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Emmanuel Discamps, Marc Thomas, Christelle Dancette, Brad Gravina, Sébastien Plutniak, Aurélien Royer, Alexandre Angelin, François Bachellerie, Cédric Beauval, Jean-Guillaume Bordes, et al.

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# Breaking Free from Field Layers: The Interest of Post-excavation Stratigraphies (PES) for Producing Reliable Archaeological Interpretations and Increasing Chronological Resolution

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## Abstract

In order to track diachronic changes in archaeological sequences, researchers typically partition time into stratigraphic layers defined during fieldwork, which serve as the framework for ensuing analyses. These analytical units have a significant impact on archaeological inference, defining its resolution, and influencing both the study of cultural assemblages and the reconstruction of past environments. However, field layers are seldom re-evaluated after excavation despite the fact that archaeological deposits are now commonly recognised as often containing material ‘mixed’ together by site formation processes, excavation techniques, or analytical practices. Although the analysis of intra-site spatial data clearly offers a means to overcome these issues, our literature review of 192 journal articles revealed the potential of this data (notably vertical projections of piece-plotted artefacts) to be under-exploited in prehistoric archaeology. Here, we advocate for the development of a more spatially informed framework for interpretation that we refer to as post-excavation stratigraphy or PES. After proposing a definition for PES, we attempt to develop a framework for theoretical considerations underlying their implication, importance, and potential. Three main benefits of PES are highlighted: ensuring assemblage reliability, increased chronological and spatial resolution, and more reliable interpretations based on a multi-stratigraphic approach. We contend that the stratigraphy defined during fieldwork is insufficient and potentially misleading. By providing a different “stratigraphic view” of the same sequence, each specialist can contribute data that, when combined, produces a better understanding of interactions between changes in, for example, technological or cultural traditions, subsistence strategies, or paleoenvironments.

**Keywords** Archaeological methods · Assemblages · Excavation · Spatial analysis · Stratigraphy · Taphonomy

## Introduction: The Influence of Field Layers as Units of Analysis

For archaeology, time is key: reliably documenting diachronic patterns of cultural and environmental change is amongst the most intensely studied and debated issues, especially in prehistory. While absolute dates occasionally provide highly resolved datasets, archaeologists frequently address chronological changes by using arbitrary “slices” of time. More often than not, attempts to trace shifts in material culture, subsistence strategies, or other aspects of human behaviour are based on comparisons of material assigned to ‘distinct’ stratigraphic layers defined during fieldwork. As such, time is partitioned into discrete spatial units, namely layers, levels, assemblages, spits, phases, or periods. These analytical units used to perceive and organise time have a dramatic impact on archaeological inference; they define its resolution and constrain the chronological grain, and they influence the way cultural assemblages or techno-complexes are defined, interpreted, and compared (e.g., Bordes, 2002, 2012; Gravina et al., 2018), as well as the manner in which past environments are reconstructed (e.g., Royer, 2014; Discamps & Dancette, 2022).

Layers or stratigraphic units are most commonly defined during fieldwork based purely on lithological observations (e.g., sedimentary colour, texture), archaeological criteria (e.g., artefact and ecofact composition and density, presence of structures), or a combination of the two. A significant amount of time is invested in the definition of the most precise stratigraphic layers possible during fieldwork, yet usable criteria are obviously limited to what can be observed in situ in the excavation window. In practice, the recovered archaeological material assigned to these field layers is subsequently grouped into ‘assemblages’, which are then stored in museums following these units. Consequently, field layers are commonly employed as the organisational framework for future analyses and interpretations. Implicitly, field layers are often presumed to be more or less coherent (i.e. they contain homogeneous material), to reflect distinct occupation phases, and to be the best means of generating a relative chronology. These ‘units’ are often uncritically adopted as the analytical framework by which diachronic changes are investigated (as discussed in McPherron et al., 2005; Royer, 2014; Romagnoli et al., 2018; Discamps et al., 2019) and later used in chronological models (see Discamps et al., 2015 for a discussion of the impact of stratigraphic units on Bayesian modelling).

Field layers are, however, seldom re-evaluated or re-defined after excavation despite the fact that most analysts are well aware of the palimpsestual nature of a majority of prehistoric assemblages, especially those from rock shelters and caves. Archaeological deposits are subject to multiple formation processes (Schiffer, 1983) that can modify the ‘original’ spatial organisation and representation of different artefact types. Moreover, the degree to which excavation methods and analytical choices (“analytical lumping”, cf. Discamps et al., 2019) can produce ‘mixed’ assemblages is also often overlooked. This is particularly important as the compositional coherence of field layers is often taken at face value during subsequent analyses. To overcome these issues, we argue in this contribution that intra-site spatial data are key to testing the pertinence of field layers, ensuring the reliability of associations between artefact types (both piece-plotted and sieved material), and

increasing the chronological resolution of archaeological interpretations. After a short review of the historical development of approaches designed to ‘break free’ from field layers, we describe a literature review that reveals vertical spatial data to be under-exploited in Palaeolithic archaeology (see McPherron et al., 2005 for a similar conclusion). Finally, we propose a definition for what we have coined “post-excavation stratigraphies” (PES) studies and frame related theoretical considerations surrounding their implication, importance, and potential for increasing both the reliability and resolution of archaeological interpretations.

## The “Mixed” Nature of Archaeological Layers

In the early days of Palaeolithic archaeology, the integrity of the stratigraphy identified during fieldwork and the composition of assemblages recovered from them were rarely questioned. As more data was accumulated and excavation techniques improved, researchers gradually recognised the “mixed” nature of most archaeological assemblages. Pleistocene deposits are now commonly considered to be complex ‘cumulative palimpsests’ (sensu Bailey, 2007), with an increasing awareness of the necessity of disentangling them in order to access meaningful data concerning human behaviour in the past. In the second half of the twentieth century, two main factors that can lead to mixed assemblages were identified:

- (1) Site formation processes. Archaeologists have become increasingly, sometimes painfully, aware that ‘time is not always on our side’ when it comes to the preservation of Palaeolithic sites. In a paper entitled “*Time’s arrow and the Archaeology of a contemporary Community*”, Ascher (1968) introduced the concept of “entropy”, defined as an archaeological assemblage’s level of disorder. According to Ascher, although the passage of time (“time’s arrow”) progressively increases assemblage entropy, it is not the only factor influencing assemblage composition. Two contemporaneous assemblages do not exhibit the same entropy, as their formation depends on different processes (Ascher, 1968). How much can be learned from the past is linked to the preservation of a site itself dependent on the time elapsed since the site’s abandonment and the processes that contributed to its formation. The reliability of a site’s or layer’s interpretation therefore must be evaluated on a case-by-case basis. M.B. Schiffer, inspired by the work of R. Ascher, warned against the overinterpretation of the archaeological record. He separated the impact of human processes (c-transforms) and natural processes (n-transforms) on site formation (Schiffer 1976, 1983). To avoid any misinterpretation, site formation processes must be identified and explained before attempting to describe past human behaviour (Schiffer, 1983; Texier, 2000). “Palimpsests sites” result from multiple superimposed occupations that occurred over a long period of time during which sedimentation rates were too slow to individualise them (Binford, 1981). The combination of behavioural and natural phenomenon thus renders most Palaeolithic archaeological sites as palimpsests; although admixture can also be

caused by disturbances linked to geological or biological processes (for reviews, see Schiffer, 1983; Texier, 2000; Bertran et al., 2019). Often lumped together under the umbrella terms of ‘taphonomy’ or ‘taphonomic approaches’, analysis of the alteration, distribution, organisation, and refitting of multiple artefact types combined with geoarchaeological data (i.e. particle-size distribution, fabric analysis) have shown how, for example, site formation processes can significantly alter the original spatial relationship between different artefact classes while creating new ones between previously unassociated remains.

- (2) The excavation itself, and the steps that follow, including analysis. Early on, Cowgill (1970: 163) acknowledged that the physical finds recovered from an archaeological site depend not only on site formation processes (cf. *supra*) but also on the “techniques, concepts, and equipment of investigators”. Archaeological material from distinct occupations can be mixed by excavators during fieldwork (“analytical lumping”, due to the untested separation of distinct assemblages following excavation or analysis, Discamps et al., 2019), or even after, depending on how archaeological collections are curated (Dibble et al., 2009).

More often than not, only the former, the consequences of site formation processes, is taken into consideration and generally encompassed in the term ‘taphonomy’. The impact of analytical lumping is either downplayed or overlooked. Here, we argue that, alongside the more widespread consideration of site formation processes, there is room for the development of an archaeological practice we referred to above as post-excavation stratigraphies, notably if spatial data is incorporated into the process.

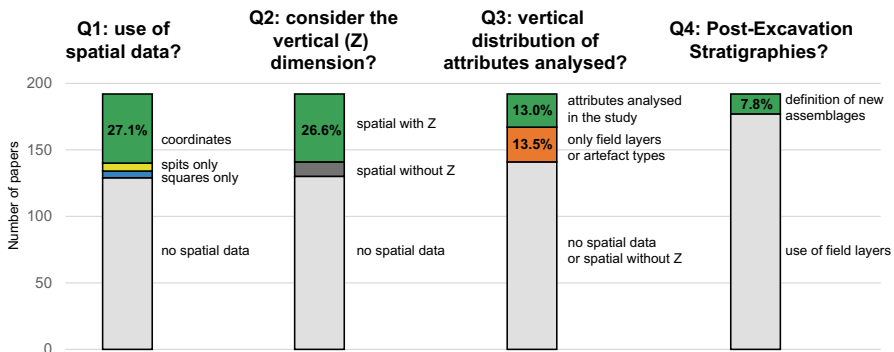
## Vertical Spatial Analyses to Break Free from Field Layers

The use of Cartesian coordinates to record the location of the objects during excavation has a long history in Palaeolithic archaeology, with researchers developing similar techniques in many parts of the world since the early twentieth century (Plutniak, 2021a). Amongst others, Laplace and Méroc (1954) significantly contributed to the formalisation of such methods, advocating for the use of Cartesian coordinates during excavation. In their view, the spatial analysis of piece-plotted materials makes it possible to test if several archaeological layers correspond to the same sedimentary unit or, inversely, if a homogeneous archaeological layer is contained within multiple sedimentary units. What we define here as post-excavation stratigraphies is rooted in this idea of critically examining field layers with spatial data.

Laplace and Méroc’s (1954) early call for a systematic, objective, spatial exploration of stratigraphies remained, for decades, technically impractical for large datasets. It is only much later thanks to the availability of computers and electronic devices during the 1970s, 1980s, and 1990s that the approach they advocated realistically and progressively became a reality. Since the 1950s, recording the spatial provenience of artefacts beyond simple layer attributions gradually became widespread in Palaeolithic archaeology. Dibble (1987) and McPherron (Dibble & McPherron, 1988) pioneered the introduction of the

electronic theodolite with a distance metre (a total station) during excavations, facilitating the 3D piece-plotting of all artefacts above a chosen size. In the late 1990s and early 2000s, computer power increasingly available to researchers allowed multiple statistical and spatial analyses thanks to new tools for exploring spatial data (e.g., Esri ARC/INFO in 1982 cf. Morehouse, 1985; Newplot developed since 1986 cf. Dibble & McPherron, 1988; the adaptation of DataDesk to archaeological applications cf. Lacrampe-Cuyaubère, 1997; Paleo III developed by P.-A. Gillioz cf. Chadelle, 2000; QGIS in 2002 cf. QGIS.org 2022). Although spatial analyses of Palaeolithic sites gradually increased, they nevertheless primarily focused on paleoethnographical reconstructions, particularly of open-air sites (e.g., Leroi-Gourhan & Brézillon, 1972) rather than stratigraphic questions, forgetting the “Z” dimension of archaeological deposits (McPherron et al., 2005).

With the increasing use of total stations in the field (Dibble, 1987; McPherron & Dibble, 2002), it is now the norm to “plot” objects of a chosen size in three dimensions, as well as the position of spits/layer limits and buckets of sieved sediment. However, spatial analyses are seldom used to explore data beyond the diachronic units provided by field layers. To better understand this practice in the context of the present study, we reviewed >1400 journal articles, published in 7 journals (*Bulletin de la Société Préhistorique Française*, *Journal of Archaeological Science: Reports*, *Journal of Paleolithic Archaeology*, *PALEO*, *PaleoAnthropology*, *PLoS ONE*, *Proceedings of the National Academy of Sciences*) in the last decade (2012 to 2022—these limits were chosen arbitrarily to sample the most recent research). Of these papers, 192 present diachronic site-based datasets concerning Palaeolithic or Mesolithic material culture or faunal assemblages, in the form of artefact counts by layer (Fig. 1). While less than a third use spatial data, only 13% ( $n=25$ ) analyse the vertical distribution of the attributes studied (e.g., identified species for faunal studies, techno-typological data or raw material types for lithic analyses). Stratigraphic units are rarely re-defined after excavation based on these analyses (e.g., vertical projections), even in the most recently published articles: only 7.8% ( $n=15$ ) use PES.



**Fig. 1** Results of the literature review used to quantify the use of spatial data in Palaeolithic/Mesolithic archaeology (192 articles from 7 journals, published between 2012 and 2022) based on four questions (Q1 to Q4). More details on the methodology used are provided in Supplementary Information #1, and the complete list of articles is available in Supplementary Information #2

The integration of three-dimensional spatial analysis in the interpretation of archaeological data is, however, key to “breaking free” from field layers and to disentangle palimpsests. A large body of work, yet relatively small in comparison to the increasing number of archaeological research articles, has clearly demonstrated the interest of critically reviewing field layers by integrating field data, projections, refitting analyses, geoarchaeological information, etc. (e.g., Villa, 1982, 2004; Cahen et al., 1980; Hahn, 1988; Petraglia, 1992; Sabatier, 1995; Pois, 1999; Bordes, 2000, 2002, 2003; McPherron et al., 2005; Perrin, 2005; Zilhão et al., 2006, 2008; Mallye, 2007, 2011; Faivre, 2008; Michel, 2010; Bachellerie, 2011; Béreiziat, 2011; Ducasse et al., 2011, 2014, 2019; Malinsky-Buller et al., 2011; Aubry et al., 2012, 2014; Discamps et al., 2012, 2019; Machado et al., 2013; Mevel, 2013; Hovers et al., 2014; Chacón et al., 2015; Discamps & Henshilwood, 2015; Langlais et al., 2015a, 2015b, 2018, 2019; Anderson et al., 2016; Bargalló et al., 2016; Machado & Pérez, 2016; Martínez-Moreno et al., 2016; Perrin & Defranould, 2016; Sánchez-Romero et al., 2016, 2020; Angelin, 2017; Bernard-Guelle et al., 2017; Gabucio et al., 2017; Angelin et al., 2018; Deschamps & Zilhão, 2018; Geiling et al., 2018; Goldberg et al., 2018; Gravina et al., 2018; Sécher et al., 2018; Deschamps, 2019; Discamps & Lemeur, 2019; Giusti et al., 2019; López-Ortega et al., 2019; Thomas et al., 2019; Thomas & Gravina, 2019; Santaniello & Grimaldi, 2019; Mora Torcal et al., 2020; Royer et al., 2021; Sanchez-Romero et al., 2021; Bel, 2022; Connet et al., 2022; Deschamps et al., 2022; Discamps & Dancette, 2022). By combining multiple different arguments, these approaches fundamentally altered the original archaeological interpretations of several Palaeolithic sequences. Much of the research cited above-integrated site formation processes, taphonomy, and spatial analysis, an approach that has been referred to as “assemblage taphonomy”, “spatial taphonomy”, “stratigraphic re-evaluation”, “revised archaeo-stratigraphy”, or simply “taphonomy”, resulting in a certain form of confusion with the original definition of the latter term (Efremov, 1940; Lyman, 2010; Domínguez-Rodrigo et al., 2011; Bordes, 2012). This confusion is especially apparent in faunal studies, where taphonomy most frequently encompasses the identification of agents responsible for the accumulation and modification of bone remains (e.g., humans, carnivores), rather than a critical examination of field layers and assemblage integrity. We contend that this plurality of terms, all of which effectively marshal a certain sort of “taphonomical analysis of archaeological assemblages”, constitutes an obstacle to its generalised use in prehistoric archaeology. This can be partly resolved by clearly distinguishing the different types of analyses and their respective goals, hence by separating the establishment of post-excavation stratigraphies from the study of site formation processes and taphonomy. PES studies constitute one of the first steps in the critical revision of an archaeological sequence. To this end, here, we propose a definition of PES and expose their general theoretical framework.

## Towards a Definition and Theoretical Framework for PES

PES studies can be defined as a post-excavation procedure that seeks, for each attribute studied in the archaeological analysis of a site, to (1) explore its spatial distribution in the three dimensions and test if any clear patterning can be identified

and (2), if possible, define boundaries or interfaces between assemblages (groups of remains) that constitute, as much as possible, spatially homogeneous stratigraphic units that are independent from the original field stratigraphy. Importantly, this homogeneity does not necessarily presuppose a genuine archaeological ‘reality’ (e.g., a unique phase of occupation). A post-excavation stratigraphy (i.e. a set of boundaries between assemblages) is defined for each explored attribute if necessary or by combining several attributes if they depict the same spatial structure. PES can then serve as a reliable scaffolding for archaeological interpretation, allowing different forms of data produced by each specialist to be mobilised, compared, and correlated.

Furthermore, there is no *a priori* reason why changes of a sedimentological, archaeozoological, technological, or environmental nature should be contemporary and thus could be synthesised within a single stratigraphy (McPherron et al., 2005; Texier, 2000). This is even more important if we consider that field stratigraphies are generally established before all the excavated material is analysed. The stratigraphic position of a change in one attribute does not necessarily coincide with changes in other attributes, as stated in the international stratigraphic guide (Hedberg, 1976). The same also applies to archaeological sequences, considering that, first, “[...] there is no *a priori* reason to think that geologically defined units map accurately onto behaviorally meaningful units, since it is much more likely that the factors controlling the geological record vary independently of human behavior” (McPherron et al., 2005: 240), and second, “accurately recording changes in the occupation history of a cave or rock shelter directly from the site stratigraphy during excavation is highly unlikely” (Discamps et al., 2019). Ideally, independent stratigraphies should be constructed after excavation based on the spatial analysis of each attribute (i.e. using vertical projections of attributes).

In practice, PES analyses are best achieved by integrating the spatial distribution of all data types and associated attributes. A non-exhaustive list of attributes that can be spatially explored includes: general density of artefacts (including the identification of sterile or nearly sterile layers), changes in the proportions of types of remains (bones, lithics, charcoal, coprolites...), or, in their size, spatial distribution of identified species, bone surface modifications (including bone colour), chrono-cultural attribution of lithic implements, raw materials, surface states, refits, fabrics, etc. Both horizontal and vertical distributions are analysed, with or without 3D plots, as well as variations in density maps. PES may also include absolute dates or data concerning site formation processes.

Each research question can potentially give rise to a new post-excavation stratigraphy: for example, the question “when did humans switch from hunting reindeer to a focus on horse?” calls for a PES defined on the spatial distribution of identified species. Similarly, “are technological innovations in material culture driven by an adaptation to the increased hunting of horse?” should call for a multi-stratigraphic approach comparing post-excavation stratigraphies defined on the basis of identified species on one hand and lithic techno-typological markers on the other. Continuing this example, PES analyses can be used to better identify the timing of environmental changes in a sequence, elucidate their potential links with behavioural patterns (e.g., horse hunting, technological innovations), or explore inconsistencies between different environmental proxies (e.g., macrofauna, microfauna, isotopes, see Pederzani et al., 2021 for an example).

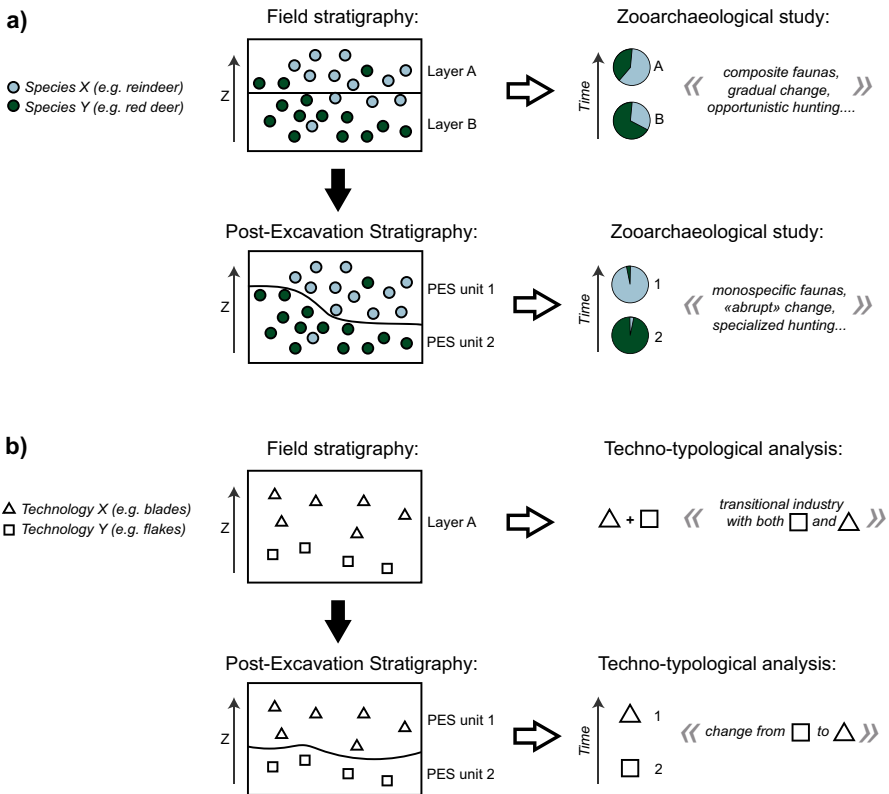
Overall, PES studies aim to establish the finest stratigraphic resolution possible to control primary data prior to interpretation. Whether remains grouped in a PES



assemblage are penecontemporaneous or not is another question, one that pertains much more to site formation processes and archaeological and taphonomical interpretations than to PES. This distinction is key, even though it could be argued that a PES study should systematically be done prior to the analysis of an assemblage. In some respects, the analysis of archaeological material and the establishment of PES can unfold in tandem, as each potentially informs the other. It is important to note that remains grouped in a given PES assemblage are not necessarily contemporaneous, and two spatially distinct PES assemblages are not necessarily temporally distinct. For example, site formation processes altering the distribution of archaeological material can produce distinct PES assemblages and give the false impression that sets of remains represent chronologically segmented events, as in the case of layers affected by solifluction or by soft-sediment deformations induced by cryoturbation.

PES have three main advantages:

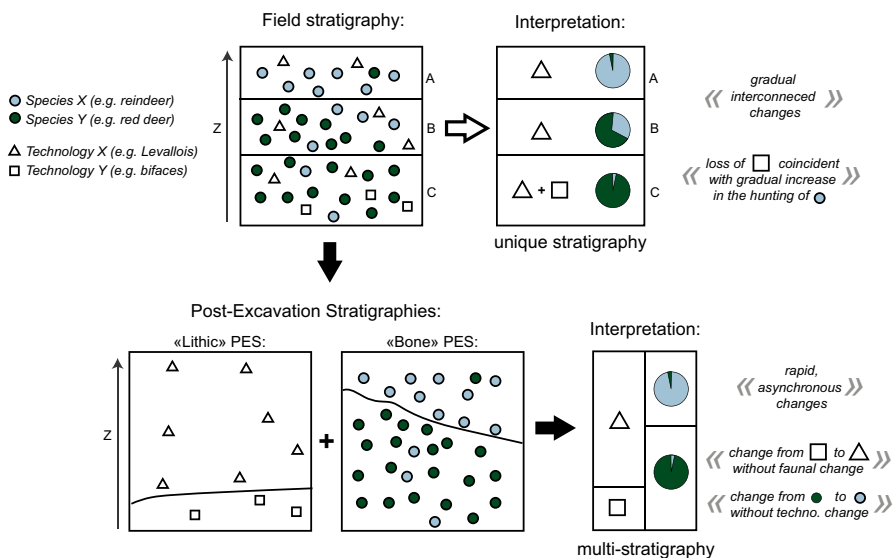
- Ensuring assemblage reliability. PES can identify errors made during excavation in layer attributions, for example, in cases where distinguishing two superimposed layers was difficult in the field (Fig. 2a);



**Fig. 2** Examples of the consequences of a PES study with one attribute highlighting the influence of assemblage boundary definitions on interpretations (in quotation marks). In these cases, PES radically impact the conclusions of the zooarchaeological (a) or techno-typological (b) analyses

- Increased chronological and spatial resolution. PES offer the possibility of redefining more spatially resolved assemblages after excavation and thus ensuring more reliable interpretations (Fig. 2b);
- A more reliable multi-stratigraphic approach. As PES are defined based on the spatial homogeneity or coherence of archaeological data, it is evident that, in many cases, a sequence cannot be described by a single stratigraphic system: each specialist can potentially generate one (or several) independent post-excavation stratigraphy/(ies) that can later be compared with others. This multi-stratigraphic approach has multiple advantages, as each material can potentially provide different scenarios for a given site (Fig. 3). By separating the chronological structure of data for each discipline, PES reduce the risk of falsely identifying environmental determinism in the context of Palaeolithic research. Often, “synchronous” cultural and faunal changes are considered evidence of environmental changes impacting material culture history. PES studies can demonstrate that this supposed synchrony is actually an artefact of analytical lumping (Fig. 3). In addition, PES studies provide a robust framework for generating site chronologies, allowing tipping points in behavioural or environmental change to be targeted. In any case, PES do not change the fact that depth should only be considered as a very broad measure of time in archaeological sites, as in the frequent case of palimpsests produced in slow sedimentation contexts.

It is important to note that PES are not limited to complex reworked deposits (for more robust interpretations) but are equally applicable to well-preserved sequences (for higher interpretative resolution).



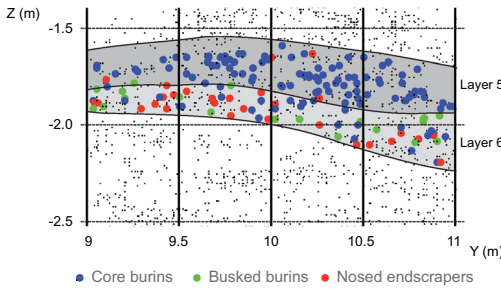
**Fig. 3** Example of the consequences of a PES study with two attributes highlighting the influence of assemblage boundary definitions on interpretations (in quotation marks). In this case, PES alter the interpretation of links between lithic and subsistence changes, switching from a vision of gradual interconnected changes in the two spheres, to a much more complex picture

Figures 4 and 5 provide several concrete examples taken from the literature, with contrasting impacts of PES on the interpretation of the chronological patterning:

- Building on previous work (Bordes, 2002, 2003), multiple proxies (conjoining blade fragments, projections of bladelets, and objects by layer) were used to test the validity of the archeo-stratigraphy proposed by the initial excavators for the Upper Palaeolithic of Roc-de-Combe (Michel, 2010). In rows J and K, vertical projections of specific tool types (Fig. 4a) show them to be clearly separated stratigraphically, with an abundance of busked burins and nosed endscrapers in layer 6, while core burins are more abundant in layer 5. Additionally, these three markers appear to be randomly distributed within each layer. In this case, PES analysis both supports the pertinence of the original field layers and helped identify the zone of the site where the cultural sequence was best preserved.
- At Le Moustier, an analysis of the vertical distribution of hunted prey in one of the Mousterian deposits (Peyrony's layer H) identified a clear shift in the proportions of deer and large bovids within the stratigraphic sequence (Discamps & Lemeur, 2019). The base of the sequence is largely dominated by deer (77% of identified remains), while the top contains deer and large bovids in comparable proportions (Fig. 4b). This change was not perceptible during excavations but was highlighted by a subsequent spatial analysis that provides a more accurate picture of what are likely rapid changes in Neanderthal subsistence strategies and environmental conditions.
- For the Port-de-Penne Upper Palaeolithic sequence, Langlais et al. (2020) explored the vertical distribution of identified species and raw material types in the Laborian occupation. This analysis identified two clear post-excavation units evinced primarily by differences in exploited raw materials: the upper unit comprising Campanian and Oligocene flints and a higher frequency of deer remains overlying a unit distinguished by a shift to the use of Coniacian and Santonian flint (Fig. 4c).
- While unidentified during initial excavations, Mallye's (2011) taphonomic analysis and refitting of badger remains from Unikoté Cave (France) produced evidence for the considerable displacement of archaeological material by this burrowing mammal. When combined with observations of bone surface weathering, long bone breakage patterns, carnivore damage, and a consideration of potential accumulation agents, Mallye's spatial analysis identified reworked Mousterian and Mesolithic occupations capped by a Holocene badger den that included archaeological material from both. Figure 5a shows the spatial distribution of faunal refits between field layers, revealing considerable movement of material by badger activity.

**Fig. 4** Concrete examples of spatial analysis of attributes in PES studies. **a)** Vertical projections of burin ► types assigned to Aurignacian layers 5 and 6 of Roc de Combe lent further support to the stratigraphy documented during fieldwork (Michel, 2010). **b)** Testing spatial patterning in the vertical distribution of prey species in the Mousterian of Le Moustier identified a clear shift in the proportions of red deer versus large bovids within the stratigraphic sequence defined in the field (Discamps & Lemeur, 2019). **c)** Finally, PES analyses of the Laborian sequence of Port-de-Penne identified simultaneous changes in two attributes (lithic raw material and identified species) that support the distinction of new assemblages independent from layers defined during fieldwork (Langlais et al., 2020)

**a) vertical projection by lithic typo-technology (Roc-de-Combe ; Michel, 2010)**

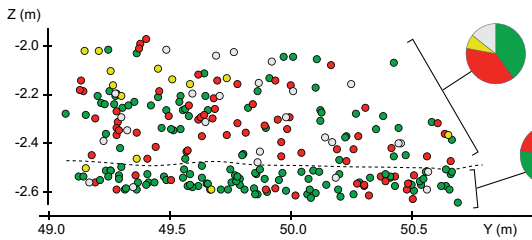


> good spatial separation of typo-technological markers between layers

> random distribution of typo-technological markers inside layers

> support for the original field layers' definition

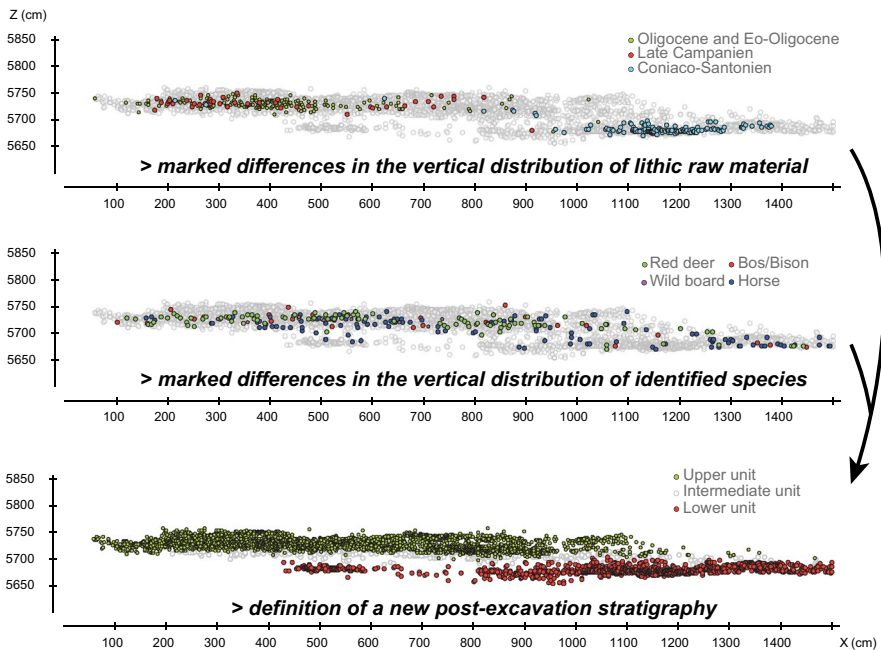
**b) proportions of identified species (Moustier ; Discamps & Lemeur, 2019)**



> marked increase in the proportion of a taxon (Bos/Bison)

> highlights a change in hunted prey that was not seen during excavation (dotted line)

**c) definition of new assemblage boundaries (Port-de-Penne ; Langlais et al., 2020)**

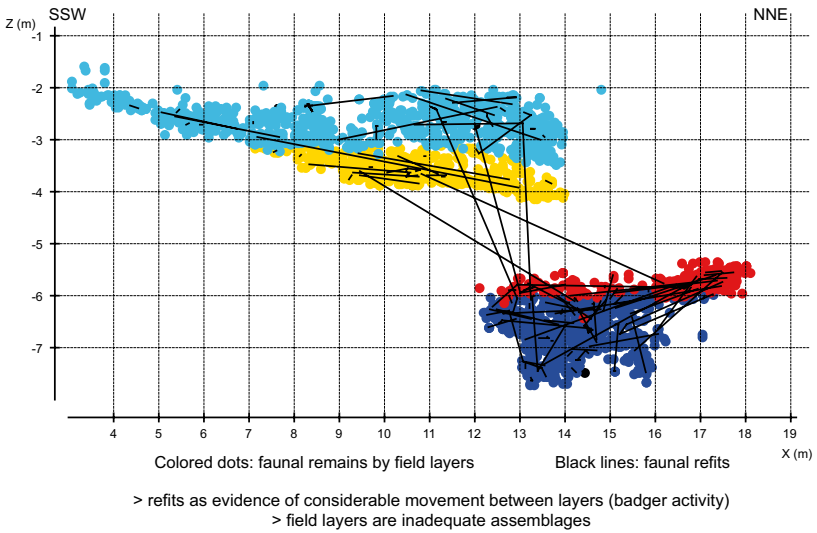


> marked differences in the vertical distribution of lithic raw material

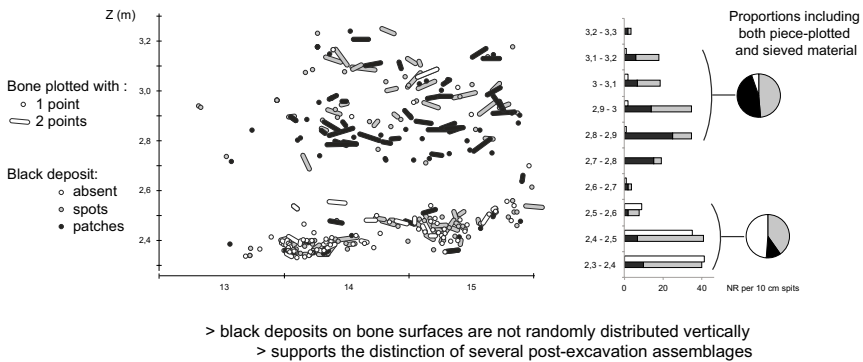
> marked differences in the vertical distribution of identified species

> definition of a new post-excavation stratigraphy

**a) refits (Unikoté ; Mallye, 2011)**



**b) surface alterations (La Chauverie ; Discamps et al., 2012)**



**Fig. 5** Concrete examples of attributes that can be explored in PES studies, in relation to taphonomical analyses. At Unikoté **(a)**, in addition to identifying major reworking of the deposits, refit faunal fragments fully invalidated field layers (Mallye, 2011). At the hyena den of La Chauverie **(b)**, the spatial distribution of taphonomic bone surface alterations contributed to the definition of distinct post-excavation assemblages (Discamps et al., 2012)

- A spatial and taphonomic analysis of bones recovered from the Pleistocene hyena den of La Chauverie identified two vertical concentrations of faunal material (Discamps et al., 2012). Several lines of evidence (distribution of species, refits, bone surface alterations) were used to suggest the existence of two successive phases of occupation. As an example, in the northern part of the central sector, black deposits on bones are nearly twice as frequent in the upper assemblage (Fig. 5b), supporting the definition of two PES units.

Additional details on each case study are available in the cited works.

PES studies have been shown to modify the chronology of techno-complexes, as in the example of Châtelperronian-Aurignacian interstratifications (cf. Bordes, 2002, 2003), alter the typo-technological characterisation of lithic industries by reducing the supposedly “transitional” aspect of some industries at the Middle-to-Upper Palaeolithic transition (cf. Gravina et al., 2018), invalidate previous environmental reconstructions by showing that non-analogue faunal associations resulted from post-occupation mixing of material by natural processes and/or analytical lumping (cf. Royer, 2014; Discamps & Dancette, 2022), or modify our perception of interactions between Neanderthals and large carnivores (cf. Discamps et al., 2012).

PES often use the 3D coordinates of plotted artefacts but can also involve other excavation units such as spits, buckets, and sub-layers, in the form of logs. This is notably the case if the goal is to analyse the distribution of small objects (e.g., rodents, burnt bones, bladelets) that cannot or are difficult to systematically plot during excavation (Royer, 2014; Laroulandie et al., 2021; Royer et al., 2021). The analytical power of PES studies is also dependent on excavation methods. Ideal excavation protocols notably include a systematic size cut-off for plotting artefacts in order to better explore changes in density, complemented by data from the systematic sieving of sediment retrieved from small spits (e.g., typically 2 to 5 cm thick, in 50 × 50 cm square units) that follow the general geometry of the deposits in order to avoid the artificial mixing of material during excavation.

## Discussion and Conclusion

Post-excavation stratigraphies (PES) have been gradually implemented in prehistoric archaeology, without researchers referring to them expressly as such. Researchers traditionally relied either on lithology and sedimentology or on “type fossils” and the frequency of tool types to define layers in archaeological sequences. This reliance on data provided by geologists and material culture specialists significantly impacted the definition of layers used to build archaeological sequences. PES seek to counterbalance this trend by generating independent stratigraphies for each discipline that can subsequently be compared and tested against one another in order to draw more reliable inferences about past human behaviour. Here, we highlighted several illustrative examples of how PES can be built and why they should be generated by different specialists, first independently and then compared with each other and with original field observations. By consolidating data and “breaking free” from the traditional dependence on field stratigraphy as the immutable framework of interpretation, PES allow observations made during fieldwork to be tested and better contextualised, ultimately producing more reliable interpretations of archaeological sequences. We argue that this type of stratigraphic re-evaluation should be the necessary first step of any study in order to produce robust, high-resolution interpretations.

Post-excavation stratigraphies can be generated for archaeological sites as well as paleontological deposits. Especially suited to the study of deeply stratified sequences typical of rock shelters and caves occupied during the Palaeolithic, the PES approach can equally be of interest for single-layered sites as well as for more

recent periods. Its application should not be restricted to reworked deposits, as PES are even more useful for well-preserved sites, where they allow diachronic patterns in human behaviour and environmental change to be traced at a higher resolution of analysis. PES also help discern the type of mixing that is the easiest to tackle in Pleistocene deposits, namely analytical lumping due to excavation or curation. Finally, the definition of PES is of particular importance for chronological studies, especially those that use Bayesian modelling with stratigraphic constraints (see Discamps et al., 2015 for a discussion of the impact of stratigraphic constraints on Bayesian modelling of radiocarbon dates).

Why the post-excavation definition of stratigraphies using vertical spatial data is not common practice probably reflects several historical factors that only a detailed historical study might one day bring to light (e.g., Plutniak, 2021a). These factors likely include the time-consuming nature of these analyses, the unavailability of adequate computer power (at least in the past), the scarcity of appropriate tools (software or statistics), the lack of a proper theoretical framework for post-excavation stratigraphies, and, potentially, the influence of research traditions still well anchored in prehistoric archaeology. Concerning this latter aspect, the view that stratigraphy is first and foremost defined in the field, cannot be revised afterwards, and should be based uniquely on lithological criteria (i.e. layers defined by geologists) appears highly debatable. The same can be said for the position that spatial analysis primarily concerns the planimetric organisation of a site and is therefore not applicable to caves and rock shelters.

The last two or three decades of Palaeolithic research have seen an increasing amount of data that can be meaningfully explored spatially. This trend is almost certainly due to shifts and refinements in fieldwork and analytical methodologies, including the emergence of technological analysis of lithic assemblages, the detailed study of bone surface alterations, the identification of long bone shaft fragments, and, more generally, the increase of science-based approaches to the archaeological record. In this sense, the potential contribution of PES to archaeology is gradually increasing.

Furthermore, it remains possible that vertical spatial data is more often included in archaeological practice than what can be seen in the literature (i.e. it is unpublished or appears only in grey literature). Even if this is the case, the absence of PES analyses in publications still poses serious questions concerning the reproducibility of the stratigraphic analysis of archaeological sequences. In some respects, the spatial analysis of piece-plotted artefacts can constitute a more objective view of a site, allowing for the redefinition of units based on explicit, clearly stated criteria that can be statistically investigated. Moreover, these types of analyses move us away from a reliance on layers defined during fieldwork following difficult-to-test criteria. In a scientific community that increasingly relies on open-data, the publication of XYZ coordinates underlying PES constitute important datasets for future studies, allowing reproducibility as well as the archiving of archaeological heritage data. While the interpretation of vertical spatial data and the definition of post-excavation assemblages remains somewhat subjective, the field data itself is significantly more objective. With this being the case, whenever possible, making freely available field data and publishing the process behind such PES studies are vital first steps towards better reproducibility (e.g., databases made available on the <http://www>.

[oldstoneage.com](https://oldstoneage.com) website; supplementary data in Gravina et al., 2018 and Discamps et al., 2019). As excavation is an irreversible process, field data, notably spatial information (piece-plotted data and the location/depth of spits), allow analysts to reconstruct sites and build as many PES as necessary, using techniques and methods that improve over time.

Pushing forward PES requires the development of tools for facilitating the spatial exploration of archaeological data in three dimensions as well as more advanced statistical treatment of data. For the former, several software or R packages specifically designed for the three-dimensional exploration of intra-site spatial data exist, such as the NewPlot program (Dibble & McPherron, 1988), scripts adapted for the DataDesk software (Lacrampe-Cuyaubère, 1997), Python scripts for ArcGIS (Roy Sunyer, 2015), and Shiny R applications designed for the Poeymaü (Plutniak, 2021b) and Saint-Césaire (Couillet et al., 2022) sequences. The development of new user-friendly tools for people unfamiliar with GIS would be useful to the more widespread application of PES studies. As a starting point, a quick and simple tutorial for basic PES analysis in QGIS is provided in the Supplementary Information (SI #3). Open-source R Shiny applications dedicated to the intra-site spatial analysis of piece-plotted archaeological remains have also recently been published by some of us: the SEAHORS application (Royer et al., 2023), the archeoviz application/R package (Plutniak, 2023), and its related web portal (<https://analytics.huma-num.fr/archeoviz/home>). For the latter issue of statistical developments, specifically, adapted statistical packages would go some way in ensuring a more robust definition of assemblages through spatial analysis, including its automatization. The TSAR (topological study of archaeological refitting) approach (Plutniak, 2021c), implemented through the archeofrag R package (Plutniak, 2022), constitutes an important step in this regard, as it allows for measurements of cohesion and admixture of spatial units based on the structural properties of groups of refits. Additionally, a R script adapting Ripley's K functions to PES studies is concurrently made available at <https://github.com/marchaeologist>. It allows the spatial association between two types of objects to be tested in 3D (e.g., whether the spatial distribution of reindeer and red deer bones are similar or not). Future developments should also tackle the specific challenges of 3D spatial analysis in which one dimension (time) often plays an overly important role.

A core idea of PES is that there is no unique stratigraphy for a given site (Hedberg, 1976; Texier, 2000); in other words, the original field stratigraphy does not accurately reflect an archaeological reality, its complexity and the singular histories of each archaeological attribute investigated (e.g., technical traditions, subsistence strategies, economy). The nature of each of these attributes within the archaeological record depends on their own history and should therefore be investigated as such. PES are reflexive rather than definitive, they can be constructed throughout the course of studying a site, with each discipline providing their own "stratigraphic views" of the sequence. It is the subsequent comparison of assemblage boundaries where the PES approach proves most interesting archaeologically. The establishment of multi-stratigraphies has the potential of considerably modifying our perception of interactions between different factors, notably by more precisely identifying synchrony or asynchrony between diachronic changes (i.e. cultural, environmental) in the archaeological record.



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**Data Availability** All the data and materials are directly available in the manuscript.

## Declarations

**Ethical Approval** Not applicable.

**Consent to Participate** All authors consent to participate.

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