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RESEARCH

Vial Excavation: Microstratigraphic Excavation in the Laboratory - A Methodology for High Resolution Sampling and Integration of Data from Multiple Analytical Methods

Dennis Sandgathe[1] · Vera Aldeias[2,3] · Paul Goldberg[1,2,4] · Shannon P. McPherron[2,3] · Deborah I. Olszewski[5] · Aylar Abdolahzadeh[6] · Angel Carrancho[7] · Dan Cabanes[8] · Giulia Gallo[9,10] · Guillaume Guerin[11] · Antonio V. Herrera-Herrera[12,13] · Li Li[2,3] · Carolina Mallol[13,14] · Judit del Río[7] · Dimitri Papavasiliou[8] · Mareike Stahlschmidt[15,16] · Teresa E. Steele[10]

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Abstract

Over the last decades, archaeology has been undergoing a revolution of sorts driven by advances in the archaeological sciences and the ability to extract data from sediments. These new methods work at the micro- or even molecular scale and thus require extremely high levels of precision for the context of the samples. While there have been significant advances in proveniencing techniques, by and large, basic excavation methods have hardly changed in half a century or more. We document excavations better, we save more things more systematically, and we move slower, but excavations are still primarily focused on the recovery of objects. In our experience, sampling for the archaeological sciences is shoehorned into the existing methodology. Here we describe an excavation methodology - vial-based excavation - that is instead designed from the start for the archaeological sciences and, in particular, to systematically collect the invisible components of the archaeological record. To do this, we remove intact blocks of sediment to a laboratory, employ a vacuum system for complete recovery of sediments, collect sediments as a large number of very small samples in glass vials, use micromorphology extensively to track micro-contexts, and use digital systems to document contexts efficiently. We applied this methodology to the investigation of fire residues in Layer 8 of the Middle Paleolithic site of Pech de l'Azé IV, France. Our purpose here is to share this methodology as a potentially useful companion to more traditional excavation methodologies.

Keywords Microarchaeology · Micromorphology · Middle Paleolithic · Fire · Pyrotechnology

Introduction

Over the last decades, archaeology has been undergoing a revolution of sorts driven by advances in the archaeological sciences. In our particular area of focus, the Paleolithic, this is illustrated, for example, by the extraction from sediments of biomolecules, like aDNA and lipid biomarkers. Such research is revolutionizing the types and resolution of data that enables us to better understand past site use and paleoenvironment. Important developments have also been made in analytical methods, and it is now somewhat standard procedure to integrate archaeological datasets with a diversity of data from: geochemistry (as environmental, behavioral and taphonomic proxies); microparticles such as phytoliths and microcharcoal; spectroscopic data (e.g. Fourier Transform Infrared - FTIR, Raman); X-Ray Diffraction (XRD), isotopes; and biomolecules (lipids, proteins and aDNA). Several of these new methods work at the micro- or even molecular scale and thus require extremely high levels of precision for the context of the samples. Further, many new methods also have challenging requirements for reducing sample contamination. On the side of the archaeological excavation methods, there have also been improvements, such as the use of high-resolution provenience technology, specifically total stations; the advent of digital photography and structure from motion (SfM) making the creation of an extensive photographic record inexpensive and easy; and the investigation of site formation processes (e.g., micromorphology and artifact orientations) becoming standard

Extended author information available on the last page of the article

components of most projects. Over the last decades, the application of a wide range of analytical methods has shown that a substantial amount of archaeological information is stored in the so-called "invisible record" of archaeological deposits (Weiner, 2010), which can be gleaned from the study of the sedimentary matrix, rather than from just the investigation of the traditional objects of interest, for instance, the lithic and faunal remains larger than the smallest screen size. The discipline-wide interest in site formation processes, associated with the increased sourcing of data from sediment-oriented analyses, have led to a newly developed appreciation for the importance of the sediments themselves as human archives, and the data they hold about how a site formed and past human activities at that location (Aldeias et al., 2014; Goldberg et al., 2009a; Stoops et al., 2010; Karkanas & Goldberg, 2018).

However, while many new analytical methods have become regular components of excavations, these analyses are typically incorporated as add-ons to projects still generally tailored towards removing relatively large volumes of sediments in the process of recovering the visible objects: lithics, bones, etc. As domains of specialists, these new analyses are not typically built into the general site excavation methodology. Often the specialists themselves collect their respective samples, which might entail a brief visit to the site during which samples may be taken from a limited area - often a single location, perhaps as a discrete column down the face of a profile - with each specialist using their respective sampling protocols. For some research projects, this may be all that is required to satisfy project goals; simple presence/absence of specific data in a layer or simple frequencies per layer will suffice (e.g., lipid n-alkane or phytolith frequencies per layer as a proxy for changes in environment and climatic regimes). Some general spatial data per layer may also be useful (e.g., presence/absence and relative frequencies of phytolith types across a layer may provide important site-use data). However, these separate sampling protocols limit the integration of different types of data because:

- sampling locations for distinct datasets are not the same,
- sampling strategies may not use the same units of measure, and
- the heterogeneity of archaeological sediments may represent distinct human actions and depositional processes across spatially limited areas.

The systematic integration of analytical techniques that focus on the invisible record is currently not done in traditional excavations. Here we argue that to effectively use a wide variety of analytical methods whose target data are dispersed throughout the sediments, either homogeneously or concentrated as potential features, the resulting data should be integrated in a detailed contextualized space. Towards this end, we developed a microstratigraphic excavation methodology with high sampling coverage and high-resolution proveniencing. This methodology is based on taking large blocks of intact sediments from the site and excavating them under controlled laboratory settings, targeting the systematic recovery of archaeological sediments along with, as opposed to solely, the artifacts. Our specific research interest is in the nature of Middle Paleolithic (Neanderthal) fire use, especially at a number of cave sites in southwest France. We developed this methodology to try to identify what were mainly invisible individual fire features at the site of Pech de l'Azé IV (hereafter Pech IV). However, we think that, in overcoming some of the limitations imposed by traditional excavation approaches on the usefulness of the data coming from these sediment-oriented analytical methods, our methodology will be appropriate and applicable to other archaeological questions and contexts. In most cases we expect it would make sense to employ our methodology in concert with traditional excavation approaches. In this paper, we will focus on presenting the microstratigraphic excavation methodology we developed. We also provide some initial examples of how different analytical methods can be integrated during the analytical process.

Fire Features at Pech de l'Azé IV

Pech IV is a Middle Paleolithic cave site in the Dordogne area of southwest France (Fig. 1). It was first discovered and tested in the 1950s while F. Bordes was working at the neighboring Pech de l'Azé I. It was then principally excavated from 1970 to 1977 by Bordes (1975) and then again from 2000 to 2003 by a team led by Dibble, McPherron, Goldberg, and Sandgathe (Dibble et al., 2018). At the base of the deposit, resting on bedrock, is a relatively thick layer (circa 30–40 cm) rich in faunal remains and lithics and with extensive evidence of burning (Figs. 2, 3 and 4). Bordes excavated this deposit in two units labeled Layers Z and Y from the bottom up. We excavated the same deposit as a single layer: Layer 8. As a result of this work, as well as subsequent excavations by our team at the nearby Middle Paleolithic cave site of Roc de Marsal, we published a series of papers on Neandertal use of fire (e.g. Sandgathe et al., 2011a, b; Aldeias et al., 2012; Goldberg et al., 2012) that have generated some debate (e.g., Sorensen, 2017, Brittingham et al., 2019, Angelucci et al., 2023).

Though Bordes (1975) mentioned the presence of evidence of fire in the basal layers in his preliminary publication of the site and though notes referencing burning were present in the field books the extent of the evidence for burning surprised us when we removed the concrete walls that

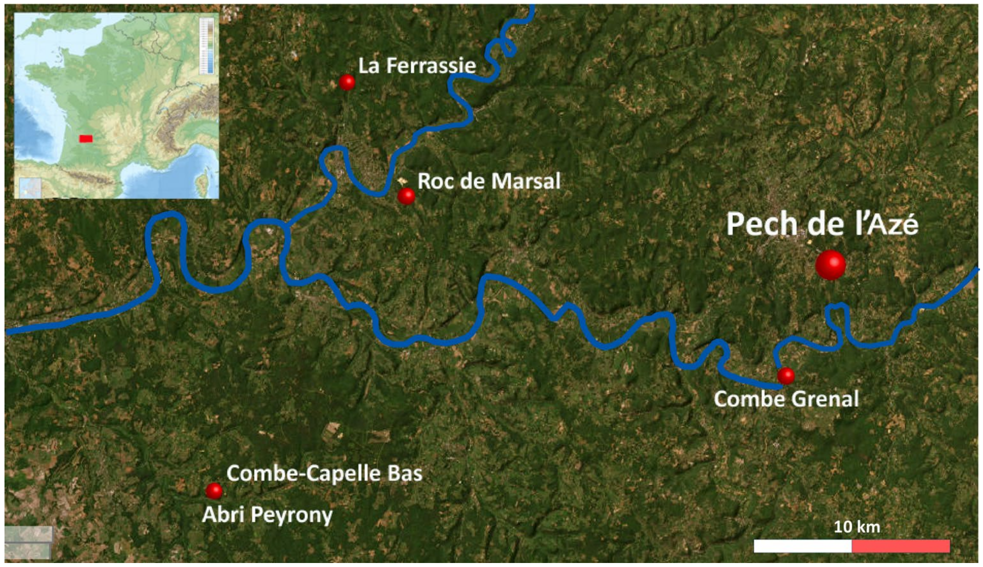

Fig. 1 The location of the Pech de l'Azé sites in southwest France along with several other Middle Paleolithic sites from the region where we have comparable data on fire use

Fig. 2 Photo looking down on the area that was the focus of the 2000–2003 excavations. The darkly colored bench of Layer 8 deposits is shown as it was left in 2003

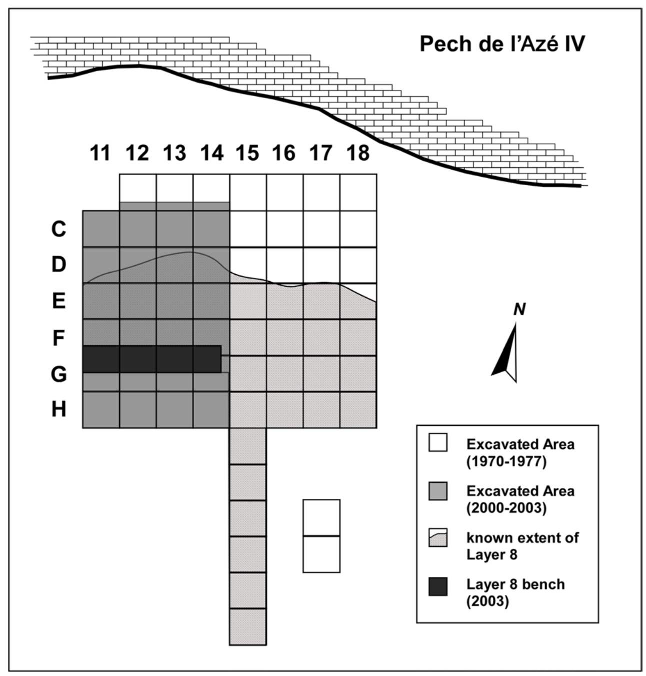

Fig. 3 Map of site indicating areas excavated by each research team, the extent of Layer 8, and the location of the Layer 8 bench. The northern extent of Layer 8 is influenced by the shape of the underlying bedrock which rises to the north

had covered the site since the late 1980s and Bordes's death. During the 2000–2003 excavations, we observed a ~ 35 cm thick massive to coarsely bedded dark reddish-brown layer with prominent ash lenses, a 'greasy' consistency, and composed of organic-rich silty sand that contained significant quantities of burned bone, heated flint, and slight amounts (~ < 5%) of heated cm-sized limestone rock fall (Fig. 4).

However, excavating these deposits and documenting the hearths was quite challenging. Initially, we attempted an area excavation ('*décapage*') aimed at delimiting individual hearths in plan view. As the deposit is a mix of partially intact hearths in a matrix of displaced hearth deposits (altered by trampling and/or raking out), this turned out to be exceedingly difficult. After excavating squares F11 through D13 this way (approximately 9 m^2), we decided to excavate the band of squares running from squares G14 to G11 (the bench) as a series of thin (~ 10 cm) vertical slices. This strategy was based on the fact that, in profile, we could clearly distinguish horizontal micro-stratigraphy including discrete lenses of ash that we assumed to be individual hearth features. Thus, the idea was to document the profile, define the strata, excavate accordingly, and then repeat on the next vertical slice. After excavating two slices, however, it was clear that this too was unsatisfactory. The microstratigraphy, locally expressed as very thin (1 cm thick or less) lenses of ash, would change dramatically between

Fig. 4 Photo of the east-facing profile of the Layer 8 bench in 2003 showing light (ashes) and dark layered residues of burning

slices: layers would come and go, with little or no horizontal continuity. Our conclusion was that the ash residues, resulting from what were originally multiple, spatially discrete fire features, had been syn-depositionally spread laterally across what was the ground surface at the time – perhaps a result of Neanderthal groups arriving on site and trampling exposed fire features left by previous groups. Whatever the cause, the result was that, while the imbrication of the remnants of ash lenses was the only truly visible component of features in profile, in plan view it was exceedingly difficult to spatially trace their lateral dispersion. As we were nearing the end of the Pech IV project in 2003, rather than remove what remained of the exposed bench of sediments with a loss of potentially important data on Neanderthal fire use, we decided to leave the deposit for a later time when, hopefully, a more effective excavation methodology would be available.

Thus, a decade after the close of the 2000–2003 project, Dibble, Sandgathe, Goldberg, and Aldeias began to consider returning to Pech IV to try to tackle the problem again. Part of the impetus for this renewed interest was the significant developments in specific types of analyses that had occurred over the decade. Most of the newly applied analytical methods that focus on invisible data coming from the sediments (geochemistry in particular) and a number of well-established methods (FTIR, thermoluminescence - TL, optically stimulated luminescence - OSL, archaeomagnetism) are particularly applicable to detecting and analyzing fire residues. While there are several types of combustion features (see Mallol et al., 2017), in general, a simple open fire might produce two distinct stratified components: (1) the upper component composed of ash, charcoal, and related residues of combustion (associated with an event or successive nested events), which are part of the depositional process and accumulated on what was the ground surface at the time, and (2) the volume of sediments (and any objects buried in them) directly beneath the combustion feature that were permanently altered by exposure to heat (Fig. 5). The upper component is typically a thin lens of combustion residues that occurs in varying degrees of preservation. The lower component occurs as a spherical cap whose dimensions are a product of the diameter of the fire feature, the temperatures reached, the duration of its use, and the nature of the sediments (Aldeias et al., 2016). Thus, while the upper component of a fire is associated with a specific depositional layer, the heat from the fire crosscuts multiple underlying layers. At Pech IV, while the upper component of most features had been syn-depositionally modified, as described above, it was clear that the lower components had not - that is, actions such as trampling act on an exposed surface, but do not entail the reworking of underlying buried deposits. From our previous work at the site (Dibble et al., 2009; Goldberg et al., 2012), it was clear that Layer 8 is primarily composed of laterally distinct microstrata, which indicates that there had been little, if any, vertical mixing of the deposits – the horizontal, bedded nature of the sediments would not have survived any serious vertical disturbance. Thus, any physical modification of the sediments was penecontemporaneous with its accumulation – i.e., occurring soon after deposition and limited to trampling of the ground surface – leaving the lower components of any fire features intact though perhaps not directly associated with a specific ash lens. We could be confident that Layer 8 contained intact lower components of a significant number of fire features, but to be able to identify such patterns we needed to obtain a wide range of higher resolution data from a large number of sampled features and sediments. We therefore set out to formulate an excavation methodology that could integrate the data from these methods in a way

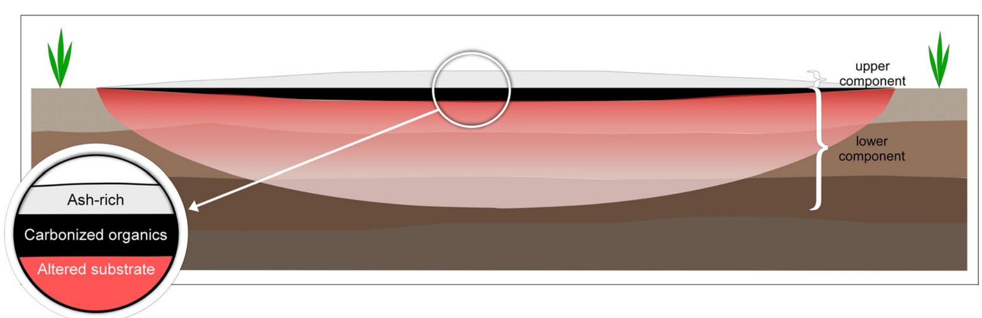

Fig. 5 Schematic illustrating the two main components of the remnants of a generic open fire feature: the upper component containing the remnants of combusted materials and the lower component comprising that portion of the substrate altered by heat conducted down beneath the fire feature in a spherical cap

that would allow the detection and analysis of fire-related patterning in the deposits.

A Novel Vial-Based Excavation Method

While the initial primary goal of our new methodology was to allow us to better observe and define fire features that we found difficult to isolate in the initial excavation, we also wanted to develop a system that allowed us to more effectively incorporate a range of analytical methods particularly useful for investigating fire residues. Besides traditional micromorphology, this includes sediment mineralogy (including infrared spectroscopy - FTIR, acid insoluble fraction - AIF, and total organic carbon - TOC), FTIR applied to lithics, single-grain OSL sensitivity analysis, lipid biomarkers, phytolith analysis, archaeomagnetism and magnetic properties, and the visual analysis of provenienced and small-finds bones and lithics for indications of exposure to heat. (A more detailed description of each of these analytical methods and their specific application here is included in the SI.)

The focus of investigation was the excavation of the bench of Layer 8 deposits that we left in place on top of the bedrock at the end of 2003. This bench was 2.5 m long, 70 cm wide, and, on average, 25 cm thick (Dibble et al., 2018). The basic strategy centered around the careful removal of ~ 10 cm-thick blocks from the end of this bench. Eleven blocks were removed; six were excavated in the lab, four (Bloc01 and then every third block: Bloc04, Bloc07, Bloc10) were 'geoblocks', which were destined for micromorphological and archeomagnetic analyses, and one block was retained as an archive (Fig. 6).

Fig. 6 Photo of bench with intended blocks superimposed and the cardinal directions of the site excavation grid

Extracting Blocks at the Site

In our situation at Pech IV, the removal of blocks was made relatively easy by the fact that we were dealing with a bench of sediments already exposed on three sides (the top, the north, and the east) and resting on bedrock. Basically, we simply had to 'slice' thin blocks off the east end of the bench like slices of bread from a loaf. However, it was, of course, imperative that the blocks were removed intact without disturbing the sediments. Some trial and error was required, but we quickly developed a reliable method that allowed us to remove one block in a day.

Prior to starting the removal process, a large number of digital photographs were taken. We made extensive use of structure from motion (SfM) to create georegistered 3D models of the profile and surrounding exposed sections and bedrock and to create a high-resolution orthogonal photo of the exposed profile of the block to be removed. These models were computed using Agisoft MetaShape Professional.

The first step of the removal process was to apply a layer of plaster of Paris bandages (the type used to stabilize broken bones) to the east profile of the bench to protect this exposed section and help stabilize it. Small clumps of plaster bandage were then used to fill in any obvious voids in the face of the profile in order to create as flat a face as possible. A piece of 6 mm plywood was cut to the shape of the east profile and applied on top of the initial layer of plaster bandage. More plaster bandage was then applied to secure the board to the profile (Figure7).

Next, a north-south line was lightly scribed on the surface of the sediments of the bench 10 cm in from (and parallel to) the east face – this marked the west edge of the block to be removed. A 15 cm-deep cut was made into the bench along the scribed line using a reciprocating saw with a diamond-coated, 1.5–2.0 mm thick blade, starting from the south and moving north and down the north profile. A second, parallel cut was then made two centimeters further in, creating a kerf

Fig. 7 Photo showing plaster bandage and plywood application to the exposed east face of the bench of sediments prior to block separation and removal

between the two cuts. The sediments in the kerf were then carefully removed. This was done with small made-to-purpose hand tools and a wet/dry vacuum. As the saw blade did not quite reach down to the bedrock, the bottom few centimeters of the kerf (the void created by the width of a blade when making a cut into something) were manually excavated. All the sediments recovered from kerfs during block removal were retained. At this point the block was physically separated from the rest of the bench, but remained stable as its base and south end was still connected to the sediments south of the bench and it was still resting securely on the bedrock. A layer of plaster bandage was then applied on the top and north face of the block and down into the kerf. This effectively covered the block on four of its six sides in a jacket of plaster bandages and held rigid by the plywood board (Figure 8).

Before any further work was done, six datum points (small X's in Fig. 9) were marked with a sharpie on the plywood-covered surface of the east face and on the top of the block. These points were recorded with a total station and given a label in the database that indicated both the number of that block and the number of each datum – e.g., 'BLOC07-DAT5' .

The west side of the kerf (what will be the face of the next block to be removed) was then lined with aluminum foil that extended down to the bedrock at the base of the kerf. Expanding polyurethane foam (commonly used in house construction for insulation and sealing gaps) was then injected into the kerf and left to expand and dry overnight (Fig. 10). Large rocks were piled against the plywood-covered east face of the block to prevent it being moved by the foam, which can exert significant pressure when expanding in a confined space (another reason why the datum points were recorded before this step). Care needed to be taken to prevent the foam from coming in contact with the sediments as there is the possibility that contamination from some modern materials could cause potential problems for the geochemical analysis (a lesson learned after the removal of the first few blocks and an example of the way in which both our field and laboratory methodologies were continually being improved through consultation with our various specialists). The layer of plaster bandages on the west face of the kerf protected the block being removed from coming into contact with the polyurethane and the layer of aluminum foil on the east face of the kerf protected the face of the next block.

The following morning, we carefully detached the block from the bedrock and from the deposits to the south through careful manual excavation. It was important to ensure that the block was completely separated on all three sides (west side, south side, and base) before attempting to move it, as even a very small point of connection could negatively impact the integrity of the block during the detachment process. When we were confident that that block was entirely disconnected, we carefully tipped it over onto its east face

Fig. 8 Photo showing use of a reciprocating saw with a diamond blade to cut the 2 cm-wide kerf separating the block from the rest of the bench

Fig. 9 Photo showing the plywood covered face of a block just prior to separation from the bench. Datums – X's – were drawn with a marker on the face and added to the site database with a total station before the block was removed. When the block was then set up in an excavation station in the lab, these datums were used to reestablish it in the site grid system

Fig. 10 Just prior to removal, expanding foam was injected into the kerf between the block and the bench and allowed to set overnight

(the side with the board attached to it). We then plastered the base and north ends and transported the block to the laboratory.

Extracting Geoblocks

While the general extraction methodology was the same, geoblocks were treated somewhat differently from the regular excavation blocks. Because a portion of them was to be used in archeomagnetic studies, they required an extra step. Prior to the final steps in detaching the block from the bench, we drew parallel vertical lines with a marker on the plaster and plywood-covered east face of the block creating a series of 11 columns, each ~5–6 cm wide. These would eventually be cut from the block as individual columns (see below). Half of these columns were intended for micromorphological thin sections, while every second column was intended for archeomagnetic analysis. The archeomagnetic analysis required that, before removal, each column be accurately and precisely oriented back in their original vertical and with magnetic north line. Thus, on the top of each, a small platform was created with a dab of plaster of Paris (Figs. 11 and 12). While still damp, the surface of the platform was flattened and made horizontal (inclination = 0º) using a bullseye level. When dry, magnetic north was measured with a magnetic compass and indicated on the surface of the platform with a marker.

At the Lab

In this section, we detail the operating procedures and strategies we employed in the project once the blocks were

Fig. 11 Photo of a block just separated from the bench, tipped over, ready to be transported to the lab. The expanding foam stays attached to the block to provide further support. Note the circular plaster discs on the left (top) side that were used in connection with the archaeomagnetic analyses

Fig. 12 Photo of a block being readied for transport from the site to the lab

successfully removed from the site and transported to the laboratory. These are summarized in a flowchart in Fig. 13.

Preparing a Block for Excavation

The blocks were excavated in what we call 'excavation stations' - we eventually had four of these set up in our laboratory (Figs. 14 and 15). Each station included a heavy wooden platform, 1 meter wide by 50 cm deep, attached to the lab countertop.

While still enclosed in plaster, the block was laid on the platform with the plywood-covered side up and foam-side down and with the top edge (what was the upper surface of the bench of Layer 8 deposits) facing the excavator and the bottom of the block (the end that was resting on bedrock) at the rear of the platform, adjacent to a microscribe (equipment used here for recording proveniencing data). The block was centered left-right on the platform and pushed back as close to the microscribe as possible. A wooden barrier, in the form of several small wooden blocks, was then fixed to the surface of the platform along the back and at the sides of the block - this barrier was placed to constrain the movement of the block. Expanding foam was then injected into the gaps between the barrier and the block of sediment. When this expanded and hardened, it prevented the block from moving (Figure 15).

Once the block was fixed in place and secured from moving, using the microscribe and the datum points marked on the plaster-covered block (before it was detached from the bench), the block coordinates were rotated in the computer so that they were back in the original site grid (see discussion below) and new datum points were established on the excavation station using Phillips screws- thereby allowing the ones drawn on the plaster-cover of the block

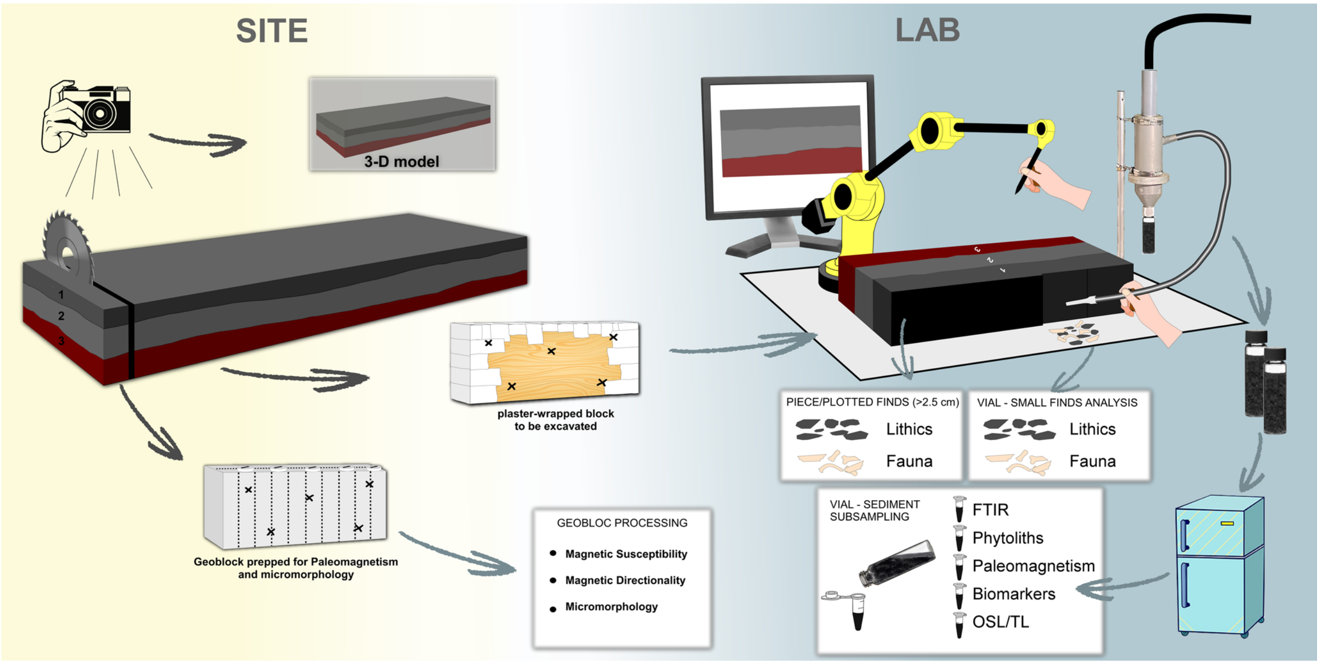

Fig. 13 Illustration laying out the methodological flow from the extraction of the blocks at the site, followed by the excavation of two of every three blocks in the lab, and the processing of every third block for micromorphological and archaeomagnetic analyses

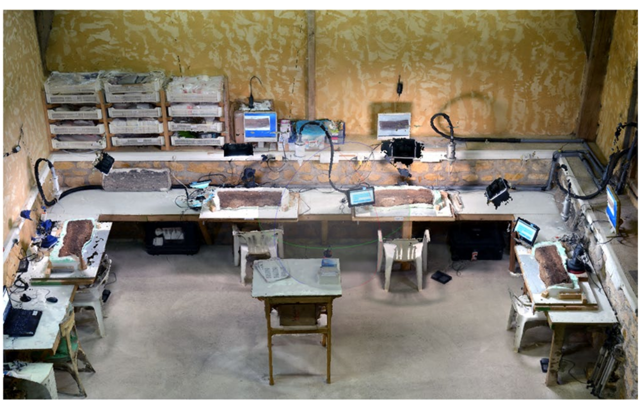

Fig. 14 Composite photo of the lab showing the four excavation stations with a block installed in each and prepared for excavation

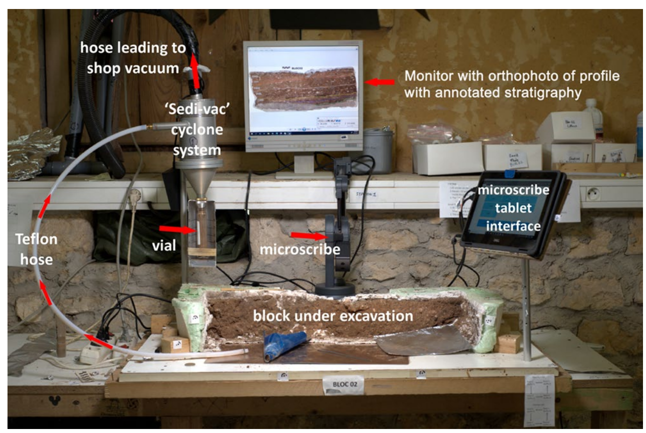

Fig. 15 Excavation station with a block almost completely excavated. The vacuum system with collection vial is to the left of center and microscribe at center. Note the touchscreen for data entry at the right and all the metallic and aluminum tools used to avoid plastic contamination. See the video in the SI of a block under excavation

to be removed when the block sediments were exposed for excavation. With these new lab datum points established in the original site grid, all subsequent points taken with the microscribe on that block would be recorded in the same grid system as all previous points taken during the previous excavation work at the site.

The block could now be prepared for excavation. The plaster bandages and plywood board were carefully removed exposing the upper surface and the front edge of the block. Layer 8 sediments are generally well consolidated, so very little loose sediment resulted from their transport, but the exposed surfaces were carefully cleaned of any loose sediments and plaster dust - the vacuum system worked well for this as its suction is not overly powerful and it provided an alternative to brushing and smearing sediments around on the exposed surfaces. The result was a fresh, clean view of the stratigraphy of the block. The microstratigraphy was then carefully examined and described in detail based on lithostratigraphic characteristics (color, composition, texture, nature of contacts, and fabric - see *Stratigraphic Descriptions* below).

Finally, the exposed profile was photographed, a high resolution SfM model was made, and an orthophoto was produced from this model. While this process duplicated what was already photographed in the field, we did note that it produced a superior result due to better controlled lighting. However, the field photos are still crucial as they show the block in its fuller context. This new lab-based orthophoto was then annotated with the microstrata descriptions that the excavator could refer to throughout the excavation process.

3D Proveniencing

A key aspect of the field recording system we designed and have used over the years is the use of a total station cabled to a field computer running self-authored software designed to efficiently collect provenience data (Dibble et al., 2018). These are merged with additional observations (e.g., layer, excavator, date, type of object, etc.) into an integrated database that is then added to the central database in the lab each night. To excavate blocks in the system described here, one possible solution was to simply set up a total station and data collection computer directly in the lab. This is, in fact, what many projects do that we are aware of, and it works rather well. However, we knew that we would be excavating several blocks at the same time (eventually we excavated four blocks simultaneously), and scaling this solution presented problems. Given space and personnel constraints, setting up a total station for each block was not feasible (see also Discussion). Alternatively, it might seem that one total station could be used to record the excavation of several blocks just as one station can be used to record several excavation units on site. However, unlike units in a site, the blocks removed from the site present the additional challenge that they are not all aligned in the same grid system once they are placed in the lab. An extra processing step (described below) is required to rotate each block from its lab coordinates back into the site grid coordinates, and each block will have its own specific rotation. Thus, if only one total station is used, the software will have to apply specific rotations keyed to the block name. We could imagine doing this in one pass at the end of the day once the data were collected. However, modifying our existing data collection program to do this in real-time (i.e., as each artifact is recorded) seemed overly complex and prone to errors. Additionally, without real-time correction, the coordinates provided by the total station during excavation would be essentially useless for observing how the excavation was progressing and also extremely difficult to error check. Thus, we very much wanted each block to have its own recording system with real-time coordinate rotation.

The solution we settled on was to adapt microscribe 3D digitizers to our purposes. Microscribes are table-top devices that consist of a set of rotating joints and arms that terminate in a stylus that comes to a fine tip. On initiation, the device creates a 3D grid and is able to precisely track the location of the tip as it is rotated. A foot pedal is attached to the microscribe, and when depressed it transmits the X, Y, and Z coordinates of the stylus tip in plain ASCII text across a USB interface. The precision of microscribe devices varies, but all are sub-millimeter, which is more precise than a total station and more precise than, in our judgment, what we need in archaeological excavation. Thus, a microscribe was fixed at the center of the back edge of each excavation station platform with a reach that covered the entire block.

Rotating the Grid

As stated above, it was critical to the project that the blocks excavated in the lab be placed into the excavation grid for the site, and we wanted to be able to do this in real time. Our solution to this problem was as follows. As described above, at the site, once the block was plastered and ready for removal, datums were marked on it and recorded with a total station aligned with the site grid. Then, when the block was securely fixed in place in the excavation station, we placed additional datums (at least four) on the wooden barrier using Phillips screws. Next, we initialized the data collection software (see below) and the microscribe. In the initialization, the operator tells the program which datums on the wooden board will be recorded along with their site coordinates. These datums are then recorded with the microscribe, which provides a new set of coordinates in the local grid that it establishes. The program then calculates the rotation required to place these local coordinates into the site grid coordinates. Once this is done, we recorded a fourth verification datum to assess the error. If the error was unacceptable, we started again with a different set of the datums marked on the block. Once the error was acceptable (< 3–4 mm in the sum of the X, Y, and Z error in most cases, otherwise we used the lowest error we could achieve), we then recorded the new, additional datums on the wooden barrier mentioned above. These points are then immediately rotated into the site grid and saved. Finally, we restart the initialization process but this time we use only the new datums on the wooden barrier and not the ones on the block itself. Three points are required for the setup itself (to compute the rotation) and a fourth point is again used to verify. Only if the error is acceptable (< 1–2 mm in the sum of the X, Y and Z error) did we then open each block by removing the plaster and board with the datums recorded on site. Once this board is removed if the new datums move or are lost the spatial association of this block with the original site grid is lost.

To accomplish the initialization step just described and to record points throughout the excavation of the blocks, we developed a new piece of software (EDMpy) that replaced the functionality of our previous field programs (EDMWin and EDM-Mobile). This program, which is available at https://github.com/surf3s/EDM, handles the tasks of:

- initializing the microscribe into the site grid (i.e., calculating the rotation),
- recording points to obtain the X, Y, and Z coordinates from the microscribe,
- adding additional observations to these points (e.g., layer, excavator, type of object, etc.),
- error checking and editing, and
- exporting data.

The data are exported in JSON or CSV formats and then transferred to a cloud-hosted main database where they are integrated with the rest of the spatial and analytical data from Pech de l'Azé IV. The latter includes all the points recorded by Bordes between 1970 and 1977 (Bordes, 1975) and all the points from our 2000–2003 excavation (Dibble et al., 2018).

Processing the Geoblocks

As explained above, four blocks were collected specifically for archaeomagnetic and micromorphological analysis. During the removal process these had lines drawn on them dividing them into columns. Once in the laboratory, the columns were cut from these blocks using an angle grinder with a rock-cutting blade (Figs. 16 , 17 and 18, and each of these smaller columns were then replastered to stabilize them. These columns were ~5 wide and ~5 cm thick, which meant that, after they were removed from the geoblock, the remaining intact slab was also ~5 cm thick. The five columns with the plaster platforms on top (Fig. 18) were sent to one of us (AC) for magnetic measurements (e.g., ferromagnetic mineralogical experiments, magnetic susceptibility – MS).

Fig. 16 Using an angle grinder with a diamond blade to cut blocks into columns

The other columns were impregnated and used to produce thin sections for micromorphology. These were simply cut into ~1–2 cm-thick 'chips' which could then be processed into thin sections. After the removal of all the columns, the remaining block was then impregnated with resin and sliced longitudinally producing two large slabs of the entire stratigraphy. One of these impregnated slabs was then used for the production of further thin sections that could be tied back into the site grid with greater precision. To do this: first, rectangles were drawn on the face of the slab indicating the desired locations of individual thin sections. Then, three small holes were drilled within these rectangles spaced out from each other. The slab was then fixed into an excavation station, its position established in the site grid, and the location of each drill hole recorded with the microscribe. These holes were visible in the resulting thin sections and served as reference points for georeferencing, in grid space, the context and location of any specific observations, objects, or features noted in the thin section. Therefore, for micromorphological analysis, thin sections were then created from two portions of the geoblocks: a) the impregnated columns and b) the ¼ slabs (see Figs. 18 and 19).

The impregnated slabs were ground flat and polished slightly with 600 grit paper (Fig. 19). Observation at this scale provided the larger context to observe variations across the entire block at a time. Thin section scans (Arpin et al., 2002) represented a continuation of the block observations, revealing overall compositional characteristics, but particularly how the components were arranged geometrically across the thin section, the *fabric.* This large area approach was complemented by observation of the thin sections with a stereo microscope employing plane polarized light (PPL) and crossed polarized light (XPL) and magnifications of ~10 x to 40 x. Specific microscopic features not visible or evident with the above were elucidated with the petrographic microscope, at ~20 x to 200 x magnification.

Definition of Stratigraphic Subdivisions During Excavation

To provide a basic, operational stratigraphic framework for the excavators, we first described and characterized the stratigraphic units that were visible in the excavation blocks. Microstratigraphic units were independently defined for each block without reference to other blocks. Attempts at correlations between blocks were made after all blocks were described, noting that even for a given stratum, there was a notable degree of lateral variability from one side of the block to the other and from block to block.

Overall, the stratigraphy was conceptualized using lithostratigraphic attributes. Criteria included color, composition, texture and grain shape, stratification, the nature of contacts (e.g., sharp vs. gradual; flat vs. undulating/wavy,

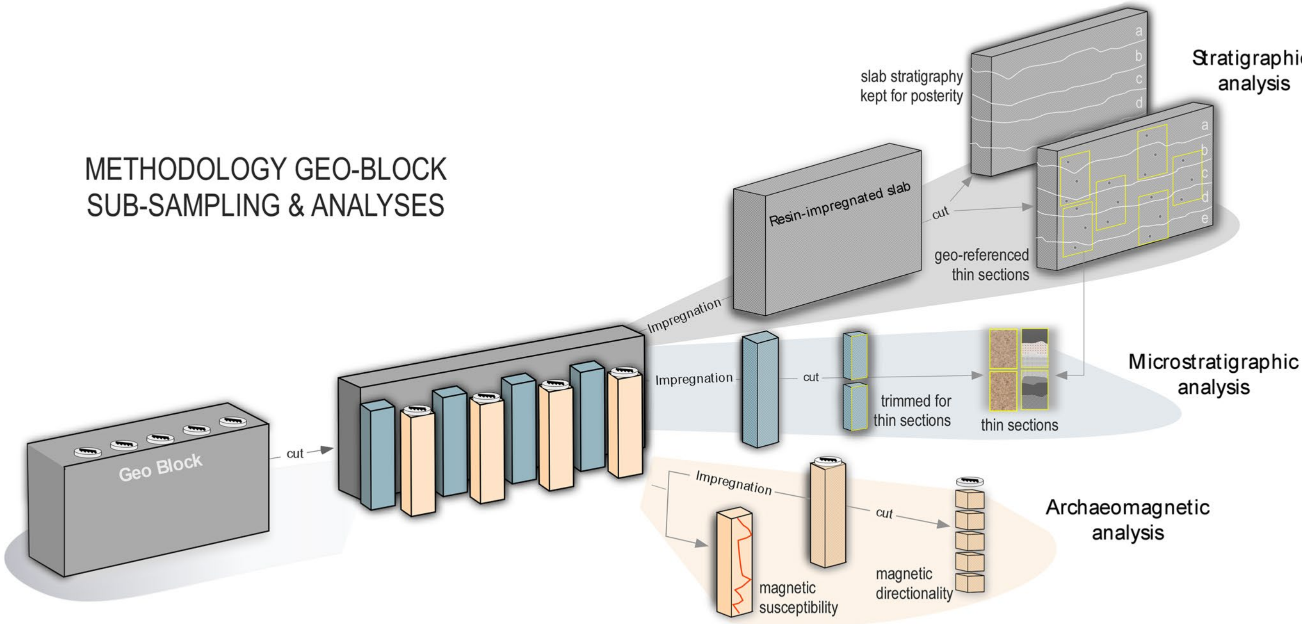

Fig. 17 Illustration laying out the steps in the processing of each geo-block into its four main products: a 2.5 cm thick impregnated slab (retained as a reference section); and 2.5 cm thick impregnated slab that is cut into thin sections; a series of 5 × 5 cm columns that are also impregnated and turned into thin sections; and a series of 5 × 5 cm columns that are used for archaeomagnetic and rock-magnetic analysis (magnetic susceptibility and magnetic directionality)

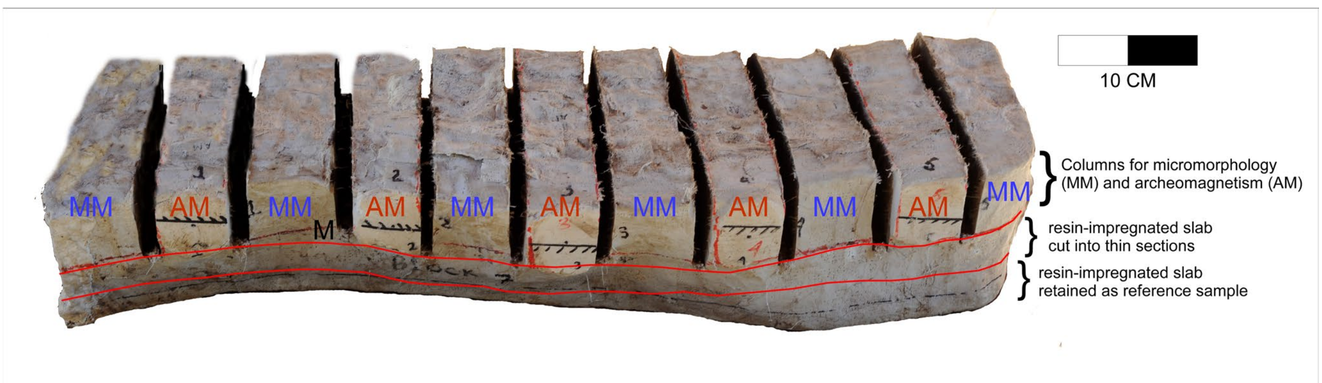

Fig. 18 Photo showing the processing of each geoblock into archaeomagnetism, micromorphological, and reference portions. The eleven columns isolated in the photo were subsequently removed from the slab portion and individually wrapped in plaster bandage

Fig. 19 A photo of an intact, resin-impregnated, 5 cm-thick slab with a clean profile. This slab was subsequently cut in half longitudinally and vertically: one half was then cut into thin sections and the other kept as a reference. Width of the block is ~70 cm

etc.), and fabric. The nomenclature for each stratigraphic unit followed a standardized hierarchical subdivision and consisted of a series of upper- and lower-case letters and numerals as shown below. The main unit is the block number, followed by the main microstratigraphic subdivision represented by sequential numerals assigned from top to bottom. The main color of the layer is assigned next using uppercase two letter codes, where BR stands for brown and BL for black, for example. In several instances, distinct domains having slightly different characteristics occurred within a layer, and these were denoted by using lowercase letters (e.g., w for white, bl for black, etc.). If more than one of such domains occurred within a layer, numerals were then used to distinguish them. An example of this standardized nomenclature is shown in Table 1.

We note, however, that this strategy was not entirely satisfactory because color, for example, is likely (at least) a partial result of post-depositional (diagenetic) overprinting, as we observed that color boundaries do not always coincide with textural ones (see Fig. 20). Therefore, although we relied heavily on color as a main attribute, we also paid close attention to other characteristics such as clast lithologies and shapes, and bedding.

Systematic recording of each microstratigraphic subdivision was done with the aid of the program E5 (https://github.com/surf3s/E5), which we set up to systematically record lithostratigraphic data for each microstratigraphic subdivision within each block; these data were exported as CSV files and merged into the main database. In this way, we could link all of the collected sediment to its stratigraphic description, and we can ask the database for sediment vials that match certain sedimentary descriptions.

Table 1 The descriptive nomenclature used to create identifiers for each microfacies in the stratigraphy of each block

Block #	Stratum ID	Main color	Domain color/character	Domain #
BLOC02	01	BR	w	2
	numeral	*uppercase*	*lowercase*	*numeral*

Despite the above comments, these stratigraphic designations were instrumental in guiding the excavators. The team geoarchaeologists (PG and VA) not only continually consulted with them during and after each stratigraphic unit was excavated, but we also interviewed the excavator(s) and took notes about their observations of each unit, and ultimately, we included their observations in the systematic recording of the data with E5.

Finally, we point out that during the excavation of a block, the stratigraphic limits of specific units were modified, as needed, to reflect new stratigraphic data obtained as the excavation progressed. For example, a layer may be thicker on the exposed face of a block, but thin out at the back of a block, or its limits might become more – or less – distinct. These distinctions, which were otherwise very difficult to see when we originally tried to excavate slices in the field, were noted in E5 during the interview with the excavator when they completed the removal of a stratigraphic unit.

Photogrammetry

We complemented standard digital photography with extensive use of structure from motion (SfM) – a photogrammetry method used for creating 3D models from photos of an object or landscape (Douglass et al., 2015; Magnani et al., 2020). Using the Agisoft Metashape Professional Edition (2022), we first made 3D models of each block in the field before it was plastered and removed from the site, and a second model after the block had been transferred and cleaned in the lab prior to excavation, with more stable and consistent lighting conditions. For each block that was excavated, we also made 3D models of the surface of each microstratigraphic unit so that individual surfaces spanning multiple blocks could be reconstructed.

All of the SfM models of the blocks were integrated into the original Pech IV site grid via georegistration of the models. To achieve this, prior to taking photos of each block that was to be removed from the site, we set up the site grid using the datums from the 2000–2003 excavation (Dibble et al., 2018), and then recorded six to seven new datums (labeled

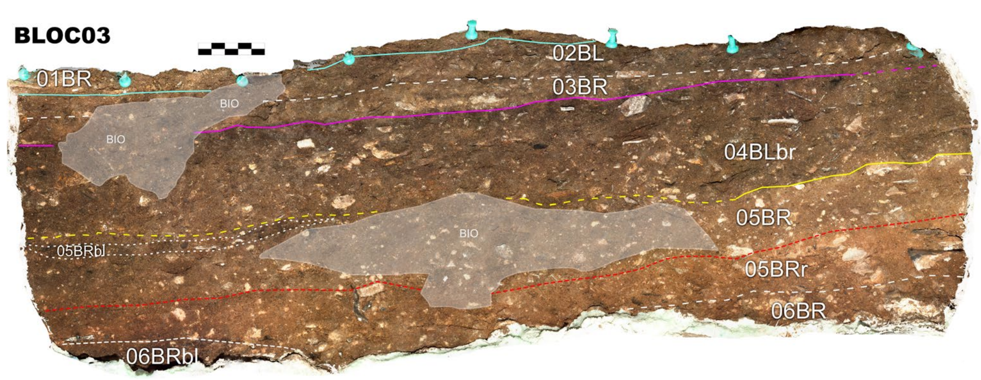

Fig. 20 Bloc03 with its stratigraphic subdivisions (BIO = bioturbated)

by the default system markers provided by Metashape Pro) for each of the blocks that was to be removed from the site. We made sure all new datums were visible in the photos used to create the block models on the site. After creating the 3D site model of the block, we used Metashape's Detect Markers function to identify the datums associated with the block and enter their coordinates, which allowed us to put the block back into the Pech IV site grid. After the blocks were plastered, we recorded an additional six datums on the plastered side of the block (Fig. 9), which would be used to set up a Pech IV site grid after the block was transported back to the lab for excavation.

Excavation Methodology

Each excavation station (Fig. 15 and see the video in the SI of a block under excavation) was equipped with one microscribe, a touchscreen computer and a cyclone vacuum system with a collection vial that captured all of the excavated sediments. To avoid plastic contaminations, the table surface in front of the excavator was covered with an aluminium plate and all the excavation tools were metal. Here, we describe all the steps involved in excavating a block with our new vial-based microstratigraphic approach.

Although each block, and thus the stratigraphic sequence, was tipped on its side, excavation was still carried out in the normal manner in that sediments were removed following the stratigraphic sequence from more recent layers to older layers. The difference was that, rather than working vertically from top to bottom, the excavator was working laterally from front to back. Sediments were removed in discrete $10 \times 10 \times 0.5$ cm (50 ml) volumes working across the uppermost sediments on the 'front' of the block and following the micro-stratigraphy. Note that the depth of each volume varied as the stopping point was set by the vial volume rather than excavation depth. Also, note that no vials crossed stratigraphic boundaries. When a vial ended early (a stratigraphic break is encountered before the vial is filled), its estimated final volume was noted in the database.

The actual removal of the sediments was carried out wearing nitrile gloves and using a combination of small, metal pointed tools and a Teflon (Polytetrafluoroethylene - PFTE) vacuum hose. As the sediments were loosened, they were suctioned up with the vacuum hose attached to a cyclone vacuum system (see the SI for a detailed description) developed for this specific application. The sediments pass through the cyclone system and are deposited directly into a 50 ml glass vial. Each $10 \times 10 \times 0.5$ cm volume, corresponding to a full 50 ml vial, was provenienced with the microscribe with eight points: four points describing the corners of the 10×10 cm area before excavation began and the four corners at the base of the volume after it was removed. Once the vial is finished (is full or a stratigraphic break is encountered), the vial is closed with a piece of aluminum preventing the sediments from touching the plastic cap, a label is attached with a unique identifying number and provenience information, and a new vial is attached to the vacuum system, ready for the next volume. The tip of the vacuum hose was fitted with a nozzle with an interior diameter of 7 mm (one of the standard dimensions PTFE hose comes in), thus, all objects (limestone fragments, bone, lithics, minerals) ≤ 7 mm in maximum dimension end up in the glass vial. All objects > 7 but < 25 mm ('small finds') were bulk provenienced with the X, Y, and Z coordinates of the $10 \times 10 \times 0.5$ cm volume they occurred in, and all objects ≥ 25 mm were individually provenienced and each given their own bag and label (any notable fragments of charcoal, regardless of size, were also individually provenienced and all objects were wrapped in aluminum foil before being placed in plastic bags). The 25 mm cutoff between 'small finds' and larger finds corresponds to the cutoff size used previously at Pech IV (and in other excavations we have done in the area). For each vial, a tiny quantity of very fine sediments would pass through the cyclone system into the wet/dry vacuum (rather than being deposited in the glass vial). To prevent the loss of this very fine fraction, a gauze filter was inserted between the cyclone and wet/dry vacuum. This was retained and stored with each vial and replaced with a new gauze for the next vial (excavators averaged 11 vials per day for each excavation station). When the excavation surface reached a contact between microfacies, a series of topographic points were taken along with a series of photos from which a SfM 3D model of that surface was made.

We were aware from the start of the development of the methodology that potential cross contamination between samples could be an issue. While all the vials were sterilized *en masse* before use, optimally, the whole system would be sterilized between each vial sample to prevent any cross contamination. However, this would add so much extra time to the process that it would make it generally untenable. Thus, we did accept that some cross contamination would be occurring, but our expectation is that this would be limited and would mainly be between adjacent vial samples which represent immediately adjacent sediments within an individual microstratum. For our project goals we did not see this as particularly problematic (though we appreciate that it could be more of an issue for other projects depending on their goals). However, we did attempt to limit the amount of cross contamination with several specific measures. The interior of the cyclone cylinder was manufactured so as to have no features or surfaces where sediments could accumulate. Also, it was made of anodized aluminum and given a powder coat finish that provided a semi-vitrified surface that substantially limited the potential for particles to adhere to it. After filling a vial (and prior to a new vial being installed), the vacuum was run and the vacuum cylinder and hose were vigorously tapped with a metal tool to dislodge any accumulated sediments. As it was, it became apparent very early in the use of the vacuum system that the tip of the hose was where the build-up of sediments was most likely to occur and so the vacuum hose was fitted with a removable Teflon nozzle. Before starting a new vial, the tip of the Teflon nozzle was dipped in an acetone bath (90%; repeating 3–4 times and allowed to dry) and surfaces and tools were sterilized. The nozzle was also replaced with a sterilized one at the start of each new microfacies. Another measure that we did not use, but might in future applications, is running a quantity of fine silica sand through the system between vials to gently scour the interior of the entire system (as it was, when the cyclone cylinders were taken apart at the end of a season there was no visible accumulation of sediments inside).

Microstratigraphic/Micromorphological Analysis Using Impregnated Blocks and Thin Sections

In a previous section ("Definition of Stratigraphic subdivisions during excavation"), we outlined the strategies for working with major stratigraphic details visible in the blocks *during the excavation*. Many more and significant stratigraphic details become visible with close observation of the deposits within impregnated blocks and thin sections.

Observation of the uncut impregnated slabs provided the larger context to observe variations across the entire block thus providing a 'bridge' between the stratigraphy of the unconsolidated sediments visible during excavation (described above) and that revealed in the impregnated blocks (Fig. 19).

The analysis of the thin section scans then provided a meso-scale observation of the deposits. The scans revealed overall compositional characteristics, and particularly how the components were arranged geometrically across the thin section, the *fabric*. This approach was complemented by observation of the thin sections with stereo and petrographic microscopes, which allowed us to better characterize mineralogy and overall composition of the deposits, as well as micro-scaled features that are unobservable with the naked eye.

Observations made at these different scales are iterative and foster a more inclusive understanding of the microstratigraphy and its vertical and lateral variability rather than relying on a single scale (Figure 21).

Using observations of the blocks and thin sections, we first sought to divide the entire stratigraphic sequence encompassed in each block into three major generalized stratigraphic groups, which we called Groups: I, II, and III, (from bottom to top) (Table 1). These Groups help to characterize the broad differences within each block and also highlight the similarities from one block to another. Defining the micro layering in Groups II and III is relatively

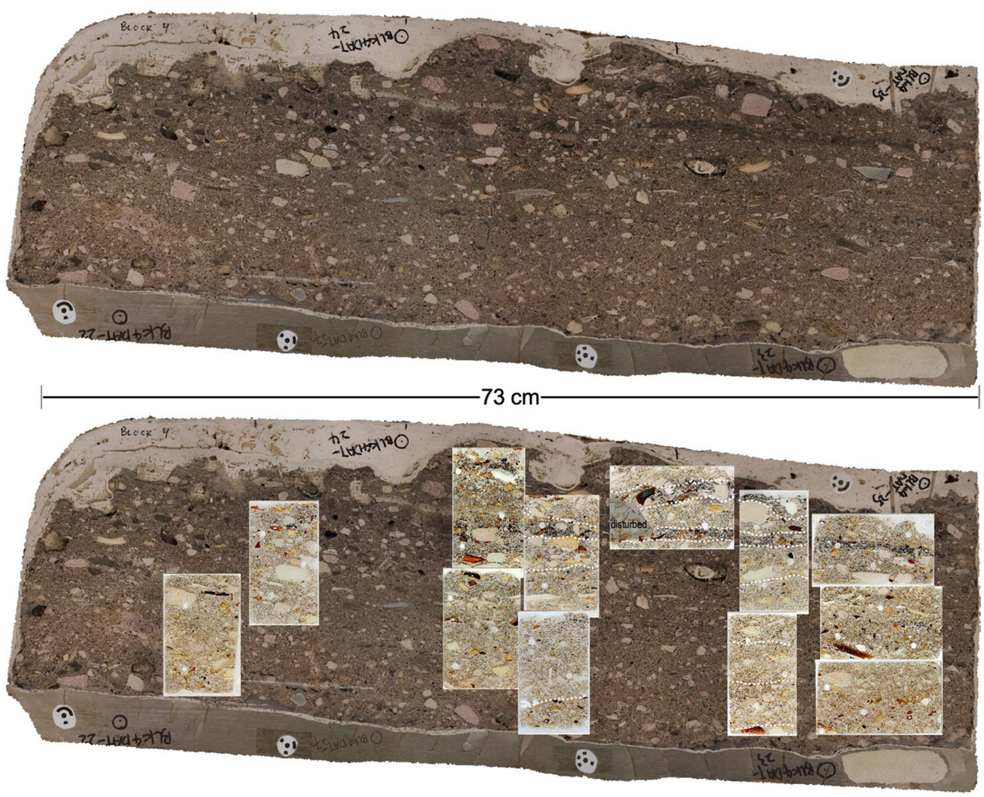

Fig. 21 Orthophotographs of the impregnated slab from Bloc04 without the superimposed thin sections (**a**) and with the georeferenced thin sections showing the lateral and diachronic change of microfacies (**b**)

straightforward due to the clear lithological differences and the sharp nature of the contacts (Fig. 22). On the other hand, in the lower deposits of Group I and lower microunits of Group II, the contacts are diffuse, often gradual, and mainly perceptible as stone lines. At a broader scale, the differences are more muted, and with less organic matter content in the deposits closer to the cave's interior (Table 2).

Discussion

Microstratigraphic Vial Excavation: Advantages and Disadvantages

The methodology we have outlined here could be developed for any on-site excavation, either in its totality or parts of it adapted for specific needs (e.g., just collecting samples using the cyclone vacuum-system, which is something one of the authors is currently experimenting with to collect samples directly from a feature exposed at a site.). However, such a detailed methodology targeting all the sediments might not be practicable for removing large volumes of deposits. Nevertheless, it is both practical and practicable for relatively small volumes of sediment (in our case we removed approximately a quarter of a cubic meter in total), which opens up the potential for laboratory-based excavation. If relatively large, intact blocks of sediment can be removed to the laboratory for excavation, there are a number of analytical and logistical advantages that come into play. It facilitates the use of a wider range of methods, it allows much more control over the conditions under which the digging and sample-taking take place and allows a more systematic and contamination-controlled approach.

The analytical advantages include much more control over lighting, with improved visibility (often a major issue in cave excavations) and the ability to employ a range of types of light, which can often allow better detection of microstratigraphic changes and improves the conditions for photography. Working in the closed conditions of the lab isolates the sediments being excavated from potential

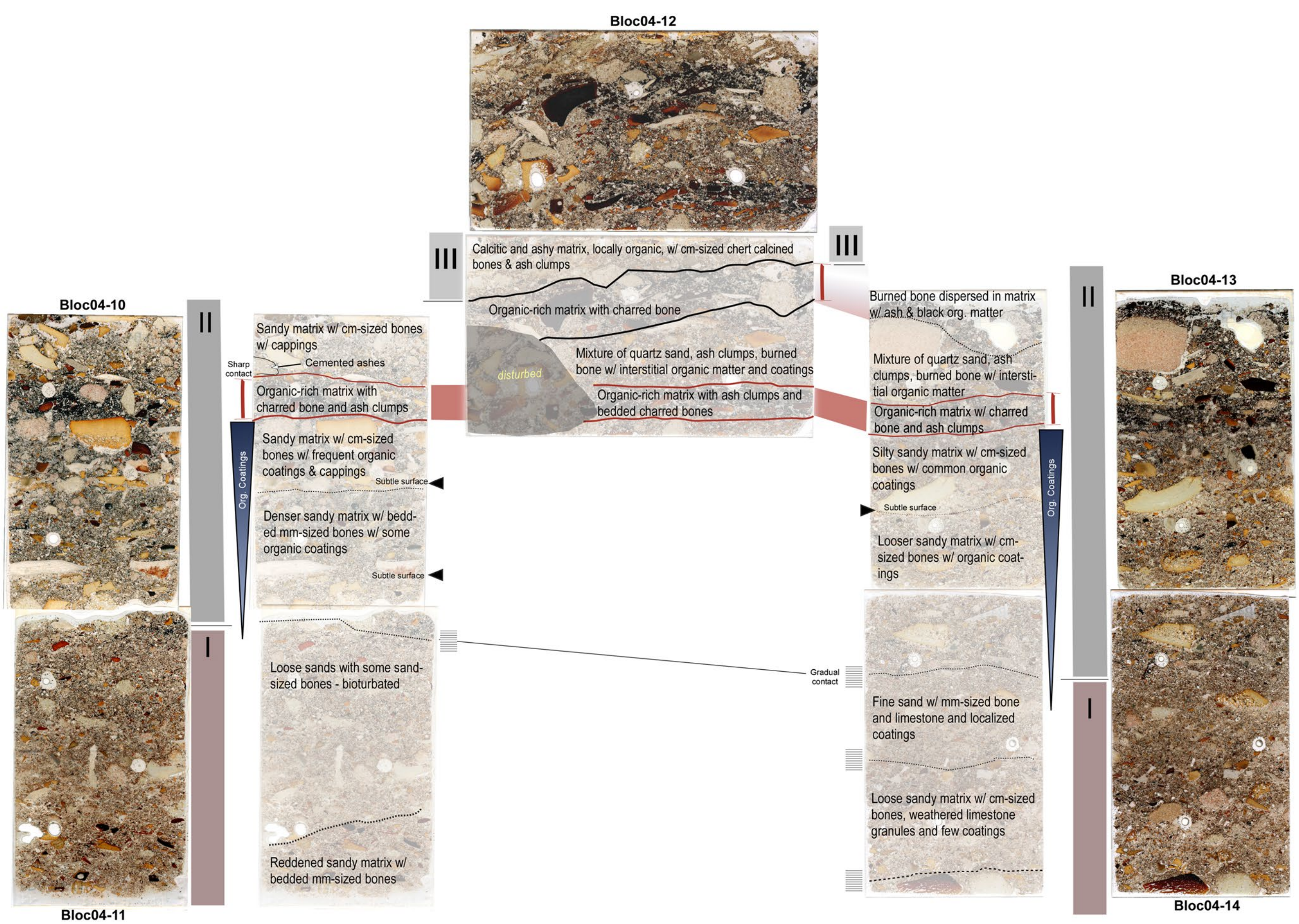

Fig. 22 Detailed microstratigraphic analysis of selected thin sections shown in Fig. 21, where annotations depict the main characteristics of the deposits, alongside the nature of contacts (sharp or gradual) and the incorporation of the microstratigraphic groups (coloured boxes). Each thin section is 7.5 × 5 cm in size. Note the lateral variability of the deposits, even at this scale of spatially adjacent thin sections. (See SI-2 Fig. 1 - a pdf that can be enlarged to examine at higher resolution the details and accompanying notations of the thin sections)

Table 2 Summary description of the general microstratigraphy comprising three major Groups; it is based mostly on examination of the polished indurated slabs, supplemented with some thin section observations. Details of the micromorphological analysis are presented in the two SI documents

Group	Description
I	These basal sediments rest on bedrock and comprise discontinuous beds of burned and unburned bones, flints, and mm-sized limestone clasts in generally massive, compact, moderately sorted reddish brown silty sands. Limestone granules are generally weathered, white and red. This ensemble is mostly red, and the color appears in part to be a diagenetic iron overprinting since the upper color limit of the Group crosscuts internal stratification of the limestone clasts. Moreover, it grades laterally and vertically into the darker, more organic-rich sediments of Group II (see below). Locally, coarse, relatively 'clean' quartzitic sandy domains occur under larger (~2–4 cm) clasts of bones, lithics, and limestone; these domains appear to be more frequent and well developed in comparison to those of Group II.
II	Group II is the middle unit in Layer 8 and is characterized as a dark brown and black, organic-rich tabular to lenticular (locally) greasy, massive and homogeneous, brownish black to black moderately to poorly sorted silty sand. Few mainly rounded to sub-rounded finer (< 1 cm) limestone clasts are heterogeneous in size, with common granules and clasts that are generally horizontally bedded; in some blocs there are lenticular concretions of limestone clasts, bone and flints. Bones, which are crumbly and splintered, are generally burned but some are not. There are some domains of dark brown mottling and fine (~5–10 mm) lenses of darker black material. Calcite cementation is localized. As in Group I, domains of coarse sand occur mainly under larger objects (flint and bones), and there are localized areas that exhibit higher abundance of bedded coarse elements (flints and bones). Some trampling is evidenced by broken/semi-articulated (snapped) bones. Groups I and II grade into each other both vertically and laterally. The interfingering contact with Group III is linear, wavy, and irregular, ranging from gradual to sharp. Its upper boundary is placed at the top of the first dark band/layer in Group III, usually at the contact between the "01" and "02" layers. At or near the boundary between Groups II and III are some well-defined black layers with sharp contacts.
III	Group III is the uppermost layer and is the richest in ashes and ashy sediments. It is characterized as a massive and homogeneous, generally crumbly, weakly to strongly cemented, light yellowish brown, moderately sorted ash and ashy silty sand, with burned bone, and rare angular limestone clasts. Common in the blocks more to the south are lenses of ash and ashy silts ~ 1–1.5 cm thick that vary in lateral extent from ~ 2 to ~ 10 cm.

sources of disturbance and cross-contamination that exist in the context of site excavation: the movement of people that can result in the trampling of deposits and the general mobilization of loose sediments across the site from both human activities and natural processes (wind and rain). It is also easier to keep the immediate work area clean during the actual collection of the sediments and, unlike in typical site excavation, this does not involve sweeping or scraping loose sediments across the intact sediments of the excavation surface. Excavating sediments in block form means that, prior to actual digging, one has multiple views of the stratigraphy - up to four different views provided by the four sides of a block - and removing multiple, adjacent blocks at the same time has the added advantage of allowing one to observe the nature of the stratigraphy (and potential horizontal and vertical changes) across the site before any actual excavation occurs. In regular site excavation, the excavator typically has either no preview of the stratigraphy (as when digging into deposits with no existing profiles) or has just a single stratigraphic profile that they might be pushing back.

There are also several major logistical advantages. Laboratory excavation can provide improved ergonomics: the actual digging can be carried out sitting in a chair at a lab table with the work surface at a comfortable level. This reduces the discomfort that comes with the hard, irregular topography and awkward body positioning often associated with excavating at an archaeological site and this, in turn, can increase the speed of excavation and, in fact, make it easier for the excavator to maintain a higher level of care and attention. The method can increase the speed of the excavation in other ways as well. For example, if (as in our case) multiple, adjacent blocks are collected, they can be excavated at the same time. It is the case that in traditional excavations multiple, adjacent units can be excavated at the same time, but not with the advantage of having multiple views of the stratigraphy as outlined above.

We think another major advantage of removing sediment blocks to a lab is that it untethers the excavation portion of a project from the scheduling limitations that are typically part of doing fieldwork. Ordinarily - due to financial limitations, conflicting schedules of individual team members, and weather conditions - field projects have a fairly narrow window of time (in academic work, usually a few weeks in the summer months) and, thus, need to get as much work done as quickly as possible during each season. Removing the blocks from the site takes very few people and very little time. Once the blocks are in the lab, it is unlikely that there will be the same pressure to excavate them as quickly or within a set period of time and the excavation schedule will not be limited by weather conditions. This may be particularly useful for time-sensitive excavations, for example, when sites are being impacted by development.

There are some potential disadvantages that should be noted. Cutting blocks from the deposits requires the creation of kerfs which can result in the loss of some sediments and potential data. In our case we needed to create three kerfs to remove each block (one separating each block from the bench, one at the base, and a small one at the south end of each block), and each was ~1.5–2.0 cm wide. This produced 4.0–5.0 L of loose sediment per block (an intact block was approximately 15 L in volume). While the preference will likely be to avoid producing any loose sediments, in our case, we retained all the kerf sediments for a number of analytical purposes including flotation for anthracological analysis.

It is also the case that linking the stratigraphy in the block back to the stratigraphy of the site might be a difficult process. This could be a particularly significant problem in the case of more complex features; for example, in the excavation of burials or the excavation of complex urban deposits such as tells. We also appreciate that there are some types of sediment that simply do not lend themselves well to being removed in block form - unconsolidated or poorly consolidated sediments like sand or shell middens or sediments with significant concentrations of large rocks. Furthermore, even in contexts where the sediments are relatively easily removed in block form, transporting them will also involve a certain degree of risk that they will be damaged in the process.

However, in our case, we believed that the potential advantages of laboratory excavation heavily outweighed the potential disadvantages, and this led us to develop a methodology for removing and safely transporting blocks of sediment from the site to our laboratory, a distance of 3 km (this process is discussed in more detail in the SI).

As we developed the methodology, we consistently ran into what, for us, were novel methodological challenges that we had to find solutions for. Some of these stemmed from the focus on sediment-based analyses and others were more logistical problems that come with excavating blocks in the laboratory and are not common in typical on-site excavation.

The Role of Micromorphology in the Excavation Process

Defining the microfacies in each block was obviously an important component of the project. However, this had to rely entirely on observations made of the sediments and stratigraphy of the blocks themselves and discussions between the geoarchaeologists and excavators as they progressed through each block. We were not able to rely on thin sections as references in defining and describing microfacies as we did not have access to these until after the excavation was completed. While this may be a relatively common situation in traditional excavations, in the future, for excavation methods like this, we would try to include in the project design access to thin sections earlier in the process.

Electrical Shock

One of the surprising methodological challenges we encountered was the risk of shock from static electricity. When a column of air is pulled through a plastic or Teflon hose, a static electrical charge is created. As a result, a large electrical charge bnltullui up very quickly (in a few minutes only) in the setup, and its discharge through the hands of the excavators was painful. This charge passed through the nitrile gloves. Initially we tried grounding the excavators and grounding the outside of the hose. After some research, we realized that the Teflon hoses we used are very poor conductors, and so the charge remained confined in the interior of the hose. The solution was to pass a very fine gauge bare copper wire through the length of the hose and ground this to the water pipes of the lab. Once we took this step, the electrical shocks were no longer an issue.

Proveniencing with a Microscribe

Considering the large quantity of samples being collected from each block (250–300 vials) as well as any lithics and fauna of a minimum size to be individually provenienced, this approach required a proveniencing method that is very precise and also quick and efficient to use in a confined space. Microscribes solved our main proveniencing issue - mainly that each excavator needed their own dedicated system that allowed them to quickly provenience and remove items during excavation in their closely confined work area without having to deal with the bottleneck often associated with multiple excavators sharing a single total station. However, microscribes do come with issues of their own: they are expensive and generally work on out-dated software. In our case, we were able to buy one reconditioned microscribe and borrow four others to have five available in our lab. We needed five because we were excavating four blocks at the same time and if one microscribe failed we had to have a backup. Microscribes also limit the size of the block that can be easily excavated because of their limited reach.

We see two solutions to this. First, if just a single large block is the focus of the excavation, then a total station could be used for proveniencing. Excavations of large Neolithic wells that take place year-round in facilities near Leipzig, Germany, work like this (Tegel et al., 2012). Second, more than one microscribe could be attached to the excavation of a single block. In this case, two separate computers would be needed to keep track of the coordinate systems of each microscribe. Third, and we consider this by far the least desirable option, a microscribe could be shifted into multiple locations around a single block as needed. Perhaps this would work if one were, for instance, sectioning a feature such as a burial or hearth into two halves and excavating one after the other. However, if shifting the microscribe has to occur more frequently so that a block can be excavated in one piece, then the overhead and danger risks of moving and reinitializing the station seem to us overly risky in terms of both the equipment and the possibility for errors.

Standardized Sampling

A core component of the methodology was collecting and managing samples for a range of types of analyses. However, we quickly realized that our overall procedure would have to take into account all the protocols associated with each analytical specialization. We saw this as being especially important as we wanted every sample taken to be potentially usable by any analyst. We did not want to be collecting unique samples for each potential analyst such that protocols would change from sample to sample so that some samples were usable by some analysts and not by others. Some types of analyses, phytoliths for example, require few specific considerations in the collection of samples and were relatively easily accommodated in designing the methodology. Others, however, required very specific protocols and considerations - some that we only became aware of as the project progressed. Also, because of the potential to recover aDNA from the sediments and because magnetism is temperature-sensitive, we needed to avoid exposing them to high temperatures so, once they were extracted from the excavation surface into vials, the vials were stored in a refrigerator. The collection of a large number of samples does raise the issue of sample storage. In our case, arrangements were made for the samples to be stored in a refrigerator and monitored throughout the year.

Deciding on the 50 ml size of the individual samples was also the result of a discussion among our various specialists who had varying requirements for sample sizes. Obviously in some respects having more, and thus smaller, samples is better as it represents increased spatial resolution in the resulting data. However, it also means increased time and effort in the collection (excavation) process. It would be easier and quicker to remove fewer, larger samples, but this represents a loss in spatial resolution. We saw 50 ml samples as a reasonable balance. This quantity still provided significant spatial resolution and was more than enough for any one specialist (most specialists required much less than 50 ml for their individual analytical samples), which meant that each vial could be subsampled for multiple analysts. It is also worth mentioning here, that, *prior to any excavation*, having to discuss with each analyst their unique requirements, meant bringing them into the development of the project very early on. We discussed the project and each analyst's unique needs in zoom sessions, but it mainly required having them come to the lab to see the system in person. These in-person, on-site discussions were both invaluable for developing the project but also resulted in a closer degree of collaboration than might normally occur in traditional excavations.

Data Management and Interactive Sampling and Interpretation

Early on in the development of this methodology, we recognized that the nature of the data resulting from excavations like this will require a special data management approach that will necessarily include some way to visualize and manipulate the results and enable the iterative subsampling process mentioned above. This is an area we are still working on as we continue to analyze the samples and interact with the team. However, the foundation of this system is a cloud-based relational database that gives all team members access to the raw data and some tools for exploring the data spatially. We also have provided tools for downloading portions of the data so that they can be processed locally using standard tools (e.g. R, Python, etc.). It is anticipated that this system will be made open as the project nears completion. An important component of the methodology, and one we did not entirely appreciate the importance of initially, is that the sub-sampling process of each vial and the subsequent interpretation of the various analyses must be interactive. As the goal was to use the combined results from a range of types of analysis to help detect and characterize (often invisible) fire features, no one member of the team was equipped to interpret the results on their own. Interpretation requires the sharing of the various types of data among all team members followed by discussions about how to integrate them and what, collectively, they might be telling us.

Sample Size and the Issue of Traditional Analyses

One of the issues with this type of excavation is that, in comparison to traditional excavation approaches, a very small volume of sediment was removed and a relatively small number of artifacts was recovered. In all, we excavated ~ 200 L of sediment from Pech IV Layer 8. This resulted in approximately 450 lithics and 560 bones large enough to be individually provenienced. These small numbers reflect a continuation of trends in Paleolithic archaeology over the last seventy years wherein we excavate more slowly and carefully and, as a result, we excavate less. However, it would not have been possible for us to have done the 2000–2003 Pech IV excavations in this manner, and it is questionable whether even a modified excavation strategy producing smaller samples from each layer would have been sufficient to adequately characterize variability in the lithic and faunal assemblages through time at Pech IV (Dibble et al., 2018).

We were able to apply the methodology described here at Pech IV because in fact we did not need more of the classic artifact categories: bones and stones. The lithic and faunal assemblages at Pech IV are already well understood from the tens of thousands of bones and artifacts already recovered, and so this combined with evidence for extensive burning in Layer 8 made this site an ideal case study. However, this said, while we do not imagine entire excavations being conducted with the methods outlined here, we can imagine that this approach could serve as a complement to standard excavation methodologies. So, for instance, if we were to re-do the 2000–2003 excavation, we could take a sample from 2 to 3 m square from each layer (as we did) and at the same time excavate approximately a quarter meter square using the methods outlined here to capture the finely contextualized kinds of samples we collected in this study. This complementarity of sampling methods strikes us as the way forward in most instances (Fig. 23).

Conclusions

Here we have attempted to describe in full an excavation methodology designed for the archaeological sciences with an emphasis on full recovery (rather than simply screening sediments) and high-resolution sampling, on documenting microstratigraphic contexts, on sediments as opposed to objects, and on the close integration of data collected for a range of macro-, micro-, and molecular-scale analyses. The basic proveniencing is a 50 ml-size vial, and this microstratigraphic methodology is designed to be relatively low cost, open source, and logistically light-weight with the idea that microstratigraphic excavation in the lab using a common sampling protocol for all types of analyses can be an integral part of excavation rather than a technique applied only in exceptional circumstances (e.g., a burial). In our particular application, we were concerned with documenting fire features. Our idea was that, while the preservation of the visible components of fire features (charcoal and ash) on the original ground surface might be poor, the effect heat has on the underlying sediments should be detectable by a number of proxies and thus, in a context with minimal reworking of sediments, we should be able to reconstruct and better understand otherwise invisible fire features. The analysis of our samples is an iterative process and

Fig. 23 Photos of 2003 excavation of Layer 8 at the site (left) and 2021 excavation of Layer 8 in the lab (right)

ongoing, but it is clear that we are detecting patterns of heating that are not visible to the naked eye and at a smaller scale than was previously possible when relying solely on either visible fire residues or the distribution of heated large lithics and bones within a layer.

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Author Contributions DS, VA, PG, SPM, and DO are the principal investigators. They designed, organized, and directed the project and wrote the bulk of the paper. VA and PG also carried out the geoarchaeology and micromorphology. SPM wrote the software for the microscribe. SPM and LL were responsible for all photogrammetry, 3-D modelling, and SfM. LL also helped direct work in the lab. DO helped direct lab work and DO and AA carried out the lithic analysis. AC and JdR carried out the Archeomagnetism and magnetic properties analysis. DC was responsible for the phytolith analysis and DC and DP carried out the sediment mineralogy (FTIR), AIF, and TOC analysis. GGu was responsible for single-grain OSL sensitivity analysis. CM and AHH carried out the lipid biomarkers analysis. MS carried out the infrared spectroscopy (FTIR) on lithics. TS was responsible for the overall faunal analysis and GGa did the analysis of burning of the small finds fauna and helped organize work in the lab. All authors edited the paper and contributed text and figures where required.

Data Availability All data used in the paper is available upon request.

Declarations

Competing Interests The authors declare no competing interests.

References

Aldeias, V., Goldberg, P., Sandgathe, D., Berna, F., Dibble, H. L., McPherron, S. P., Turq, A., & Rezek, Z. (2012). Evidence for neandertal use of fire at Roc de Marsal (France). *Journal of Archaeological Science*, *39*(7), 2414–2423.

Aldeias, V., Goldberg, P., Dibble, H. L., & El-Hajraoui, M. (2014). Deciphering site formation processes through soil micromorphology at Contrebandiers Cave, Morocco. *Journal of Human Evolution, 69*, 8–30.

Aldeias, V., Dibble, H., Goldberg, P., McPherron, S., & Sandgathe, D. (2016). How heat alters underlying deposits and implications for archaeological fire features: A controlled experiment. *Journal of Archaeological Science*, *67*, 64–79.

Angelucci, D. E., Nabais, M., & Zilhão, J. (2023). Formation processes, fire use, and patterns of human occupation across the Middle Palaeolithic (MIS 5a-5b) of Gruta da Oliveira (Almonda karst system, Torres Novas, Portugal). *PLoS One, 18*(10), Article e0292075.

Arpin, T. L., Mallol, C., & Goldberg, P. (2002). Short contribution: A new method of analyzing and documenting micromorphological thin sections using flatbed scanners: Applications in Geoarchaeological Studies. *Geoarchaeology, 17*(3), 305–313.

Bordes, F. (1975). Le gisement du Pech de l'Azé IV. Note Préliminaire. *Bulletin de la Société Préhistorique Française, 72*, 293–308.

Brittingham, A., Hren, M. T., Hartman, G., Wilkinson, K. N., Mallol, C., Gasparyan, B., & Adler, D. S. (2019). Geochemical evidence for the control of fire by middle palaeolithic hominins. *Scientific Reports*, *9*, 15368. https://doi.org/10.1038/s41598-019-51433-0

Dibble, H., Berna, F., Goldberg, P., McPherron, S., Mentzer, S., Niven, L., Richter, D., Théry-Parisot, I., Sandgathe, D., & Turq, A. (2009). A preliminary report on Pech de l'Azé IV, layer 8 (Middle Paleolithic, France). *PaleoAnthropology, 2009*, 182–219.

Dibble, H., McPherron, S. P., Goldberg, P., & Sandgathe, D. (2018). *The Middle Paleolithic Site of Pech de l'Azé IV*. Springer International.

Douglass, M., Lin, S., & Chodoronek, M. (2015). The application of 3D photogrammetry for in-field documentation of archaeological features. *Advances in Archaeological Practice, 3*(2), 136–152.

Goldberg, P., Meignen, L., & Mallol, C. (2009a). Geoarchaeology, site Formation, and transitions. In J. Bar-Yosef, Shea, & D. Lieberman (Eds.), *Transitions in prehistory: Essays in honor of Ofer* (pp. 431–444). American School of Prehistoric Research Publication, Oxbow/David Brown.

Goldberg, P., Dibble, H., Berna, F., Sandgathe, D., & McPherron, S., A Turq (2012). New evidence on neandertal use of fire: Examples from Roc de Marsal and Pech de l'Azé IV. *Quaternary International Vol*, *247*, 325–340.

Karkanas, P., & Goldberg, P. (2018). *Reconstructing Archaeological Sites: Understanding the Geoarchaeological Matrix*. Wiley-Blackwell.

Magnani, M., Douglass, M., Schroder, W., Reeves, J., & Braun, D. R. (2020). The digital revolution to come: Photogrammetry in archaeological practice. *American Antiquity*, *85*(4), 737–760.

Mallol, C. M., Mentzer, S. M., & Miller, C. E. (2017). Combustion Features. In C. Nicosia & G. Stoops (Eds.), *Encyclopedia of*

Archaeological Soil and Sediment Micromorphology (pp. 299–330). Wiley-Blackwell.

Sandgathe, D., Dibble, H., Goldberg, P., McPherron, S., Turq, A., & Niven, L. (2011a). J Hodgkins. On the Role of Fire in Neandertal Adaptations in Western Europe: Evidence from Pech de l'Azé IV and Roc de Marsal, France. PaleoAnthropology 2011: 216–242.

Sandgathe, D., Dibble, H., Goldberg, P., McPherron, S., Turq, A., & Niven, L., J Hodgkins (2011b). *Timing of the Appearance of Habitual Fire Use Letter PNAS* 108(29): E298.

Sorensen, A. C. (2017). On the relationship between climate and neandertal fire use during the last glacial in south-west France. *Quaternary International*, *436*, 114–128.

Stoops, G., Marcelino, V., & Mees, F. (2010). Phosphatic features. In V. M. G. Stoops & F. Mees (Eds.), Interpretation of Micromorphological Features of Soils and Regoliths (pp. 521–541). Elsevier.

Tegel, W., Elburg, R., Hakelberg, D., Stäuble, H., & Büntgen, U. (2012). Early neolithic water wells reveal the world's oldest wood architecture. *PloS One*, *7*(12), e51374.

Weiner, S. (2010). *Microarchaeology: Beyond the visible archaeological record*. Cambridge University Press.

Authors and Affiliations

Dennis Sandgathe[1] · Vera Aldeias[2,3] · Paul Goldberg[1,2,4] · Shannon P. McPherron[2,3] · Deborah I. Olszewski[5] · Aylar Abdolahzadeh[6] · Angel Carrancho[7] · Dan Cabanes[8] · Giulia Gallo[9,10] · Guillaume Guerin[11] · Antonio V. Herrera-Herrera[12,13] · Li Li[2,3] · Carolina Mallol[13,14] · Judit del Río[7] · Dimitri Papavasiliou[8] · Mareike Stahlschmidt[15,16] · Teresa E. Steele[10]

✉ Shannon P. McPherron
mcpherron@eva.mpg.de

Dennis Sandgathe
dms@sfu.ca

1 Department of Archaeology, Simon Fraser University, Burnaby, BC, Canada

2 ICArEHB - Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour, Universidade do Algarve, Faro, Portugal

3 Department of Human Origins, Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany

4 Institute for Archaeological Sciences, Department of Geosciences, University of Tübingen, 72074 Tübingen, Germany

5 Department of Anthropology and Penn Museum, University of Pennsylvania, Philadelphia, PA, USA

6 School of Human Evolution and Social Change, Arizona State University, Tempe, AZ, USA

7 Área de Prehistoria, Departamento de Historia, Geografía y Comunicación, Universidad de Burgos, Burgos, Spain

8 Department of Anthropology and Center for Human Evolutionary Studies (CHES), Rutgers, the State University of New Jersey, New Brunswick, NJ, USA

9 Chaire de Paléoanthropologie, CIRB-Collège de France, CNRS/INSERM, Paris, France. TRACES laboratoire - Université Toulouse Jean Jaurès, Toulouse, France

10 Department of Anthropology, University of California, Davis, CA, USA

11 Chargé de recherche CNRS, UMR 6118 Géosciences Rennes, Université de Rennes 1, Rennes, France

12 Departamento de Química, Unidad Departamental de Química Analítica, Facultad de Ciencias, Universidad de La Laguna, Tenerife, Spain

13 Instituto Universitario de Bio-Orgánica Antonio González, Universidad de La Laguna, Tenerife, Spain

14 Departamento de Geografía e Historia, Facultad de Humanidades, Instituto Universitario de Bio-Orgánica Antonio González, Universidad de La Laguna, Universidad de La Laguna, San Cristóbal de La Laguna, Spain

15 Department of Evolutionary Anthropology, University of Vienna, Vienna, Austria

16 Human Evolution and Archaeological Sciences, University of Vienna, AustriaVienna