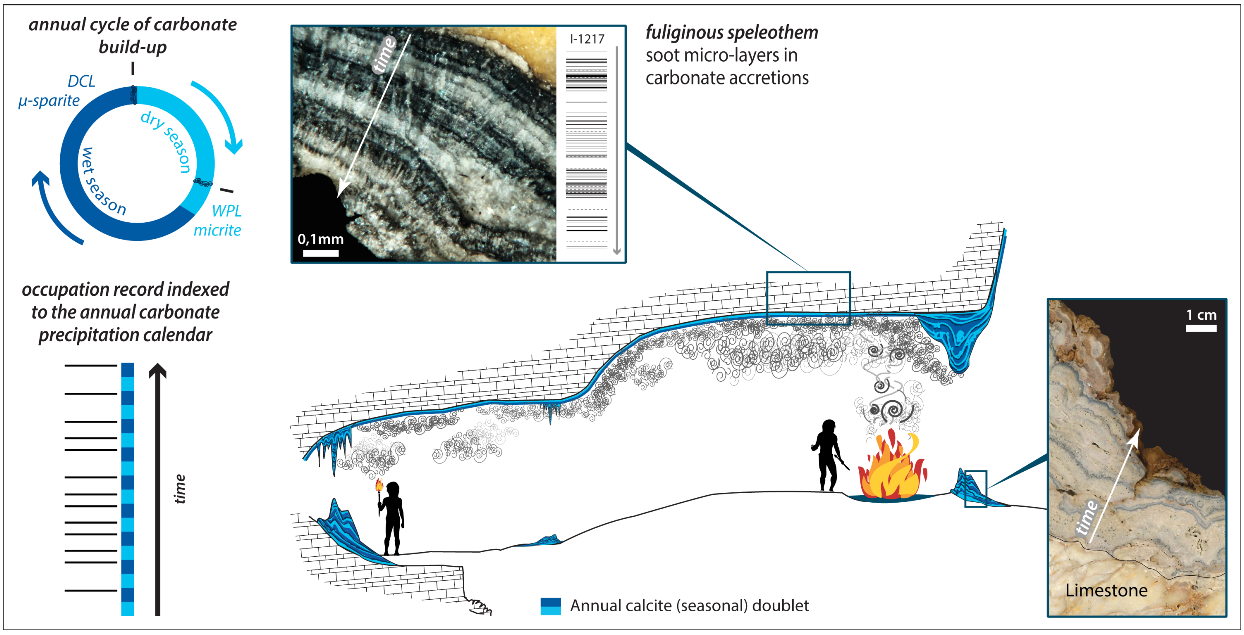

Figure 2. Fuliginochronology aims to study the traces of soot from past anthropogenic fires in carbonate accretions. The results can reveal details of both paleoenvironments and patterns of human occupation at seasonal or annual timescales (figure courtesy of Ségolène Vandevelde).

Thin sections and/or polished cross-sections exposing the growth axes of sooty concretions can reveal sequences of soot films testifying to past human activities nearby. Such sequences can be photographed at high magnification and converted to 'barcode' diagrams, each line on the barcode representing an accreted soot deposit (Figure 2). If multiple sooty carbonate samples with overlapping barcodes were thus obtained for analysis from a given site, a longer sequence than preserved in any single sample could be obtained. In the best-case scenario, such multi-sample sequences could chronicle the entire span of human occupation in a cave or rockshelter (Vandevelde et al. 2017, 2018). The number of soot layers trapped in these laminated carbonate accretions can be read as a Minimum Number of Occupations (MNO) for this part of the site. When concretions with sooty layers exhibit annual carbonate laminae, the position of the sooty layers can be indexed in the annual calendar of the total sequence (Figure 3). It then becomes possible to determine the frequency (in MNO/year) and rhythms of human occupation across a shelter or cave, and to accurately assess the duration of the occupation phases and their seasonality (by studying the position of the traces of soot in DCL or WPL laminae).

This innovative approach to the cultural past was applied to Mandrin Cave, which experienced a number of phases of occupation, the earliest set of which have been attributed to Neanderthals (Figure 4). This site is a vast rockshelter under a limestone spur, with an entrance 12 m wide and open to the north. This configuration favoured sediment input from the Mistral winds that descend the Rhone valley from the north. The loess sediments and limestone fragments fallen from the shelter's walls and roof occur throughout the floor deposit. Archaeological excavations coupled with thermoluminescene, optically stimulated luminescence and radiocarbon dates have made it possible to distinguish and determine the ages of 10 stratigraphic layers and several major phases of human occupation (Figure 4; see Slimak et al. 2022). Carbonate crusts had formed on the walls during all the phases of occupation, and indeed they continue to form today. This continuous formation process is evident by the thin calcite crusts on the clasts that fell from the walls and ceiling of the shelter, to become buried by accumulating sediments on the ground. High-resolution micro-stratigraphic study of these crusts has revealed many traces of trapped soot in the laminae.

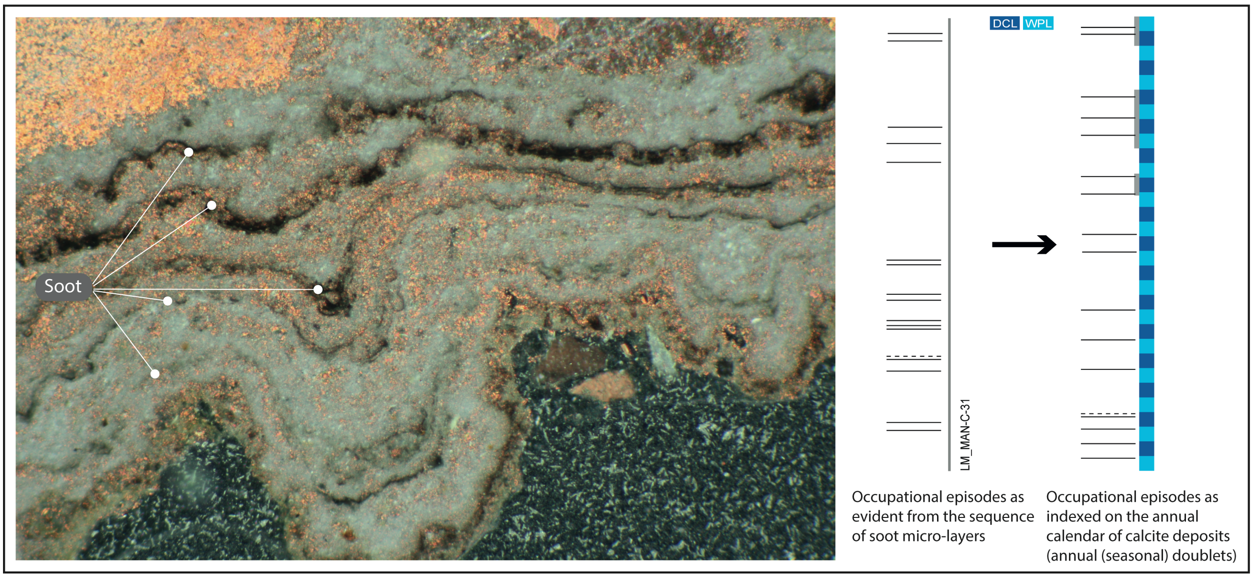

Figure 3. Interpretation and indexing of the succession of sooty layers (proxies for occupational events) on the annual calendar growths recorded from carbonate crust sample MAN-C-31 (Mandrin Cave, excavation Layer C, photographed at ×50 magnification under crossed-polarized transmitted (XPL) and reflected (RL) light). The photo and barcode to its immediate right show the thickness of 'clean' carbonate laminae separating the black sooty micro-layers. The diagram further to the right shows the sequence of carbonate layers scaled to time (figure by Ségolène Vandevelde).

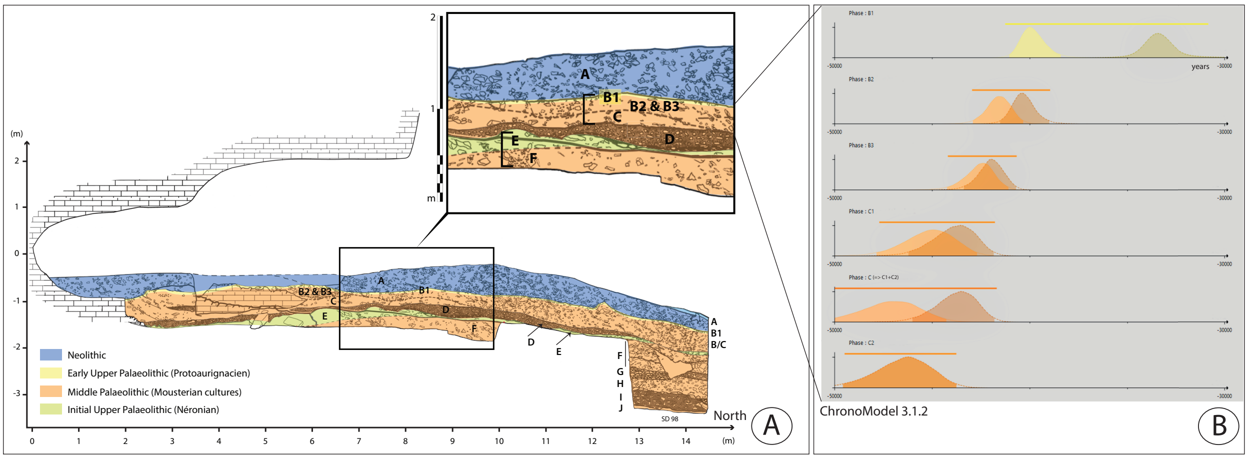

Figure 4. A: Mandrin Cave's stratigraphy and archaeological phases. B: Bayesian modelling of the ages obtained from the upper part of the excavated deposit, documenting the transition from the Middle Palaeolithic to the Upper Palaeolithic (figure courtesy of Ségolène Vandevelde, Processus de Transfert et d'Échanges dans l'Environnement (PROTÉE) and Ludovic Slimak).

Buried fragments of fallen wall crust have been collected for several years from the rockshelter's excavated deposits. Each carbonate crust was examined for the presence of soot micro-layers. The individual laminae of each piece were drawn, and the overlaps in their barcodes cross-correlated to create a long sequence of sequential laminae, as described above (Figures 2, 3). The synchronisation of overlapping sections of the total sequence of laminae across samples, and in the process of matching soot micro-layers, made it possible to correlate individual occupational levels or events (as revealed by the archaeological excavations) with the soot micro-layers from hearths (as originally deposited on the adjacent cave wall and ceiling whose carbonate crusts subsequently fell onto the ground to become buried in accumulating deposits) (see Figure 4). In this way we were able to correlate several samples from the same archaeological layer, but not from samples between different stratigraphic layers (Vandevelde et al. 2017, 2018). These results show that at Mandrin Cave the progressive disintegration of the walls was rapid enough for the encrusted fragments found in sedimentary units to be contemporaneous of with the sediment layers on which they had fallen. The radiocarbon dating of the soot micro-layers, and of the carbonate laminae by a combination of radiocarbon and U-series dating, has further enabled the cross-correlation of the two sequences, further enriching the story of the cave's occupation in the process.

The fuliginochronological study of the ten stratigraphic layers of Mandrin Cave's excavated deposits (sub-divided into 13 archaeological levels) have already revealed a minimum of 446 successive occupational episodes in the cave. Minimum Numbers of Occupation (MNO) have also been determined for each archaeological level. The seasonally paired laminae ('doublets') in the carbonate crusts were also counted, making it possible to specify the frequency of occupation (number of occupation episodes per year) by dividing the incidence of sooty micro-layers by the number of annual calcite doublets for each period of interest (Vandevelde 2019, 2021). For example, the results show that during the Post-Neronian I archaeological phase (Layer D of the excavated deposit), and during the Proto-Aurignacian phase (Level B1), the site was occupied on average once per year, whereas during one of the Post-Neronian II occupation phases (Level B3) it was occupied almost twice as often (Figure 5A).

Indexing the occupational episodes on the annual calendar of the carbonates' growth laminae also allowed us to evaluate the lapse of time that separated each occupational event. Occupation phases were thus distinguished, each with its characteristic seasonality (Figure 5B). By quantifying the proportion of soot films associated with micrite (representing a relatively dry period of build-up) and sparite (wet period), we were able to determine when in the year the rockshelter was frequented for each archaeological horizon in which carbonate crusts fell. The changing frequency of occupation now also informs the site's life story over tens of thousands of years. It is thus possible to establish that c. 54,000 years ago (Slimak et al. 2022), the site was occupied mainly in the dry season by Neanderthals (*Homo neanderthalensis*). At that time the cave's Neanderthal inhabitants engaged with a Rhodanian Quina type of Mousterian material culture (Layer F of the excavated deposit). In Layer E during the Neronian archaeological phase, however, the first known *Homo sapiens* in the region mainly occupied the site during the wet season.

Last but not least, by studying more closely the evidence for occupation in the different excavated strata, several rhythms of occupation can be identified (Vandevelde 2019, 2021). Some of these temporal patterns, such as breaks in occupancy every three years, or occupancy during the dry season every two years, have been interpreted as part of multi-annual cycles of regional movement. These multi-annual cycles were repeated in a number of excavated layers (Layers C, E, F and G), making it possible to discuss both the seasonality and longer-term planning of movements across the landscape.

Other rhythms of occupation, as in Layer D when the site was occupied only once a year and always during the same season (dry season), make it possible to determine that Mandrin Cave was then part of an annual subsistence and social cycle that connected different parts of the landscape in an anticipated way.

Fuliginochronology makes it possible to study a site's occupation in ways, and in details, that were not previously available. The levels of information such studies reveal enable some aspects of group mobility to be determined, including frequencies and seasonality. They enable questions of social and territorial organisation to be broached at nested temporal scales ranging from seasons to trans-generational phases, thus enriching the material evidence to a more social history of the experienced landscape.

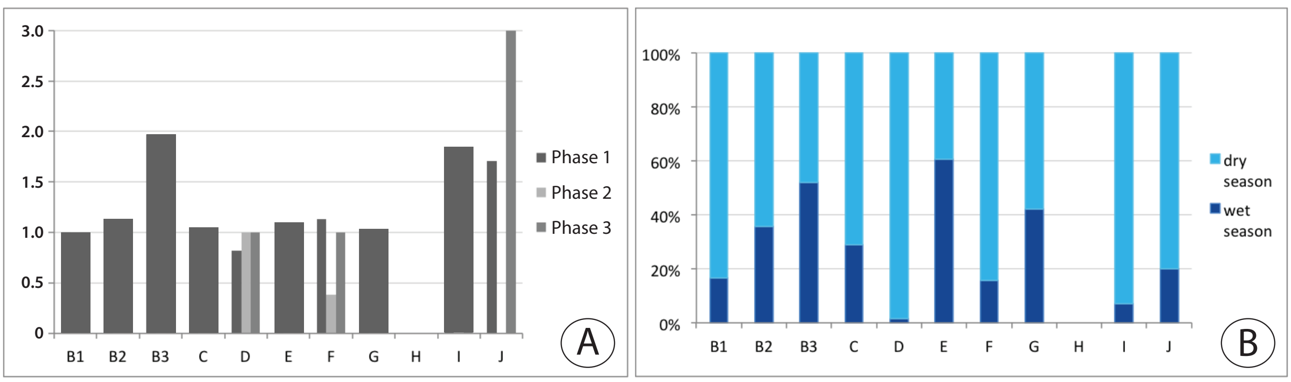

Figure 5. A: Frequency of occupation (in average number of occupation episodes per year) for each occupation phase identified by the excavated Palaeolithic deposits (Levels J to B1) and the fuliginochronological study (Phases 1 to 3). B: Diagram showing the proportions of soot micro-layers associated with micritic (light blue, representing dry season accretions) and microsparitic (dark blue, representing wet season) laminae, by archaeological horizon.

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