

Application of spatial statistics to the study of site formation processes

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Abstract

Space is an ineluctable reference dimension in Palaeolithic research for monitoring site formation and modification processes. Quantitative, hypothesis-driven analyses of spatial patterns are paramount to understand the dynamics of cultural and natural processes and, therefore, to correctly interpret past human behaviours. However, spatial statistics are seldom used in a taphonomic perspective. This cumulative dissertation aims to contribute to the development of a spatial taphonomic approach to the study of site formation processes. Multilevel multiscale spatial statistics are applied to the taphonomic study of *I*) the Lower Palaeolithic site of Pirro Nord 13, Italy; *II*) the Middle Pleistocene open-air site of Marathousa 1, Greece and *III*) the Late Villafranchian palaeontological locality of Tsiotra Vryssi, Greece.

The first study evaluates the reliability of the spatial and stratigraphic association of the lithic artefacts with the faunal remains that are used for the biochronological estimate of the site of Pirro Nord 13. The spatial properties of both biostratigraphic and diagenetic processes are investigated. Results of our analyses confirm the stratigraphic integrity of the deposit. In the second study, statistical inference is conducted in order to test two contrasting models of deposition - autochthonous vs. allochthonous. A geoarchaeological approach is adopted for the analysis of the orientation and three-dimensional distribution of the finds. Results of our analyses are consistent with minor transportation and substantial spatio-temporal association of the lithic and faunal assemblages, thus supporting the current interpretation of Marathousa 1 as a butchering site. The third study elaborates on a hitherto little investigated aspect of spatial taphonomy: multilevel anisotropy. Recursive anisotropy is detected both at the level of taphonomic elements and at the assem-

blage level at Tsiotra Vryssi. Along with analysis of the differential preservation of skeletal elements and sedimentological observations, the taphonomic history of the site is unravelled. Furthermore, by conducting a spatial taphonomic analysis of a non-human related faunal assemblage, this study contributes to the building of an essential referential framework for the interpretation of human-related fossil assemblages deposited in fluvial environments.

Spatial taphonomy complements the traditional archaeological, geoarchaeological and taphonomic approaches. It enhances our understanding of the processes forming archaeological and palaeontological assemblages, with implications for palaeoecological reconstruction, biochronological estimates and the interpretation of past human behaviours.

Zusammenfassung

Raum ist eine wesentliche Referenzdimension in der paläolithischen Forschung um die Bildungs- und Modifizierungsprozesse archäologischer Fundstellen zu untersuchen. Quantitative und hypothesenbasierte Analysen räumlicher Muster sind von entscheidender Bedeutung um die Dynamik kultureller und natürlicher Prozesse zu verstehen und um vergangenes menschliches Verhalten korrekt interpretieren zu können. Räumliche Statistiken wurden bislang jedoch eher selten in einer taphonomischen Perspektive angewendet. Diese kumulative Dissertation leistet einen wesentlichen Beitrag zur Entwicklung eines raum-taphonomischen Ansatzes zur Untersuchung von Fundstellenbildungsprozessen. Mehrstufige und mehrfach-skalierte räumliche Statistiken werden zur Untersuchung der Taphonomie folgender drei Fundstellen angewendet: I) die altpaläolithische Fundstelle Pirro Nord 13, Italien; II) die mittelpleistozäne Freilandfundstelle Marathousa 1, Griechenland; und III) die paläontologische Fundstelle des späten Villafranchiums Tsiotra Vryssi, Griechenland.

Die erste Studie untersucht die Verlässlichkeit des räumlichen und stratigraphischen Zusammenhangs zwischen lithischen Artefakten und Faunenresten, anhand derer die Fundstelle biochronologisch eingeordnet wurde. Dabei werden die räumlichen Eigenschaften von biostratinomischen und diagenetischen Prozessen untersucht. Die Ergebnisse unserer Analysen bestätigen die stratigraphische Integrität der Ablagerungen. In der zweiten Studie wird eine statistische Inferenz durchgeführt, um zwei gegensätzliche Ablagerungsmodelle zu testen – autochthon vs. allochthon. Dabei wird ein geoarchäologischer Ansatz zur Analyse der Orientierung und dreidimensionalen Verteilung der Funde herangezogen. Die Ergebnisse unserer Analysen bestätigen eine geringe Fundverlagerung sowie eine eindeutige raum-zeitliche Vergesellschaftung der lithischen Funde und Faunen-

reste und unterstützen somit die aktuelle Interpretation von Marathousa 1 als Schlachtplatz. Die dritte Studie beschäftigt sich mit einem nur selten untersuchten Aspekt der räumlichen Taphonomie – der mehrstufigen Anisotropie. Rekursive Anisotropie wird sowohl auf der Ebene taphonomischer Elemente als auch auf der Ebene der Fundvergesellschaftung festgestellt. Zusammen mit der Analyse der unterschiedlichen Erhaltung der Skelettelemente und sedimentologischen Beobachtungen wird die taphonomische Geschichte der Fundstelle offenbart. Desweiteren trägt die Studie durch eine raumtaphonomische Analyse einer nicht vom Menschen verursachten Ansammlung von Faunenresten zur Erstellung eines Referenzrahmens für die Interpretation von menschlich verursachten fossilen Fundvergesellschaftungen in fluvialen Umgebungen bei.

Räumliche Taphonomie ergänzt die traditionellen archäologischen, geoarchäologischen und taphonomischen Untersuchungsansätze. Sie verbessert unser Verständnis um die zugrundeliegenden Prozesse, die archäologische und paläontologische Ansammlungen generieren, und hat Auswirkungen für paläoökologische Rekonstruktionen, biochronologische Einschätzungen und Interpretationen vergangener menschlicher Verhaltensweisen.

List of publications for cumulative dissertation

Publications submitted in fulfilment of the requirements of this cumulative dissertation. Numbers in parenthesis represent percentage of own contribution to the: (scientific idea/data generation/analysis and interpretation/paper writing).

Accepted papers:

- Appendix A (100/80/100/90):
Giusti D. and M. Arzarello. 2016. The need for a taphonomic perspective in spatial analysis: Formation processes at the Early Pleistocene site of Pirro Nord (P13), Apricena, Italy. *Journal of Archaeological Science: Reports* 8, 235–249.
DOI: [10.1016/j.jasrep.2016.06.014](https://doi.org/10.1016/j.jasrep.2016.06.014).
- Appendix B (100/80/100/90):
Giusti D., V. Turloukis, G. E. Konidaris, N. Thompson, P. Karkanas, E. Panagopoulou and K. Harvati. (*In press*). Beyond maps: Patterns of formation processes at the Middle Pleistocene open-air site of Marathousa 1, Megalopolis Basin, Greece. *Quaternary International*.
DOI: [10.1016/j.quaint.2018.01.041](https://doi.org/10.1016/j.quaint.2018.01.041).

Manuscript ready for submission:

- Appendix C (100/80/100/80):
Giusti D., G. E. Konidaris, V. Turloukis, N. Thompson, D. S. Kostopoulos, G. Koufos and K. Harvati. (*To be submitted*). Recursive anisotropy: A spatial taphonomic study of the Late Villafranchian vertebrate assemblage of Tsiotra Vryssi, Mygdonia Basin, Greece.

Introduction

Space, conceived as a collection of three-dimensional relationships between objects, is an indispensable analytic dimension in investigating the archaeological record. Accurate measurements and rigorous analyses of relative distances and directions between entities are paramount to understanding the correlation between events and, therefore, correctly interpreting past human behaviours.

Spatial associations, or the degree to which archaeological remains occur in spatial proximity, have long been used as key arguments for modelling past human behaviours - e.g., based on geological context, vertical distribution and spatial association of artifacts and bones, [Leakey \(1971\)](#) classified the Olduvai sites from Beds I and II as living floors, butchering sites and sites with diffused material or channel sites. However, spatial patterns are rarely a snapshot in time and space of past human activities and most likely the emerging products of syn- and post-depositional processes. Indeed, these processes may rework or obliterate the original patterns and create spurious spatial associations - e.g., see [Benito-Calvo and de la Torre \(2011\)](#), [Domínguez-Rodrigo et al. \(2012\)](#), [Petraglia and Potts \(1994\)](#), and [Potts \(1988\)](#) for later reexaminations of the Olduvai sites based on analyses of orientation patterns.

With a better understanding of the complex nature of the archaeological record, regarded as the by-product of the heterogeneous disposition of syn- and post-depositional processes, an old question rises again: to what extent do the observed spatial patterns reliably reflect past human behaviours, and how informative can they be on the dynamics of natural processes?

The archaeological record, “at best a static pattern of associations and covariations among things distributed in space” ([Binford, 1980](#), p.4), nonetheless retains information about the dependencies,

relationships and interactions between the past cultural system and its surrounding environment. Variations in the observed spatial patterns can be explained by the dynamics of formation processes. Therefore, the spatial distribution of entities is among the most informative aspects of the archaeological variability. Following [Binford \(1972\)](#), time and space in Paleolithic research can only be conceived as

“[...] reference dimensions serving as reference frameworks for monitoring systemic processes. Propositions set forth about the disposition of particular cultural referents in time or space can never serve other than descriptive functions. Such facts only become relevant in the context of hypothetical arguments dealing with the dynamics of processual functioning or change.” – LR Binford (1972). Contemporary model building: paradigms and the current state of Paleolithic research. In: *Models in Archaeology*. Ed. by DL Clarke. London: Methuen & Co. LTD, 109–166, p.123

Similarly, propositions about cultural dynamics only become relevant if determined in a hypothesis-testing framework that takes into account cultural and natural formation processes ([Schiffer, 1983](#)). Hence, in order to draw reliable inferences about past human behaviours, one must consider the spatio-temporal context of syn- and post-depositional processes, and identify the relevant spatio-temporal scales at which they occur ([Bailey, 2007](#); [Butzer, 1982](#); [Dibble et al., 1997](#); [Goldberg et al., 1993](#); [Nash and Petraglia, 1987](#); [Rapp and Hill, 2006](#); [Schick, 1986](#); [Schiffer, 1987](#); [Texier, 2000](#)).

The spatial implications of behavioural processes have long been understood and analysed in quantitative manners ([Clarke, 1977](#); [Hodder and Orton, 1976](#); [Whallon, 1974](#)). However, while space is an inherent property of any biotic or abiotic process, spatial statistics are seldom used in a taphonomic perspective. Whereas well established quantitative methods are generally employed for the analysis

of orientation patterns of finds, the analysis of archaeological spatial patterns is most commonly conducted by visual, intuitive examination of distribution maps. On the other hand, statistical inference of spatial variations, in combination with the traditional archaeological, geoarchaeological and taphonomic approaches, enhances our understanding of the processes that generated the observed patterns.

The main aim of this PhD project is to contribute to the development of a new methodological approach (namely, spatial taphonomy) to the study of site formation processes. In its broadest sense, spatial taphonomy refers to the quantitative, hypothesis-driven analytical approach to the study of the spatial properties of taphonomic processes. Founded on formation theory and evolutionary taphonomy, this cumulative dissertation builds upon three applications of advanced multilevel multiscale spatial statistics to the study of the biostratigraphic and diagenetic processes at:

- **(Paper I)** the Lower Paleolithic site of Pirro Nord 13, Italy;
- **(Paper II)** the Middle Pleistocene open-air butchering site of Marathousa 1, Greece;
- **(Paper III)** the Late Villafranchian palaeontological locality of Tsiotra Vryssi, Greece (Fig. 1.1).

The following sections introduce the theoretical and methodological backgrounds of this PhD project. Chapter 2 (Objectives) presents the main research goal and the specific objectives of the three papers that form this cumulative dissertation. Chapter 3 (Results and discussion) summarises the key results of the three papers and reviews the fundamental contribution of this dissertation to the definition of spatial taphonomy. Finally, the last chapter (Concluding remarks) discusses future research directions.

Theoretical background: formation processes

From the beginning of Paleolithic research, the spatial and stratigraphic association of stone artifacts with remains of extinct animals

Introduction



Figure 1.1: Geographical locations of the three studied sites: paper I) Pirro Nord 13; paper II) Marathousa 1; paper III) Tsiotra Vryssi.

was critical to assessing the antiquity of the human occupation of Europe. Evidence was based on stratigraphic sequences and the contextual integrity of the assemblages (Lyell, 1863). Already in the end of the 19th century, scholars were interested in the geological processes involved in the formation of archaeological deposits. Concepts and methods that originated in earth sciences were pivotal in interpreting evidence of the human past.

This early geoarchaeological approach continued to develop in the 20th century. In the '60s, the work of Isaac (1967) at Olorgesailie (Africa) put the bases for the development in the '70s and '80s of a mostly Anglo-American research tradition in site formation processes (Binford, 1978, 1979, 1980, 1981b; Clarke, 1973; Schick, 1984, 1986; Schiffer, 1972, 1976, 1983, 1987, among others). With the realization of the importance of adopting a natural science perspective in understanding the broader context of the archaeological deposit, archaeologists explicitly shifted their interest towards the processes

(natural and cultural) involved in the formation and modification of the archaeological record. Despite the many conceptual differences that fed several scientific disputes (e.g., the Binford-Schiffer controversy), processual archaeologists shared the main concern for the validity of the behavioural inferences made from the material record, and promoted similar theoretical frameworks and methods, critical to the understanding of past dynamic systems from the static archaeological record. Under the auspices of formation theory (as later defined by [Shott, 1998](#) who reconciliated Binford's middle-range theory ([Binford, 1977](#)) and Schiffer's reconstruction theory ([Schiffer, 1988](#))), a number of actualistic researches attempted to establish causal links between processes and patterns of cultural and environmental systems, using ethnographic ([Binford, 1978](#); [Gifford-Gonzalez et al., 1999](#); [Haynes, 1988](#); [Hill, 1979](#); [Yellen, 1977](#)) or experimental ([Gifford-Gonzalez et al., 1985](#); [Schick, 1987a](#)) sources of information. The seek for a quantitative and hypothetical-deductive methodological framework was fundamental to the development of archaeology as a scientific discipline.

Meanwhile, contemporary research on early hominid evolution ([Behrensmeier, 1975a](#); [Boaz and Behrensmeier, 1976](#); [Brain, 1981](#); [Gifford and Behrensmeier, 1977](#); [Hill, 1976](#)) extended the original definition of taphonomy as "the study of the transition [...] of animal remains from the biosphere into the lithosphere" ([Efremov, 1940](#)) to include also the archaeological record. The ephemeral dichotomy between 'taphonomy' and 'site formation processes', based on the nature of remains, eventually dissolved in the last decades towards an integrative and multidisciplinary investigation of the processes, both natural and cultural, that modify the original properties of organic and inorganic material ([Domínguez-Rodrigo et al., 2011](#)).

It is currently firmly established that the interpretation of the archaeological record may be profoundly affected by distortion, disturbance and poor preservation. Biostratigraphic and diagenetic modifications occur in a spatio-temporal dimension as a consequence of the interaction of the deposit with the biosphere and the lithosphere. Accordingly, a variety of human behaviours (e.g., site re-occupation,

trampling), as well as biological (e.g., trampling caused from other animals, ravaging, burrowing), geological (e.g., deflation, erosion, swelling and shrinking of clay) and chemical processes (e.g., oxidation) can modify the archaeological context before final burial (Rapp and Hill, 2006). Diagenetic processes include physical, chemical and biological modifications at work after burial. Furthermore, re-elaboration (*sensu* Fernández-López, 1991) may occur, such that already buried material is exhumed (Fig. 1.2). Nevertheless, taphonomic alteration processes imply modification, but not necessarily destruction. The positive role of taphonomic alteration processes is expressed in the differential preservation of taphonomic products, at different levels of organization (Fernández-López, 2006). For example, dispersion processes (such as fluvial processes) may modify the spatial location, orientation and removal degree of basic taphonomic elements (bone specimens), causing at the same time changes in the structural properties (size, density, spatial distribution and diversity) of higher level entities (e.g., taphonic population).

By rejecting the simplistic notion that a site formation study can remove the negative veil of natural post-depositional modification processes and reveal the original, pristine archaeological occurrence, it must be understood that cultural and natural processes of different frequency and intensity are dynamically linked in a spatio-temporal framework. In a sense, a spatio-temporal multiscale palimpsest of processes is set from the time the site is occupied/revisited to its abandonment and recovery. Each process depends on the outcome of the former, and has the potential to rework, obliterate or preserve it. Thus, the retention of traces of the earliest cultural processes is a function of the type, number and intensity of the latest processes. As mentioned, such a hierarchical organization works in a spatio-temporal dimension, and generates stratified spatio-temporal patterns which may retain important traces of the systemic processes. The archaeological record, more than a simple two-layer structure (cultural/natural), is composed of a complex palimpsest of processes (Fig. 1.2).

In analysing such a spatial palimpsest, different scales bring into

focus different processes - as also suggested by the ‘time perspectivism’ approach (Bailey, 2007). The spatial scale refers to both the physical extent of a process (range) and the resolution of the measured traces of that process. Hence, according to ‘space perspectivism’, our perception of the spatial structure of a process is directly related, and limited, to both the extent of the study area and the resolution of the sampling design. Statistical methods also affect our ability to identify spatial patterns (Dale and Fortin, 2014). Consequently, the spatio-temporal scale (range) of the process of interest, requires adequate pattern resolution and extent. The investigation of such patterns, by multiscale multilevel spatial statistics, may inform our understanding of the contextual system and enhance the reconstruction of past human behaviours. Limitations can only be specified with reference to given research problems (Binford, 1981a).

Yet, besides the palimpsest nature of formation processes, other analytical issues in formation theory are those of equifinality and multifinality. Equifinality refers to the capacity of open systems to achieve the same or similar outcome states from different starting points, and/or through different processes (Lyman, 2004; Premo, 2010). Thus, spatial equifinality refers to the ability of different processes to generate similar spatial patterns. Conversely, the related concept of multifinality holds that a single process may lead to dissimilar outcomes. Nevertheless, embracing a configurational approach (Binford, 1981b; Bunn, 1991; Domínguez-Rodrigo et al., 2010), the uncertainty caused by equifinality/multifinality can be reduced by using several distinctive criteria to characterize the process, as well as comprehensive analytical methods and statistical inference. Indeed, limited variables and statistics may not be sufficient to unequivocally discriminate different processes. Moreover, employing a hypothesis testing framework for selecting multiple competing models is a compelling strategy to bypass with confidence the equifinality/multifinality inferential pitfalls. Nevertheless, it is necessary to build a rich, exhaustive frame of references from actualistic studies and archaeological or palaeontological cases where the signature might be more explicitly recognizable and attributable to

particular sets of circumstances. Hypothesis-testing methods need empirically grounded references. Far from being analogues of general validity, the utility of such comparative references lies in the use of interpretation-neutral units of analysis and relevant, quantitative methods.

By using exhaustive, advanced spatial statistics and hypothesis-testing methods, this dissertation contributes to the development of a spatial taphonomic approach for the investigation of the multi-level and multiscale spatial properties of taphonomic processes. Spatial taphonomy represents a synthesis, the integration in a spatio-temporal framework of the methodological inputs from the extended taphonomic approach.

Methodological background: spatial statistics

Among other taphonomic analyses, such as particle size distribution, weathering stages and skeletal part representation, spatial analysis has long been universally recognized to be paramount in the investigation of the depositional context (Butzer, 1982; Dibble et al., 1997; Lyman, 1994; Rapp and Hill, 2006; Texier, 2000, among others). However, besides well developed quantitative methods for the fabric analysis of orientation patterns, spatial statistics are still insufficiently applied to the study of spatial patterns.

Fabric analysis has its origin in earth sciences and is defined as the study of the orientation (plunge and bearing) of particles within a sedimentary matrix. It was early introduced in the taphonomic study of the orientation of mammal bones as an indicator of the depositional context (Toots, 1965; Voorhies, 1969). Subsequently, the first archaeological applications (Bar-Yosef and Tchernov, 1972; Isaac, 1967) led to an increasing number of studies of the effect of natural processes (most readily water-flows) on palaeontological and

¹Model of taphonomic modifications modified after Fernández-López (1991). Environmental processes background modified after Dale and Fortin (2014). *P.antiquus* illustration by DFoidl, used under CC BY.

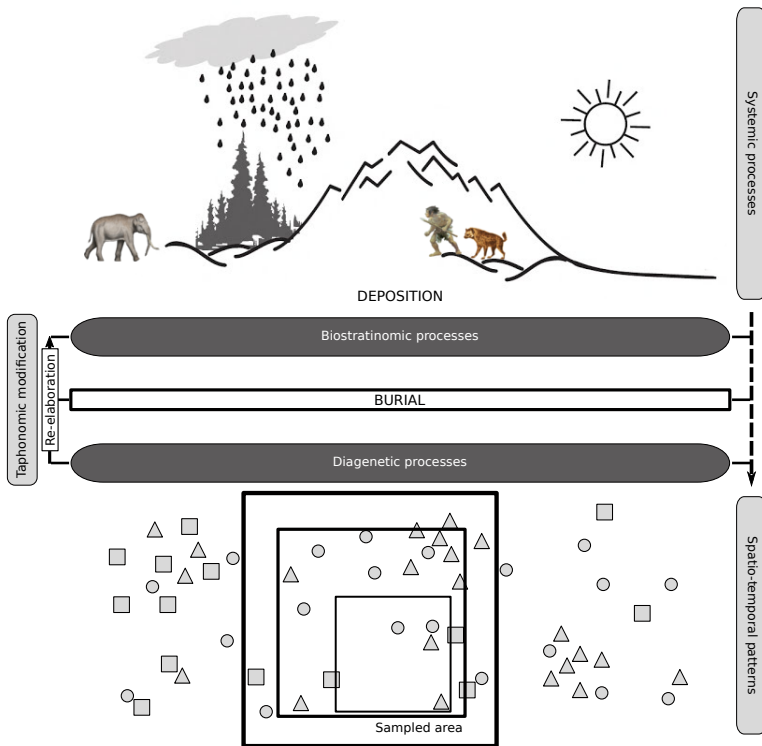


Figure 1.2: Natural and cultural formation processes, working in a spatio-temporal framework, produce spatio-temporal point patterns, subject to ulterior modification by taphonomic processes. The recorded spatial pattern retains taphonomic information, and eventually traces of the systemic processes. Thus, the multiscale statistical analysis of static spatial patterns aims to recover the dynamic interactions between taphonomic and past human behavioural processes. ¹

archaeological assemblages (Benito-Calvo et al., 2009; Bertran and Texier, 1995; Domínguez-Rodrigo et al., 2012; Domínguez-Rodrigo and García-Pérez, 2013; Domínguez-Rodrigo et al., 2014d; Fiorillo, 1991; Lenoble and Bertran, 2004; McPherron, 2005, 2018; Petraglia and Potts, 1994; Schick, 1987b, among others). Circular statistics are used to evaluate with certain level of confidence the observed fabric pattern. Interpretations are given within frames of experimental and actualistic reference studies.

On the other hand, the analysis of archaeological spatial patterns lacks a more formal, quantitative framework, being on the contrary mostly based on visual examinations and intuitive interpretations of distribution maps and cross-sectional plots alike (Bevan et al., 2013). Yet, since the early '70s, quantitative methods have been borrowed from neighbouring disciplines (namely, geography and ecology) in the attempt to abandon the traditional, intuitive 'eyeballing' practice of spotting spatial patterns (Clarke, 1977; Hodder and Orton, 1976; Whallon, 1974). However, only a relatively small number of studies have continued to adopt advanced spatial statistics to unravel past human behaviours from scatters of material culture (Bevan and Conolly, 2006, 2009; Bevan and Wilson, 2013; Crema, 2015; Crema et al., 2010; Crema and Bianchi, 2013; Djindjian, 1999; Domínguez-Rodrigo and Cobo-Sánchez, 2017; Eve and Crema, 2014; Hietala and Larson, 1984; Kintigh and Ammerman, 1982; Orton, 1982, 2004; Palmisano, 2013). Although these studies acknowledged post-depositional effects, they lack explicit consideration of the spatial structure of natural processes. Application of advanced spatial statistics to the study of taphonomic processes is scarce. A first attempt to adopt a taphonomic perspective in spatial analysis dates back to the early '80s (Hivernel and Hodder, 1984). Yet, more recent taphonomic studies only made secondary, limited use of spatial statistics (Domínguez-Rodrigo et al., 2014b,c; Lenoble et al., 2008).

Along with fabric and patterns analyses, from a different spatial perspective, refitting analysis is as well fundamental to the study of site formation processes (Morin et al., 2005; Petraglia, 1992; Todd

and Stanford, 1992; Villa, 1982, 2004, among others). It commonly consists of vertical and horizontal plotting of join lines and subsequent visual evaluation of spatial patterns. In this sense, like the analysis of distribution maps, it lacks a more formal, quantitative framework. Quantitative analysis of different aspects of the refitting (i.e., line length and orientation) is rare (Bargalló et al., 2016; Romagnoli and Vaquero, 2016; Vaquero et al., 2017). Moreover, if important data are not published, it is often difficult to evaluate inter-assemblage variability (Vaquero et al., 2017). Indeed, refitting analysis requires an as yet undeveloped, formal referential framework built upon actualistic studies as well. Furthermore, because refitting is particularly demanding, it is far from being systematically used.

Therefore, by moving beyond the intuitive analysis of distribution maps and applying a comprehensive set of multilevel multiscale spatial statistics, this dissertation aims to contribute to the development of a new spatial taphonomic approach that, along with fabric analysis, makes strong use of point pattern analysis.

Two main properties of spatial processes are of interest in point pattern analysis: the intensity, or the distribution of entities (points) in space (1st order property), and the interactions between them (2nd order property). The intensity of a point pattern is defined as the average number of random points per unit area. It informs about homogeneity or inhomogeneity in the distribution of points (e.g., artifacts) generated by a point process (e.g., knapping, trampling, winnowing events) - i.e., it addresses the question of whether the rate of occurrence is uniform or spatially varying across the study area. Intensity is generally evaluated by means of kernel density estimation (Diggle, 1985). Although informative and widespread in the literature, it does not provide sufficient information to reliably infer point interactions. On the other hand, multiscale inter-point interactions are measured by second or higher-order moment quantities, such as the Ripley's K correlation function (Ripley, 1976, 1977) and the distance G-, F- and J-functions. Three different types of inter-point interaction are possible: random, regular or cluster. Regular patterns are assumed to be the result of inhibition processes,

while cluster patterns are the result of attraction processes. Complete spatial randomness (CSR) is sometimes used as reference null hypothesis - the typical research question concerns whether or not the observed pattern is consistent with a CSR process. More often, even if CSR is not scientifically plausible, it still represents a crucial dividing hypothesis that separates spatial clustering from spatial regularity. Statistical inference is achieved by Monte Carlo random simulations of the null hypothesis (Fig. 1.3).

Multitype point patterns consist of several different types of points. The classification of points into types can be based on different criteria: it may be an intrinsic attribute such as the type of find (lithic/fossil), the technological attribute (debris/flake/tool/core) or the dimensional class (small/large). Alternatively, the type may indicate a status (low/medium/high) induced by extrinsic processes (e.g., weathering). Therefore, multitype point patterns are extremely useful to represent the variability of the archaeological record. By using cross-type functions, the analysis of intensities and interactions between different types of entities opens a wide range of applications for spatial taphonomy.

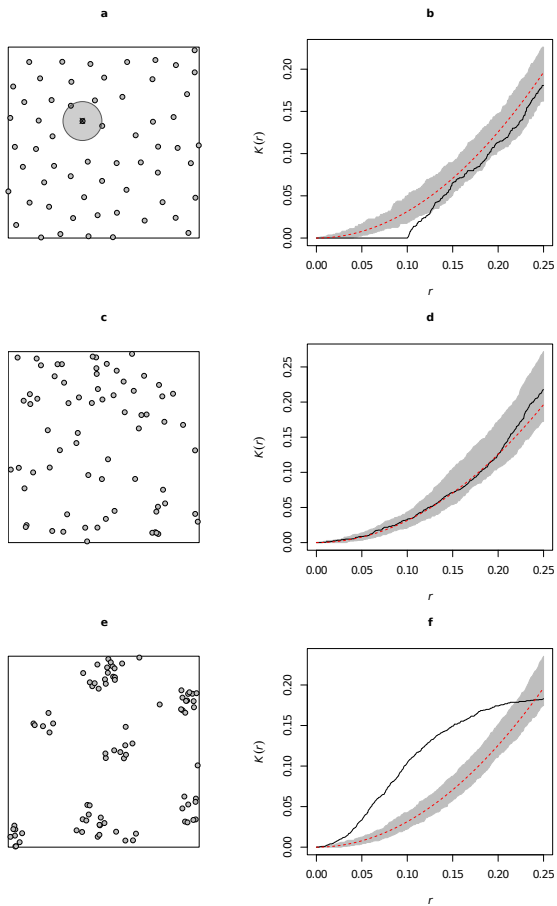


Figure 1.3: Simulated realizations of regular (a), independent (c) and clustered (e) point patterns. The geometry of the empirical K-function is illustrated in (a). It is defined as the cumulative average number of data points lying within a distance r of a typical point. Results of the empirical K-functions (solid black lines) are compared with the theoretical K-function for a Poisson process (red dashed lines) and the grey envelopes of 199 simulated realization of CSR for each of the three patterns (b,d,f).

Objectives

The primary aim of this dissertation is to contribute to the development of a new methodological approach (spatial taphonomy) for the study of site formation processes. By using advanced spatial statistics, spatial taphonomy complements the traditional taphonomic approach and aims to investigate the multilevel and multiscale spatial properties of biostratigraphic and diagenetic processes. It enhances our understanding of the processes forming archaeological and palaeontological assemblages, with implications for palaeoecological reconstruction, biochronological estimates and the interpretation of past human behaviours. Each of the three papers that form this cumulative dissertation contributes to the definition of spatial taphonomy while addressing specific research questions.

Paper I: site integrity and biochronology at Pirro Nord 13

Paper I investigates the processes involved in the formation of the Early Pleistocene site of Pirro Nord 13, Italy ([Arzarello et al., 2007, 2009, 2012](#); [Arzarello and Peretto, 2010](#); [Arzarello et al., 2015](#)). The site provides evidences for one of the earliest hominin occurrences in Western Europe. A Mode 1 lithic assemblage was identified in spatial and stratigraphic association with late Villafranchian/early Biharian mammal remains, including the extinct vole *Allophaiomys ruffoi*, which allowed for a biochronologically refined age between 1.3 and 1.6 Ma ([Lopez-García et al., 2015](#)). The deposit occurs as the fill of a karst fissure, exposed and partially destroyed by ongoing mining activities of a Mesozoic limestone quarry. Since post-depositional processes, such as water-flows internal to the karst sys-

tem, may have put in spatial and stratigraphic contact material of diverse provenience, it is of crucial importance to assess the integrity of the deposit. Therefore, the specific goal of this study is to evaluate the degree and reliability of the spatial association of the lithic artifacts with the faunal remains that were used for the biochronological estimate of the site.

Paper II: autochthonous vs. allochthonous assemblage at Marathousa 1

Paper II uses a comprehensive set of spatial statistics in order to disentangle the formation processes acting at the Middle Pleistocene open-air site of Marathousa 1, Megalopolis Basin, Greece (Harvati et al., 2016; Panagopoulou et al., 2015). The site, dated between 400 and 500 ka on the basis of biochronological (Doukas et al., In press; Konidaris et al., In press), radiometric (Jacobs et al., In press) and palaeomagnetic (Touroloukis et al., In press) results, offers important insights to the understanding of the broader context of the Middle Pleistocene mega-faunal exploitation sites in Europe (Touroloukis et al., In press). In one of the two excavated areas (Area A), a partial skeleton of a *Palaeoloxodon antiquus* and other faunal remains were unearthed spatially and stratigraphically associated with lithic artifacts. A second excavated area (Area B), about 60m from Area A, yielded a rich lithic assemblage also associated with faunal remains, including specimens of other elephants. Cut-marks were identified on bones of the elephant skeleton in Area A and other faunal remains in Area B (Konidaris et al., In press). The find-bearing units in both areas are stratigraphically correlated and represent an *en-mass* deposition by mud- and hyperconcentrated flows in a lake margin environment (Karkanis et al., In press). Due to the secondary depositional context of the site, questions arise about the reliability of the spatial association between the lithic artifacts and the faunal remains. The main aim of this paper is to test two contrasting hypotheses about the autochthony of the archaeological record,

with important consequences for the interpretation of the site in the broader context of the Middle Pleistocene human-proboscidean interactions.

Paper III: anisotropy and selective preservation at Tsiotra Vryssi

Paper III analyses orientation patterns and differential preservation of the fossil record at the Early Pleistocene locality of Tsiotra Vryssi (TSR), Greece (Konidaris et al., 2016, 2015). TSR is located in the Mygdonia Basin, in the fluvio-terrestrial Gerakarou Formation, which consists mainly of a suite of alluvial deposits, including channel-fill sands and gravels, floodplain silty muds and red clays (Koufos et al., 1995). The TSR faunal assemblage is preliminary dated on biochronological grounds between 1.8 and 1.2 Ma (late Villafranchian) (Konidaris et al., 2015). The main goal of this paper is to disentangle the taphonomic history of the TSR locality. Specific research questions address the depositional environment, the number of depositional events (single or multiple) and the degree of transportation of the fossil record (autochthonous vs. allochthonous). Furthermore, a complementary goal of this paper is to contribute to the building of an essential spatial taphonomic reference framework (Domínguez-Rodrigo et al., 2017). Undoubtedly, the spatial taphonomic analysis of non-anthropogenic fossil assemblages is of fundamental importance for the taphonomic interpretation of many Pleistocene sites bearing archaeological material.

Results and Discussion

This section summarizes the key results from the three papers forming this cumulative dissertation and reviews the main contributions of this PhD project to the application of spatial taphonomy in archaeological and palaeontological research.

Paper I: developing a multilevel and multiscale spatial taphonomy

Paper I investigates syn- and post-depositional processes at the archaeological karst deposit of Pirro Nord 13, Italy. The main aim is to assess the stratigraphic integrity of the site and confirm the association of the lithic artifacts with the fossil remains used for its biochronological estimate. By applying spatial point pattern analyses, the paper investigates both *i*) the spatial association of the archaeological and palaeontological remains, and *ii*) the spatial distribution of diagenetic surface alterations on lithic artifacts and fossils (i.e., Fe-Mn oxides, commonly deposited in karst environments by circulating waters).

This is the first study to systematically employ in a taphonomic perspective advanced point pattern analysis of biostratigraphic and diagenetic processes. Specifically, by applying cross-type functions to *i*) the spatial distribution of the finds, this study aims to quantitatively evaluate fieldwork observations regarding their spatial and stratigraphic association. In a hypothesis testing framework, a positive spatial correlation between the two types of finds would indicate that they are more likely found close to each other than would be expected under the alternative hypothesis that they were deposited by

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two independent processes. Therefore, in order to further evaluate the degree of post-depositional disturbance of the deposit, cross-type functions are applied to *ii*) the spatial distribution of the observed diagenetic alterations on the lithic and faunal assemblages, regarded as the outcome of related diagenetic processes. Taphonomic processes are treated as spatial point processes and the observed spatial distribution of taphonomic features is regarded as generated by those processes. Therefore, elaborating on the first law of geography (Tobler, 1970), it is assumed that taphogenic products in space are not mutually independent and that entities which are close to each other are likely to have followed the same genesis. Like in spatial epidemiological studies (Diggle, 2003; Gatrell et al., 1996), a conditional analysis of the distribution of diagenetic alterations is conducted under a random labelling hypothesis: the finds are randomly labelled as *cases* (remains with positive taphonomic status) or *controls* (non-altered remains). Accordingly, the null hypothesis to be tested states that the taphonomic status of each find is random, independent and with a constant risk of occurrence. Thus, the diagenetic process can be regarded as random and independent from the original condition of the finds. The alternative hypothesis assumes that the spatial aggregation of Fe-Mn coated faunal remains and lithic artifacts - and consequently spatial segregation from non-oxidized ones - indicates the action of localized diagenetic agents.

Results of the analyses confirm the field observations about the close stratigraphic association between lithic artifacts and faunal remains, supporting the previous interpretation of the deposit as the result of repeated mass-wasting processes, filling the karst sink-hole directly opening to the outside (Arzarello et al., 2012). The presence of partially articulated vertebrate skeletal elements and their general low degree of weathering also suggest a quick burial and minor transport (Bagnus, 2011). The autochthony of the assemblage is further corroborated by the fresh conditions of the lithic artifacts (Arzarello et al., 2015). Furthermore, no statistically significant evidence of post-depositional reworking processes are found.

The random distribution of diagenetic alterations most probably occurred as the result of independent processes, such as the content of moisture or organic matter in the sedimentary body (Burrioni et al., 2002). Integrating previous taphonomic observations on the lithic and faunal assemblages, this study confirms from a spatial taphonomic perspective the stratigraphic integrity of the Pirro Nord 13 deposit.

With this study, the analysis of taphonomic spatial patterns contributes to a so far unexplored field of research which finds compelling applications in Paleolithic research. As an example, karst systems, working as sediment traps, constitute secure archives of the early past of human evolution. However, interpretations of karst deposits require accurate taphonomic analyses, especially when spatial associations are used as key arguments for supporting human behavioural interpretations (Dirks et al., 2015; Egeland et al., 2018; Sala et al., 2015, among others).

Paper II: working in hypothesis testing frameworks

Paper II tests two contrasting models of deposition (autochthonous vs. allochthonous; *sensu* Domínguez-Rodrigo et al., 2012; Fernández-López, 1991) at the open-air site of Marathousa 1, Greece. The main aim is to evaluate the ‘behavioural reliability’ of the observed spatial association between lithic artifacts and faunal remains - i.e., estimate the extent to which the recorded spatial association is effectively indicative of past human activities.

As pointed out earlier, behavioural inferences must be supported by statistical inferences in a hypotheses testing framework when analysing spatial patterns. Paper II addresses this need, by moving beyond the traditional intuitive method of eye-spotting spatial patterns and by applying in a geoarchaeological perspective comprehensive spatial statistics. Fabric analysis is employed to statistically test isotropic patterns and correlate the orientation assumed by elements from different stratigraphic units with plausible geological

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processes. Point pattern analysis is used to investigate the multiscale relative distances between finds of different types and from different stratigraphic units. Moreover, a new method for the analysis of the vertical distribution is developed, which overcomes the limitations of traditional cross-section projections. Monte Carlo simulations are used in a hypothesis testing framework, in order to have appropriate confidence levels of inferences.

According to the autochthonous hypothesis, the carcass of the *Palaeoloxodon antiquus*, together with other faunal remains and lithic artifacts, was slightly buried in, or lying on the exposed surface of a lake shore mudflat area of the site. A subsequent mud- or hyperconcentrated flow event would have eroded and scoured that surface, entraining the clastic material (including artifacts) and re-depositing it (*sensu* Fernández-López, 1991) at a short distance. The flow would have as well buried the elephant carcass, eventually displacing its elements at a small scale. This model implies the loss of any original spatial relations between remains, but minor transport from the primary depositional location. Thus, although in secondary position, the lithic assemblage can be regarded as spatially correlated with the faunal assemblage, supporting the current interpretation of Marathousa 1 as a butchering site. On the other hand, according to the alternative allochthonous hypothesis, the massive mud- or hyperconcentrated flow would have re-elaborated material (*sensu* Fernández-López, 1991) and significantly transported it from the original loci of deposition to the site. Consequently, the recorded spatial association between the lithic artefacts and the faunal remains would not support drawing inferences about on-site human exploitation of faunal resources. The two models are spatially exclusive. However, a certain degree of contemporaneous presence of humans and animals before final burial is expected in either cases. Indeed, the *en mass* deposition of mud- and hyperconcentrated flows, entraining lithic artifacts, faunal remains and capping the elephant skeleton, represents a *terminus ante quem* for the deposition of the archaeological and palaeontological material, independently of its location. Since spatial association does not necessarily imply causa-

tion, here the research question is whether the archaeological assemblage, composed of small-sized lithic and bone artifacts, is correlated with the remains of the elephant *Palaeoloxodon antiquus* as well as other mammals.

In order to test the two mutually exclusive depositional models, this study explicitly adopts a geoarchaeological approach. By considering the archaeological material as a sedimentary component (i.e., remains are treated as geological clasts), the spatial distribution of the finds (orientation of elongated elements and three-dimensional position) is interpreted on the basis of actualistic and experimental observations of mud- and hyperconcentrated flows (Benvenuti and Martini, 2002; Lindsay, 1968; Pierson, 2005). Therefore, complementary spatial statistics (fabric and point pattern analyses) are used in an hypothesis testing framework. The allochthonous model assumes continuous vertical distribution of the material. Indeed, massive processes such as mud- or hyperconcentrated flows have high erosional power and rather chaotic structure, which may result in inverse or normal grading (Benvenuti and Martini, 2002). Linear fabric, parallel or normal to the flow direction, is also reported (Benvenuti and Martini, 2002; Lindsay, 1968). Moreover, consistency with a spatial random and independent distribution of clasts is expected for the material entrained in a massive, chaotic flow.

On the other hand, lithic artifacts are found rather clustered and aggregated around the elephant skeleton in Area A. In Area B, the distribution of finds suggest also clustering and significant spatial correlation. Absence of vertical grading and concentration of unsorted material in the proximity of the erosional surfaces associated with the flow are observed in both areas. An isotropic pattern is detected in Area B, while the elephant skeletal elements lie in close anatomical association, slightly displaced and preferentially oriented. All together, the results of the spatial analyses reject with confidence the null hypothesis of an allochthonous deposition in favour of the alternative autochthonous model. Hence, significant displacement of the material can be excluded. The same flow that

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capped the elephant in Area A most probably locally reworked at a small scale the already exposed or slightly buried and spatially associated lithic and faunal assemblages. Minor transportation is further confirmed by preliminary taphonomic observations conducted on the archaeological and faunal assemblages. Lithic artefacts are very well preserved and technologically consistent (Tourloukis et al., [In press](#)). Faunal remains, although highly fragmented, do not show traces of rounding and are in a good state of preservation (Konidaris et al., [In press](#)). Therefore, multiple lines of evidences support the current interpretation of Marathousa 1 as a butchering site.

However, high-resolution inferences about the use of space by human groups at the site are unreliable. The observed spatial pattern is indeed the result of a massive geological event capping a palimpsest of spatial processes. Considering the rate of bone fragmentation, the high frequency of lithic debris and the spatial density of the finds, it is likely that the assemblage represents locally repeated events of hunting/scavenging and exploitation of lake shore resources. Clearly, such mixed palimpsest of events constrains the spatio-temporal resolution of our inferences. It does not intuitively retain information regarding the short-time episodes of past humans activities. Most likely, it allows us to identify patterns and trends in longer time spans and to discern behavioural significance over the middle- to long-terms.

Nevertheless, with reference to a given set of research problems (Binford, 1981a) and in favorable depositional context, spatial taphonomy, along with the traditional archaeological, geoarchaeological and taphonomic approaches, may enhance our understanding of palimpsests and better approximate the spatio-temporal scale of archaeological inferences. With regard to high-resolution short-term reconstruction, actualistic research provides suitable guidelines, but not universally valid analogues. Moreover, the use of ethnographic or experimental models as referential framework retains a structural tension - a mismatch between the time range of the ethnographic or experimental observation and the time span of the archaeological record. On the other hand, palaeontological assemblages in fa-

vorable, explicit depositional context offer an opportunity to build important references to the middle- to long-term natural processes.

Paper III: building frames of references

Paper III analyses site formation processes at the vertebrate locality of Tsiotra Vryssi, Greece. By conducting a spatial taphonomic study of a non-human related faunal assemblage, this study contributes to the building of an essential referential framework for the taphonomic interpretation of human-related fossil assemblages deposited in fluvial environments (Domínguez-Rodrigo et al., 2017).

Fluvial deposits are essential archives for Paleolithic research. Water-flow processes, among the most important natural processes involved in the formation and modification of palaeontological and archaeological sites, have long been the focus of rigorous investigations (Behrensmeier, 1975b, 1982, 1988; Nash and Petraglia, 1987; Petraglia and Nash, 1987; Petraglia and Potts, 1994; Schick, 1987b; Schiffer, 1987; Toots, 1965; Voorhies, 1969, among others). From a spatial perspective, anisotropy is one of the main proxies traditionally used for discriminating autochthonous vs. allochthonous assemblages. Since elongated bones have been observed to preferentially align along the flow direction, spatial anisotropy, detected by fabric analysis, would therefore suggest substantial transport prior to final burial. Nevertheless, anisotropy has been equally documented in autochthonous lag assemblages undergoing minimal re-sedimentation (Domínguez-Rodrigo et al., 2014a, 2012, 2017, 2014c). Therefore, fabric analysis, although powerful and widely applied in Paleolithic research (Aramendi et al., 2017; Benito-Calvo and de la Torre, 2011; Cobo-Sánchez et al., 2014; de la Torre and Benito-Calvo, 2013; Domínguez-Rodrigo et al., 2014b, 2012, 2014d; Organista et al., 2017, among others), is however not sufficient to unequivocally discriminate processes and should be integrated with the analysis of other diagnostic features (Lenoble and Bertran, 2004). Skeletal element representation, size sorting, breakage pattern and surface

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modification are other commonly investigated taphonomic variables potentially indicative of the selective action of water-flows (Behrensmeyer, 1975a; Kaufmann et al., 2011; Lyman, 1994; Voorhies, 1969, among others). The morphology of the assemblage itself is another variable indicative of formation processes, although rarely investigated (Schiffer, 1983).

This study elaborates on a seldom investigated aspect of spatial taphonomy (multiscale multilevel anisotropy) which enhances our understanding of natural processes. Anisotropy is indeed the product of physical anisotropic processes, such as fluvial or eolian processes, which modify at multiple scales and levels of organisation the original spatial properties of taphonomic entities. Thus, multiscale multilevel spatial anisotropy refers to the preferential orientation adopted, at variable scales of analysis, by different levels of a taphonomic system: basic taphonomic elements, groups, populations and taphoclares (*sensu* Fernández-López, 2006). This is the first study to specifically employ advanced spatial statistics (fabric analysis, geostatistics, wavelet analysis and point pattern analysis) for the analysis of orientation patterns both at the level of simple taphonomic elements (i.e., elongated faunal remains) and at the assemblage level. Furthermore, analyses of spatial anisotropy are supported by traditional observations regarding the differential preservation of skeletal elements.

In a terrestrial alluvial environment such as that of TSR, a linear fabric of basic taphonomic elements (i.e., elongated bones) would suggest a strong preferential orientation of the sample, that might be indicative of channelised water flows (Petraglia and Potts, 1994). At the higher level of the taphonomic population (i.e., the fossil assemblage), spatial anisotropy is expected to be detected as well, and most likely to share the same preferential orientation with the basic taphonomic elements. Indeed, elongated lag deposits are characteristic patterns observed in association with water-flows (Domínguez-Rodrigo et al., 2012). Notably, results of our multiscale multilevel spatial analyses suggest recursive anisotropy both at the level of basic taphonomic elements and at the assemblage level. Fabric anal-

ysis, geostatistics, wavelet and point pattern analyses all indicate preferential orientation towards the same direction, suggesting the action of relatively high-energy water-flow processes. Moreover, they reveal secondary anisotropy towards other directions, mostly orthogonal to the main one. Whereas long bones can roll orthogonally to the direction of the flow (Voorhies, 1969), noise in the main directional trend at the assemblage level may indicate multiple depositional processes, or secondary reworking by post-depositional processes. Analysis of the differential preservation of skeletal elements suggests minor winnowing of the assemblage, with taphonomic sieve of the smallest, cancellous bones. Indeed, assemblages subject to moderate to high-energy water-flows would typically show an under-represented number of smaller, less dense bones (Voorhies, 1969). However, under-representation of less dense, axial elements may similarly indicate carnivore ravaging (Domínguez-Rodrigo et al., 2012). Nevertheless, the multilevel recursive anisotropy and the overall distribution of finds suggest multiple dispersion events and recurrent spatial re-arrangement of a lag, (peri)autochthonous assemblage. From an independent line of evidence and in agreement with the spatial analyses, sedimentological results indicate consistency with cyclical lateral switching of a braided fluvial system.

Fossil assemblages deposited in fluvial environments may assume a wide range of forms, ranging from (peri)autochthonous, rearranged and biased lag assemblages to transported, allochthonous or even mixed assemblages (Behrensmeier, 1988; Domínguez-Rodrigo and García-Pérez, 2013; Petraglia and Potts, 1994). By unravelling site formation processes at the vertebrate locality of Tsiotra Vryssi, this study contributes to the building of a referential framework for the study of early hominin sites found close to fresh water bodies. In order to fully comprehend the archaeological record, it is essential to test within a referential framework alternative taphonomic hypotheses. Controlled flume experiments provide replicable results. However, they cannot reproduce spatial patterns that had been developing over an extended period of time. Therefore, more data have to be collected from undisturbed human-made, carnivore-made and

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human-made/carnivore modified assemblages (Domínguez-Rodrigo et al., 2017). Spatial taphonomy complements, in archaeological and palaeontological research programs, the traditional taphonomic and geological approaches. It enhances our understanding of multiscale and multilevel taphonomic processes with implications for palaeoecological reconstruction, biochronological estimates and the interpretation of past human behaviours.

Concluding remarks

Space is an ineluctable analytic dimension in investigating the archaeological record. The extent to which any observed spatial patterns reliably reflect past human behaviour is essentially related to the preservation of the archaeological record and to the spatio-temporal perspectivism of given research problems. Nevertheless, spatial patterns are highly informative of the dynamics of cultural and natural processes. However, along with the sampling range and resolution, the employed analytical methods systematically affect our ability to identify spatial patterns.

Over the last 40 years, paradigms and methodological approaches have been largely fixed in formation theory. However, the need remains for the use of more quantitative, hypothesis-driven analytical approaches to the study of the spatial properties of taphonomic processes. Moreover, further research is needed if we are to fully understand the mode of action of different processes, to link these processes to the resulting spatial patterns, and enrich our frame of references.

This dissertation makes an important contribution to the development of a quantitative spatial taphonomic approach to the study of formation processes. Bridging the traditional archaeological, geoarchaeological and taphonomic approaches in a spatio-temporal framework, this dissertation paves the way for future studies in site formation processes.

References

- Aramendi J, Uribelarrea D, Arriaza MC, Arráiz H, Barboni D, Yravedra J, Ortega MC, Gidna A, Mabulla A, Baquedano E, and Domínguez-Rodrigo M. 2017. The paleoecology and taphonomy of AMK (Bed I, Olduvai Gorge) and its contributions to the understanding of the “Zinj” paleolandscape. *Palaeogeography, Palaeoclimatology, Palaeoecology* (in press). DOI: [10.1016/j.palaeo.2017.02.036](https://doi.org/10.1016/j.palaeo.2017.02.036).
- Arzarello M, Marcolini F, Pavia G, Pavia M, Petronio C, Petrucci M, Rook L, and Sardella R. 2007. Evidence of earliest human occurrence in Europe: the site of Pirro Nord (Southern Italy). English. *Naturwissenschaften* 94 (2), 107–112. DOI: [10.1007/s00114-006-0173-3](https://doi.org/10.1007/s00114-006-0173-3).
- Arzarello M, Marcolini F, Pavia G, Pavia M, Petronio C, Petrucci M, Rook L, and Sardella R. 2009. L'industrie lithique du site Pléistocène inférieur de Pirro Nord (Apricena, Italie du sud): une occupation humaine entre 1,3 et 1,7Ma. *L'Anthropologie* 113.1, 47–58. DOI: [10.1016/j.anthro.2009.01.004](https://doi.org/10.1016/j.anthro.2009.01.004).
- Arzarello M, Pavia G, Peretto C, Petronio C, and Sardella R. 2012. Evidence of an Early Pleistocene hominin presence at Pirro Nord (Apricena, Foggia, southern Italy): P13 site. *Quaternary International* 267, 56–61. DOI: [10.1016/j.quaint.2011.01.042](https://doi.org/10.1016/j.quaint.2011.01.042).
- Arzarello M and Peretto C. 2010. Out of Africa: The first evidence of Italian peninsula occupation. *Quaternary International* 223–224, 65–70. DOI: [10.1016/j.quaint.2010.01.006](https://doi.org/10.1016/j.quaint.2010.01.006).
- Arzarello M, Peretto C, and Moncel MH. 2015. The Pirro Nord site (Apricena, Fg, Southern Italy) in the context of the first European peopling: Convergences and divergences. *Quaternary International* 389, 255–263. DOI: [10.1016/j.quaint.2014.08.051](https://doi.org/10.1016/j.quaint.2014.08.051).
- Bagnus C. 2011. *Analisi tafonomica delle associazioni a vertebrati del Pleistocene Inferiore di Pirro Nord*. PhD thesis. Italy: Università degli Studi di Torino.
- Bailey G. 2007. Time perspectives, palimpsests and the archaeology of time. *Journal of Anthropological Archaeology* 26.2, 198–223. DOI: [10.1016/j.jaa.2006.08.002](https://doi.org/10.1016/j.jaa.2006.08.002).

- Bargalló A, Gabucio MJ, and Rivals F. 2016. Puzzling out a palimpsest: Testing an interdisciplinary study in level O of Abric Romani. *Quaternary International* 417, 51–65. DOI: [10.1016/j.quaint.2015.09.066](https://doi.org/10.1016/j.quaint.2015.09.066).
- Bar-Yosef O and Tchernov E. 1972. *On the palaeo-ecological history of the site of Ubeidiya*. Vol. 35. Jerusalem: Israel Academy of Sciences and Humanities.
- Behrensmeyer AK. 1975a. Taphonomy and paleoecology in the hominid fossil record. *Yearbook of Physical Anthropology* 19, 36–50.
- Behrensmeyer AK. 1975b. The taphonomy and paleoecology of Plio-Pleistocene vertebrate assemblages East of Lake Rudolf, Kenya. *Bulletin of the Museum of Comparative Zoology* 146, 473–578.
- Behrensmeyer AK. 1982. Time resolution in fluvial vertebrate assemblages. *Paleobiology* 8.3, 211–227. DOI: [10.1017/s0094837300006941](https://doi.org/10.1017/s0094837300006941).
- Behrensmeyer AK. 1988. Vertebrate preservation in fluvial channels. *Palaeogeography, Palaeoclimatology, Palaeoecology* 63.1, 183–199. DOI: [10.1016/0031-0182\(88\)90096-X](https://doi.org/10.1016/0031-0182(88)90096-X).
- Benito-Calvo A and de la Torre I. 2011. Analysis of orientation patterns in Olduvai Bed I assemblages using GIS techniques: Implications for site formation processes. *Journal of Human Evolution* 61.1, 50–60. DOI: [10.1016/j.jhevol.2011.02.011](https://doi.org/10.1016/j.jhevol.2011.02.011).
- Benito-Calvo A, Martínez-Moreno J, Pardo JFJ, de la Torre I, and Torcal RM. 2009. Sedimentological and archaeological fabrics in Palaeolithic levels of the South-Eastern Pyrenees: Cova Gran and Roca del Bous Sites (Lleida, Spain). *Journal of Archaeological Science* 36.11, 2566–2577. DOI: [10.1016/j.jas.2009.07.012](https://doi.org/10.1016/j.jas.2009.07.012).
- Benvenuti M and Martini IP. 2002. Analysis of Terrestrial Hyperconcentrated Flows and their Deposit. In: *Flood and Megaflood Processes and Deposits*. Ed. by IP Martini, VR Baker, and G Garzón. Vol. 32. Special Publication of the International Association of Sedimentologists. Blackwell Publishing Ltd., 167–193. DOI: [10.1002/9781444304299.ch10](https://doi.org/10.1002/9781444304299.ch10).
- Bertran P and Texier JP. 1995. Fabric Analysis: Application to Paleolithic Sites. *Journal of Archaeological Science* 22.4, 521–535. DOI: [10.1006/jasc.1995.0050](https://doi.org/10.1006/jasc.1995.0050).
- Bevan A and Conolly J. 2006. Multiscalar approaches to settlement pattern analysis. In: *Confronting Scale in Archaeology: Issues of Theory and Practice*. Ed. by G Lock and B Molyneaux. New York: Springer, 217–234. DOI: [10.1007/0-387-32772-3_14](https://doi.org/10.1007/0-387-32772-3_14).
- Bevan A and Conolly J. 2009. Modelling spatial heterogeneity and nonstationarity in artifact-rich landscapes. *Journal of Archaeological Science* 36.4, 956–964. DOI: [10.1016/j.jas.2008.11.023](https://doi.org/10.1016/j.jas.2008.11.023).
- Bevan A, Crema E, Li X, and Palmisano A. 2013. Intensities, Interactions, and Uncertainties: Some New Approaches to Archaeological Distributions. In: *Computational Approaches to Archaeological Spaces*. Ed. by A Bevan and M Lake. Walnut Creek: Left Coast Press, 27–52.

References

- Bevan A and Wilson A. 2013. Models of settlement hierarchy based on partial evidence. *Journal of Archaeological Science* 40.5, 2415–2427. DOI: [10.1016/j.jas.2012.12.025](https://doi.org/10.1016/j.jas.2012.12.025).
- Binford LR. 1972. Contemporary model building: paradigms and the current state of Paleolithic research. In: *Models in Archaeology*. Ed. by DL Clarke. London: Methuen & Co. LTD, 109–166.
- Binford LR. 1977. General Introduction. In: *For Theory Building in Archaeology: Essays on Faunal Remains, Aquatic Resources, Spatial Analysis, and Systemic Modeling*. Ed. by LR Binford. New York: Academic Press, 1–10.
- Binford LR. 1978. *Nunamiut: Ethnoarchaeology*. Studies in Archaeology Series. Academic Press.
- Binford LR. 1979. Organization and Formation Processes: Looking at Curated Technologies. *Journal of Anthropological Research* 35.3, 255–273. DOI: [10.1086/jar.35.3.3629902](https://doi.org/10.1086/jar.35.3.3629902).
- Binford LR. 1980. Willow Smoke and Dogs' Tails: Hunter-Gatherer Settlement Systems and Archaeological Site Formation. *American Antiquity* 45.1, 4–20. DOI: [10.2307/279653](https://doi.org/10.2307/279653).
- Binford LR. 1981a. Behavioral Archaeology and the "Pompeii Premise". *Journal of Anthropological Research* 37.3, 195–208.
- Binford LR. 1981b. *Bones: ancient men and modern myths*. Studies in archaeology. Academic Press.
- Boaz NT and Behrensmeier AK. 1976. Hominid taphonomy: Transport of human skeletal parts in an artificial fluvial environment. *American Journal of Physical Anthropology* 45.1, 53–60. DOI: [10.1002/ajpa.1330450107](https://doi.org/10.1002/ajpa.1330450107).
- Brain CK. 1981. *The Hunters or the Hunted? An Introduction to African Cave Taphonomy*. Chicago: University of Chicago Press.
- Bunn HT. 1991. A taphonomic perspective on the archaeology of human origins. *Annual Review of Anthropology* 20, 433–467.
- Burroni D, Donahue RE, Pollard A, and Mussi M. 2002. The Surface Alteration Features of Flint Artefacts as a Record of Environmental Processes. *Journal of Archaeological Science* 29.11, 1277–1287. DOI: [10.1006/jasc.2001.0771](https://doi.org/10.1006/jasc.2001.0771).
- Butzer K. 1982. *Archaeology as Human Ecology: Method and Theory for a Contextual Approach*. New York: Cambridge University Press.
- Clarke DL. 1973. Archaeology: the loss of innocence. *Antiquity* 47, 6–18. DOI: [10.1017/s0003598x0003461x](https://doi.org/10.1017/s0003598x0003461x).
- Clarke DL. 1977. *Spatial Archaeology*. London: Academic Press.
- Cobo-Sánchez L, Aramendi J, and Domínguez-Rodrigo M. 2014. Orientation patterns of wildebeest bones on the lake Masek floodplain (Serengeti, Tanzania) and their relevance to interpret anisotropy in the Olduvai lacustrine floodplain. *Quaternary International* 322–323.0, 277–284. DOI: [10.1016/j.quaint.2013.07.130](https://doi.org/10.1016/j.quaint.2013.07.130).

- Crema ER. 2015. Time and Probabilistic Reasoning in Settlement Analysis. In: *Mathematics and Archaeology*. Ed. by IB Juan A. Barcelo. Boca Raton, FL: CRC Press, 314–334. DOI: [10.1201/b18530-20](https://doi.org/10.1201/b18530-20).
- Crema ER, Bevan A, and Lake MW. 2010. A probabilistic framework for assessing spatio-temporal point patterns in the archaeological record. *Journal of Archaeological Science* 37.5, 1118–1130. DOI: [10.1016/j.jas.2009.12.012](https://doi.org/10.1016/j.jas.2009.12.012).
- Crema ER and Bianchi E. 2013. Looking for patterns in the noise: non-site spatial-analysis in Sebkhla Kelbia. In: *Le Capsien de hergla (Tunisie). Culture, environnement et économie*. Ed. by S Mulazzani. Frankfurt: Africa Magna Verlag, 385–395.
- Dale M and Fortin M. 2014. *Spatial Analysis: A Guide for Ecologists*. Second Edition. Cambridge University Press.
- De la Torre I and Benito-Calvo A. 2013. Application of GIS methods to retrieve orientation patterns from imagery; a case study from Beds I and II, Olduvai Gorge (Tanzania). *Journal of Archaeological Science* 40.5, 2446–2457. DOI: [10.1016/j.jas.2013.01.004](https://doi.org/10.1016/j.jas.2013.01.004).
- Dibble HL, Chase PG, McPherron SJP, and Tuffreau A. 1997. Testing the Reality of a "Living Floor" with Archaeological Data. *American Antiquity* 62.4, 629–651. DOI: [10.2307/281882](https://doi.org/10.2307/281882).
- Diggle PJ. 1985. A kernel method for smoothing point process data. *Applied Statistics (Journal of the Royal Statistical Society, Series C)* 34, 138–147.
- Diggle PJ. 2003. *Statistical analysis of spatial point patterns*. London: Hodder Arnold.
- Dirks PH, Berger LR, Roberts EM, Kramers JD, Hawks J, Randolph-Quinney PS, Elliott M, Musiba CM, Churchill SE, de Ruiter DJ, Schmid P, Backwell LR, Belyanin GA, Boshoff P, Hunter KL, Feuerriegel EM, Gurtov A, Harrison JdG, Hunter R, Kruger A, Morris H, Makhubela TV, Peixotto B, and Tucker S. 2015. Geological and taphonomic context for the new hominin species *Homo naledi* from the Dinaledi Chamber, South Africa. *eLife* 4. Ed. by NJ Conard and J Krause, e09561. DOI: [10.7554/eLife.09561](https://doi.org/10.7554/eLife.09561).
- Djindjian F. 1999. L'analyse spatiale de l'habitat: un état de l'art. *Archeologia e Calcolatori* X, Edizioni All'Insegna del Giglio, 17–32.
- Domínguez-Rodrigo M, Bunn HT, and Yravedra J. 2014a. A critical re-evaluation of bone surface modification models for inferring fossil hominin and carnivore interactions through a multivariate approach: Application to the FLK Zinj archaeofaunal assemblage (Olduvai Gorge, Tanzania). *Quaternary International* 322–323.0. The Evolution of Hominin Behavior during the Oldowan-Acheulian Transition: Recent Evidence from Olduvai Gorge and Peninj (Tanzania), 32–43. DOI: <http://dx.doi.org/10.1016/j.quaint.2013.09.042>.
- Domínguez-Rodrigo M, Bunn H, Mabulla A, Baquedano E, Uribelarrea D, Pérez-González A, Gidna A, Yravedra J, Díez-Martin F, Egeland C, Barba R, Arriaza M, Organista E, and Ansón M. 2014b. On meat eating and human evolution: A taphonomic analysis of BK4b (Upper Bed II, Olduvai Gorge,

References

- Tanzania), and its bearing on hominin megafaunal consumption. *Quaternary International* 322–323, 129–152. DOI: [10.1016/j.quaint.2013.08.015](https://doi.org/10.1016/j.quaint.2013.08.015).
- Domínguez-Rodrigo M, Bunn H, Pickering T, Mabulla A, Musiba C, Baquedano E, Ashley G, Diez-Martin F, Santonja M, Uribelarrea D, Barba R, Yravedra J, Barboni D, Arriaza C, and Gidna A. 2012. Autochthony and orientation patterns in Olduvai Bed I: a re-examination of the status of post-depositional biasing of archaeological assemblages from FLK North (FLKN). *Journal of Archaeological Science* 39.7, 2116–2127. DOI: [10.1016/j.jas.2012.02.027](https://doi.org/10.1016/j.jas.2012.02.027).
- Domínguez-Rodrigo M and Cobo-Sánchez L. 2017. A spatial analysis of stone tools and fossil bones at FLK Zinj 22 and PTK I (Bed I, Olduvai Gorge, Tanzania) and its bearing on the social organization of early humans. *Palaeogeography, Palaeoclimatology, Palaeoecology* 488, 21–34. DOI: <https://doi.org/10.1016/j.palaeo.2017.04.010>.
- Domínguez-Rodrigo M, Cobo-Sánchez L, Yravedra J, Uribelarrea D, Arriaza CC, Organista E, and Baquedano E. 2017. Fluvial spatial taphonomy: a new method for the study of post-depositional processes. *Archaeological and Anthropological Sciences*. DOI: [10.1007/s12520-017-0497-2](https://doi.org/10.1007/s12520-017-0497-2).
- Domínguez-Rodrigo M, Diez-Martín F, Yravedra J, Barba R, Mabulla A, Baquedano E, Uribelarrea D, Sánchez P, and Eren MI. 2014c. Study of the SHK Main Site faunal assemblage, Olduvai Gorge, Tanzania: Implications for Bed II taphonomy, paleoecology, and hominin utilization of megafauna. *Quaternary International* 322–323, 153–166. DOI: <http://dx.doi.org/10.1016/j.quaint.2013.09.025>.
- Domínguez-Rodrigo M, Fernández-López S, and Alcalá L. 2011. How Can Taphonomy Be Defined in the XXI Century? *Journal of Taphonomy* 9.1, 1–13.
- Domínguez-Rodrigo M and García-Pérez A. 2013. Testing the Accuracy of Different A-Axis Types for Measuring the Orientation of Bones in the Archaeological and Paleontological Record. *PLoS ONE* 8.7, e68955. DOI: [10.1371/journal.pone.0068955](https://doi.org/10.1371/journal.pone.0068955).
- Domínguez-Rodrigo M, Pickering TR, and Bunn HT. 2010. Configurational approach to identifying the earliest hominin butchers. *Proceedings of the National Academy of Sciences* 107.49. DOI: [10.1073/pnas.1013711107](https://doi.org/10.1073/pnas.1013711107).
- Domínguez-Rodrigo M, Uribelarrea D, Santonja M, Bunn HT, García-Pérez A, Pérez-González A, Panera J, Rubio-Jara S, Mabulla A, Baquedano E, Yravedra J, and Diez-Martín F. 2014d. Autochthonous anisotropy of archaeological materials by the action of water: experimental and archaeological reassessment of the orientation patterns at the Olduvai sites. *Journal of Archaeological Science* 41, 44–68. DOI: [10.1016/j.jas.2013.07.025](https://doi.org/10.1016/j.jas.2013.07.025).
- Doukas C, van Kolfshoten T, Papayianni K, Panagopoulou E, and Harvati K. In press. The small mammal fauna from the Palaeolithic site Marathousa 1 (Greece). *Quaternary International*. In press.

- Efremov IA. 1940. Taphonomy: a new branch of paleontology. *Pan American Geologist* 74, 81–93.
- Egeland CP, Dominguez-Rodrigo M, Pickering TR, Menter CG, and Heaton JL. 2018. Hominin skeletal part abundances and claims of deliberate disposal of corpses in the Middle Pleistocene. *Proceedings of the National Academy of Sciences*. DOI: [10.1073/pnas.1718678115](https://doi.org/10.1073/pnas.1718678115).
- Eve SJ and Crema ER. 2014. A House with a View? Multi-model inference, visibility fields, and point process analysis of a Bronze Age settlement on Leskernick Hill (Cornwall, UK). *Journal of Archaeological Science* 43, 267–277. DOI: [10.1016/j.jas.2013.12.019](https://doi.org/10.1016/j.jas.2013.12.019).
- Fernández-López RS. 1991. Taphonomic concepts for a theoretical biochronology. *Revista Española de Paleontología* 6, 37–49.
- Fernández-López RS. 2006. Taphonomic Alteration and Evolutionary Taphonomy. *Journal of Taphonomy* 4.3, 111–142.
- Fiorillo AR. 1991. Taphonomy and depositional setting of Careless Creek Quarry (Judith River Formation), Wheatland County, Montana, U.S.A. *Palaeogeography, Palaeoclimatology, Palaeoecology* 81.3, 281–311. DOI: [10.1016/0031-0182\(91\)90151-g](https://doi.org/10.1016/0031-0182(91)90151-g).
- Gatrell AC, Bailey TC, Diggle PJ, and Rowlingson BS. 1996. Spatial point pattern analysis and its application in geographical epidemiology. *Transactions of the Institute of British Geographers* 21, 256–274.
- Gifford DP and Behrensmeyer AK. 1977. Observed Formation and Burial of a Recent Human Occupation Site in Kenya. *Quaternary Research* 8, 245–266.
- Gifford-Gonzalez D, Damrosch D, Damrosch D, Pryor J, and Thunen R. 1985. The Third Dimension in Site Structure: An Experiment in Trampling and Vertical Dispersal. *American Antiquity* 50.4, 803–818. DOI: [10.2307/280169](https://doi.org/10.2307/280169).
- Gifford-Gonzalez D, Stewart KM, and Rybczynski N. 1999. Human Activities and Site Formation at Modern Lake Margin Foraging Camps in Kenya. *Journal of Anthropological Archaeology* 18.4, 397–440. DOI: [10.1006/jaar.1999.0337](https://doi.org/10.1006/jaar.1999.0337).
- Goldberg P, Nash DT, and Petraglia MD. 1993. *Formation Processes in Archaeological Context*. Madison: Prehistoric Press.
- Harvati K, Panagopoulou E, Tourloukis V, Thompson N, Karkanas P, Athanasiou A, Konidaris GE, Tsartsidou G, and Giusti D. 2016. New Middle Pleistocene elephant butchering site from Greece. In: *Paleoanthropology Society Meeting*. Atlanta, Georgia, A14–A15.
- Haynes G. 1988. Longitudinal studies of african elephant death and bone deposits. *Journal of Archaeological Science* 15.2, 131–157. DOI: [http://dx.doi.org/10.1016/0305-4403\(88\)90003-9](http://dx.doi.org/10.1016/0305-4403(88)90003-9).
- Hietala H and Larson P. 1984. *Intrasite Spatial Analysis in Archaeology*. Monographs of the Physiological Society. Cambridge University Press.
- Hill A. 1976. On carnivore and weathering damage to bone. *Current Anthropology* 17, 335–336. DOI: [10.1086/201732](https://doi.org/10.1086/201732).

References

- Hill A. 1979. Disarticulation and Scattering of Mammal Skeletons. *Paleobiology* 5.3, 261–274.
- Hivernel F and Hodder I. 1984. Analysis of artifact distribution at Ngenym (Kenya): depositional and postdepositional effects. In: *Intrasite Spatial Analysis in Archaeology*. Ed. by H Hietala and P Larson. Cambridge University Press. Chap. 7, 97–115.
- Hodder I and Orton C. 1976. *Spatial Analysis in Archaeology*. New Studies in Archaeology. Cambridge: Cambridge University Press.
- Isaac GL. 1967. Towards the interpretation of occupation debris: Some experiments and observations. *Kroeber Anthropological Society Papers* 37.37, 31–57.
- Jacobs Z, Li B, Karkanas P, Tourloukis V, Thompson N, Panagopoulou E, and Harvati K. In press. Dating of Middle Pleistocene Marathousa 1 (Greece) lacustrine sediment using multiple-aliquot pre-dose multi-elevated-temperature post-infrared stimulated luminescence (MET-pIRIR). *Quaternary International*.
- Karkanas P, Tourloukis V, Thompson N, Giusti D, Panagopoulou E, and Harvati K. In press. Sedimentology and micromorphology of the Lower Palaeolithic lakeshore site Marathousa 1, Megalopolis basin, Greece. *Quaternary International* in press.
- Kaufmann C, Gutiérrez MA, Álvarez MC, González ME, and Massigoge A. 2011. Fluvial dispersal potential of guanaco bones (*Lama guanicoe*) under controlled experimental conditions: the influence of age classes to the hydrodynamic behavior. *Journal of Archaeological Science* 38.2, 334–344. DOI: <https://doi.org/10.1016/j.jas.2010.09.010>.
- Kintigh KW and Ammerman AJ. 1982. Heuristic Approaches to Spatial Analysis in Archaeology. *American Antiquity* 47.1, 31–63.
- Konidaris GE, Athanassiou A, Tourloukis V, Thompson N, Giusti D, Panagopoulou E, and Harvati K. In press. The skeleton of a straight-tusked elephant (*Palaeoloxodon antiquus*) and other large mammals from the Middle Pleistocene locality Marathousa 1 (Megalopolis Basin, Greece): preliminary results. *Quaternary International*. DOI: doi.org/10.1016/j.quaint.2017.12.001.
- Konidaris GE, Kostopoulos D, Koufos GD, Tourloukis V, and Harvati K. 2016. Tsiotra Vryssi: a new vertebrate locality from the Early Pleistocene of Mygdonia Basin (Macedonia, Greece). In: *XIV Annual Meeting of the European Association of Vertebrate Palaeontologists*. Haarlem, The Netherlands: Koninklijke Nederlandse Akademie Van Wetenschappen, 37.
- Konidaris GE, Tourloukis V, Kostopoulos DS, Thompson N, Giusti D, Michailidis D, Koufos GD, and Harvati K. 2015. Two new vertebrate localities from the Early Pleistocene of Mygdonia Basin (Macedonia, Greece): Preliminary results. *Comptes Rendus Palevol* 14.5, 353–362. DOI: <http://doi.org/10.1016/j.crpv.2015.05.004>.

- Koufos GD, Syrides GE, Kostopoulos DS, and Koliadimou KK. 1995. Preliminary results about the stratigraphy and the palaeoenvironment of Mygdonia Basin, Macedonia, Greece. *Geobios* 28, Supplement 1. First European Palaeontological Congress, 243–249. DOI: [10.1016/S0016-6995\(95\)80171-5](https://doi.org/10.1016/S0016-6995(95)80171-5).
- Leakey MD. 1971. *Olduvai Gorge. Excavations in Beds I and II, 1960–1963*. Vol. vol. 3. Cambridge: Cambridge University Press.
- Lenoble A and Bertran P. 2004. Fabric of Palaeolithic levels: methods and implications for site formation processes. *Journal of Archaeological Science* 31.4, 457–469. DOI: [10.1016/j.jas.2003.09.013](https://doi.org/10.1016/j.jas.2003.09.013).
- Lenoble A, Bertran P, and Lacrampe F. 2008. Solifluction-induced modifications of archaeological levels: simulation based on experimental data from a modern periglacial slope and application to French Palaeolithic sites. *Journal of Archaeological Science* 35.1, 99–110. DOI: [10.1016/j.jas.2007.02.011](https://doi.org/10.1016/j.jas.2007.02.011).
- Lindsay JF. 1968. The development of clast fabric in mudflows. *Journal of Sedimentary Research* 38.4, 1242–1253. DOI: [10.1306/74D71B40-2B21-11D7-8648000102C1865D](https://doi.org/10.1306/74D71B40-2B21-11D7-8648000102C1865D).
- Lopez-García JM, Luzi E, Berto C, Peretto C, and Arzarello M. 2015. Chronological context of the first hominin occurrence in southern Europe: the *Allophaiomys ruffoi* (Arvicolinae, Rodentia, Mammalia) from Pirro 13 (Pirro Nord, Apulia, southwestern Italy). *Quaternary Science Reviews* 107, 260–266. DOI: [doi:10.1016/j.quascirev.2014.10.029](https://doi.org/10.1016/j.quascirev.2014.10.029).
- Lyell C. 1863. *Geological Evidences of the Antiquity of Man*. Ed. by Murray. London.
- Lyman RL. 1994. *Vertebrate Taphonomy*. Cambridge Manuals in Archaeology. Cambridge University Press.
- Lyman RL. 2004. The concept of equifinality in taphonomy. 2, 15–26.
- McPherron SJP. 2005. Artifact orientations and site formation processes from total station proveniences. *Journal of Archaeological Science* 32.7, 1003–1014. DOI: [10.1016/j.jas.2005.01.015](https://doi.org/10.1016/j.jas.2005.01.015).
- McPherron SJP. 2018. Additional statistical and graphical methods for analyzing site formation processes using artifact orientations. *PLOS ONE* 13.1, 1–21. DOI: [10.1371/journal.pone.0190195](https://doi.org/10.1371/journal.pone.0190195).
- Morin E, Tsanova T, Sirakov N, Rendu W, Mallye JB, and Lèveque F. 2005. Bone refits in stratified deposits: testing the chronological grain at Saint-Cesaire. *Journal of Archaeological Science* 32, 1083–1098. DOI: [10.1016/j.jas.2005.02.009](https://doi.org/10.1016/j.jas.2005.02.009).
- Nash DT and Petraglia MD, eds. 1987. *Natural formation processes and the archaeological record*. Vol. 352. International Series. Oxford: British Archaeological Reports.
- Organista E, Domínguez-Rodrigo M, Yravedra J, Uribelarra D, Arriaza MC, Ortega MC, Mabulla A, Gidna A, and Baquedano E. 2017. Biotic and abiotic processes affecting the formation of BK Level 4c (Bed II, Olduvai Gorge)

References

- and their bearing on hominin behavior at the site. *Palaeogeography, Palaeoclimatology, Palaeoecology* (in press). DOI: [10.1016/j.palaeo.2017.03.001](https://doi.org/10.1016/j.palaeo.2017.03.001).
- Orton CR. 1982. Stochastic process and archaeological mechanism in spatial analysis. *Journal of Archaeological Science* 9.1, 1–23. DOI: [10.1016/0305-4403\(82\)90002-4](https://doi.org/10.1016/0305-4403(82)90002-4).
- Orton CR. 2004. Point pattern analysis revisited. *Archeologia e Calcolatori* 15, 299–315.
- Palmisano A. 2013. Zooming patterns among the scales: a statistics technique to detect spatial patterns among settlements. In: *CAA 2012: Proceedings of the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA)*. Ed. by G Earl, T Sly, A Chrysanthi, P Murrieta-Flores, C Papadopoulos, I Romanowska, and D Wheatley. Southampton: Pallas Publications, 348–356.
- Panagopoulou E, Tourloukis V, Thompson N, Athanassiou A, Tsartsidou G, Konidaris G, Giusti D, Karkanas P, and Harvati K. 2015. Marathousa 1: a new Middle Pleistocene archaeological site from Greece. *Antiquity* Project Gallery 89.343. DOI: [10.15496/publikation-5878](https://doi.org/10.15496/publikation-5878).
- Petraglia MD. 1992. Stone artifact refitting and formation processes at the Abri Dufaure: an Upper Paleolithic site in Southwest France. In: *Piecing Together the Past: Applications of Refitting Studies in Archaeology*. Ed. by JL Hofman and JG Enloe. Vol. 578. BAR International Series. Oxford: Archaeopress, 163–178.
- Petraglia MD and Nash DT. 1987. The impact of fluvial processes on experimental sites. In: *Natural formation processes and the archaeological record*. Ed. by DT Nash and MD Petraglia. Vol. 352. International Series. Oxford: British Archaeological Reports, 108–130.
- Petraglia MD and Potts R. 1994. Water Flow and the Formation of Early Pleistocene Artifact Sites in Olduvai Gorge, Tanzania. *Journal of Anthropological Archaeology* 13.3, 228–254. DOI: [10.1006/jaar.1994.1014](https://doi.org/10.1006/jaar.1994.1014).
- Pierson TC. 2005. *Distinguishing between debris flows and floods from field evidence in small watersheds*. USGS Numbered Series. U.S. Geological Survey.
- Potts R. 1988. *Early Hominid Activities at Olduvai*. New York: Aldine and Gruyter.
- Premo L. 2010. Equifinality and explanation: the role of agent-based modeling in postpositivist archaeology. In: *Simulating Change: Archaeology into the Twenty-First Century*. Ed. by A Costopoulos and M Lake. Salt Lake City: University of Utah Press, 28–37.
- Rapp G(and Hill CL. 2006. *Geoarchaeology: the earth-science approach to archaeological interpretation*. 2nd. New Haven and London: Yale University Press. DOI: [10.1007/978-1-4419-0465-2_812](https://doi.org/10.1007/978-1-4419-0465-2_812).
- Ripley BD. 1976. The second-order analysis of stationary point processes. *Journal of Applied Probability* 13.2, 255–266. DOI: [10.2307/3212829](https://doi.org/10.2307/3212829).


- Ripley BD. 1977. Modelling spatial patterns. *Journal of the Royal Statistical Society, series B* 39, 172–212.
- Romagnoli F and Vaquero M. 2016. Quantitative stone tools intra-site point and orientation patterns of a Middle Palaeolithic living floor: A GIS multi-scalar spatial and temporal approach. *Quartär* 63, 47–60. DOI: [10.7485/QU63_3](https://doi.org/10.7485/QU63_3).
- Sala N, Arsuaga JL, Martínez I, and Gracia-Téllez A. 2015. Breakage patterns in Sima de los Huesos (Atapuerca, Spain) hominin sample. *Journal of Archaeological Science* 55.0, 113–121. DOI: <http://dx.doi.org/10.1016/j.jas.2015.01.002>.
- Schick KD. 1984. *Processes of Paleolithic site formation: an experimental study*. PhD thesis. US: University of California, Berkeley.
- Schick KD. 1986. *Stone Age sites in the making: experiments in the formation and transformation of archaeological occurrences*. Vol. 319. International Series. Oxford: British Archaeological Reports.
- Schick KD. 1987a. Experimentally-derived criteria for assessing hydrologic disturbance of archaeological sites. In: *Natural formation processes and the archaeological record*. Ed. by DT Nash and MD Petraglia. Vol. 352. International Series. Oxford: British Archaeological Reports, 86–107.
- Schick KD. 1987b. Modeling the formation of Early Stone Age artifact concentrations. *Journal of Human Evolution* 16, 789–807.
- Schiffer MB. 1972. Archaeological Context and Systemic Context. *American Antiquity* 37.2, 156–165.
- Schiffer MB. 1976. *Behavioral Archeology*. New York: Academic Press.
- Schiffer MB. 1983. Toward the identification of formation processes. *American Antiquity* 48.4, 675–706.
- Schiffer MB. 1987. *Formation processes of the archaeological record*. Albuquerque: University of New Mexico Press.
- Schiffer MB. 1988. The Structure of Archaeological Theory. *American Antiquity* 53.3, 461–485. DOI: [10.2307/281212](https://doi.org/10.2307/281212).
- Shott MJ. 1998. Status and role of formation theory in contemporary archaeological practice. *Journal of Archaeological Research* 6.4, 299–329. DOI: [10.1007/BF02446082](https://doi.org/10.1007/BF02446082).
- Texier JP. 2000. A propos des processus de formation des sites préhistoriques / About prehistoric site formation processes. fre. *Paléo* 12.1, 379–386. DOI: [10.3406/pal.2000.1610](https://doi.org/10.3406/pal.2000.1610).
- Tobler WR. 1970. A computer movie simulating urban growth in the Detroit region. *Economic Geography* 46.2, 234–240.
- Todd L and Stanford D. 1992. Application of conjoined bone data to site structural studies. In: *Piecing Together the Past: Applications of Refitting Studies in Archaeology*. Ed. by J Hofman and J Enloe. Vol. 578. International Series. Oxford: BAR, 21–35.

References

- Toots H. 1965. Orientation and distribution of fossils as environmental indicators. In: *Nineteenth Field Conference of the Wyoming Geological Association*, 219–292.
- Tourloukis V, Muttoni G, Karkanas P, Monesi E, Scardia G, Panagopoulou E, and Harvati K. In press. Magnetostratigraphic and chronostratigraphic constraints on the Marathousa 1 Lower Palaeolithic site and the Middle Pleistocene deposits of the Megalopolis basin, Greece. *Quaternary International*. DOI: <https://doi.org/10.1016/j.quaint.2018.03.043>.
- Tourloukis V, Thompson N, Panagopoulou E, Giusti D, Konidaris GE, Karkanas P, and Harvati K. In press. Lithic artifacts and bone tools from the Lower Palaeolithic site of Marathousa 1, Megalopolis, Greece: preliminary results. *Quaternary International*.
- Vaquero M, Fernández-Laso MC, Chacón MG, Romagnoli F, Rosell J, and Sañudo P. 2017. Moving things: Comparing lithic and bone refits from a Middle Paleolithic site. *Journal of Anthropological Archaeology* 48, 262–280. DOI: <https://doi.org/10.1016/j.jaa.2017.09.001>.
- Villa P. 1982. Conjoinable Pieces and Site Formation Processes. *American Antiquity* 47.2, 276–290. DOI: [10.2307/279901](https://doi.org/10.2307/279901).
- Villa P. 2004. Taphonomy and stratigraphy in European prehistory. *Before Farming* 2004.1, 1–20. DOI: [10.3828/bfarm.2004.1.1](https://doi.org/10.3828/bfarm.2004.1.1).
- Voorhies M. 1969. Taphonomy and population dynamics of an early Pliocene vertebrate fauna, Knox County, Nebraska. *Contributions to Geology, University of Wyoming* Special Paper 1, 1–69. DOI: [10.2113/gsrocky.8.special_paper_1.1](https://doi.org/10.2113/gsrocky.8.special_paper_1.1).
- Whallon R.J. 1974. Spatial Analysis of Occupation Floors II: The Application of Nearest Neighbor Analysis. *American Antiquity* 39.1, 16–34. DOI: [10.2307/279216](https://doi.org/10.2307/279216).
- Yellen J.E. 1977. *Archaeological approaches to the present*. New York: Academic Press.

The need for a taphonomic perspective in spatial analysis: Formation processes at the Early Pleistocene site of Pirro Nord (P13), Apricena, Italy

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Abstract

Ever since their percolation from neighbour disciplines, archaeology has employed spatial statistics to unravel, at different scales, past human behaviors from scatters of material culture. However, in the interpretation of the archaeological record, particular attention must be given to disturbance factors that operate in post-depositional processes. In this paper, we answer the need for a specific taphonomic perspective in spatial analysis by applying point pattern analysis of taphonomic alterations on the faunal and lithic assemblages from the Early Pleistocene site of Pirro Nord 13, Italy. The site, biochronologically dated between 1.3 and 1.6 Ma BP, provides evidence for an early hominin presence in Europe. The archaeological and paleontological deposits occur as filling of a karst structure that is currently exposed. We investigated the distribution of the archaeological and paleontological assemblages, as well as the distribution of identified taphonomic features, in order to evaluate the degree and reliability of the spatial association of the lithic artifacts with the faunal remains. Our results contribute to the interpretation of the diagenetic history of Pirro Nord 13 and support the stratigraphic integrity of the site.

A.1 Introduction

Studies of site formation processes and spatial analyses have long recognized the role of post-depositional factors in affecting the integrity of archaeological assemblages (Hodder and Orton, 1976; Petraglia and Nash, 1987; Schick, 1984, 1986; Schiffer, 1972, 1983, 1987; Wood and Johnson, 1978). More recently, a number of scholars have stressed the importance of establishing the degree of disturbance to archaeological deposits to fully comprehend the archaeological record (Dibble et al., 1997; Djindjian, 1999; Texier, 2000).

Besides geoarchaeological techniques, several archaeological and paleontological methods are widely applied to characterize the processes involved in the formation of an archaeological site and to assess any post-depositional ‘background noise’. Taphonomy moves from its original definition (Efremov, 1940) to a wider conceptual framework, targeting vertebrate assemblages, as well as taphonomic entities produced by human behaviour (Domínguez-Rodrigo et al., 2011). Moreover and often in joint effort, from different spatial perspectives, fabric analysis (Benito-Calvo and de la Torre, 2011; Bernatchez, 2010; Bertran et al., 1997; Bertran and Texier, 1995; de la Torre and Benito-Calvo, 2013; Domínguez-Rodrigo et al., 2014c; Lenoble and Bertran, 2004; McPherron, 2005); refitting analysis (López-Ortega et al., 2011; Sisk and Shea, 2008; Villa, 1982); vertical (Anderson and Burke, 2008) and size distribution analysis (Bertran et al., 2006, 2012; Petraglia and Potts, 1994) offer meaningful contributions in the unraveling of site formation and modification processes.

The importance of spatial statistics in the interpretation of archaeological sites has long been recognized (Hodder and Orton, 1976; Whallon, 1974). However, studies of spatial patterning mostly focus on the behaviour of past populations, assuming that scatters of material culture (if not disturbed) are reflections of prehistoric activities. Moreover, distribution maps still rely mainly on visual examinations and subjective interpretations (Bevan et al., 2013). On the other hand, quantitative methods, adopted from neighbor disci-

plines since the early 1970s (see [Hodder and Orton \(1976\)](#) and [Orton \(1982\)](#); and references therein), continue to promote new impulses to archaeological spatial analyses and allow for the characterization of spatial patterns by adopting a more formal, inductive approach. Recent studies ([Bevan and Conolly, 2006, 2009, 2013](#); [Bevan et al., 2013](#); [Bevan and Wilson, 2013](#); [Crema, 2015](#); [Crema et al., 2010](#); [Crema and Bianchi, 2013](#); [Eve and Crema, 2014](#); [Orton, 2004](#)), even acknowledging post-depositional effects or research biases, have continued to adopt at different scales (from intra-site to regional scales) improvements in spatial statistics to unravel past human behaviors from scatters of material culture. Yet, only a relatively limited number of scholars have applied spatial statistics to site formation and modification processes analysis ([Carrer, 2015](#); [Domínguez-Rodrigo et al., 2014a,b](#)).

In this paper, we adopt a taphonomic perspective to spatial point pattern analysis of the lithic and faunal assemblages from the Early Pleistocene site of Pirro Nord 13, Italy ([Arzarello et al., 2007, 2009, 2012](#); [Arzarello and Peretto, 2010](#)).

The site (P13) provides important contributions to the ongoing debate about the first hominin occurrence in Europe ([Carbonell et al., 2008](#); [Crochet et al., 2009](#); [Despriée et al., 2006, 2009, 2010](#); [Lumley et al., 1988](#); [Parés et al., 2006](#); [Toro-Moyano et al., 2011, 2009, 2013](#)). A ‘Mode 1’ lithic assemblage has been identified in stratigraphic association with late Villafranchian/early Biharian paleontological remains. Furthermore, the presence of the Arvicolinae species *Allophaiomys ruffoi* correlated to the *Mymomis savini-Mymomis pusillus* biozone, allows for a biochronologically refined age between 1.3 and 1.6 Ma, making P13 one of the most ancient localities with human evidence currently known in Western Europe ([Lopez-García et al., 2015](#)).

The paleontological and archaeological remains are preserved inside a complex karst system, exposed and partially destroyed by mining activities of a Mesozoic limestone quarry. The fissure P13 is a vertical fracture located at the stratigraphic boundary between the Mesozoic limestone and the Pleistocene calcarenite formation.

The deposit of the fissure is, at the time of writing, more than 4 m thick. Four Sedimentary Units (SUs) have been distinguished on lithological basis. From the top to the bottom of the section, units A to D are characterized by sediments of clayey-sand of increasing thickness (Fig. C.1). Unit A includes few coarse gravels and a very low number of paleontological and archaeological remains. Unit B contains more gravels, while an abrupt increase in the number and dimension of clasts and large blocks of Pleistocene calcarenite is evident within units C and D. These last units show poor size sorting of angular and sub-rounded gravels, probably correlating to a low degree of reworking that took place during a short interval of time. We also record a significant increase in the number of fossils and artifacts.

As a residual component of a wider karst system, it is worthwhile to assess the degree of any potential post-depositional reworking of the archaeological and paleontological remains and to evaluate the stratigraphic integrity of the site.

The main goal of our study is to use a taphonomic perspective in spatial data analysis, in order to evaluate degree and reliability of the spatial association of the lithic artifacts with the faunal remains that were used for the biochronological dating of the site.

By applying point pattern analysis of the spatial distribution of the lithic and faunal assemblages, we aim to

1. investigate the processes involved in the formation of the Pirro Nord (P13) deposit.

A positive spatial association of the two types of find would support the assumption, base on field observations, that the deposition of the archaeological and paleontological materials occurred simultaneously, as a result of subsequent mass wasting events.

With the application of point pattern analysis to identified taphonomic features on the lithic and faunal assemblages, our ultimate objective is to

2. evaluate the degree of post-depositional disturbance of the site.

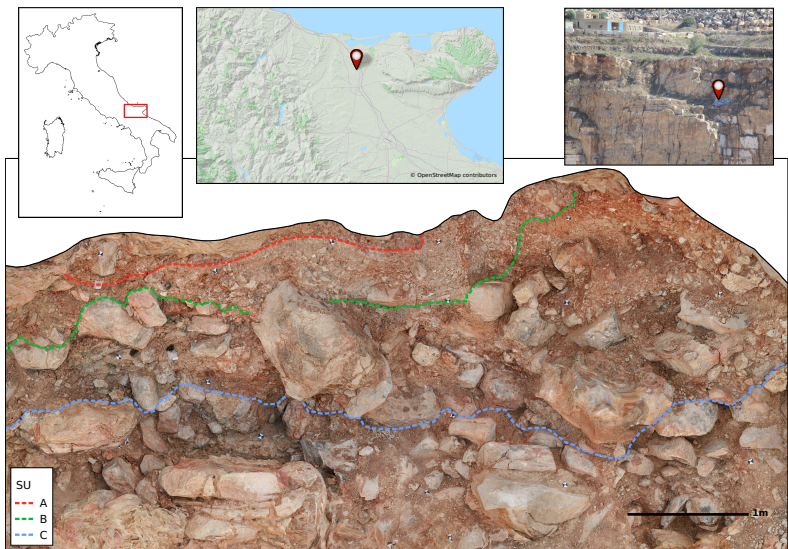


Figure A.1: Geographical location of the Pirro Nord site. Picture of the fissure P13 inside the Cave Dell'Erba quarry and view of the excavated area (2013), with marked bases of the sedimentary units.

Indeed, reworking and re-deposition processes could put in stratigraphic contact materials from diverse provenience. The identification of taphonomic spatial patterns allows us to model the spatial processes that produced them and thus propose a reconstruction of the agents involved in the formation and modification of the deposit.

A.2 Background

With the authors' permission, we integrate in our study unpublished (Bagnus, 2011) and published (Arzarello et al., 2012, 2015) data from previous taphonomic studies. A brief report is presented here.

A.2.1 Taphonomy of macrovertebrate fossils

Taphonomic analysis (Bagnus, 2011) on macrovertebrate fossils evaluated biostratinomic and diagenic processes and grouped faunal remains into different sub-categories: three main taphorecords (TRs, *sensu* Fernández-López, 1987) are defined according to different stages of bone surface modifications by physical and chemical agents (Tab. C.1). Grouping was based mainly on weathering (Behrensmeyer, 1978; Díez et al., 1999; Kos, 2003; Torres et al., 2003), abrasion (Behrensmeyer, 1991) and oxidation (Hill, 1982; López-González et al., 2006; White, 1976; White et al., 2009), because these alterations prevail and are widespread across all the sedimentary units.

Based on macroscopic observations of these main taphonomic features, fossils from TR2 and TR3 are interpreted as re-deposited fossils: displaced bones along the sedimentary surface before burial; whereas fossils from TR1 are considered re-elaborated (*sensu* Fernández-López, 1991, 2007, 2011). The higher degree of abrasion and the presence in the latter sub-group of multiple generations of oxides, non-uniformly distributed on the fossil, are explained with repeated exhumations and dislocations of previously buried elements (López-González et al., 2006).

Therefore, a hypothetical model of site formation processes has been proposed: animals died close to the karst sinkhole and the

action of heavy rains transported sediments and partially articulated carcasses into the fissure. The rapid burial of fossils is confirmed by the general low degree of weathering. Karst erosional processes are responsible for the very large percentage of fractured fossils, as a result of the collapse of rock blocks from the vault. The TR1 group of fossils points to internal water-flows, reworking and transportation of already fossilized bones. Finally, manganese oxides that give the external widespread black color to all the fossils, stones and part of the lithic artifacts are products of the phreatic water fluctuation.

Although the taphonomic analysis definitely improved the interpretation of the P13 fossiliferous deposit, the interactions between bones and karst water flow have not been studied in relation to the spatial distribution and orientations of the skeletal elements.

Taking into account the inherent spatial properties of taphonomic processes, we assume that taphogenic products (*sensu* [Fernández-López, 2000](#)) in space are not mutually independent and that entities which are close to each other, are likely to have followed the same genesis.

Thus, in order to tackle our second objective, we analyze the spatial distribution of Fe-Mn oxides on the fossils, since the cause of their formation may derive from the action of circulating waters. Three ordinal degrees of oxidation (low, medium and high) are recognized, based on its aspect, intensity and extension. We assume that spatial aggregation of heavily-coated faunal remains (and consequently segregation from non-oxidized ones) is an indication of interactions with karst water flow.

A.2.2 Taphonomy of lithic artifacts

The degree of natural alterations (thermal, tribological and chemical) of the lithic artifact surface, as a result of contact with the sediments, is a valuable index of integrity of the depositional context and it can usefully support spatial analysis in reconstructing both the past environmental conditions and the site formation processes ([Burroni et al., 2002](#)).

Table A.1: Contingency table of taphorecords (reproduced from [Bagnus, 2011](#)).

SU	TR1	TR2	TR3	Total by SU
A	10	30	45	85
B	26	86	114	226
C	34	69	179	282
Total by TR	70	185	338	593

According to a recent review of preliminary technological analyses ([Arzarello et al., 2012, 2015](#)), the lithic assemblage shows a general good state of preservation. If we consider the degree of patination as a good indicator of the intensity, and not necessary of the duration, of chemical processes to which the deposit has been subjected ([Burroni et al., 2002](#)), artifacts undergo non-homogeneous interactions with chemical agents. Besides fresh artifacts, many of the specimens (35%) bear Fe-Mn coatings (Fig. [B.2a](#)). Iron-manganese, as well as white superficial patina (5%), seems to equally affect artifacts of different flint raw materials, more readily on those with a porous structure (Fig. [B.2b](#)).

Macroscopic observations of tribological features on the assemblage reveal mint to sharp, not rounded, artifact ridges and edges. Post-depositional fractures affect 20% of the lithic material (Fig. [B.2c](#)).

No refittings were found, as it is reasonable to expect for materials in a secondary context.

As particle size distribution of lithic assemblages has great implications in interpreting site formation processes ([Bertran et al., 2012](#)), systematic screen-washing of sediments was carried out in order to guarantee recovery of lithic debris, even though a very low percentage of small-size specimens has been noted. This result can be initially explained either as a function of the mode of knapping, which did not produce a lot of debris, or is more likely due to natural post-depositional processes (winnowing of low energy agents),

prior to final burial, possibly outside the karst fissure. Moreover, the dimensional analysis of the complete lithic assemblage (Fig. B.2d) does not show sorting effects.

We analyze the spatial distribution of taphonomic features on the lithic assemblage, considering that various natural mechanisms, disturbing the spatial arrangement of artifacts and sediments, will produce distinctive combinations of wear features on the surfaces of lithic artifacts (Burroni et al., 2002).

As for the faunal assemblage, we focus the analysis on the distribution of Fe-Mn patinae. Three ordinal degrees of patination (absent, spotted and covering) are recognized, based on its presence and extension. In order to evaluate the impact of post-depositional processes at the site, we conduct independent and comparative taphonomic spatial analyses with the fossil remains.

A.3 Spatial data collection and sampling

Since 2007, systematic field investigations of the P13 fissure have been carried out by the University of Ferrara (in collaboration with the Universities of Torino and Roma Sapienza, until 2010).

From the first excavation season, a grid of 1 square meter units has been set. Since 2010, the three-dimensional coordinates of the finds are recorded with a Total Station, which replaced the use of a water level. Orientation (dip and strike) of coordinated faunal remains (length ≥ 2 cm), geological clasts (length ≥ 5 cm) and all the lithic artifacts is estimated with a 45 degree of accuracy, which is not precise enough for detailed fabric analysis.

In order to avoid possible sampling issues in spatial data analysis due to the variation in the recording methods, we select subsets of the lithic and faunal collection, excluding SUs A and B, because they have been excavated prior the use of the Total Station.

Focusing on SUs C and D, we scale the windows of analysis according to the extension of excavated areas for each SU, excluding the presence of the large blocks of rock. We reduce in this way

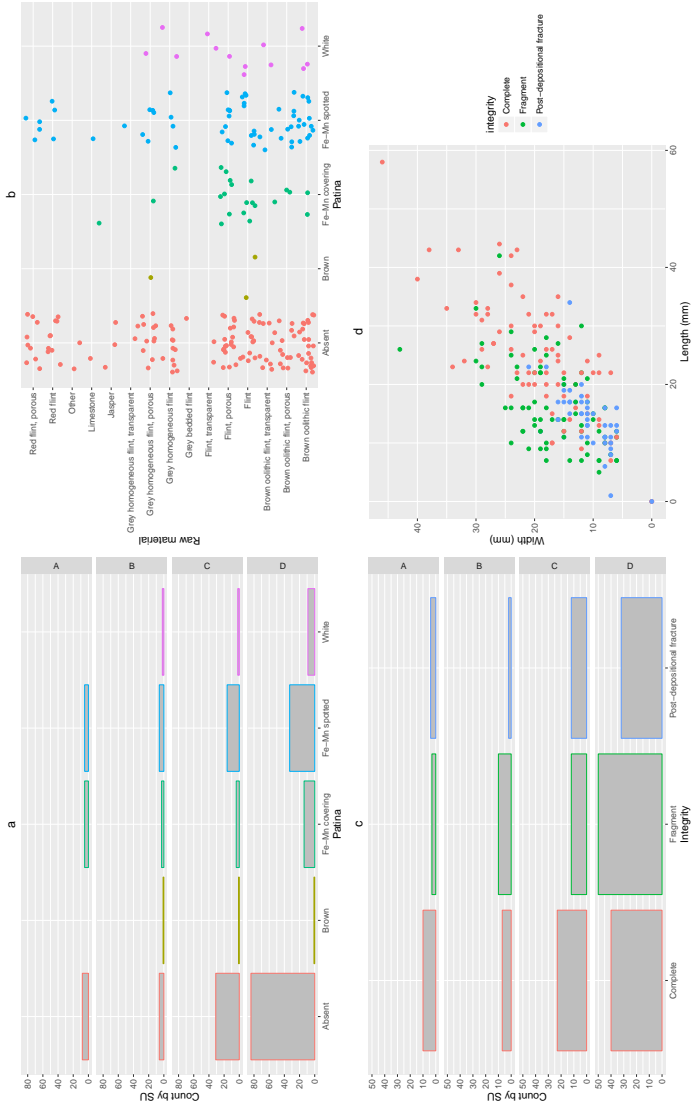


Figure A.2: Frequency of patinae on the lithic assemblage, grouped by SUs (a) and their distribution on raw materials (b); frequency of fractures on the lithic assemblage, grouped by SUs (c); scatterplot of artifact dimensions (d).

the impact of the Modifiable Area Unit Problem (MAUP) in point pattern analysis (Openshaw, 1996), especially insidious in this study due to the particular geological setting of the site. The analyzed areas of SUs C and D are respectively 4.34 m^2 and 5.82 m^2 .

During 6 years of excavations, more than 1600 of 2152 macrovertebrate fossils have been spatially recorded: 471 from SU C and 916 from SU D. However, Bagnus (2011) conducted taphonomical analysis on fossils recovered during the 2007 to 2010 field seasons and only 593 of these are classified in one of the three taphorecords (Tab. C.1). Our sample includes 135 coordinated elements of the 282 analyzed fossils from SU C. From the total number of 366 lithic artifacts collected until the 2014 field season, 147 have been recorded with three-dimensional coordinates. Our sample includes 34 lithics from SU C and 84 from SU D. From the micro-mammal assemblage, we include in this study only the *Allophaiomys ruffoi* species. Of the 53 arvicoline teeth collected from the screen-washed sediments, 49 have secure provenance attribution from SU B ($n = 2$), C ($n = 14$) and D ($n = 33$) (Lopez-García et al., 2015). However, the *A. ruffoi* point pattern does not represent the exact distribution of the remains. Indeed, we randomly displaced ($r = 0.5$) each point indicating the provenience of the sieved sediment.

A.4 Vertical distribution

The vertical distribution of finds is a key factor in the analysis of site formation processes. Many processes can be well approximated by a ‘nearly’ normal distribution. However, testing the appropriateness of this assumption is an essential step in spatial data analysis. Strongly right skewed distribution would occur in case of a non-uniform vertical distribution of finds; thus requiring the analysis to acknowledge the covariate effect of gravity in the observed spatial pattern.

The vertical distribution of finds within SU C is globally unimodal, roughly symmetric (slightly left skewed), in spite of some out-

liers (Fig. B.3a). It ‘nearly’ approximates the maximum-likelihood fitting of a normal curve (red line) with mean (μ) = -1.53 m and standard deviation (σ) = 0.27 m. However the Shapiro-Wilk normality test rejects the null hypothesis of a gaussian distribution (p – value = 0.0005). On the other hand, the Q-Q plot (Fig. B.3b) shows deviations from the theoretical normal distribution (red line) between one (68.27% of the sample) and two (95.45%) standard deviations from the mean. The S-shaped empirical distribution recalls its left skew.

The global vertical distribution of finds resemble that of the faunal assemblage, due to the weight of the latter on the sample data ($n = 471$). The distribution of the lithic artifacts is more left skewed, while the small sample of micromammals follows a multimodal distribution with a prominent peak at -1.2 m (Fig. B.3a). Although the difference in size of the two samples, it is worth notice that the mean value of the vertical distribution of *A. ruffoi* is very close to that of the lithic artifacts (Welch Two Sample t-test p – value = 0.5803).

The vertical distribution of finds in SU D is globally unimodal, slightly left skewed, with one peak at -2.10 m and no outliers (Fig. B.3c). Although the distribution is close to the best fitting normal curve (red line) with $\mu = -2.34$ m and $\sigma = 0.33$ m, the Shapiro-Wilk test rejects the hypothesis of normality (p – value = $2.497e - 12$). The Q-Q plot (Fig. B.3d) shows a more dispersed distribution with respect to the former one. Its steeper line follows the theoretical normal distribution within one standard deviation from the mean (68.27% of the sample).

Compared with the global distribution, the vertical distribution of lithic artifacts slightly skews to the right. Nevertheless, the Shapiro-Wilk test fails to reject the normality hypothesis (p – value = 0.2742). On the other hand, the micromammal distribution is multimodal and slightly shifted to the right (Fig. B.3c). Its mean (-2.284 m) is quite close to the mean of the lithic sample (-2.423 m). However, the Welch t-test rejects the hypothesis of two equal sample means (p – value = 0.0141). If we cannot state that the two distributions have the same mean, we remark the highest

density of both the assemblages at around -2.5 m.

As for the vertical distribution of the identified taphonomic features on the lithic and faunal assemblages, Fig. B.4a,b illustrates the overall distribution of patinae on the lithic artifacts, across SUs C and D. The histogram shows the increasing number of finds between the two sedimentary units. This trend is reflected as well in the rise of Fe-Mn patinated artifacts (41% in SU C and 45% in SU D), compared to non-patinated ones (respectively 50% and 48%). The kernel density estimation (blue and green lines) shows a slightly higher occurrence of patinated artifacts at the lower part of the sequence (below -2.5 m), whereas in SU C (up to -2 m) there is no evident preference in the vertical distribution of patinae. The higher density of patinated artifacts, linked to the concentration of lithics observed in Fig. B.3c at about -2.5 m, can be localized in a restricted spot at the bottom right corner of the excavated area (Fig. B.4a).

Restricting the analysis to SU C, the vertical distribution of coordinated macrovertebrate fossils analyzed by Bagnus (2011) spans 71% of the elevation range of the complete assemblage from the same SU. However, being only the 29% of the population, we acknowledge that our sample cannot be considered representative.

The densities of the low and medium rate of oxides resemble the general distribution (Fig. B.4c,b). Low values follow a ‘nearly’ normal distribution (Shapiro-Wilk normality test p - value = 0.2186). The density of high oxidized remains (54% of the sample) draws a left skewed distribution, with a peak at about -1.3 m; whereas fossils with a medium degree of oxides are skewed to the right. However there is no clear preference for oxides to occur deeper in the sequence. The mean values are very close to each other and lower values of oxides are more dense at the bottom of the SU.

As for the distribution of the three taphorecords, the prominent peak of TR1 at -1.6 m (Fig. B.4f) contrasts with a more distributed and mixed distribution of the second and third groups of fossils. However, the very low frequency of TR1 ($n = 9$) limits further analyses.

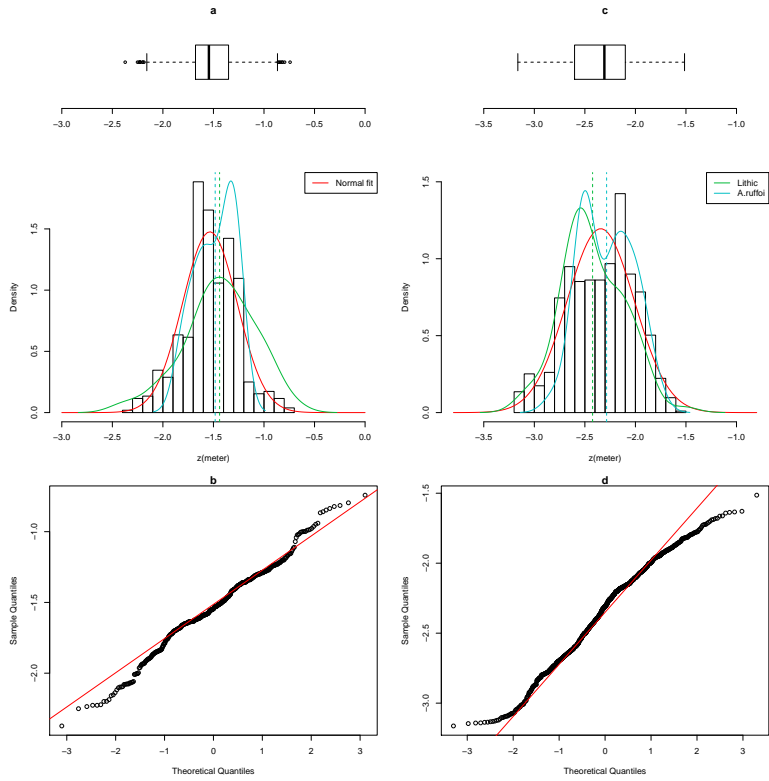


Figure A.3: Vertical distribution of finds in SUs C (a,b) and D (c,d).

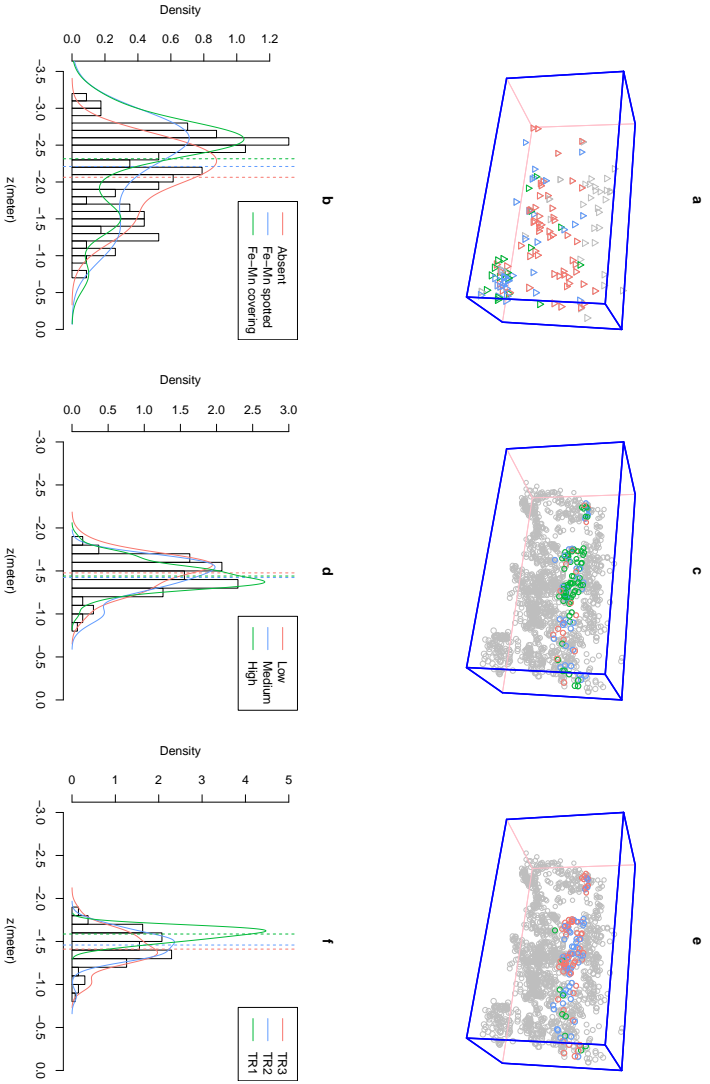


Figure A.4: 3D and vertical distributions of Fe-Mn patinae on the lithic assemblage from SUs C and D (a,b); oxides (c,d) and taphorecords (e,f) from the faunal sample.

Although our study is constrained by the small sample of fossils and by its limited spatial extension to SU C, the analysis of the vertical distribution of Fe-Mn oxides in the faunal and lithic assemblages does not show any clear global pattern. Indeed, even taking into account the localized cluster of artifacts at the very bottom of SU D (Fig. B.4a), the process responsible for the distribution of Fe-Mn oxides seems to operate indistinctly through the complete stratigraphic sequence, with no explicit preference for lower elevations.

With no evidence for strong right skewed distributions of finds in SUs C and D, we have reasons to exclude the covariate effect of gravity in the observed spatial pattern. The subsequent point pattern analyses are directed to the study of the 2D spatial distribution of fossils, lithics and their taphonomic status.

A.5 Point pattern analysis

The observed patterns of the archaeological and paleontological remains within SUs C and D, as well as the patterns of taphonomic features recognized on them, have been treated as realizations of spatial point processes, i.e. site formation and modification processes.

Indeed, a spatial point pattern is generally defined as the location of events generated by a point process, operating simultaneously at different scales: a first-order global scale and a second-order local scale (Bailey and Gatrell, 1995). The former results from the frequency (density) of events within a bounded region; the latter results from spatial dependency between points, e.g. from a tendency for values of the process at nearby locations to interact with each other. Three different types of interpoint interaction are possible: random (or Poisson); regular and cluster. Regular patterns are assumed to be the result of inhibition processes, while cluster patterns are the result of attraction processes. Therefore, two main issues of interest are explored by spatial point pattern analyses: the distribution (density) of entities in space and the existence of possible interactions between them (Ord, 1972).

First-order effect in the observed point-pattern is generally non-parametrically evaluated by means of kernel density estimation (Diggle, 1985). As an average density of points in the study region, intensity informs about uniform or inhomogeneous distribution of events.

Multiple scales of second-order patterning and the probability of a stochastic occurrence are explored by the Ripley's K summary function (Ripley, 1976, 1977) and derivatives, for both univariate and bivariate point patterns. The K function is designed to identify the relative aggregation and segregation of point data at different scales. The univariate $K(r)$ function measures the expected number of events found up to a given distance r around an arbitrary event. By comparing the estimated value $\hat{K}(r)$ to its theoretical Complete Spatial Randomness (CSR) value, it is possible to assess what kind of interaction exists between events. The bivariate function, or cross-type $K_{ij}(r)$ function seeks to evaluate, at each distance r , the spatial relation between two types ij of observed events. In this case, the definition of the null hypothesis uses a randomization technique of either the location of one of the types (random shift hypothesis), or the type itself of the event at each point, preserving the original location (random labeling hypothesis) (Goreaud and Pélissier, 2003). The former aims to evaluate the spatial relationship between patterns of two independent processes, while the latter assumes the same process in determining the pattern for different types.

Especially in small dataset, the estimation of correlations between points is biased by edge effects, arising from the unobservability of points outside the window of analysis. In order to reduce that bias, we implement here Ripley's isotropic edge correction (Ohser, 1983; Ripley, 1988).

Monte Carlo simulations (Robert and Casella, 2004) are used to generate pointwise critical envelopes of random expected values for the null hypotheses, providing an adequate level of statistical significance. We choose a small significance level ($\alpha = 0.01$ obtained with 199 simulations), due to the higher possibility of committing a Type 1 error by testing our hypotheses. Values of the empiri-

cal distribution (black solid line) are plotted against the theoretical Poisson distribution (red dotted line) and the simulated global envelope of significance (grey area). For $K(r)$, when the solid line of the observed distribution is above or below the shaded grey area, the pattern is significantly clustered (points are closer together than would be expected for a complete random pattern) or dispersed. For $K_{ij}(r)$, the benchmark value πr^2 is consistent with independence between the points of types i and j , and does not imply a Poisson distribution.

A.5.1 Formation processes

In order to investigate the processes involved in the formation of the Pirro Nord deposit, we provisionally assume the deposition of each sedimentary unit to be the result of mass wasting events filling the fissure and resulting in the distribution of fossils and artifacts independently of each other.

To test the appropriateness of our working assumption, we first analyze the overall distributions of finds, treated as univariate point patterns. Applying a set of exploratory statistics, we aim to determine the nature of the depositional processes, e.g. if they raise in- or homogeneous distributions. Then, we analyze the relative patterns of the faunal and lithic assemblages from SUs C and D. In this case, we treat the two distributions as multitype point patterns.

The intensity of the lithic and faunal assemblages is non-parametrically estimated by first performing a Gaussian smoothing kernel of their distributions, for both SUs. Likelihood cross-validation bandwidth, which assumes an inhomogeneous process, is selected for each pattern. Edge correction is applied using the method of Diggle (1985). Then, Berman's Z_2 test is used to determine whether or not the intensity depends on a spatial covariate Z , assuming that the spatially varying (inhomogeneous) intensity is a function of Z . Thus, in order to measure the strength of dependence on the covariate, we use the Receiver Operating Characteristic (ROC) curve. Spatially adaptive smoothing, nearest-neighbour density and scan tests have been used

in order to assess for the evidence of hot spots in the intensities of the unmarked point patterns. Estimations of the $K(r)$ and the Kaplan-Meier corrected empty-space $F(r)$ functions provide further methods for the interpretation of the distributions.

Multitype summary functions are used in the analysis of the dependence between points of the two assemblages. In this case, our main research question is whether different types of finds have the same spatial distribution. The cross-type $K_{ij}(r)$ function and the Kaplan-Meier corrected nearest-neighbour $G_{ij}(r)$ function are used to estimate the association between points of types i and j , for any pair of types of finds. Positive spatial correlation between the two types of finds would suggest that lithic artifacts are more likely to be found close to fossils than would be expected for the hypothesis of *independence*. It would confirm the field observations about their close stratigraphic association and further support our hypothesis that both patterns are the realization of one depositional process. On the other hand, segregation of the two patterns is equivalent to variation in the probability distribution of types. Segregation could be interpreted as the expression of preferential/differential depositional processes. In this case, more detailed analyses would be necessary.

A.5.2 Post-depositional processes

In order to evaluate the degree of post-depositional disturbance of the deposit, the spatial dependence of observed taphonomic features is assumed to be the expression of a related diagenetic process. Measured phenomena that are closer together in space, tend to be more related than those further apart (Tobler, 1970).

Like in applications of point pattern analysis in spatial epidemiology (Diggle, 2003; Gatrell et al., 1996), we distinguish between *cases* and *controls*. The distribution of cases of a certain taphonomic alteration can be regarded as the realization of a diagenetic point process, whereas control points refer to non-altered remains. In a conditional analysis of a spatial case-control study the locations

are fixed covariates, and the taphonomic status is treated as a random variable. The simplest null model (*random labelling*) is that the taphonomic status of each find is random, independent and with constant risk of occurrence.

Spatial correlations of diagenetic alterations on the lithic and faunal assemblage are explored by the $K_{ij}(r)$ function, random labelling the pair case/control of Fe-Mn oxidation. We assume in this case that an independent process (karst water circulation), subsequent to the initial event responsible for the accumulation of the finds in each SU, determined their preservation status. Positive deviations from the null hypothesis, suggest that cases are more likely to be found close to controls than would be expected if their status was randomly determined. On the other hand, negative deviations would indicate segregation between cases and controls. Thus, it would suggest that the action of post-depositional water-related processes could have locally reworked the original distribution, determining the altered status of the remains.

All the spatial analyses were performed using the *spatstat* package (Baddeley and Turner, 2005) in R statistical software (R Core Team, 2015).

A repository containing a compendium of data, source code and text (Marwick, 2017) is archived at the DOI: [10.5281/zenodo.55736](https://doi.org/10.5281/zenodo.55736).

A.6 Results

A.6.1 Formation processes

Fig. B.5c,d shows the smoothing kernel estimation of the faunal assemblage intensity respectively in SUs C and D. Lithic artifacts and micromammals remains of *A. ruffoi* are superimposed on it. The visual assessment of the plot suggests positive spatial association between the three types of finds. Higher intensities in the distributions are evident at specific values of the x coordinate ($6 < x < 7$ and $8 < x < 9$), in both the sedimentary units. Yet, a concentration of artifacts, already observed in Fig. B.3c and B.4a,b, is evident at

the lower right corner of SU D (Fig. B.5e). Such higher densities of finds are clearly shown as well in the scatterplots of the projected third coordinate (Fig. B.5a,b). Notably, the thickness of the sedimentary unit cannot be accounted to be responsible for those hot spots with higher density of finds. Neither the apparent inhomogeneous intensities along the x axes are supported by the ROC curves (Fig. B.5e,f). Even if Bermans's Z_2 tests suggest significant evidence of dependence on the x covariate, the ROC curves show that it does not have strong discriminatory power.

Fig. B.6a,d shows the resulting p - values of likelihood ratio scan test statistic. The test detects differences in the densities of the distributions, showing zones with high abundance of finds. The estimated homogeneous $\hat{K}(r)$ and $\hat{F}(r)$ functions are consistent with this result. For both SUs C (Fig. B.6b,c) and D (Fig. B.6e,f) they suggest strong deviation from the null hypothesis of CSR towards aggregation, at any scale.

In analyzing a point pattern, it is confounding and it may be impossible to distinguish between clustering and spatial inhomogeneity (Baddeley et al., 2015). Given the context of the site, and the results of our non-parametric analyses, we proceed considering the distributions of finds as the results of cluster homogeneous processes. The bivariate version of the homogeneous $K_{ij}(r)$ and $G_{ij}(r)$ functions allows us to statistically test the hypothesis of aggregation between the types of remains.

In Fig. B.7, the top line of panels (a,b,c) shows the ordinary estimations of the K function for the three types of finds (Fauna, Lithic and *A. ruffoi*) from SU C. Panel B.7a resembles Fig. B.6b and indicates statistical significant clustering of the faunal remains for any values of r . The lithic assemblage shows as well a significant cluster tendency, for $r > 0.1$, while it fails to reject the null hypothesis of CSR for lower values. Instead, the estimated $\hat{K}(r)$ for the micromammals shows aggregation, but, for all values of r , we cannot state that the distribution is not random. This result might reflect the random displacement applied to the micromammal point pattern.

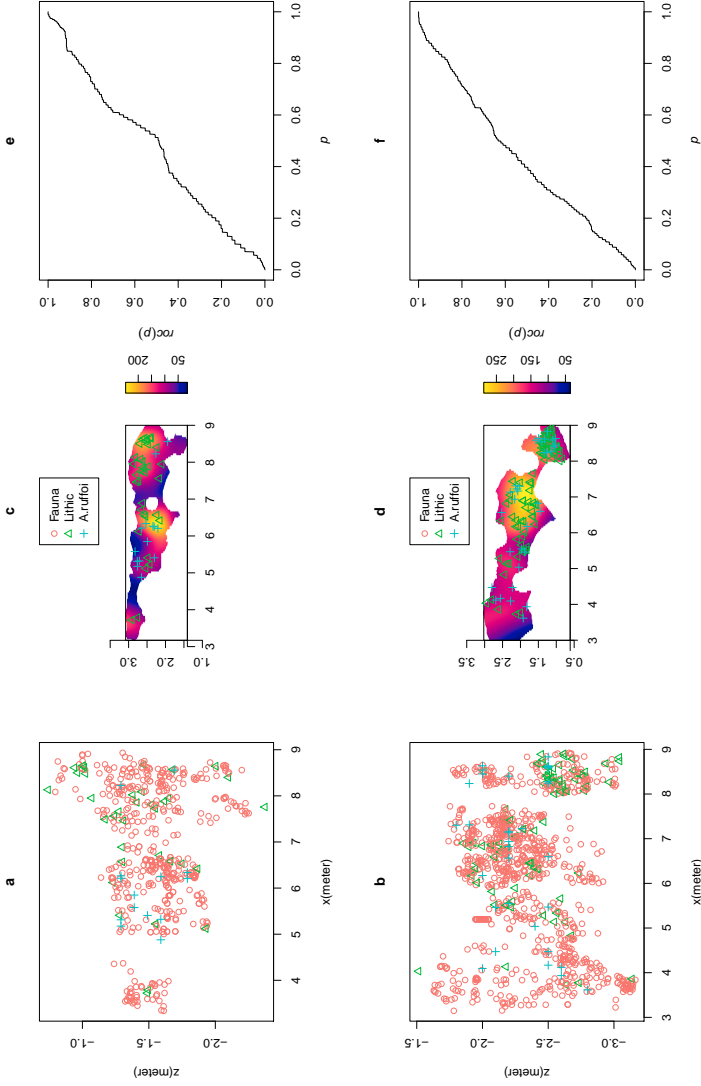


Figure A.5: Scatterplot of finds from SU's C (a) and D (b); Smooth density estimation of the faunal assemblage and distribution of lithic artifacts and *A. ruffoi* remains in SU's C (c) and D (d); ROC curves for the covariate x coordinate in SU's C (e) and D (f).

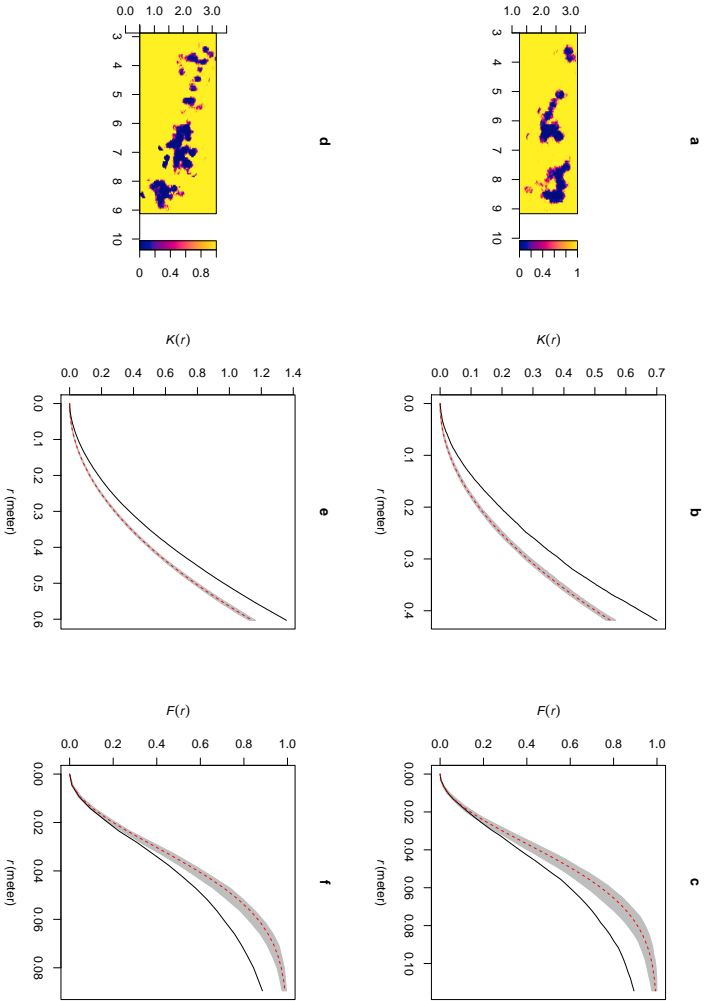


Figure A.6: p-values of the likelihood ratio scan test, with logarithmic colour scale, for SUs C (a) and D (d); pointwise envelopes of the homogeneous $K(r)$ and $F(r)$ functions for unmarked finds from SUs C (b,c) and D (e,f).

The middle and bottom lines of panels in Fig. B.7 show estimations of the homogeneous cross-type K and G functions for all pairs of types i and j . Interestingly, Fig. B.7d suggests positive spatial correlation between lithic and faunal remains at any values of $r > 0.05$. The corresponding $G_{ij}(r)$ function measured the cumulative distance from each point of type i (Lithic) to the nearest point of type j (Fauna). It shows (Fig. B.7g) that the nearest-neighbour distances are significantly shorter than expected, but we cannot reject the hypothesis of independence between fossils and artifacts. However, the short scale of the function suggests that any artifact is surrounded by fossils. This result statistically confirms the stratigraphic association of artifacts and fossils, previously based on field observations. On the other hand, deviations between the $\hat{K}_{ij}(r)$ function and the benchmark πr^2 suggest segregation between lithics and *A. ruffoi* specimens, but the hypothesis of independence between the two types is more significant (Fig. B.7e,h). Conversely, the small mammal assemblage is closer to the rest of the fossils than expected for independent distributions, for $r > 0.2$. For lower values of r , the K and G functions fail to reject the hypothesis of independence.

The top line of panels in Fig. B.8 (a,b,c) shows estimations of the $K(r)$ function for the three types of finds from SU D. Panel B.8a confirms the same clustering trend of the faunal assemblage. Analogous to the distribution of finds from SU C, the global pattern is mostly weighted on the faunal assemblage (Fig. B.6e). Conversely, in SU D the distribution of lithics shows stronger significant clustering for $r > 0.1$. Again, the resulting $\hat{K}(r)$ for the micromammal assemblage suggests a statistically insignificant aggregation tendency for all values of r , but $0.4 < r < 0.5$. In contrast to the previous result, estimations of the $K_{ij}(r)$ function support significant positive correlation between the lithic artifacts and the *A. ruffoi* remains (Fig. B.8e). Thus, they occur closer than expected in the case of independent distributions. Panel B.8f shows the same positive correlation also between micro- and macro-mammals for $r > 0.2$. The panels B.8d,g show as well a significant positive aggregation between

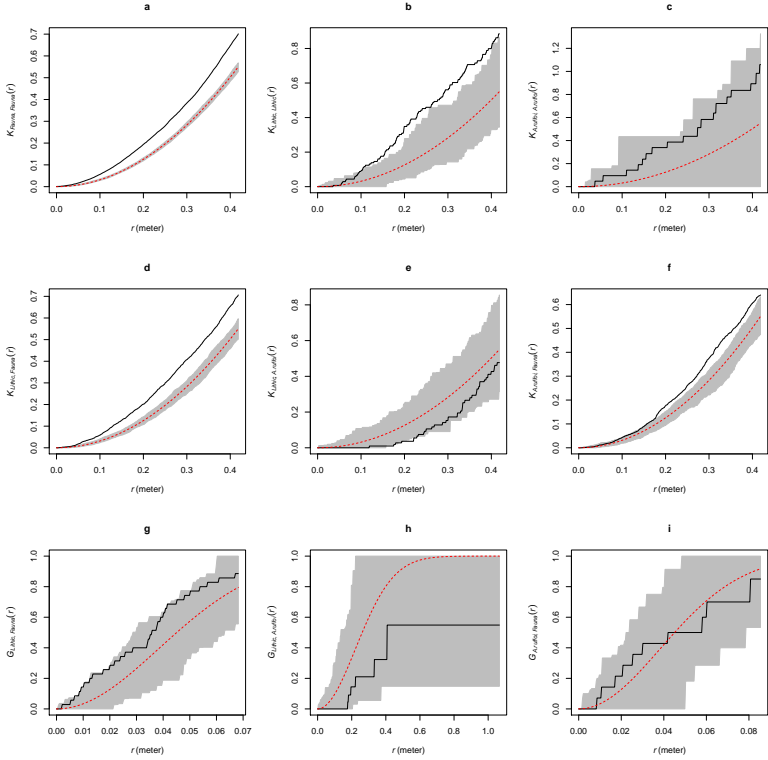


Figure A.7: Pointwise envelopes of the homogeneous cross-type $K_{ij}(r)$ and $G_{ij}(r)$ functions for all pairs of types i and j in SU C.

lithics and fossils for values of $r > 0.1$. In addition, the estimated $\hat{G}_{ij}(r)$ function offers a closer view of the distribution. For values of $r < 0.1$, it fails to reject the hypothesis of independence.

A.6.2 Post-depositional processes

To achieve our second objective, namely to evaluate the degree of post-depositional disturbance of the deposit, we first analyzed spatial distribution of oxides on the lithic and faunal assemblages independently, then we moved to a comparative analysis. We are particularly interested in the spatial distribution of Fe-Mn oxides (cases) compared with the absence of them (controls).

Fig. B.4a does not suggest segregation of patinated and non-patinated lithics. If we perform random labeling of the presence of Fe-Mn (spotted and covering) with its absence in both the stratigraphic units, the outputs of the cross-type function (Fig. B.9a, b) show that the observed altered artifacts are, with a 0.01 level of significance, randomly and independently located in SU C. The positive discrepancy between the estimated $\hat{K}_{ij}(r)$ and the benchmark πr^2 indicates aggregation of cases and controls, but it lies within the grey envelope of the *random labeling* hypothesis. Conversely, patinated and non-patinated lithics in SU D appear to be closer to each other than expected for the null hypothesis. In this unit the observed $\hat{K}_{ij}(r)$ function over-exceeds the envelope at values of $r > 0.4m$, hence it indicates statistically significant aggregation. Such pattern statistically confirms the visual assessment of Fig. B.4a. Consequently, oxidized and non-oxidized artifacts most probably occur in SU D well aggregated in space, while their aggregation is not statistically significant in the above unit.

We could not compare the oxidation patterns between lithics and fossils from SU D, because the taphonomic analysis of Bagnus (2011) did not include fossils from this unit. Thus, we focused our analysis on SU C.

The distribution map (Fig. B.4c) does not suggest any evident pattern. When we apply random labelling of the absence of oxidation

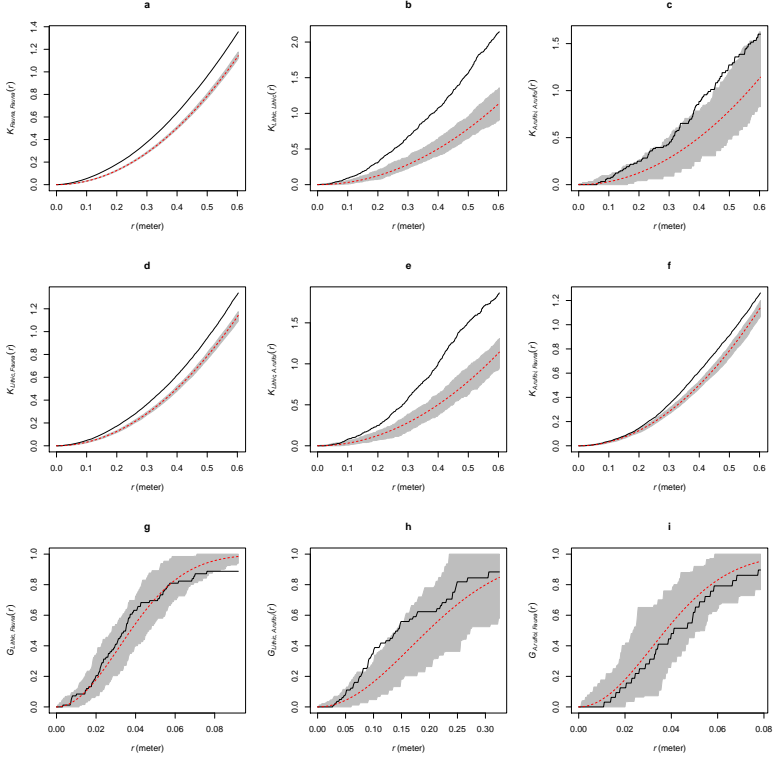


Figure A.8: Pointwise envelopes of the homogeneous cross-type $K_{ij}(r)$ and $G_{ij}(r)$ functions for all pairs of types i and j in SU D.

with the medium and high degrees of its presence, the output of the bivariate $K_{ij}(r)$ function shows a segregation tendency between them, but it is not statistically significant. (Fig. B.9c). A random and independent distribution of oxides is more plausible.

Finally, Fig. B.9d shows the result of the $K_{ij}(r)$ function, random labeling the cases (medium and high degrees) and controls (absent or low degree) of Fe-Mn oxides on the lithic and faunal assemblages from SU C. The empirical values of the cross-type function are balanced on the theoretical expectation for complete spatial independence (red line). It clearly lies inside the grey envelope of significance. Therefore, our analysis shows an independent spatial distribution of Fe-Mn patinated and non-patinated lithic artifacts and fossils from SU C. In the lower unit (SU D), where Fig. B.4b indicates higher density of oxidized artifacts, estimations of the cross-type K function suggests that they occur closer than expected to fresh ones.

A.7 Discussion

The Early Pleistocene site of Pirro Nord (fissure P13) has yielded evidence for one of the earliest occurrences of hominins in Europe. The importance of the evidence calls for a multivariate taphonomic analysis in order to establish the nature of the processes involved in the formation of the deposit and the degree of its post-depositional disturbance. We address that need by investigating the spatial association of the archaeological and paleontological remains, as well as the spatial distribution of artifacts and fossils with diagenetic alterations. We focused our analysis on the lower stratigraphic units C and D, since they provide the most significant corpus of finds and they have been studied with the same research protocol.

A.7.1 Formation processes

Non-parametric analyses have been carried out in order to characterize the processes responsible for the formation of the deposit. Then,

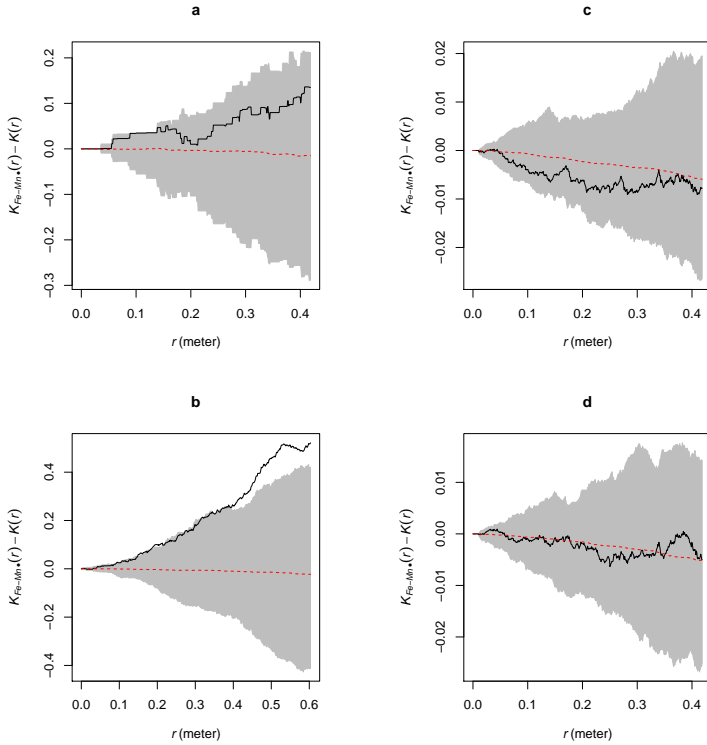


Figure A.9: Pointwise envelopes of the homogeneous bivariate $K_{ij}(r)$ function, random labeling *cases/controls* of patinated lithics in SUs C (a) and D (b); oxidated fossils in SU C (c); Fe-Mn oxides on the lithic and faunal assemblages from SU C (d).

we accounted for the relative spatial pattern of the different types of finds.

The vertical distribution of the archaeological and paleontological assemblages does not appear to be affected by strong gravitational effects. On the other hand, it resembles a 'nearly' normal distribution and suggests a very close mean occurrence of lithic artifacts and *A. ruffoi* remains, despite the small sample of micromammals (Fig. B.3). A visual interpretation of the projected third coordinate (Fig. B.5a,b) also suggests that the intensity of finds is not a function of the covariate z . Moreover, higher densities are not linked to the thickness of the stratigraphic units. They are clearly localized at values of $6 < x < 7$ and $8 < x < 9$ in both the SUs, as shown also by Fig. B.5c,d and B.6a,d. Indeed, the Berman's Z_2 test for the dependence of the point process on the spatial covariate x failed to reject the null hypothesis for SU C (p -value = 0.0044) and D (p -value = 1.913e - 14). However, even if it suggests significant evidence that the intensity depends on some covariate, the effect of that covariate could still be weak. ROC curves (Fig. B.5e,f) indicate that the x coordinate does not have discriminatory power.

Bartlett (1963) showed that it is possible to formulate a point pattern which can be equally interpreted as a Poisson inhomogeneous process, or a homogeneous cluster process. According to our non-parametric analyses, we proceeded under the assumption that the processes involved in the formation of the Pirro Nord (P13) deposit are homogeneous and clustered. The scan tests in Fig. B.6a,d show hot spots of points, mostly localized between $6 < x < 7$ and $8 < x < 9$. The cluster correlation between all the finds is significantly confirmed by the estimations of the K and F functions (Fig. B.6). The first lines of panels in Fig. B.7 and B.8 offer a type-based view of these patterns. Indeed, the estimated $\hat{K}(r)$ functions of the faunal assemblage (Fig. B.7a and B.8a), which constitute the bigger part of the analyzed sample of data, resemble the results for the complete populations (Fig. B.6b,e). The lithic assemblage also shows significant aggregation; while the small sample of *A. ruffoi* falls inside the envelope of CSR.

Faunal remains and lithic artifacts show some overlapping when evaluated by means of Gaussian smoothing kernel (Fig. B.5c,d). Positive spatial association between fossils and lithics is statistically confirmed by the cross-type K and G functions for the examined SUs (Fig. B.7 and B.8). Fossils and artifacts tend then to occur aggregated with each other (they are closer than expected for an independent process). Significant spatial proximity is also shown between artifacts and micromammal remains, especially in SU D.

According to the results of our analyses, the stratigraphic and spatial association between the types of remains should be considered as the result of the same formation process. Finds occur in the clayey-sand sediment together with a high number of angular to sub-rounded gravels and boulder-sized rock clasts. Such a stratigraphic setting suggests repeated mass-wasting processes (at least two events, represented by SUs C and D, which were included in this study) with a low degree of reworking in a relatively short span of time (Arzarello et al., 2012). Rapid-moving and chaotic water-laden masses, such as mud-flows or earth-flows, of soilwash and rock rubble with fossils and artifacts (Butzer, 1982, p. 46), could have been triggered by intense rainfalls and became trapped in the karst sink-hole directly opening to the outside. The sedimentary fill would have derived from the top, by gravity, directed into the empty space between the large limestone blocks that made up the internal structure of the fissure. The thickness of the layers is likely correlated to the intensity of such events.

On the other hand, the clustered distribution of all the finds cannot be linked to the thickness of the stratigraphic units. The big blocks of calcarenite, which in some places transect the stratigraphic units (Fig. C.1), created a complex internal structure and might have influenced the direction of sediment accumulation. However, sedimentation rate, driven by the rugged topography of the site, does not seem to be spatially associated with the localized hot spots (Fig. B.6a,d). Thus, clustering might have been a correlated effect of the formation process.

The presence of partially articulated vertebrate skeletal elements

and their general low degree of weathering indicate fast burial and transport of bones from nearby locations (Bagnus, 2011). A close spatial proximity between the original location of the finds and the karst fissure, as well as a relatively fast burial, is also corroborated by the unrounded ridges and edges of the lithic artifacts and by the technological consistency of the assemblage (Arzarello et al., 2015).

In conclusion, our spatial statistics analyses confirm the field observations about the spatial association of archaeological and paleontological remains.

A.7.2 Post-depositional processes

After dealing with our first research question (to examine the spatial distribution of finds in the context of the site formation processes), our analyses were particularly directed to test the hypothesis of post-depositional processes reworking the deposit. We assume that the spatial aggregation of taphonomic surface alterations, and their relative segregation compared to non-altered finds, would indicate the localized activity of diagenetic agents.

We focused more on the spatial distribution of oxides, because traditional explanations for the development of Fe-Mn patinas on the surface of flint refer to the deposition of various iron and manganese oxides and hydroxides out of soil water (Stapert, 1976). Similarly, the origin of manganese coatings on fossils, in karst environments, may derive from circulating water, or from the manganese present in the surrounding limestone rock dissolved by groundwater (Hill, 1982).

The vertical distribution of oxides on the lithic artifacts and the sample of faunal remains (Fig. B.4) spans the complete stratigraphic sequence and apparently shows a gradual increase through the lower layers, especially in the lithic assemblage. Intensity of oxides is indeed more likely proportional to the density of finds and not related to the depth.

By applying a set of spatial statistics (namely cross-type $K_{ij}(r)$ function) to the archaeological and paleontological remains, we searched

for evidence of localized areas, which might have been subjected to the presence of water, especially water-flows.

In SU C, the spatial distribution of Fe-Mn patinas on lithics and fossils is, with a certain degree of significance, the result of independent processes (Fig. B.9a,c,d). We cannot state that there is aggregation (spatial proximity) between oxidized finds and fresh ones. Neither the results of the bivariate K function, random labeling the cases/controls of Fe-Mn coating, show segregation, which is indicative of spatially defined diagenetic processes. In contrast, in SU D (Fig. B.9b), patinated and fresh artifacts occur significantly spatially aggregated to each other for values of $r > 0.4m$. They occur closer than expected by an independent process at bigger scale. However, the pattern is, with a certain confidence level, independent.

Rottländer (1975) identified a possible different cause of Fe-Mn coatings in the iron that is already present in the flint. In this light, the spatial association of flint artifacts with and without patination also depends on the chemical and microstructural composition of the raw material itself. On the other hand, the same oxides affecting a good percentage of finds, have been equally found broadly scattered on the numerous clasts of calcarenite that are included in the matrix, thus supporting an external origin of the Fe-Mn coating process.

The content of water and organic matter in the sedimentary body could be responsible for the randomly diffuse Fe-Mn patinations. In the presence of organic matter, indeed, it is likely that the release of organic acids will accelerate patination on chert (Burroni et al., 2002). Moisture of the sedimentary body could also be accounted for the wide random spread of Fe-Mn coatings.

We did not find statistically significant evidence of aggregation of oxidized records compared to non-oxidized ones (Fig. B.9c); thus, we can exclude the assumption of localized concentration of water, which is included in the hypothesis advanced by Bagnus (2011) for the presence of interstitial flows reworking the deposit.

Due to the small sample size, we did not apply spatial analysis to the distribution of the three taphorecords. However, Fig. B.4e,f suggests that fossils from the TR1 group occur spatially aggregated

with fossils from the TR2 and TR3 groups. Considering the distribution of Fe-Mn oxides on the lithic and faunal assemblages, the re-elaborated TR1 (*sensu* Fernández-López, 1991, 2007, 2011) might not be associated with the reworking action of water-flows and might be more likely correlated to random and limited rearrangement of parts of the sedimentary matrix.

A possible cause of some localized movement of sediments could be the rock falls from the vault of the karst fissure, during the deposition of SUs C and D. As showed in Fig. C.1, an abrupt increase in the number of boulder-sized rocks is observed within the lower layers. Moreover, rock falls caused most of the post-depositional fractures on the faunal assemblage (Bagnus, 2011). Such intense erosional process could most likely be correlated to the seismic activity of the region (Bertok et al., 2013).

Results of our analyses suggest that post-depositional taphonomic alterations occurred with a certain significance as a result of independent processes. However, keeping a cautious approach to spatial analysis, a documented point pattern can be most realistically thought of as the result of multiple processes heterogeneously working at different scales (Bevan and Wilson, 2013). Multiple or repeated post-depositional processes could obliterate contemporaneous or preceding patterns, resulting in a final random distribution of the record.

Moreover, karst site formation processes are highly dependent on the structure and extension of the overall karstic system, as well as on the surrounding environment. The lack of information about the original characteristics of the system and the reduced area of excavation strongly limit the analysis.

Furthermore, although the need for considering three dimensional distributions in site formation processes study, spatial point pattern statistics are at the moment not fully equipped to analyze three-dimensional patterns, especially when the study-area corresponds to a three-dimensional volume with a complex shape such as a karstic structure.

On the other hand, "one must look to non-spatial evidence to

corroborate or disprove theories about spatial processes" (Hodder and Orton, 1976, p. 8). The integration with other taphonomic disciplines reinforces the results of spatial analyses and outlines new opportunities for point pattern analyses. As recently remarked (Cobo-Sánchez et al., 2014), taphonomic research should be multivariate (Domínguez-Rodrigo and Pickering, 2010) and it should include spatial analysis as a heuristic tool in the interpretation of site integrity. This is especially demanding when the research questions deal with past human behaviour and even more so when site dating is based on the stratigraphic association of artifacts and fossils.

A.8 Conclusions

The Early Pleistocene site of Pirro Nord 13 provides evidence of the earliest human presence in Western Europe. Lithic artifacts have been found in a karst fissure filling, together with late Villafranchian/early Biharian paleontological remains.

The main goals of our study were:

1. to investigate the depositional processes involved in the formation of the deposit and
2. to assess the degree of any potential post-depositional reworking of the archaeological and paleontological remains.

The integration of spatial point pattern analyses with previous taphonomic studies on the faunal and lithic assemblages allowed us to test different hypotheses of site formation and modification processes.

On the basis of our analyses,

1. we consider the deposit to be the result of subsequent events of some type of mass-wasting process, such as a mud-flow or earth-flow, carrying rock rubble with fossils and artifacts. The applied set of spatial analyses confirms, with an adequate level of statistical significance, the assumption, based on field observations, regarding the spatial association between the finds.

2. Based on our taphonomic point pattern analyses of several diagenetic features on the lithic and faunal assemblages, we reject the hypothesis of a substantial post-depositional reworking and mixture of the sedimentary deposit and we corroborate the stratigraphic integrity of the Pirro Nord 13 site.

Finally, the present study answers the need for a taphonomic perspective in spatial analysis, by applying well developed quantitative methods in spatial statistics. Point pattern analysis can be very flexible and useful in the investigation of both cultural and taphonomic processes. Until now it has found limited application on taphonomic studies, but, as our study demonstrates, it offers new analytical opportunities to the multidisciplinary study of the complex processes that operate in the formation and modification of archaeological sites. It allows analysts to test multiscale patterns and to model the taphonomic processes underlying archaeological distributions, which are otherwise difficult to identify from the simple visualization of maps, especially for those sites characterized by complex geo-stratigraphic settings.

References

- Anderson KL and Burke A. 2008. Refining the definition of cultural levels at Karabi Tamchin: a quantitative approach to vertical intra-site spatial analysis. *Journal of Archaeological Science* 35.8, 2274–2285. DOI: [10.1016/j.jas.2008.02.011](https://doi.org/10.1016/j.jas.2008.02.011).
- Arzarello M, Marcolini F, Pavia G, Pavia M, Petronio C, Petrucci M, Rook L, and Sardella R. 2007. Evidence of earliest human occurrence in Europe: the site of Pirro Nord (Southern Italy). English. *Naturwissenschaften* 94 (2), 107–112. DOI: [10.1007/s00114-006-0173-3](https://doi.org/10.1007/s00114-006-0173-3).
- Arzarello M, Marcolini F, Pavia G, Pavia M, Petronio C, Petrucci M, Rook L, and Sardella R. 2009. L'industrie lithique du site Pléistocène inférieur de Pirro Nord (Apricena, Italie du sud): une occupation humaine entre 1,3 et 1,7Ma. *L'Anthropologie* 113.1, 47–58. DOI: [10.1016/j.anthro.2009.01.004](https://doi.org/10.1016/j.anthro.2009.01.004).
- Arzarello M, Pavia G, Peretto C, Petronio C, and Sardella R. 2012. Evidence of an Early Pleistocene hominin presence at Pirro Nord (Apricena, Foggia, southern Italy): P13 site. *Quaternary International* 267, 56–61. DOI: [10.1016/j.quaint.2011.01.042](https://doi.org/10.1016/j.quaint.2011.01.042).

- Arzarello M and Peretto C. 2010. Out of Africa: The first evidence of Italian peninsula occupation. *Quaternary International* 223–224, 65–70. DOI: [10.1016/j.quaint.2010.01.006](https://doi.org/10.1016/j.quaint.2010.01.006).
- Arzarello M, Peretto C, and Moncel MH. 2015. The Pirro Nord site (Apricena, Fg, Southern Italy) in the context of the first European peopling: Convergences and divergences. *Quaternary International* 389, 255–263. DOI: [10.1016/j.quaint.2014.08.051](https://doi.org/10.1016/j.quaint.2014.08.051).
- Baddeley A, Rubak E, and Turner R. 2015. *Spatial Point Patterns: Methodology and Applications with R*. London: Chapman and Hall/CRC.
- Baddeley A and Turner R. 2005. spatstat: an R package for analyzing spatial point patterns. *Journal of Statistical Software* 12.6, 1–42.
- Bagnus C. 2011. *Analisi tafonomica delle associazioni a vertebrati del Pleistocene Inferiore di Pirro Nord*. PhD thesis. Italy: Università degli Studi di Torino.
- Bailey T and Gatrell A. 1995. *Interactive spatial data analysis*. Harlow Essex, England: Longman Scientific and Technical.
- Bartlett MS. 1963. The spectral analysis of point processes. *Journal of the Royal Statistical Society, Series B* 29, 264–296.
- Behrensmeier AK. 1978. Taphonomic and ecologic information from bone weathering. *Paleobiology* 4.2, 150–162.
- Behrensmeier AK. 1991. Terrestrial vertebrate accumulations. In: *Taphonomy: Releasing the Data Locked in the Fossil Record: Topics in Geobiology*. Ed. by P Allison and D Briggs. Vol. 9. New York: Plenum Press, 291–327.
- Benito-Calvo A and de la Torre I. 2011. Analysis of orientation patterns in Olduvai Bed I assemblages using GIS techniques: Implications for site formation processes. *Journal of Human Evolution* 61.1, 50–60. DOI: [10.1016/j.jhevol.2011.02.011](https://doi.org/10.1016/j.jhevol.2011.02.011).
- Bernatchez JA. 2010. Taphonomic implications of orientation of plotted finds from Pinnacle Point 13B (Mossel Bay, Western Cape Province, South Africa). *Journal of Human Evolution* 59.3–4, 274–288. DOI: [10.1016/j.jhevol.2010.07.005](https://doi.org/10.1016/j.jhevol.2010.07.005).
- Bertok C, Masini F, Donato VD, Martire L, Pavia M, Zunino M, and Pavia G. 2013. Stratigraphic framework of the type-locality of Pirro Nord mammal Faunal Unit (Late Villafranchian, Apricena, south-eastern Italy). *Palaeontographica* 298.6, 5–17. DOI: [DOI:10.1127/pala/298/2013/5](https://doi.org/10.1127/pala/298/2013/5).
- Bertran P, Claud É, Detrain L, Lenoble A, Masson B, and Vallin L. 2006. Composition granulométrique des assemblages lithiques, application à l'étude taphonomique des sites paléolithiques. *Paléo* 18, 7–36.
- Bertran P, Hetù B, Texier JP, and Steijn HV. 1997. Fabric characteristics of subaerial slope deposits. *Sedimentology* 44.1, 1–16. DOI: [10.1111/j.1365-3091.1997.tb00421.x](https://doi.org/10.1111/j.1365-3091.1997.tb00421.x).
- Bertran P, Lenoble A, Todisco D, Desrosiers PM, and Sørensen M. 2012. Particle size distribution of lithic assemblages and taphonomy of Palaeolithic sites.

- Journal of Archaeological Science* 39.10, 3148–3166. DOI: [10.1016/j.jas.2012.04.055](https://doi.org/10.1016/j.jas.2012.04.055).
- Bertran P and Texier JP. 1995. Fabric Analysis: Application to Paleolithic Sites. *Journal of Archaeological Science* 22.4, 521–535. DOI: [10.1006/jasc.1995.0050](https://doi.org/10.1006/jasc.1995.0050).
- Bevan A and Conolly J. 2006. Multiscalar approaches to settlement pattern analysis. In: *Confronting Scale in Archaeology: Issues of Theory and Practice*. Ed. by G Lock and B Molyneaux. New York: Springer, 217–234. DOI: [10.1007/0-387-32772-3_14](https://doi.org/10.1007/0-387-32772-3_14).
- Bevan A and Conolly J. 2009. Modelling spatial heterogeneity and nonstationarity in artifact-rich landscapes. *Journal of Archaeological Science* 36.4, 956–964. DOI: [10.1016/j.jas.2008.11.023](https://doi.org/10.1016/j.jas.2008.11.023).
- Bevan A and Conolly J. 2013. *Mediterranean Islands, Fragile Communities and Persistent Landscapes: Antikythera in Long-term Perspective*. Cambridge: Cambridge University Press.
- Bevan A, Crema E, Li X, and Palmisano A. 2013. Intensities, Interactions, and Uncertainties: Some New Approaches to Archaeological Distributions. In: *Computational Approaches to Archaeological Spaces*. Ed. by A Bevan and M Lake. Walnut Creek: Left Coast Press, 27–52.
- Bevan A and Wilson A. 2013. Models of settlement hierarchy based on partial evidence. *Journal of Archaeological Science* 40.5, 2415–2427. DOI: [10.1016/j.jas.2012.12.025](https://doi.org/10.1016/j.jas.2012.12.025).
- Burroni D, Donahue RE, Pollard A, and Mussi M. 2002. The Surface Alteration Features of Flint Artefacts as a Record of Environmental Processes. *Journal of Archaeological Science* 29.11, 1277–1287. DOI: [10.1006/jasc.2001.0771](https://doi.org/10.1006/jasc.2001.0771).
- Butzer K. 1982. *Archaeology as Human Ecology: Method and Theory for a Contextual Approach*. New York: Cambridge University Press.
- Carbonell E, Bermudez de Castro JM, Pares JM, Perez-Gonzalez A, Cuenca-Bescos G, Olle A, Mosquera M, Huguet R, van der Made J, Rosas A, Sala R, Vallverdu J, Garcia N, Granger DE, Martinon-Torres M, Rodriguez XP, Stock GM, Verges JM, Allue E, Burjachs F, Caceres I, Canals A, Benito A, Diez C, Lozano M, Mateos A, Navazo M, Rodriguez J, Rosell J, and Arsuaga JL. 2008. The first hominin of Europe. *Nature* 452, 465–469. DOI: [10.1038/nature06815](https://doi.org/10.1038/nature06815).
- Carrer F. 2015. Interpreting Intra-site Spatial Patterns in Seasonal Contexts: an Ethnoarchaeological Case Study from the Western Alps. *Journal of Archaeological Method and Theory*, 1–25. DOI: [10.1007/s10816-015-9268-5](https://doi.org/10.1007/s10816-015-9268-5).
- Cobo-Sánchez L, Aramendi J, and Dominguez-Rodrigo M. 2014. Orientation patterns of wildebeest bones on the lake Masek floodplain (Serengeti, Tanzania) and their relevance to interpret anisotropy in the Olduvai lacustrine floodplain. *Quaternary International* 322–323.0, 277–284. DOI: [10.1016/j.quaint.2013.07.130](https://doi.org/10.1016/j.quaint.2013.07.130).

- Crema ER. 2015. Time and Probabilistic Reasoning in Settlement Analysis. In: *Mathematics and Archaeology*. Ed. by IB Juan A. Barcelo. Boca Raton, FL: CRC Press, 314–334. DOI: [10.1201/b18530-20](https://doi.org/10.1201/b18530-20).
- Crema ER, Bevan A, and Lake MW. 2010. A probabilistic framework for assessing spatio-temporal point patterns in the archaeological record. *Journal of Archaeological Science* 37.5, 1118–1130. DOI: [10.1016/j.jas.2009.12.012](https://doi.org/10.1016/j.jas.2009.12.012).
- Crema ER and Bianchi E. 2013. Looking for patterns in the noise: non-site spatial-analysis in Sebkhia Kelbia. In: *Le Capsien de hergla (Tunisie). Culture, environnement et économie*. Ed. by S Mulazzani. Frankfurt: Africa Magna Verlag, 385–395.
- Crochet JY, Welcomme JL, Ivorra J, Ruffet G, Boulbes N, Capdevila R, Claude J, Firmat C, Métais G, Michaux J, and Pickford M. 2009. Une nouvelle faune de vertébrés continentaux, associée à des artefacts dans le Pléistocène inférieur de l'Hérault (Sud de la France), vers 1,57 Ma. *Comptes Rendus Palevol* 8.8, 725–736. DOI: [10.1016/j.crpv.2009.06.004](https://doi.org/10.1016/j.crpv.2009.06.004).
- De la Torre I and Benito-Calvo A. 2013. Application of GIS methods to retrieve orientation patterns from imagery; a case study from Beds I and II, Olduvai Gorge (Tanzania). *Journal of Archaeological Science* 40.5, 2446–2457. DOI: [10.1016/j.jas.2013.01.004](https://doi.org/10.1016/j.jas.2013.01.004).
- Despriée J, Gageonnet R, Voinchet P, Bahain JJ, Falguères C, Varache F, Courcimault G, and Dolo JM. 2006. Une occupation humaine au Pléistocène inférieur sur la bordure nord du Massif central. *Comptes Rendus Palevol* 5.6, 821–828. DOI: [10.1016/j.crpv.2006.03.001](https://doi.org/10.1016/j.crpv.2006.03.001).
- Despriée J, Voinchet P, Gageonnet R, Dépont J, Bahain JJ, Falguères C, Tissoux H, Dolo JM, and Courcimault G. 2009. Les vagues de peuplements humains au Pléistocène inférieur et moyen dans le bassin de la Loire moyenne, région Centre, France. Apports de l'étude des formations fluviales. *L'Anthropologie* 113.1, 125–167. DOI: [10.1016/j.anthro.2009.01.007](https://doi.org/10.1016/j.anthro.2009.01.007).
- Despriée J, Voinchet P, Tissoux H, Moncel MH, Arzarello M, Robin S, Bahain JJ, Falguères C, Courcimault G, Dépont J, Gageonnet R, Marquer L, Messager E, Abdessadok S, and Puaud S. 2010. Lower and middle Pleistocene human settlements in the Middle Loire River Basin, Centre Region, France. *Quaternary International* 223–224, 345–359. DOI: [10.1016/j.quaint.2009.07.019](https://doi.org/10.1016/j.quaint.2009.07.019).
- Dibble HL, Chase PG, McPherron SJP, and Tuffreau A. 1997. Testing the Reality of a "Living Floor" with Archaeological Data. *American Antiquity* 62.4, 629–651. DOI: [10.2307/281882](https://doi.org/10.2307/281882).
- Diez JC, Fernández-Jalvo J, Rossel J, and Cáceres I. 1999. Zooarchaeology and taphonomy of Aurora Stratum (Gran Dolina, Sierra de Atapuerca, Spain). *Journal of Human Evolution* 37, 623–652.
- Diggle PJ. 1985. A kernel method for smoothing point process data. *Applied Statistics (Journal of the Royal Statistical Society, Series C)* 34, 138–147.
- Diggle PJ. 2003. *Statistical analysis of spatial point patterns*. London: Hodder Arnold.

- Djindjian F. 1999. L'analyse spatiale de l'habitat: un état de l'art. *Archeologia e Calcolatori* X, Edizioni All'Insegna del Giglio, 17–32.
- Domínguez-Rodrigo M, Bunn H, Mabulla A, Baquedano E, Uribelarrea D, Pérez-González A, Gidna A, Yravedra J, Diez-Martín F, Egeland C, Barba R, Arriaza M, Organista E, and Ansón M. 2014a. On meat eating and human evolution: A taphonomic analysis of BK4b (Upper Bed II, Olduvai Gorge, Tanzania), and its bearing on hominin megafaunal consumption. *Quaternary International* 322–323, 129–152. DOI: [10.1016/j.quaint.2013.08.015](https://doi.org/10.1016/j.quaint.2013.08.015).
- Domínguez-Rodrigo M, Diez-Martín F, Yravedra J, Barba R, Mabulla A, Baquedano E, Uribelarrea D, Sánchez P, and Eren MI. 2014b. Study of the SHK Main Site faunal assemblage, Olduvai Gorge, Tanzania: Implications for Bed II taphonomy, paleoecology, and hominin utilization of megafauna. *Quaternary International* 322–323, 153–166. DOI: <http://dx.doi.org/10.1016/j.quaint.2013.09.025>.
- Domínguez-Rodrigo M, Fernández-López S, and Alcalá L. 2011. How Can Taphonomy Be Defined in the XXI Century? *Journal of Taphonomy* 9.1, 1–13.
- Domínguez-Rodrigo M and Pickering TR. 2010. A multivariate approach for discriminating bone accumulations created by spotted hyenas and leopards: harnessing actualistic data from east and southern Africa. *Journal of Taphonomy* 8.2-3, 155–179.
- Domínguez-Rodrigo M, Uribelarrea D, Santonja M, Bunn HT, García-Pérez A, Pérez-González A, Panera J, Rubio-Jara S, Mabulla A, Baquedano E, Yravedra J, and Diez-Martín F. 2014c. Autochthonous anisotropy of archaeological materials by the action of water: experimental and archaeological reassessment of the orientation patterns at the Olduvai sites. *Journal of Archaeological Science* 41, 44–68. DOI: [10.1016/j.jas.2013.07.025](https://doi.org/10.1016/j.jas.2013.07.025).
- Efremov IA. 1940. Taphonomy: a new branch of paleontology. *Pan American Geologist* 74, 81–93.
- Eve SJ and Crema ER. 2014. A House with a View? Multi-model inference, visibility fields, and point process analysis of a Bronze Age settlement on Leskernick Hill (Cornwall, UK). *Journal of Archaeological Science* 43, 267–277. DOI: [10.1016/j.jas.2013.12.019](https://doi.org/10.1016/j.jas.2013.12.019).
- Fernández-López RS. 1987. Unidades registráticas, biocronología y geocronología. *Revista Española de Paleontología* 2, 65–85.
- Fernández-López RS. 1991. Taphonomic concepts for a theoretical biochronology. *Revista Española de Paleontología* 6, 37–49.
- Fernández-López RS. 2000. *Temas de Tafonomía*. Departamento de Paleontología, Universidad Complutense de Madrid.
- Fernández-López RS. 2007. Ammonoid taphonomy, palaeoenvironments and sequence stratigraphy at the Bajocian/Bathonian boundary on the Bas Auran area (Subalpine Basin, SE France). *Lethaia* 40, 377–391.

- Fernández-López RS. 2011. Taphonomic analysis and sequence stratigraphy of the Albarracinites beds (lower Bajocian, Iberian Range, Spain). An example of shallow condensed section. *Bulletin de la Société Géologique de France* 182, 405–415.
- Gatrell AC, Bailey TC, Diggle PJ, and Rowlingson BS. 1996. Spatial point pattern analysis and its application in geographical epidemiology. *Transactions of the Institute of British Geographers* 21, 256–274.
- Goreaud F and Péliissier R. 2003. Avoiding misinterpretation of biotic interactions with the intertype K_{12} -function: population independence vs. random labelling hypotheses. *Journal of Vegetation Science* 14.5, 681–692. DOI: [10.1111/j.1654-1103.2003.tb02200.x](https://doi.org/10.1111/j.1654-1103.2003.tb02200.x).
- Hill A. 1982. Origin of black deposits in caves. *National Speleological Society Bulletin* 44, 15–19.
- Hodder I and Orton C. 1976. *Spatial Analysis in Archaeology*. New Studies in Archaeology. Cambridge: Cambridge University Press.
- Kos AM. 2003. Characterization of post-depositional taphonomic processes in the accumulation of mammals in a pitfall cave deposit from southeastern Australia. *Journal of Archaeological Science* 30, 781–796.
- Lenoble A and Bertran P. 2004. Fabric of Palaeolithic levels: methods and implications for site formation processes. *Journal of Archaeological Science* 31.4, 457–469. DOI: [10.1016/j.jas.2003.09.013](https://doi.org/10.1016/j.jas.2003.09.013).
- Lopez-García JM, Luzi E, Berto C, Peretto C, and Arzarello M. 2015. Chronological context of the first hominin occurrence in southern Europe: the *Allophaiomys ruffoi* (Arvicolinae, Rodentia, Mammalia) from Pirro 13 (Pirro Nord, Apulia, southwestern Italy). *Quaternary Science Reviews* 107, 260–266. DOI: [doi:10.1016/j.quascirev.2014.10.029](https://doi.org/10.1016/j.quascirev.2014.10.029).
- López-González F, Grandal-d'Anglade A, and Vidal-Romaní JR. 2006. Deciphering bone depositional sequences in caves through the study of manganese coatings. *Journal of Archaeological Science* 33.5, 707–717. DOI: [10.1016/j.jas.2005.10.006](https://doi.org/10.1016/j.jas.2005.10.006).
- López-Ortega E, Rodríguez XP, and Vaquero M. 2011. Lithic refitting and movement connections: the NW area of level TD10-1 at the Gran Dolina site (Sierra de Atapuerca, Burgos, Spain). *Journal of Archaeological Science* 38.11, 3112–3121. DOI: [10.1016/j.jas.2011.07.011](https://doi.org/10.1016/j.jas.2011.07.011).
- Lumley H, Krzepakowska A, and Echassoux A. 1988. L'industrie du Pleistocene inferieur de la grotte du Vallonnet, Roquebrune-Cap Martin, Alpes Maritimes. *L'Anthropologie* 92, 501–614.
- Marwick B. 2017. Computational Reproducibility in Archaeological Research: Basic Principles and a Case Study of Their Implementation. *Journal of Archaeological Method and Theory* 24.2, 424–450. DOI: [10.1007/s10816-015-9272-9](https://doi.org/10.1007/s10816-015-9272-9).


- McPherron SJP. 2005. Artifact orientations and site formation processes from total station proveniences. *Journal of Archaeological Science* 32.7, 1003–1014. DOI: [10.1016/j.jas.2005.01.015](https://doi.org/10.1016/j.jas.2005.01.015).
- Ohser J. 1983. On estimators for the reduced second moment measure of point processes. *Mathematische Operationsforschung und Statistik, series Statistics* 14, 63–71.
- Openshaw S. 1996. Developing GIS-relevant zone-based spatial analysis methods. In: *Spatial analysis: modelling in a GIS environment*. Ed. by P Longley and M Batty. London: Geoinformation International, 55–73.
- Ord JK. 1972. *Density estimation and tests for randomness, using distance methods*. Draft for lecture to Advanced Institute on statistical ecology in the United States. (Mimeo). The Pennsylvania State University.
- Orton CR. 1982. Stochastic process and archaeological mechanism in spatial analysis. *Journal of Archaeological Science* 9.1, 1–23. DOI: [10.1016/0305-4403\(82\)90002-4](https://doi.org/10.1016/0305-4403(82)90002-4).
- Orton CR. 2004. Point pattern analysis revisited. *Archeologia e Calcolatori* 15, 299–315.
- Parés JM, Pérez-González A, Rosas A, Benito A, de Castro JB, Carbonell E, and Huguet R. 2006. Matuyama-age lithic tools from the Sima del Elefante site, Atapuerca (northern Spain). *Journal of Human Evolution* 50.2, 163–169. DOI: [10.1016/j.jhevol.2005.08.011](https://doi.org/10.1016/j.jhevol.2005.08.011).
- Petraglia MD and Nash DT. 1987. The impact of fluvial processes on experimental sites. In: *Natural formation processes and the archaeological record*. Ed. by DT Nash and MD Petraglia. Vol. 352. International Series. Oxford: British Archaeological Reports, 108–130.
- Petraglia MD and Potts R. 1994. Water Flow and the Formation of Early Pleistocene Artifact Sites in Olduvai Gorge, Tanzania. *Journal of Anthropological Archaeology* 13.3, 228–254. DOI: [10.1006/jaar.1994.1014](https://doi.org/10.1006/jaar.1994.1014).
- R Core Team. 2015. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.
- Ripley BD. 1976. The second-order analysis of stationary point processes. *Journal of Applied Probability* 13.2, 255–266. DOI: [10.2307/3212829](https://doi.org/10.2307/3212829).
- Ripley BD. 1977. Modelling spatial patterns. *Journal of the Royal Statistical Society, series B* 39, 172–212.
- Ripley BD. 1988. *Statistical inference for spatial processes*. Cambridge University Press. DOI: [10.1017/CB09780511624131](https://doi.org/10.1017/CB09780511624131).
- Robert C and Casella G. 2004. *Monte Carlo Statistical Methods*. second edition. Springer Texts in Statistics. New York: Springer New York.
- Rottländer R. 1975. The formation of patina on flint. *Archaeometry* 17.1, 106–110. DOI: [10.1111/j.1475-4754.1975.tb00120.x](https://doi.org/10.1111/j.1475-4754.1975.tb00120.x).
- Schick KD. 1984. *Processes of Paleolithic site formation: an experimental study*. PhD thesis. US: University of California, Berkeley.

- Schick KD. 1986. *Stone Age sites in the making: experiments in the formation and transformation of archaeological occurrences*. Vol. 319. International Series. Oxford: British Archaeological Reports.
- Schiffer MB. 1972. Archaeological Context and Systemic Context. *American Antiquity* 37.2, 156–165.
- Schiffer MB. 1983. Toward the identification of formation processes. *American Antiquity* 48.4, 675–706.
- Schiffer MB. 1987. *Formation processes of the archaeological record*. Albuquerque: University of New Mexico Press.
- Sisk ML and Shea JJ. 2008. Intrasite spatial variation of the Omo Kibish Middle Stone Age assemblages: Artifact refitting and distribution patterns. *Journal of Human Evolution* 55.3, 486–500. DOI: [10.1016/j.jhevol.2008.05.016](https://doi.org/10.1016/j.jhevol.2008.05.016).
- Stapert D. 1976. Some natural surface modifications on chert in the Netherlands. *Palaeohistoria* 18, 7–41.
- Texier JP. 2000. A propos des processus de formation des sites préhistoriques / About prehistoric site formation processes. fr. *Paléo* 12.1, 379–386. DOI: [10.3406/pal.2000.1610](https://doi.org/10.3406/pal.2000.1610).
- Tobler WR. 1970. A computer movie simulating urban growth in the Detroit region. *Economic Geography* 46.2, 234–240.
- Toro-Moyano I, Barsky D, Cauche D, Celiberti V, Grégoire S, Lebegue F, Moncel MH, and de Lumley H. 2011. The archaic stone tool industry from Barranco León and Fuente Nueva 3, (Orce, Spain): Evidence of the earliest hominin presence in southern Europe. *Quaternary International* 243.1, 80–91. DOI: [10.1016/j.quaint.2010.12.011](https://doi.org/10.1016/j.quaint.2010.12.011).
- Toro-Moyano I, de Lumley H, Fajardo B, Barsky D, Cauche D, Celiberti V, Grégoire S, Martínez-Navarro B, Espigares MP, and Ros-Montoya S. 2009. L'industrie lithique des gisements du Pléistocène inférieur de Barranco León et Fuente Nueva 3 à Orce, Grenade, Espagne. *L'Anthropologie* 113.1, 111–124. DOI: [10.1016/j.anthro.2009.01.006](https://doi.org/10.1016/j.anthro.2009.01.006).
- Toro-Moyano I, Martínez-Navarro B, Agustí J, Souday C, de Castro JB, Martínón-Torres M, Fajardo B, Duval M, Falguères C, Oms O, Parés J, Anadón P, Julià R, García-Aguilar J, Moigne AM, Espigares M, Ros-Montoya S, and Palmqvist P. 2013. The oldest human fossil in Europe, from Orce (Spain). *Journal of Human Evolution* 65.1, 1–9. DOI: [10.1016/j.jhevol.2013.01.012](https://doi.org/10.1016/j.jhevol.2013.01.012).
- Torres T, Ortiz JE, and Cobo R. 2003. Features of deep cave sediments: their influence on fossil preservation. *Estudios Geológico* 59, 195–204.
- Villa P. 1982. Conjoinable Pieces and Site Formation Processes. *American Antiquity* 47.2, 276–290. DOI: [10.2307/279901](https://doi.org/10.2307/279901).
- Whallon R.J. 1974. Spatial Analysis of Occupation Floors II: The Application of Nearest Neighbor Analysis. *American Antiquity* 39.1, 16–34. DOI: [10.2307/279216](https://doi.org/10.2307/279216).

- White WB. 1976. Cave minerals and speleothems. In: *The Science of Speleology*. Ed. by T Ford and C Cullingford. London: Academic Press, 267–327.
- White WB, Vito C, and Scheetz BE. 2009. The mineralogy and trace element chemistry of black manganese oxide deposits from caves. *Journal of Cave and Karst Studies* 71.2, 136–143.
- Wood RW and Johnson DL. 1978. A survey of disturbance processes in archaeological site formation. In: *Advances in archaeological method and theory*. Ed. by MB Schiffer. Vol. 1. New York: Academic Press. Chap. 9, 315–381.

Beyond maps: Patterns of formation processes at the Middle Pleistocene open-air site of Marathousa 1, Megalopolis Basin, Greece

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Abstract

Recent excavations at the Middle Pleistocene open-air site of Marathousa 1 have unearthed in one of the two investigated areas (Area A) a partial skeleton of a single individual of *Palaeoloxodon antiquus* and other faunal remains in spatial and stratigraphic association with lithic artefacts. In Area B, a much higher number of lithic artefacts was collected, spatially and stratigraphically associated also with faunal remains. The two areas are stratigraphically correlated, the main fossiliferous layers representing an *en mass* depositional process in a lake margin context. Evidence of butchering (cut-marks) has been identified on bones of the elephant skeleton, as well on elephant and other mammal bones from Area B. However, due to the secondary deposition of the main find-bearing units, it is of primary importance to evaluate the degree and reliability of the spatial association of the lithic artefacts with the faunal remains. Indeed, spatial association does not necessarily imply causation, since natural syn- and post-depositional processes may equally produce spatial association. Assessing the degree and extent of post-depositional reworking processes is crucial to fully comprehend the archaeological record, and therefore to reliably interpret past human behaviours. The present study uses a comprehensive set of spatial statistics in order to disentangle the depositional processes behind the distribution of the archaeological and palaeontological record at Marathousa 1. Preliminary results of our analyses suggest that a high-energy erosional process, attributed to a hyperconcentrated flow deposited at the margin of a swamp, reworked an autochthonous, exposed or slightly buried, scatter of lithic artefacts and faunal remains. Minor reworking and substantial spatial association of the lithic and faunal assemblages support the current interpretation of Marathousa 1 as a butchering site.

B.1 Introduction

Archaeological site formation processes, intensively studied since the early 1970s (Binford, 1981; Isaac, 1967; Petraglia and Nash, 1987; Petraglia and Potts, 1994; Schick, 1984, 1986, 1987; Schiffer, 1972, 1983, 1987; Shackley, 1978; Wood and Johnson, 1978, among others), “still insufficiently taken in consideration” (Texier, 2000, p.379) at the beginning of the 21st century, are nowadays fully acknowledged in the archaeological practice (Bailey, 2007; Bargalló et al., 2016; Brantingham et al., 2007; Malinsky-Buller et al., 2011; Vaquero et al., 2012; Villa, 2004, among others). Drawing inferences about past human behaviours from scatters of archaeological remains must account for syn- and post-depositional contextual processes.

Several methods are currently applied in order to qualify and quantify the type and degree of reworking of archaeological assemblages. Within the framework of a geoarchaeological and taphonomic approach, spatial statistics offer meaningful contributions in unravelling site formation and modification processes from spatial patterns. However, while the spatio-temporal dimension is an ineluctable inherent property of any biotic and abiotic process, spatial statistics are still insufficiently applied.

Distribution maps are cornerstones of the archaeological documentation process and are primary analytic tools. However, their visual interpretation is prone to subjectivity and is not reproducible (Bevan et al., 2013). Since the early 1970’s (see Hodder and Orton (1976) and Orton (1982) and references therein), the traditional, intuitive, ‘eyeballing’ method of spotting spatial patterns has been abandoned in favour of more objective approaches, extensively borrowed from other fields. Nevertheless, quantitative methods, while still percolating in the archaeological sciences from neighbouring disciplines, are not extensively used. Moreover, only a relatively small number of studies have explicitly applied spatial point pattern analysis or geostatistics to the study of site formation and modification processes (Carrer (2015), Domínguez-Rodrigo et al. (2014a, 2017,

2014b), Giusti and Arzarello (2016), Lenoble et al. (2008), and Organista et al. (2017); but see Hivernel and Hodder (1984) for an earlier work on the subject).

The goal of a taphonomic approach to spatial analysis is to move beyond distribution maps by applying a comprehensive set of multi-scale and multivariate spatial statistics in order to reliably construct inferences from spatial patterns. An exhaustive spatial analytic approach to archaeological inference, combined with a taphonomic perspective, is essential for evaluating the depositional processes and integrity of the archaeological assemblage, and consequently for a reliable interpretation of past human behaviours.

The present study uses a comprehensive set of spatial statistics in order to disentangle the depositional processes behind the spatial distribution of the archaeological and palaeontological record recovered during excavation at the Middle Pleistocene open-air site of Marathousa 1, Megalopolis, Greece (Harvati et al., 2016; Panagopoulou et al., 2015).

B.1.1 Marathousa 1

The site (Fig. C.1), discovered in 2013 at the edge of an active lignite quarry, is located between two lignite seams in the Pleistocene deposits of the Megalopolis basin, Marathousa Member of the Choremi Formation (van Vugt et al., 2000). The regular alternation of lacustrine clay, silt and sand beds with lignite seams has been interpreted having cyclic glacial (or stadial) and interglacial (or interstadial) origin (Nickel et al., 1996). The half-graben configuration of the basin, with major subsidence along the NW-SE trending normal faults along the eastern margin, resulted in the gentle dip of the lake bottom at the opposite, western, margin of the lake, enabling the formation of swamps and the accumulation of organic material for prolonged periods of time (van Vugt et al., 2000).

Two excavation areas have been investigated since 2013 (Fig. B.2): Area A, where several skeletal elements of a single individual of *Palaeoloxodon antiquus* have been unearthed, together with a num-

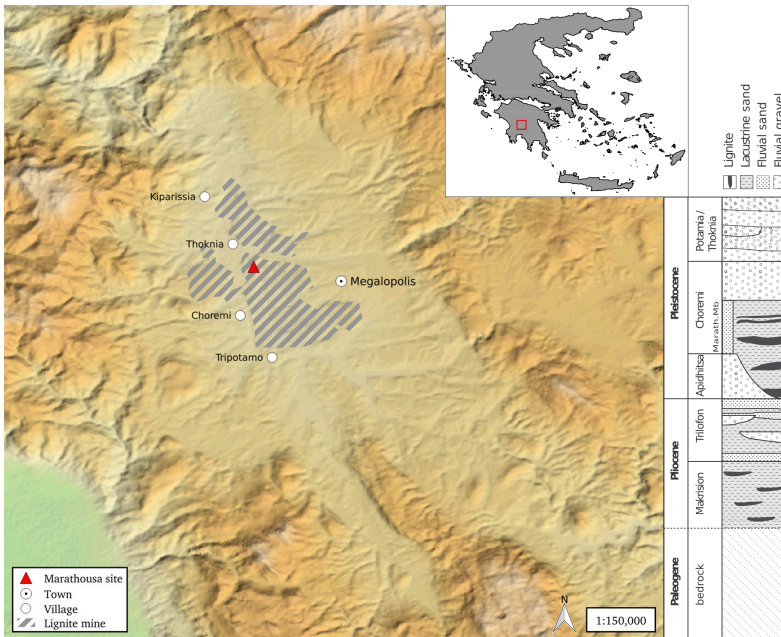


Figure B.1: Geographical location of the Marathousa 1 site in the Megalopolis basin and stratigraphic column of the basin, modified after [van Vugt et al. \(2000\)](#).

ber of lithic artefacts and other faunal remains; and Area B, located 60 m to the South along the exposed section, where the lithic assemblage is richer and occurs in association with a faunal assemblage composed of isolated elephant bones, cervids and carnivores among others. Bones from Area B are characterized by a high degree of fragmentation (bone fragments make up 93.4% of the assemblage), with their maximal diameter mostly measuring less than 80mm (Konidaris et al., *In press*; Turloukis et al., *In press*). Evidence of butchering (cut-marks) have been identified on two of the elephant bones from Area A, as well on elephant and other mammal bones from Area B (Konidaris et al., *In press*).

The sedimentary sequence of the site (Fig. B.3) includes lacustrine and fluvio-lacustrine clastic deposits sandwiched between two lignite seams (UA7-UB10 and UA1-UB1) (Karkanas et al., *In press*). A major hiatus (contacts between UA3 and UA4, and between UB5 and UB6), attributed to exposure and erosion of a lake shore mudflat, divides the sequence in two parts. The lower part is characterised by relatively high rate sub-aqueous sedimentation of bedded sands and silts, containing low organic and carbonate content. The upper one is characterised by a series of erosional bounded depositional units, attributed to sub-aerial originated organic- and carbonate-rich mud flows and hyperconcentrated flows deposited at the margin of a swamp (Karkanas et al., *In press*).

The erosional contacts UA3c/4 and UB4c/5a separate the two main find-bearing units in both areas (Fig. B.3). In Area A, the elephant remains lie at the contact of UA3c/4 and are covered by UA3c (Fig. B.4a); while in Area B, most of the remains were collected from unit UB4c (Figs. B.2 and B.4b). Units UA3c and UB4c (organic- and intraclast-rich silty sands) resemble dilute mud flows, showing a chaotic structure of rip-up clasts from the underlying unit, small-to-large wood fragments and rare rock clasts. In Area B, a relatively low number of remains was also found in massive organic-rich silty sands (UB5a, Fig. B.2), which locally overlay channelised sands (UB5b/c), probably not preserved in Area A (Karkanas et al., *In press*).

The flow event described above (units UA3c and UB4c), and

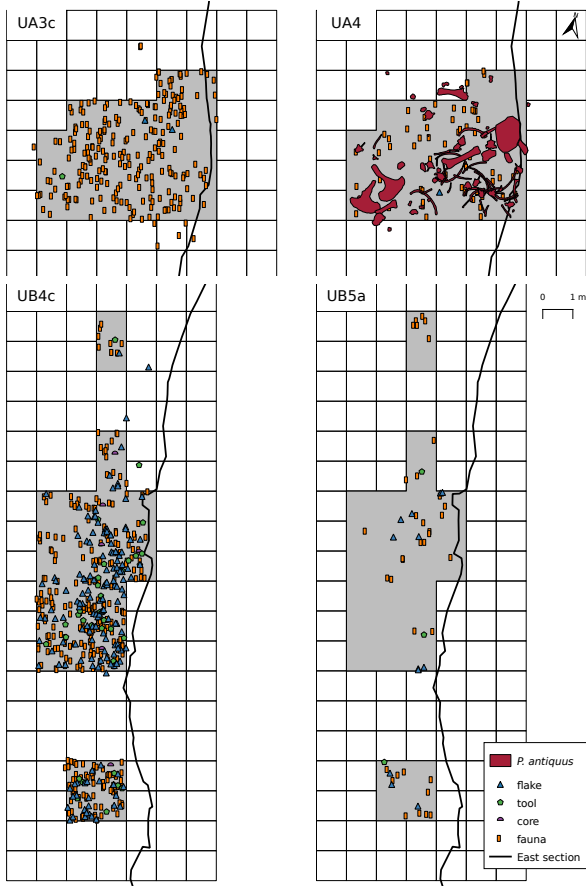


Figure B.2: Distribution maps of the plotted remains from areas A (units UA3c and UA4) and B (units UB4c and UB5a), collected until 2015. Due to their high number, lithic debris/chips are not plotted. The plotted remains of the *P. antiquus* skeleton were collected until 2016. Grey zones mark the 2013-2015 excavation areas. Area B is located 60 m to the South, along the exposed East section of the lignite quarry.

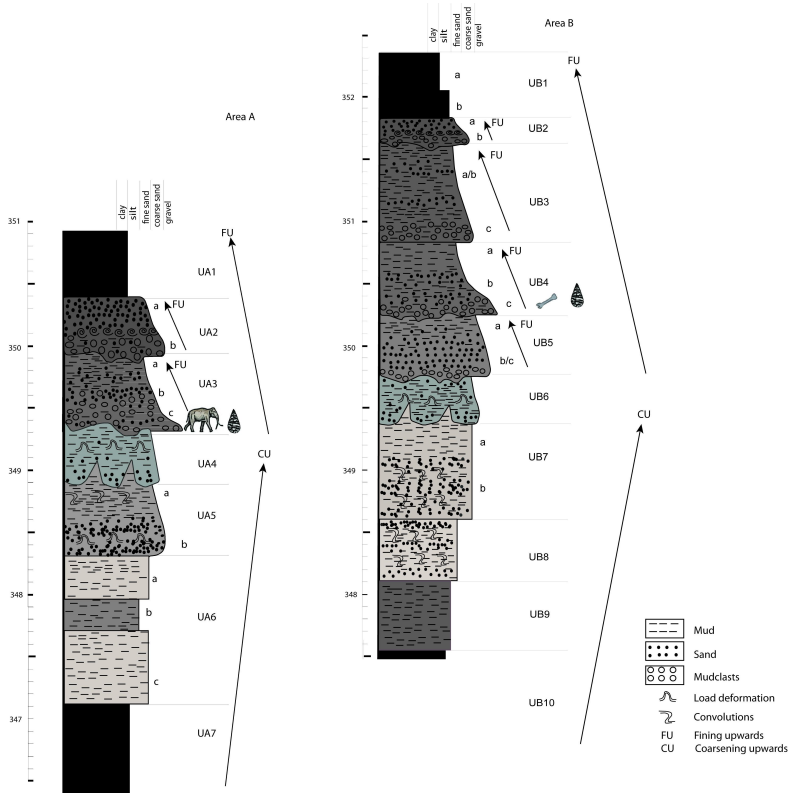


Figure B.3: Stratigraphic setting of the Marathousa 1 site, modified after Karkanas et al. (In press). Absolute elevations in m a.s.l.

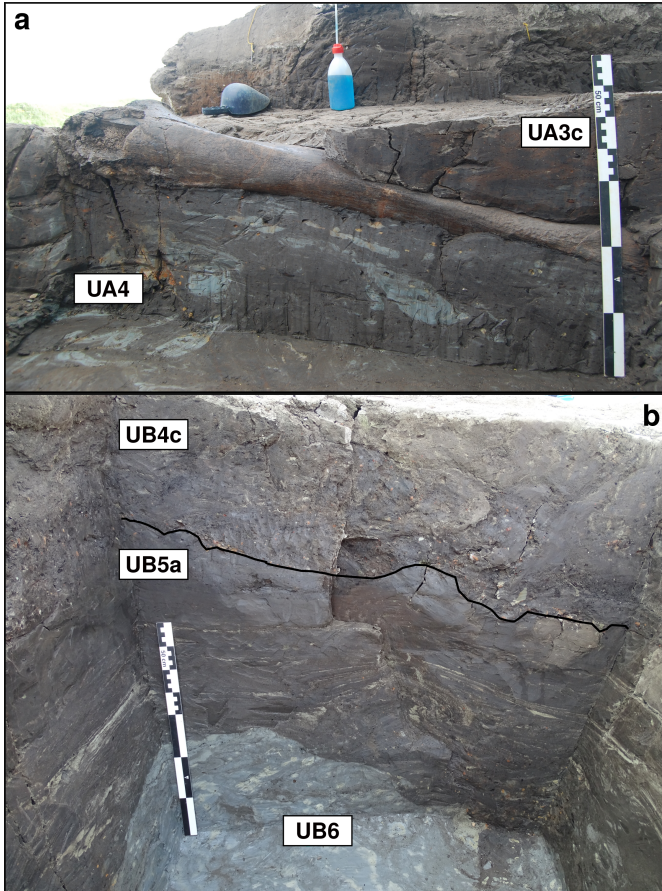


Figure B.4: Photograph (2017) of the left femur of the *P. antiquus* skeleton, lying at the UA3c/4 contact and covered by unit UA3c (a). West profile (2014) of the excavation Area B (square 932/603), exposing the UB4c/5a (black solid line) and the UB5/6 erosional contacts (b).

specifically the erosional contacts between the fossiliferous horizons in the two areas (UA3c/4 and UB4c/5a), provide the essential background for the analysis and interpretation of the spatial distributions at Marathousa 1. The secondary depositional nature of the main find horizons raises the question of how reliable is the spatial association between the lithic artefacts and the partial skeleton of a single *Palaeoloxodon antiquus* individual and other faunal remains. Since spatial association does not necessarily imply causation, and consequently synchrony, the answer has important consequences for the interpretation of the site in the broader context of the Middle Pleistocene human-proboscidean interactions. We aim to tackle this question and disentangle the formation processes acting at Marathousa 1 on the basis of spatial patterns through a three-prong spatial analytic approach:

1. By analysing, in a frame of references, the orientation patterns of remains from relevant stratigraphic units;
2. By quantifying and comparing their relative vertical distributions;
3. By identifying spatial trends in either the assemblage intensities and the associations between classes of remains.

Two contrasting models of deposition are tested: the autochthonous hypothesis (*sensu* Domínguez-Rodrigo et al., 2012; Fernández-López, 1991) states that the flow event, represented by units UA3c and UB4c, eroded and scoured the exposed surface (where the elephant was lying), thereby entraining clastic material (including artefacts) and re-depositing (*sensu* Fernández-López, 1991) this material at a close distance. This model implies the loss of any original, pristine spatial relations between remains, but minor transport from the primary depositional *loci*. On the other hand, the allochthonous hypothesis (*sensu* Domínguez-Rodrigo et al., 2012; Fernández-López, 1991) implies significant transport from the original *loci* of deposition and re-elaboration (*sensu* Fernández-López, 1991). According

to this model, the spurious spatial association between the lithic artefacts and faunal remains does not support any behavioural interpretation.

B.2 Material and methods

Since 2013, systematic investigation of the Marathousa 1 site has been carried out by a joint team from the Ephoreia of Palaeoanthropology-Speleology (Greek Ministry of Culture) and the University of Tübingen. A grid system of 1 square meter units was set up, oriented -14 degrees off the magnetic North, and including the two areas of investigation. The excavation of the deposit proceeded in 50x50 cm sub-squares in Area B and 1x1 m squares in Area A, and spits of 5 to 10 cm thickness, respectively. Systematic water-screening of sediments was carried out on-site using 1 mm sieves in order to guarantee recovery of the small-size fraction (e.g., micro-artefacts, small mammal remains, fish, molluscs and small fragments of organic and inorganic material). The three-dimensional coordinates of finds (i.e., all the lithic artefacts, teeth and diagnostic bones; bones and organic material with a-axis ≥ 20 mm), collected spits of sediment, samples and geological features (e.g., erosional contacts and mud cracks) were recorded with a total station. Specifically, the three-dimensional position of the finds was always recorded at the lowest point of contact of the item with the sediment. Dense clouds of surface points of the elephant skeletal elements were acquired using both a total station and a close-range photogrammetric technique.

The dimensions (length, width and thickness) of registered finds were measured on-site with millimetre rules. Orientation (plunge and bearing) of elongated particles (i.e., faunal remains, large wood fragments and lithic artefacts) was recorded since 2013 using a clock-like system (the bearing was measured, relatively to the grid North, in twelve clockwise intervals of 30°; the plunge with a 22.5° accuracy). In 2015, the use of a compass and inclinometer with an accuracy of 1° was introduced in Area B to gradually replace the former

method.

The widespread use of a compass and inclinometer to record orientation data (Benito-Calvo et al., 2011; Bertran et al., 1997; Bertran and Texier, 1995; Cobo-Sánchez et al., 2014; Domínguez-Rodrigo et al., 2012; Domínguez-Rodrigo and García-Pérez, 2013; Domínguez-Rodrigo et al., 2014c; Eberth et al., 2007; Eren et al., 2010; Fiorillo, 1991; Lenoble and Bertran, 2004; Organista et al., 2017; Voorhies, 1969, among others) was favoured over the alternative use of a total station (Bernatchez, 2010; Dibble et al., 1997; Enloe, 2006; Kluskens, 1990; McPherron, 2005, among others), mostly due to the time-restricted conditions of the rescue excavation conducted at Marathousa 1.

Measurements of the bearing (azimuth) and plunge (dip) of elongated finds were taken along the symmetrical longitudinal a-axis (SLA) of elongated bones (Domínguez-Rodrigo and García-Pérez, 2013), lithic artefacts (Bertran and Texier, 1995) and wood fragments (Macdonald and Jefferson, 1985), using the lowest endpoint of the a-axis as an indicator of the vector direction.

Other major axes have been alternatively used with the recent application of GIS techniques to retrieve orientation data from secondary source, i.e., from excavation photographs, drawings or maps (Benito-Calvo and de la Torre, 2011; Boschian and Saccà, 2010; de la Torre and Benito-Calvo, 2013; García-Moreno et al., 2016; Sánchez-Romero et al., 2016; Walter and Trauth, 2013). However, the experimental works of Domínguez-Rodrigo and García-Pérez (2013) and Domínguez-Rodrigo et al. (2014c) showed that the SLA, defined as the major axis which symmetrically divide the bone, is more accurate in estimating the flow direction, regardless of bone shape. This a-axis is widely used in taphonomic studies (Aramendi et al., 2017; Domínguez-Rodrigo et al., 2014a, 2012; Eberth et al., 2007; Toots, 1965; Voorhies, 1969, among others) for determining the preferential orientation of anisotropic assemblages. The a-axis or major axis of the artefact, measured as the long diameter of the triaxial ellipsoid that approximates the particle shape (Krumbein, 1941), is as well used in studies which employ a sedimentological approach

to archaeological fabric (Benito-Calvo et al., 2009; Bertran et al., 1997; Bertran and Texier, 1995; Lenoble and Bertran, 2004, among others).

The present study focuses on the excavated stratigraphic units in which most of the archaeological and palaeontological remains were recovered in both excavation areas, namely in UA3c and UA4 in Area A, and UB4c and UB5a in Area B. From the total, subset samples of material were used for each specific spatial analysis. For the fabric analysis we included material collected until 2016. For the vertical distribution and point pattern analyses, the region of investigation was limited to the squares excavated from 2013 until 2015, 25 and 29 square meters respectively in each area (Fig. B.2).

The analyses were performed in R statistical software (R Core Team, 2017). In order to make this research reproducible (Marwick, 2017; Marwick et al., 2017), a repository containing a compendium of data, source code and text is open licensed and available at the DOI: [10.5281/zenodo.822272](https://doi.org/10.5281/zenodo.822272)

B.2.1 Fabric analysis

The taphonomic study of the orientation pattern of elongated sedimentary particles, including bones and artefacts, first addressed by Bar-Yosef and Tchernov (1972), Isaac (1967), Schick (1986), and Voorhies (1969), more recently led to a noteworthy development of methods and propagation of applications in Palaeolithic site formation studies (Benito-Calvo and de la Torre, 2011; Benito-Calvo et al., 2011, 2009; Bernatchez, 2010; Bertran et al., 1997; Bertran and Texier, 1995; Boschian and Saccà, 2010; de la Torre and Benito-Calvo, 2013; Domínguez-Rodrigo et al., 2012; Domínguez-Rodrigo and García-Pérez, 2013; Domínguez-Rodrigo et al., 2014c; García-Moreno et al., 2016; Lenoble and Bertran, 2004; Lenoble et al., 2008; McPherron, 2005; Sánchez-Romero et al., 2016; Walter and Trauth, 2013, among others).

Fabric analysis can provide valuable insight into site formation and taphonomic processes, allowing discrimination between different

orientation patterns (isotropic, linear or planar) possibly associated with a range of sedimentary processes. Whereas water-flow deposits are generally characterised by relatively good sorting and preferred orientation of clasts parallel, or normal to the flow direction (linear fabric) (Petraglia and Potts, 1994); debris-flow deposits mostly exhibit massive, poorly bedded mixtures of unsorted sediments and random orientation of clasts (isotropic fabric), except at the flow margins where linear fabric may occur (Pierson, 2005). On the other hand, undisturbed archaeological sites, as well as experimental assemblages, have been observed to have planar fabric (Bertran et al., 1997; Lenoble and Bertran, 2004). Nevertheless, grey zones exist between depositional processes, so that an unequivocal discrimination based only on fabric observations is often not possible, and other taphonomic criteria must also be considered (Lenoble and Bertran, 2004). As an example, while overland flows (runoff) have been observed to show some degree of planar fabric (Lenoble and Bertran, 2004), anisotropy without significant transport can be caused in a lacustrine floodplain by low-energy processes such as lake transgression and regression, as well as water-sheet flows formed during rainy seasons (Cobo-Sánchez et al., 2014).

At the margin of a lacustrine environment, relatively close to the surrounding relief, a combination of high- and low-energy processes can be expected. According to the sedimentological and micromorphological study of the Marathousa 1 site, the main find-bearing horizon is associated with hyperconcentrated flows (Karkanas et al., *In press*). Hyperconcentrated flows are intermediate states, defined by sediment concentration, in the continuum between sub-aerial water flows and debris flows. Benvenuti and Martini (2002) reported that, when a turbulent hyperconcentrated flow expands over a surface - as in the case of Marathousa 1 - a two-phase flow may develop, with a more concentrated, coarser grained bottom flow-layer (traction carpet) moving slower than the upper turbulent flow-layer carrying wash-load and suspended load. Resultant deposit may exhibit diagnostic inverse grading, or a continuously aggrading bed. Parallel or normal orientation of the clasts to the flow direction can

be observed (Benvenuti and Martini, 2002). A simulation model also showed that linear fabric can develop in mud flows. However, after deposition, settling of the clasts may affect the fabric to some extent, depending on the viscosity of the mud flow (Lindsay, 1968).

As part of our three-prong spatial analytic approach, we conducted comparative fabric analysis with the aim to investigate the dynamics of the depositional processes at Marathousa 1. Since fabric strength has been found to be positively correlated with the shape and size of the clast, for the fabric analysis we subset samples of remains with length ≥ 2 cm and elongation index (the ratio length/width) $I_e \geq 1.6$ (Lenoble and Bertran, 2004). The samples are listed in Table C.1 and include mostly wood fragments and faunal remains from the four stratigraphic units under investigation. Bones have been found to readily react to water flow and show very early anisotropic patterns (Domínguez-Rodrigo et al., 2014c). Flume experiments showed that wood fragments as well tend to align parallel to the current direction (Macdonald and Jefferson, 1985). No distinction of skeletal elements was made, both due to the high fragmentation rate of faunal remains in Area B, and because recent experiments showed a similar orientation pattern for different bone shapes (Domínguez-Rodrigo et al., 2012; Domínguez-Rodrigo and García-Pérez, 2013).

The sample of bones belonging to the individual of *P. antiquus* from Area A was analysed separately and included the humerus, ulna, femur and tibia; the atlas, axis and other 16 complete vertebrae or vertebral fragments; 29 complete ribs or rib fragments; 2 calcanea; 4 metatarsals/metacarpals; the pyramidal; the trapezoid and the pelvis. The sample from UB5a was too small (only 7 observations) and was therefore excluded. In order to assess the reliability of the orientation data recorded using the clock method, we separately analysed two sub-samples from unit UB4c, selected from a set of finds recorded using both methods. All the sampled observations are representative of the whole study area.

Rose diagrams and uniformity tests, such as Rayleigh, Kuiper, Watson and Rao tests (Jammalamadaka et al., 2001), were used to

Table B.1: List of sampled observations for the fabric analysis.

Sample	n	Type		
		Fauna	Wood	Lithic
UA3c	49	23	25	1
UA4	38	8	30	-
<i>P. antiquus</i>	63			
UB4c	38	30	1	7

visualise and evaluate circular isotropy in the sample distribution. The Rayleigh test is used to assess the significance of the sample mean resultant length (\bar{R}), assuming that the distribution is unimodal and not bi- or plurimodal. The \bar{R} ranges from 0 to 1: values close to 1 indicate that the data are closely clustered around the mean direction; when the data are evenly spread \bar{R} has a value close to 0. A p – value lower than 0.05 rejects the hypothesis of uniformity with a 95% confidence interval. Kuiper, Watson and Rao are omnibus tests used to detect multimodal departures from circular uniformity. The Kuiper test (Kuiper, 1960) is a rotation-invariant Kolmogorov-Smirnov test statistic for testing the null hypothesis that the empirical distribution function fits a uniform distribution function. The Watson test (Watson, 1961) is instead related to the Cramer-von Mises test. The Rao’s spacing test (Jammalamadaka et al., 2001) is based on the idea that in a uniform distribution successive observations should be approximately evenly spaced and it tests deviation from this distribution. For all the tests, results are evaluated against critical values: a result higher than the critical value rejects with confidence the null hypothesis. We applied three omnibus tests since none of them have very high power and some studies suggested that there is no test that is superior to the others under all circumstances (Pewsey et al., 2013).

Randomness testing of three-dimensional data was conducted with the Woodcock S_1/S_3 test (Woodcock and Naylor, 1983). Considering both the plunge and bearing of the oriented items, this method, based on three ordered eigenvalues (S_1, S_2, S_3), is able to

discriminate the shape and strength of the distributions. The shape parameter $K = \frac{\ln(S_1/S_2)}{\ln(S_2/S_3)}$ ranges from zero (uni-axial girdles) to infinite (uni-axial clusters). The parameter $C = \ln(S_1/S_3)$ expresses the strength of the preferential orientation, and its significance is evaluated against critical values from simulated random samples of different sizes. A perfect random uniform distribution would have $C = 0$ and $K = 1$.

The Benn diagram (Benn, 1994) adds to the Woodcock test an isotropy ($IS = S_3/S_1$) and an elongation ($ES = 1 - (S_2/S_1)$) index. Like the former method, it is able to differentiate between linear (cluster), planar (girdle) or isotropic distributions. There are no published raw data from actualistic studies on hyperconcentrated flows or other depositional processes affecting the orientation of bones and artefacts deposited on lacustrine floodplains (but see Morton (2004) and Cobo-Sánchez et al. (2014) as pioneer studies on this subject). However, we included in the Benn diagram relevant references to published results from observation of fabrics in modern subaerial slope deposits, i.e., debris flow and runoff (Bertran et al., 1997; Lenoble and Bertran, 2004).

B.2.2 Vertical distribution

The vertical distribution of materials has been long investigated with the aim of identifying cultural levels, by visually interpreting cross-sectional plots. However, recent advances in GIS techniques allow to inspect at higher resolution the three-dimensional distributions of archaeological remains (Anderson and Burke, 2008; McPherron et al., 2005, among others).

In analysing the vertical dispersion of material at Marathousa 1, we provisionally assume that a general concentration of unsorted lithic artefacts and faunal remains in the proximity of the erosional surfaces would support an autochthonous origin of the assemblages; whereas a homogeneous vertical distribution of remains from the UA3c and UB4c units would suggest an allochthonous origin, significant transport and subsequent re-deposition of the material. In-

Table B.2: List of sampled observations for the vertical distribution and point pattern analyses.

Sample	<i>n</i>	Lithic class						Faunal class		
		Debris/chip	Flake	Bone flake	Tool	Core	Indet.	Bone	Tooth	Microfauna
UA3c	279	46	2	-	1	-	1	171	14	44
UA4	61	3	1	-	-	-	-	45	4	8
UB4c	1243	753	154	1	34	6	2	246	28	19
UB5a	101	50	12	-	3	-	-	30	3	3

deed, massive process such as hyperconcentrated flows, have high erosional power and rather chaotic structure, which may result in inverse or normal grading (Benvenuti and Martini, 2002).

In order to estimate the degree of vertical dispersion while controlling for the size of the archaeological material, dimensional classes were set up following typological criteria. Lithic artefacts were classified as debris/chips when smaller than a cutoff length of 15 mm (Tourloukis et al., In press). Other classes include flakes, tools and cores; the latter being the bigger and heavier debitage product. Table B.2 summarises the sample size for each class. Lithic debris/chips constitute the larger part of the assemblage from UB4c (60%) and UB5a (49%); whereas in Area A they represent only a moderate percentage in the upper UA3c unit (16%). The very rare presence of lithic artefacts in the underlying unit UA4 is nevertheless significant. In this unit, the faunal remains are also found in much lower numbers, their number reduced to one fourth of those found in UA3c. For the point pattern analysis (see below), we used the same subset of material for both excavation areas.

For Area B, the material recovered from the water-screening was randomly provenanced according to the 5 cm depth of the excavated spit and the coordinates of the 50x50 cm quadrant of the excavation square. Following the same excavation protocol, the same procedure was applied for the water-screened material of Area A, which was randomly provenanced according to 3D-coordinates of the 1x1 m excavation square and 10 cm spit.

Since the merely projection of points to virtual profiles is not a

suitable method of analysis in presence of erosional, and thus uneven, geological contacts - such as those at Marathousa 1, ordinary Kriging interpolation of the recorded points of contact between the UA3c/UA4 and the UB4c/UB5a stratigraphic units were used to reconstruct the UA3c/4 and UB4c/5a erosional surfaces (Fig. B.5a,b). In geostatistics, Kriging is a method of interpolation which, from a modelled function of spatial autocorrelation between known points (e.g., recorded elevations), calculates values of unknown points (e.g., predicted elevations). Thus, in order to address our specific objective, i.e., to quantify and analyse the vertical distribution of the archaeological and palaeontological material, we measured the minimum orthogonal distance (d) of each specimen to the interpolated erosional surface (Fig. B.5c). For the units above and below this surface (i.e., UB4c and UB5a), the relative distribution of lithic classes and faunal remains was informally tested by means of density estimations.

In Area A, the UA3c/4 erosional contact is locally sharp, but, in contrast to Area B, parts of the eroded unit UA4 are mixed with pockets of the UA3c organic-rich silty sands and intraclast-rich mud flows (Karkanis et al., *In press*). However, from sparse known points of the erosional contact, the UA3c/4 surface was interpolated and the vertical dispersion of remains estimated as well. The elephant remains were excluded from this analysis, since they clearly lie horizontally at the UA3c/4 contact (Fig. B.4a). Finally, a Student's two sample t-test allowed us to compare the empirical distributions of different groups of remains for each stratigraphic unit.

B.2.3 Point pattern analysis

A spatial point pattern is defined as the outcome of a random spatial point process (repetitions of it would always create a different pattern). The observed patterns of the archaeological and palaeontological remains were treated as manifestations of spatial point processes, i.e., site formation processes. Point pattern analysis investigates the spatial arrangement of points with the aim of identifying

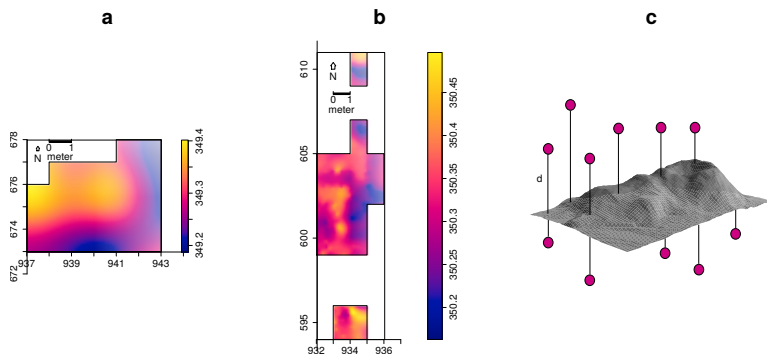


Figure B.5: Ordinary Kriging interpolation of the UA3c/4 (a) and UB4c/5a (b) erosional surface; the colour scale denotes absolute elevation in m a.s.l. (c) Illustration of the method used to quantify the vertical dispersion of remains (d) with respect to the UA3c/4 (a) and UB4c/5a (b) surface.

spatial trends. In order to integrate the previous studies of the fabric and vertical distributions, we directed our point pattern analysis equally to the intensity of the patterns (the rate of occurrence of the recorded finds) and to the spatial interaction between different types of finds.

As the average number of random points per unit area, intensity informs about homogeneity or inhomogeneity in the distribution of events (e.g., clasts) generated by a point process (e.g., mud flow), i.e., whether the rate of occurrence is uniform or spatially varying across the study area. Intensity, usually non-parametrically evaluated by means of kernel density estimation (Diggle, 1985), was assessed for the distribution of material from the UB4c, UB5a and UA3c units. Cross-validation bandwidth, which assumes a Cox process, and edge correction were applied using the methods described in Diggle (1985).

In the presence of a covariate, it is recommended to further in-

investigate the dependence of intensity on that explanatory variable (Baddeley et al., 2012). In order to evaluate whether variation in the density of materials was correlated to the topography of the erosional surface, we computed a local likelihood smoothing estimate of the intensity of remains from UB4c as a function of the UB4c/5a surface elevation model. Formal tests enabled us to assess the evidence of that dependence and to quantify the strength of the covariate. The Kolmogorov-Smirnov test of CSR (Complete Spatial Randomness) and Berman's Z_2 statistics were used to test the strength of evidence for a covariate effect. The Receiver Operating Characteristic (ROC) plot, and the area under the ROC curve (AUC), closely related to Berman's Z_2 test, measure the magnitude of the covariate effect. AUC values close to 1 or 0 indicate strong discrimination, whereas intermediate values (0.5) suggest no discrimination power.

Intensity, evaluated by means of kernel density maps, although informative and widespread in the literature, nonetheless does not provide sufficient information to reliably infer about site formation processes. Whereas intensity is a first-order property of the point process, multiscale inter-point interaction is measured by second or higher-order moment quantities, such as the Ripley's K correlation function (Ripley, 1976, 1977) and the distance G -, F - and J -functions. Three different types of inter-point interaction are possible: random, regular or cluster. In a hypothesis-testing framework, point-wise envelopes are computed by a number of random simulations of the null hypothesis (i.e., random/Poisson distribution). Thus, values of the empirical distribution (black solid line) are plotted against the benchmark value (red dotted line) and the envelopes (grey area) which specify the critical points for a Monte Carlo test (Ripley, 1981). Regular patterns are assumed to be the result of inhibition processes, while cluster patterns are the result of attraction processes.

In order to test the spatial interaction between remains associated with the erosional event of UB4c and those associated with the underlying UB5a unit, we treated the data as a multivariate point pattern, assuming that the point patterns in UB4c and UB5a are

expressions of two different stationary point processes, i.e., depositional events. We performed a cross-type pair correlation function $g_{ij}(r)$, derivative of the multitype $K_{ij}(r)$ function, which is the expected number of points of type j lying at a distance r of a typical point of type i . The function is a multiscale measurement of the spatial dependence between types i (UB4c) and j (UB5a). Randomly shifting in 199 Monte Carlo permutations each of the two patterns, independently of each other, estimated values of $\hat{g}_{ij}(r)$ are compared to a benchmark value $g_{ij}(r) = 1$, which is consistent with independence or at least with lack of correlation between the two point processes.

In addition to the pair correlation function, the multitype nearest-neighbour $G_{ij}(r)$ function was used to estimate the cumulative distribution of the distance from a point of type i (UB4c) to the nearest point of type j (UB5a). It measures the spatial association between the two assemblages. For the cross-type G -function, the null hypothesis states that the points of type j follow a Poisson (random) distribution in addition to being independent of the points of type i . Thus, in a randomisation technique, when the solid line of the observed distribution ($\hat{G}_{ij}(r)$ or $\hat{g}_{ij}(r)$) is above or below the shaded grey area, the pattern is significantly consistent with clustering or segregation, respectively. In order to reduce the edge effect bias in estimating the correlation between points, we implemented Ripley's isotropic edge correction (Ohser, 1983; Ripley, 1988).

Complete spatial randomness and independence (CSRI) of the two point processes (UB4c and UB5a) would support an allochthonous origin hypothesis for the assemblage recovered from the UB4c unit. According to the allochthonous model, the massive, chaotic UB4c flow event randomly re-elaborated the material entrained in it, independently from the material deposited in UB5a. On the other hand, positive or negative association can be interpreted as expressions of different autochthonous processes.

As for the three-dimensional distribution of the lithic artefacts in Area A, and their spatial association with the partial skeleton of the *P. antiquus*, we applied three-dimensional univariate and bivariate

second-order functions. A rectangular box of 20 square meters and 80 cm vertical extent was selected for the analyses (green outline in Fig. B.11a). Assuming homogeneity, the univariate pair correlation function $g_3(r)$ was estimated for the pattern of all the artefacts (mostly debris/chips) from UA3c and UA4. In the specific context of the site, complete spatial randomness (CSR) would suggest that the pattern most probably is the result of a random distribution process, such as a high energy mass movement, thus supporting an allochthonous model of deposition. On the other hand, spatial aggregation would support a primary origin of the assemblage. Nevertheless, topography and natural obstructions may generate spatial clustering as well.

In support to the pair correlation function, the cross-type nearest-neighbour function has been applied in order to compute, for each artefact recovered from the UA3c and UA4 units, the nearest point of the three-dimensional clouds of points associated with the elephant skeleton. A prevalence of short distances would indicate aggregation of the lithic artefacts around the mass of the elephant; whereas a uniform or symmetric distribution would support the action of random independent processes.

B.3 Results

B.3.1 Fabric analysis

The rose diagrams in Fig. B.6 visualise the circular distributions of the examined specimens. Overall, the UA4 sample and the sample of elephant bones show unimodal distributions with predominant peaks in the NE quadrant; while the ones from units UA3c and UB4c suggest multimodal distributions. Specifically, the UA4 sample distribution (Fig. B.6b) spreads largely in the NE quadrant. Similarly, the circular distribution of the elephant sample (Fig. B.6c), mainly lying in UA4, resembles the former distribution: it is skewed to the SW and concentrated in the NE quadrant. On the other hand, the UA3c sample (Fig. B.6a) shows a bimodal distribution

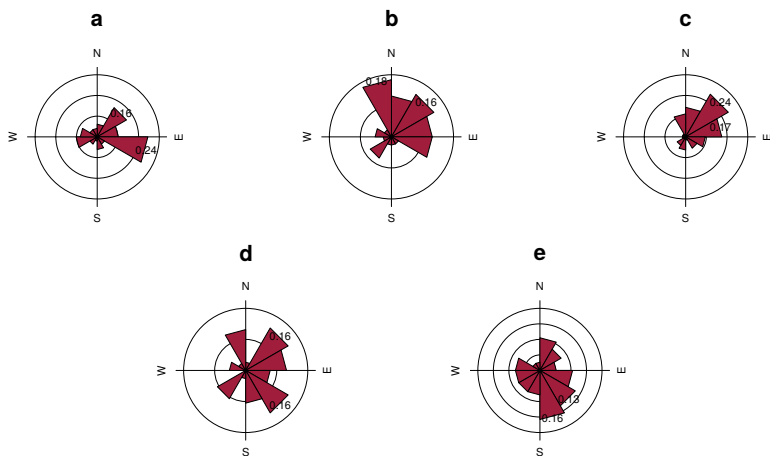


Figure B.6: Rose diagrams showing the bearing patterns of samples from UA3c (a), UA4 (b), the elephant carcass (c) and UB4c (d: clock method, e: compass method).

with two peaks to the E and NE, and the two samples from Area B (Fig. B.6d,e) suggest a different multimodal scenario uniformly distributed.

Table B.3 summarises the results of the circular uniformity tests. With regard to the UA3c sample, the Rayleigh test ($p - value = 0.03$) rejected the null hypothesis of circular uniformity. The mean resultant length ($\bar{R} = 0.27$) and the mean direction of 77° are thus significant, assuming the distribution is unimodal. However, the rose diagram (Fig. B.6a) showed a bimodal distribution. The Kuiper, Watson and Rao omnibus tests, more powerful than the Rayleigh test in detecting multimodal deviation from uniformity, also rejected the null hypothesis of uniformity, therefore suggesting significant anisotropy in the distribution. For the UA4 sample and the subset of elephant bones, all the uniformity tests agreed in rejecting the null hypothesis in favour of a preferentially oriented distribution.

Table B.3: Value and p – value of circular uniformity test statistics.

Sample	mean dir.	Rayleigh		Kuiper		Watson		Rao	
		\bar{R}	p	V_n	p	U^2	p	U	p
UA3c	77.17°	0.268	0.029	2.4698	<0.01	0.2967	<0.01	271.8367	<0.001
UA4	35.79°	0.386	0.003	2.5656	<0.01	0.3437	<0.01	246.3158	<0.001
<i>P. antiquus</i>	54.64°	0.489	2.775e-07	3.4811	<0.01	0.906	<0.01	291.4286	<0.001
UB4c (clock)	91.66°	0.276	0.054	1.8963	0.01< p <0.025	0.1937	0.025< p <0.05	255.7895	<0.001
UB4c (compass)	151.17°	0.243	0.106	1.3944	>0.15	0.1268	>0.10	128.5263	>0.10

The elephant sample, with respect to the other, showed significantly higher test results, thus stronger anisotropy. As suggested by the rose diagrams (Fig. B.6c), this sample has a mean direction towards the NE (55°) and relatively low circular variance (29°).

The UB4c sub-samples had discordant test results when considering the omnibus statistics. However, according to the Rayleigh test, the mean resultant lengths (\bar{R}) and the mean directions were not significant for both sub-samples of measurements: p – values > 0.05 failed to reject the null hypothesis of isotropy with 95% confidence interval. This result is well confirmed by the Kuiper, Watson and Rao tests for the sub-sample of measurements recorded using the compass. Conversely, the omnibus tests failed to reject the hypothesis of uniformity for the other sub-sample of measurements recorded with the clock method. The rose diagram (Fig. B.6d) suggested for the latter distribution strong multimodality, with uniformly spread peaks. The contrasting results obtained for the UB4c sub-samples are most probably due to the shape of those distributions. Indeed, the clock system, being less accurate, tends to produce a less dense distribution, more subject to show a multimodal shape when the distribution is actually uniform.

The Woodcock eigenvalues ratio graph (Fig. B.7a) presents the shape (K) and strength (C) of the distributions. Fig. B.7b plots confidence levels of Monte-Carlo critical C values, varying for sample sizes. The two sub-samples from Area B nearly overlapped, thus suggesting reliability of the orientation measurements collected using the clock system, although of low accuracy. The two sub-samples, together with the UA3c sample, having low C values, plotted close to

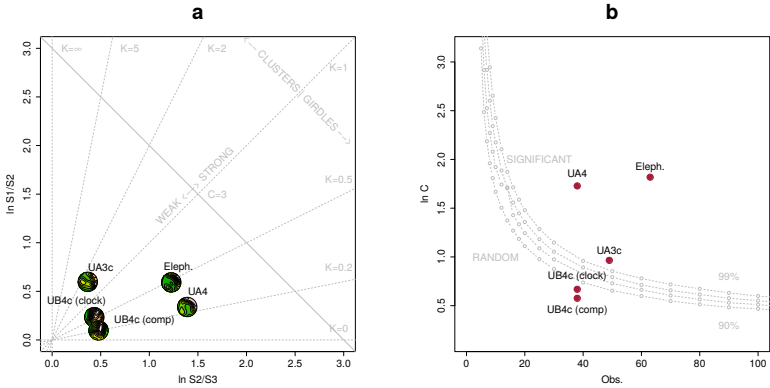


Figure B.7: Woodcock's eigenvalues ratio graph (a) and plot of the Monte-Carlo critical S_1/S_3 test values, for varying sample sizes and confidence levels (b), modified from Woodcock and Naylor (1983).

the origin of the ratio graph. Therefore, they indicate weak preferential orientation (UA3c) and significant randomness (UB4c). On the other hand, the UA4 and the elephant samples, with higher C values, showed a stronger and significant tendency to orient preferentially. The shape parameter K of the samples varied from $K = 0.25$ for the UB4c sample measured with the compass, to $K = 0.66$ for the one measured with the clock, to $K = 0.48$ for the elephant sample. Overall, all the samples, except the UA3c one ($K = 1.63$), plotted below the average shape value ($K = 1$) between girdles and clusters distributions.

The Benn diagram (Fig. B.8) resembles the Woodcock ratio graph (Fig. B.7a). The samples from units UB4c and UA3c clearly plotted at a distance from the UA4 and the elephant samples. The UB4c samples plotted in the upper corner of the ternary graph, with the UB4c sub-sample of measurements taken with the compass exhibiting more isotropy. The UA3c sample, with an elongation index similar to the elephant sample, but higher isotropic index, plotted

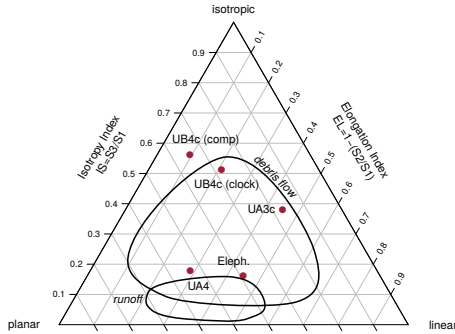


Figure B.8: Benn's diagram. Fabric ranges of natural processes modified from [Lenoble and Bertran \(2004\)](#).

towards the centre. Compared to the ranges of fabrics recorded for modern natural processes (debris flow and runoff), the fabric from the UA3c and UB4c units plotted well inside the cluster of debris flows, with the UB4c (comp) sample suggesting even more random orientations. On the other hand, the sample of elephant remains, which lie mostly on UA4 and are covered by UA3c, plotted significantly close to the sample from unit UA4. They both presented the lowest isotropy index (IS), but not high elongation index (EL). Thus, they plotted in the average between linear and planar orientations, at the margins of the range of runoff processes. Yet they still plotted within the cluster of debris flows fabrics. Moreover, as suggested also by the uniformity tests (Tab. B.3), the elephant sample showed a more linear attitude with respect to the UA4 sample.

B.3.2 Vertical distribution

Fig. B.9 compares the vertical distribution of the finds from units UA3c and UA4, by means of empirical density functions of the minimum distances (d) from each specimen to the UA3c/4 erosional contact (Fig. B.5a). Three lithic artefacts (two flakes and one tool)

from the UA3c unit, not included in Fig. B.9, plotted within 15 cm from the interpolated surface. Only one flake has been found in the lower UA4, at about 17 cm from the UA3c/4 contact, together with three chips. Despite the scarcity of debitage products in this area, waste products (debris/chip) are relatively well represented (16% of the UA3c sample). Their vertical dispersion approximated a normal distribution ($\mu = 0.24$, $\sigma = 0.15$): the Kolmogorov-Smirnov and Shapiro tests failed to rejected the null hypothesis of normality ($p - value = 0.83$ and 0.075 , respectively). Notably, the distributions of the faunal remains from the same unit UA3c were all right skewed, with means (μ) about 20 cm above the UA3c/4 contact. Nevertheless, the Welch two sample t-test ($p - value = 0.61$) failed to reject the null hypothesis that the lithic and faunal sample means are equal. The total distribution of remains from unit UA3c showed a unimodal distribution, skewed to the right, with mode in the proximity of the UA3c/4 surface. Similarly, the vertical distribution of faunal remains recovered from unit UA4 concentrate in the first 10 cm below surface. The density functions altogether clearly confirmed one of the main observations assessed during excavation, namely that, with the elephant remains lying at the UA3c/4 contact and covered by unit UA3c, most of the faunal and lithic material were recovered from unit UA3c (Fig. B.2) and predominantly in the proximity of the UA3c/4 contact (Fig. B.9).

Fig. B.10 shows the empirical density functions of the minimum distances from each specimen from Area B to the UB4c/5a erosional contact (Fig. B.5b). The combined distribution of any type of find from the UB5a unit (Fig. B.10a) skewed to the left with a short tail (up to -0.3 m). The mode, between 5 and 10 cm below the roof of UB5a, indicates a general concentration of material very close to the contact of this unit with the overlying UB4c, in accordance with the mean distribution of the different classes of remains. Although the majority of both the lithic and faunal assemblages were found in the uppermost 15 cm of UB5a, few debris/chips and bone fragments occur lower in the sequence, yet no more than 30 cm below the roof of this unit. Very few flakes, three tools and no cores have been

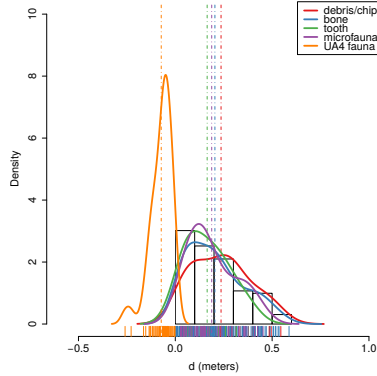


Figure B.9: Empirical density functions of minimum orthogonal distances (d) to the UA3c/4 surface. The histogram represents the total distribution of remains from UA3c; dashed lines indicate mean values.

found in this unit. As a whole, the lithic assemblage from UB5a, mostly composed by debris/chips, is only 7% of the most conspicuous assemblage from UB4c.

The global distribution of unit UB4c was right skewed (up to almost 0.6 m) and centred at about 5 cm above the contact with the underlying unit UB5a (Fig. B.10b). Almost 30% of the sample fell exactly at the erosional contact that separates UB4c from UB5a. The density estimations of the lithic debris/chip, flakes, tools and faunal remains significantly overlap, whereas the distribution of the six cores shows a bimodal shape with peaks at 5 and 20 cm above the contact. Moreover, the Welch Two Sample t-test of the lithic and faunal sample means failed to reject the null hypothesis (p -value = 0.6295).

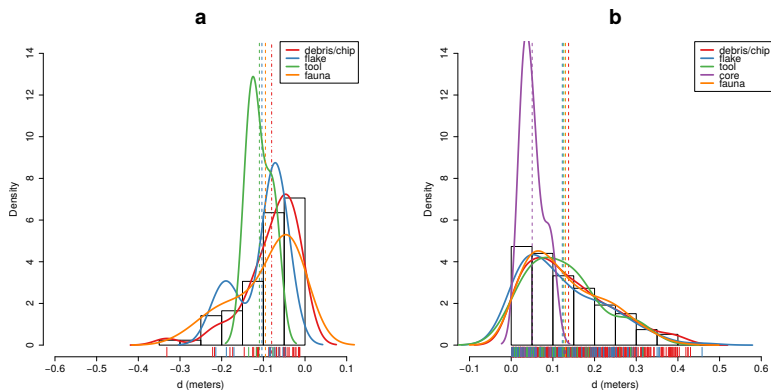


Figure B.10: Empirical density functions of minimum orthogonal distances (d) to the UB4c/5a surface. The histogram represents the total distribution of remains from UB5a (a) and UB4c (b); dashed lines indicate mean values.

B.3.3 Point pattern analysis

Results of the point pattern analysis are complementary to those obtained from the analysis of the fabric and vertical distributions. Regarding Area A, kernel density estimation and three-dimensional functions were applied in order to quantitatively depict the spatial distribution of the lithic assemblage in relation to the elephant skeleton. Fig. B.11a shows the smoothing kernel intensity estimation of the faunal assemblage from the UA3c unit. Contour lines delimit the density of the lithic sample. The partial skeleton of the *P. antiquus* is superimposed on it. A preliminary visual examination of the plot suggests a homogeneous distribution of lithics (mostly debris/chips) and fossils. Spots of higher density appear to be spread around and in association with the elephant remains.

The univariate pair correlation function of the joined lithic assemblage from the UA3c and UA4 units (Fig. B.11b) suggests ag-

gregation of finds. The estimated $\hat{g}_3(r)$ function (black solid line) wanders above the benchmark value (red dotted line) until values of $r = 0.8$. However, for distances between 35 and 65 cm, it lies above the grey envelope of significance for the null hypothesis of CSR, indicating that at those distances artefacts occur significantly closer than expected in the case of random processes. For values of $r > 0.8$, the function stabilises at values close to 0, suggesting a Poisson distribution. The plot illustrates the random distribution of finds between patches of clusters that we observe in Fig. B.11a.

The histogram in Fig. B.11c shows the density of the distances calculated from each artefact to the nearest-neighbour elephant remain. A right skewed distribution, with a prevalent peak at 10 cm and mean (μ) 30 cm is an indication of the relatively strong aggregation of lithics around the mass of the elephant skeleton.

As for Area B, the analysis focused on the spatial distribution and cross-correlation of the assemblages from UB4c and UB5a. Figs. B.12a,b respectively show kernel density estimations of the combined lithic and faunal assemblages from both the units analysed. Despite the samples size difference, a first visual examination suggests the presence of interesting spatial structures. Regarding the UB4c unit (Fig. B.12a), the high density of material concentrated around the western square 934/600 suggests that the pattern could have been the result of an inhomogeneous, non-uniform depositional process. Visual comparison of the density plot with the elevation model of the erosional contact between the UB4c and UB5a units (Fig. B.5b) suggests positive correlation between lower elevations (topographic depressions) and higher density of remains.

Fig. B.12c shows the results of the ρ -function, which estimates the intensity of the UB4c sample assemblage as a function of the covariate underlying topography created by the erosional event. Within the range of elevation between 350.2 and 350.4 m, the occurrence of finds is higher and the intensity decreases with the rise of elevation, i.e., finds are more likely to be found at lower elevations than would be expected if the intensity was constant. Spatial Kolmogorov-Smirnov (KS) and Berman's Z_2 (Berman, 1986) statistics were used

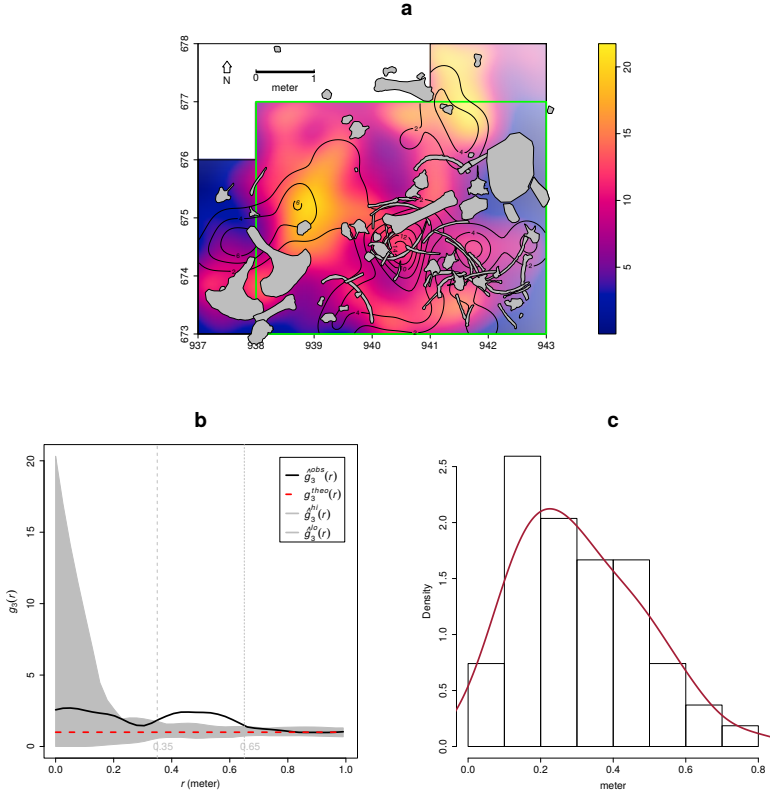


Figure B.11: Kernel smoothed intensity function of the faunal assemblages from UA3c. Isolines mark the density of the lithic artefacts from UA3c (a). Pair correlation function ($g_3(r)$) of a three-dimensional pattern of lithic artefacts from UA3c and UA4. Grey envelope of 999 Monte Carlo simulations under the CSR null hypothesis (b). Three-dimensional distance from each lithic artefact from UA3c and UA4 to the nearest neighbour elephant remain (c).

in order to test the dependence of the UB4c pattern on the covariate erosional surface. Both KS ($D = 0.11952$, $p\text{-value} = 7.772e - 16$) and Z_2 ($Z_2 = -7.8447$, $p\text{-value} = 4.34e - 15$) significantly rejected the null hypothesis of CSR. Although the tests suggested evidence that the intensity depends on the covariate, the effect of the covariate is weak and it seems to have no discriminatory power. The ROC curve and AUC statistics (0.56), which measure the strength of the covariate effect, suggest that the underlying UB4c/5a topography does not completely explain the localised high density of occurrence in the UB4c.

Relative spatial segregation seems to occur between the assemblages from UB4c (Fig. B.12a) and UB5a (Fig. B.12b), with high density of the former distribution corresponding to low density of the latter. The former analysis of the vertical distribution showed that the two assemblages occur very close to their stratigraphic contact (Fig. B.10). In order to further investigate the spatial interaction between the two depositional events, we applied multitype pair correlation $g_{ij}(r)$ and nearest-neighbour $G_{ij}(r)$ functions. Fig. B.12d shows the estimated values of the multivariate $\hat{g}_{ij}(r)$ function against the envelope of the null hypothesis, obtained by randomly shifting the position of remains from the two distributions in 199 Monte Carlo simulations. For fixed values of r less than 30 cm the observed function lies below the benchmark value of independence, thus indicating segregation; but it wanders at the lower edge of the grey envelope. For fixed distances of $r > 0.3$ m the observed and theoretical lines significantly overlap. Overall, the function suggests independence of the two point processes (UB4c and UB5a) at multiple scales. However, the estimated $\hat{G}_{ij}(r)$ function (Fig. B.12e), running well below the significance grey envelope for fixed values of $r > 0.3$ m, confirms that the nearest-neighbour distances between remains from UB4c and UB5a are significantly longer than expected in the case of independent processes. Interestingly, at values of $r < 0.2$ m the observed function failed to reject the null hypothesis of Complete Spatial Randomness and Independence (CSRI).

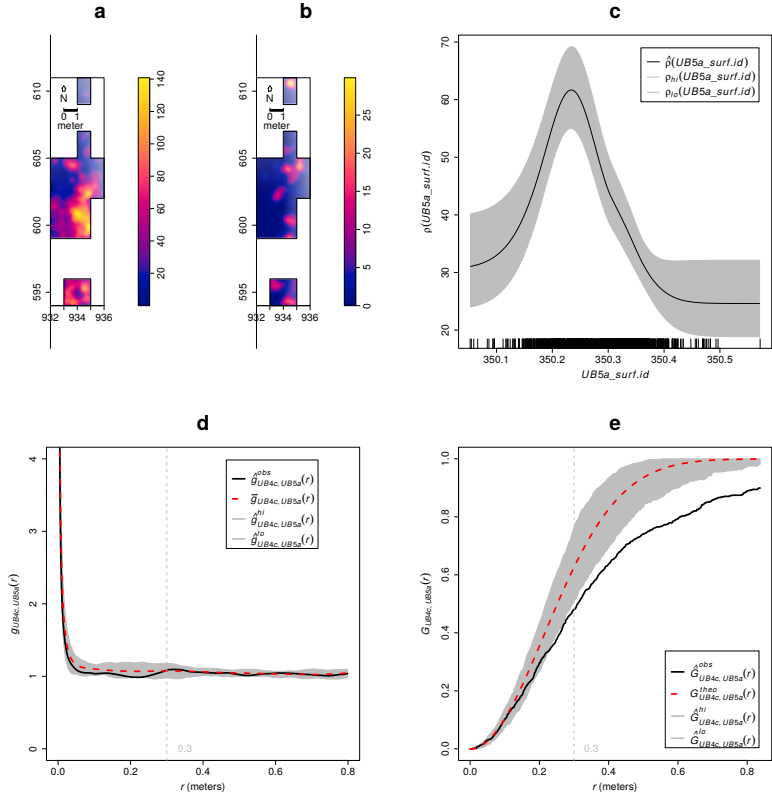


Figure B.12: Kernel smoothed intensity function of the lithic and faunal assemblages from UB4c (a) and UB5a (b). Smoothing estimate of the intensity of remains from UB4c, as a function of the erosional surface UB4c/5a. Grey shading is point-wise 95% confidence bands (c). Cross-pattern pair correlation function ($g_{ij}(r)$) between the UB4c and UB5a distributions. Grey envelope of 199 Monte Carlo simulations under the independence of components null hypothesis (d). Multitype nearest-neighbour function ($G_{ij}(r)$) between the UB4c and UB5a distributions (e).

B.4 Discussion

Recent excavations at the Middle Pleistocene site of Marathousa 1 have unearthed in one of the two investigated areas (Area A) a partial skeleton of a single individual of *Palaeoloxodon antiquus*, whose bones are in close anatomical association, and spatially and stratigraphically associated with lithic artefacts and other faunal remains. In Area B, 60 m to the South of Area A, we collected a much higher number of lithic artefacts (Touroloukis et al., In press), spatially and stratigraphically associated with other faunal remains, including isolated elephant bones, cervids and carnivores among others (Konidaris et al., In press). The two areas are stratigraphically correlated, the main fossiliferous layers (UA3c and UB4c) representing a massive depositional process, such as a hyperconcentrated flow that dumped material in a lake margin context (Karkanas et al., In press). To date, evidence of butchering (cut-marks) has been identified on two bones of the elephant skeleton from Area A, as well on elephant and other mammal bones from Area B (Konidaris et al., In press).

However, due to the secondary depositional nature of the main fossiliferous horizon, it is of primary importance to evaluate the degree and reliability of the spatial association of the lithic artefacts with the faunal remains, and especially with the elephant skeleton. In order to tackle our main objective, we applied a comprehensive set of spatial statistics to the distributions of the archaeological and zooarchaeological/palaeontological remains from relevant stratigraphic units of the two areas of investigation. Preliminary results of our analyses are here discussed for both areas.

B.4.1 Fabric analysis

The analysis of the orientation (plunge and bearing) of subsets of remains, mostly bone, wood fragments and lithic artefacts, showed different patterns for the two main find-bearing units. In Area B, two sub-samples from the same stratigraphic unit were analysed, in

order to assess the reliability of the orientation data measured with the clock system. Due to the different shapes of the distributions (Figs. B.6d,e), test statistics reported contrasting results (Tab. B.3). Indeed, the clock system, recording non-continuous circular data, tends to produce a distribution more subject to show a multimodal shape when it is actually uniform. However, the two sub-samples nearly overlapped when plotted in the three-dimensional Woodcock (Fig. B.7) and Benn (Fig. B.8) diagrams, thus suggesting some degree of reliability of the clock method. Nevertheless, despite minor differences between the two samples, caution should be paid in analysing grouped circular data.

The test results (Tab. B.3) for the UA4 sample and the sample of elephant remains - which lie on unit UA4 and are covered by UA3c - indicated significant preferential orientations towards the NE (Figs. B.6b,c). As shown by the Woodcock's (Fig. B.7) and the Benn's diagrams (Fig. B.8), these samples plotted together at a distance from the others. Such convergence suggests that the elephant carcass, the other faunal remains and the organic material, deposited on unit UA4, were subject to the same processes. Far from the isotropic corner in the Benn's diagram these two samples from Area A plotted approximately in between the linear and planar extremes, with the elephant sample showing a more linear fabric. When the results published by [Bertran et al. \(1997\)](#) and [Lenoble and Bertran \(2004\)](#) from observations of fabrics in modern subaerial slope deposits were used as a reference, the two samples aggregated at the extreme margins of runoff processes. Yet, they plotted well within the cluster of debris flows and relatively distant from the linear corner.

Although [Bertran et al. \(1997\)](#) studied runoff deposits from different environments (channel-lag gravels in rills, small gullies, and inter-rill surfaces on alpine slopes; and faintly laminated gravel lenses on an inactive, small colluvial fan), this result is consistent with the exposure of unit UA4 to overland water-laden processes that occurred before the flood event

UA3c/UB4c. Notably, the erosive nature of low-energy processes

triggered by rain-water has been observed on lacustrine floodplains, and is associated with anisotropic patterns in autochthonous assemblages (Cobo-Sánchez et al., 2014; Domínguez-Rodrigo et al., 2014c; García-Moreno et al., 2016).

Pockets of thinly bedded organic-rich silty sands have been found mixed in UA4. These sands in Area A resemble the UB5b/c sandy deposit in Area B, which is associated with relatively high energy fluvial flows entering the lake margins (Karkanas et al., In press). Eventually, such relatively high energy flood (UB5b/c) would have had the power to significantly reorient elements of the elephant carcass and slightly displace them. However, the elephant skeleton clearly lies on top of unit UA4 and is covered by UA3c (see Fig.B.4).

Moreover, unlike bones with a tubular shape (i.e., long bones), ribs and vertebrae are prone to orient preferentially under high energy processes, less likely under low energy processes (Domínguez-Rodrigo and García-Pérez, 2013; Domínguez-Rodrigo et al., 2014c). Interestingly, whereas some of the ribs share the same preferential orientation with the long bones, others are oriented NW/SE. However, a NW/SE orientation could be consistent with a prevalent NE direction of the flow (and vice-versa), since long bones could roll orthogonally to the flow direction (Voorhies, 1969). On the other hand, a higher energy flood would lead to an under-representation of skeletal elements with FTI (Fluvial transport Index) values ≥ 75 (sacrum, patella, astragalus, calcaneum, cervical, thoracic and lumbar vertebrae), which are more prone - when disarticulated - to be easily transported by water induced processes (Frison and Todd, 1986). Yet, several of these bones are present and in close spatial association with the elephant cranium and other skeletal elements. The presence of many of the skeletal elements with different transportation properties suggests that the elephant carcass was not subjected to high energy processes (and probably still articulated) before the flood event UA3c/UB4c.

The fabrics of the UA3c and UB4c samples, with higher isotropic index (*IS*), plotted at a significant distance from the elephant sam-

ple, yet within the cluster of debris flows (Fig. B.8). Indeed, random distribution and orientation of clasts is expected for debris flows, except at flow margins, where preferential orientation and clusters of clasts have been observed (Pierson, 2005). However, hyperconcentrated flows, such as the

UA3c/UB4c flood event, which fall in between the spectrum of water and debris flows, may develop parallel or normal orientation to the flow direction (Benvenuti and Martini, 2002; Lindsay, 1968). Notably, with respect to the UB4c sample, the UA3c sample exhibits a higher elongation index (ES), similar to that of the elephant sample (Fig. B.8). Rose diagrams (Fig. B.6) and uniformity tests (Tab. B.3) also suggest similar fabrics of the samples from Area A.

Thus, we can assume that an overland flow, namely UA3c/UB4c, is likely to have slightly reworked and preferentially oriented to the NE the exposed elements of the already dismembered (and probably already marginally displaced) elephant carcass, which mostly preserves close anatomical associations, but not anatomical connections. Although little is currently known about the spatial extension of the UA3c/UB4c flow event, the different orientation patterns between the two areas could probably be explained with lateral variability. Indeed, the same event could exhibit different behaviours at different temporal and spatial points, giving rise to different distribution patterns. However, as suggested by Lenoble and Bertran (2004), fabric analysis is not sufficient to unequivocally discriminate processes and should therefore be integrated with the analysis of other diagnostic features.

B.4.2 Vertical distribution

As for the vertical distribution, we assumed that mass processes, such as hyperconcentrated flows, would predominantly distribute poor to very poor sorted clasts homogeneously throughout the sequence (Pierson, 2005). Diagnostic inverse grading, or a continuously aggrading bed can be observed in the resultant deposits (Benvenuti and Martini, 2002). A concentration of unsorted elements in

the proximity of the erosional surface, as well as the absence of any grading, would in turn suggest an autochthonous assemblage.

The lithic assemblage from Area A - the combined units UA3c and UA4 ($n = 54$), composed by a few debitage products and a relatively high number of debris/chips and retouch waste products (Tab. B.2) - plotted predominantly in the proximity of the erosional surface created by the UA3c/UB4c event (Fig. B.5a). The faunal remains from unit UA3c resemble the distribution of the archaeological assemblage; whereas the ones from the underlying unit UA4 plotted within 10 cm below the erosional contact. Overall, the material recovered from unit UA3c did not show any grading and mainly plotted at the bottom of the unit (Fig. B.9). Thus, its vertical distribution is consistent with the hypothesis of an autochthonous assemblage.

In Area B, two samples from units UB4c ($n = 1243$) and UB5a ($n = 101$) respectively, were analysed (Tab. B.2) for quantifying the minimum orthogonal distance of each item to the modelled erosional surface (Fig. B.5b). The vertical distribution of lithic artefacts and fossils from unit UB4c showed a predominant peak right at the contact with the erosional surface. Almost 30% of this rich sample plotted at a distance between 0 and 5 cm from the erosional contact; whereas the rest gently skewed to the upper part of the unit, up to about 50 cm. The same distribution was observed for all classes of remains, suggesting no size sorting and an origin very close to the erosional surface (Fig. B.10b).

The density distribution of the sample from the underlying UB5a unit (Fig. B.10a) globally indicates a more constrained vertical displacement of remains (within 30 cm below the erosional surface). Whereas lithic artefacts and fossils mostly plot right at the contact and just below it, a few debris/chips and faunal remains were found lower in the sequence. No size sorting was observed, but, notably, lithic cores are absent and the debris/chip distribution is wider than the distribution of the few flakes and tools. Field observations of cracks in the clayey UB5a unit testify to shrinking and swelling during wet and dry cycles (Karkanas et al., *In press*), which suggests

that vertical displacement of some small lithics and fossil fragments at lower depths with respect to the UB5a/4c contact probably resulted from clay desiccation. Likewise, [Lenoble and Bertran \(2004\)](#) documented up to 30 cm vertical dispersion and frequent vertical plunge of artefacts from the marshy silty clay of the Croix-de-Canard site, sector 3. Furthermore, a recent experimental study of animal trampling in water saturated substrates reported negative correlation with artefact size, significant inclination and greater vertical displacement than any former work: a maximum between 16 and 21 cm, with a mean of about 6 cm ([Eren et al., 2010](#)).

The fact that the majority of the remains from units UB4c and UB5a plotted at, or very close to the contact between these two layers, the relatively high percentage of lithics in both units, as well as the absence of grading, suggest autochthonous assemblages, deposited in UB5a and subsequently eroded *in situ* by the UA3c/UB4c flood event.

B.4.3 Point pattern analysis

The autochthonous hypothesis was further explored by means of point pattern analysis. According to this model, in both areas the lithic and faunal assemblages were primarily deposited *in situ* and were subsequently eroded and re-deposited (*sensu* [Fernández-López, 1991](#)) by the hyperconcentrated flow

UA3c/UB4c. We assumed that a completely random spatial distribution of the lithic artefacts and faunal remains would suggest an allochthonous origin and subsequent re-elaboration (*sensu* [Fernández-López, 1991](#)), with transport to the site by the action of a random massive process. Nevertheless, clustering of artefacts is not necessarily evidence of human presence. Aggregation or segregation patterns could be produced by a range of biotic and/or natural processes. Human activities, topography and physical obstructions alike could trigger spatial aggregation.

The three-dimensional distribution of lithic artefacts from unit UA3c shows significant clustering for values of r between 35 and

65 cm. Lithic artefacts occur relatively close to the skeletal elements of the elephant, at a distance between 20 and 50 cm at most (Fig. B.11). The richest cluster of about 20 lithic artefacts is located to the SW of the cranium, close to the right femur and the scatter of ribs and vertebrae. Considering the prevalent NE orientation of the elephant bones and the other faunal remains from UA4 and UA3c, it is not unlikely that a SW/NE oriented flood could have been responsible for the observed accumulation to the SW of the elephant cranium, which would have represented an important obstruction to the flow. A similar case of clustering of small remains, apparently dammed by a long elephant tusk, has also been observed at Castel di Guido (Italy) by [Boschian and Saccà \(2010\)](#). Secondary deposition by low-energy flows and clustering of artefacts and bones blocked by an aurochs carcass have been as well documented at the site of 'Ein Qashish (Israel) ([Hovers et al., 2014](#)). However, the pair correlation function (Fig. B.9b) suggests significant clustering of lithic artefacts at relatively small scale: a pattern less likely to be produced by a large scale massive process such as a hyperconcentrated flow. Moreover, clusters of lithic artefacts occur as well in areas with lower densities of elephant bones.

Small scale clustering; proximity to the elephant remains and the erosional surface; absence of spatial size sorting and, on the contrary, the presence of a relatively high number of lithic debris/chips associated with some flakes, tools and a rich faunal assemblage; close anatomical spatial association of the elephant skeletal elements, slightly displaced and preferentially oriented: altogether these lines of evidence support the hypothesis of an autochthonous deposition, subject to localised minor reworking.

A similar pattern can be observed in Area B, where an initial set of spatial statistics confirmed that the inhomogeneous density of remains from unit UB4c (Fig. B.12a) is not completely explained by the covariate effect of the underlying complex topography created by the erosional event UA3c/UB4c (Fig. B.5b). Thus, we explored the relative spatial interaction between the UB4c and the underlying UB5a samples. We assumed that complete spatial randomness

of the two independent depositional processes would occur in case of an allochthonous origin and transportation of the UB4c assemblage. The hypothesis of an autochthonous original deposition of the faunal and lithic assemblages on the UB5a unit, subsequently eroded *in situ* by a relatively high energy flood (UB4c), was tested by cross-pattern spatial correlation functions (Figs. B.12d,e). Whereas the two samples are vertically adjacent to the erosional surface (Fig. B.10), on the horizontal plane they are both more segregated than expected for a random distribution.

Conversely, the extraordinary preservation and number of mint to sharp, unsorted lithic artefacts from the UB4c unit; their density, positively correlated to the topography, and significantly segregated from the underlying distribution of remains; the vertical proximity of both assemblages from UB4c and UB5a to the erosional surface; as well as the random orientation pattern of the former, suggest that significant displacement of materials due to the erosional event can be excluded. The faunal and lithic assemblages from unit UB4c therefore most likely derived from the local erosion of exposed mud-flat areas (unit UB5a) and have been slightly redistributed by the same flood event that capped the elephant in Area A.

Further evidence that the recovered assemblage has not undergone substantial reworking and has retained its original characteristics would come from the refitting analysis, currently in progress. To date, 4 bone refits have been found in Area B: three from unit UB4c, respectively at 4.77, 0.05 and 0.01 m distance; and one between two mammal bone fragments from units UB4c and UB5a, at a very short distance (0.09 m). Interestingly, one of the elements of the most distant refit (a *Dama* sp. mandibular fragment) shows traces of carnivore gnawing (Konidaris et al., *In press*).

In conclusion, multiple lines of evidence reject an allochthonous hypothesis of deposition in favour of an autochthonous model. The erosional event UA3c/UB4c represents an *en mass* depositional process, i.e. a hyperconcentrated flow, in the continuum between water and debris flow, which would have locally reworked at a small scale the already exposed or slightly buried and spatially associated lithic

and faunal assemblages.

Although the UA3c/UB4c process represents a snapshot of a relatively short time-frame, high resolution inferences about the use of space by human groups, in terms of knapping episodes and butchering activities, are unreliable in light of the current information. The spatial pattern observed at the site is indeed the result of the last episode in a palimpsest of spatial processes. Whereas the erosional event represented by the hyperconcentrated flow UA3c/UB4c caps the fossiliferous horizon and preserves the record, little is known about the underlying, eroded 'occupational' surface.

However, whereas hunting or scavenging in the Lower Palaeolithic is still an unsolved matter of debate, considering the rate of bone fragmentation, the density of lithic debris/chips, the number of processed bones and their spatial density and association, it is likely that the assemblage represents a complex palimpsest of locally repeated events of hunting/scavenging and exploitation of lake shore resources. More data from high resolution excavations in the coming years will allow us to refine the coarse-grained spatio-temporal resolution of our inferences about past human behaviour at Marathousa 1.

B.5 Conclusions

At the Middle Pleistocene open-air site of Marathousa 1, a partial skeleton of a single individual of *Palaeoloxodon antiquus* was recovered in stratigraphic association with a rich and consistent lithic assemblage and other vertebrate remains. Cut-marks and percussion marks have been identified on the elephant and other mammal bones excavated at the site. The main find-bearing horizon represents a secondary depositional process in a lake margin context.

Understanding the site formation processes is of primary importance in order to reliably infer hominin exploitation of the elephant carcass and other animals. To meet this aim, we applied a comprehensive set of multivariate and multiscale spatial analyses in a

taphonomic framework.

Results from the fabric, vertical distribution and point pattern analyses are consistent with a high-energy erosional process, such as a hyperconcentrated flow deposited at the margin of a swamp, reworking at a small scale an exposed (or slightly buried) and consistent scatter of lithic artefacts and faunal remains. These results are in agreement with preliminary taphonomic observations of the lithic artefacts (Tourloukis et al., In press) and the faunal remains (Konidaris et al., In press), which also indicate minor weathering and transportation. Our analyses show that multiple lines of evidence support an autochthonous origin of the lithic and faunal assemblages, subject to minor post-depositional reworking.

References

- Anderson KL and Burke A. 2008. Refining the definition of cultural levels at Karabi Tamchin: a quantitative approach to vertical intra-site spatial analysis. *Journal of Archaeological Science* 35.8, 2274–2285. DOI: [10.1016/j.jas.2008.02.011](https://doi.org/10.1016/j.jas.2008.02.011).
- Aramendi J, Uribelarra D, Arriaza MC, Arráiz H, Barboni D, Yravedra J, Ortega MC, Gidna A, Mabulla A, Baquedano E, and Domínguez-Rodrigo M. 2017. The paleoecology and taphonomy of AMK (Bed I, Olduvai Gorge) and its contributions to the understanding of the “Zinj” paleolandscape. *Palaeogeography, Palaeoclimatology, Palaeoecology* (in press). DOI: [10.1016/j.palaeo.2017.02.036](https://doi.org/10.1016/j.palaeo.2017.02.036).
- Baddeley A, Chang YM, Song Y, and Turner R. 2012. Nonparametric estimation of the dependence of a point process on spatial covariates. *Statistics and Its Interface* 5.2, 221–236.
- Bailey G. 2007. Time perspectives, palimpsests and the archaeology of time. *Journal of Anthropological Archaeology* 26.2, 198–223. DOI: [10.1016/j.jaa.2006.08.002](https://doi.org/10.1016/j.jaa.2006.08.002).
- Bargalló A, Gabucio MJ, and Rivals F. 2016. Puzzling out a palimpsest: Testing an interdisciplinary study in level O of Abric Romaní. *Quaternary International* 417, 51–65. DOI: [10.1016/j.quaint.2015.09.066](https://doi.org/10.1016/j.quaint.2015.09.066).
- Bar-Yosef O and Tchernov E. 1972. *On the palaeo-ecological history of the site of Ubeidiya*. Vol. 35. Jerusalem: Israel Academy of Sciences and Humanities.
- Benito-Calvo A and de la Torre I. 2011. Analysis of orientation patterns in Olduvai Bed I assemblages using GIS techniques: Implications for site for-

- mation processes. *Journal of Human Evolution* 61.1, 50–60. DOI: [10.1016/j.jhevol.2011.02.011](https://doi.org/10.1016/j.jhevol.2011.02.011).
- Benito-Calvo A, Martínez-Moreno J, Mora R, Roy M, and Roda X. 2011. Trampling experiments at Cova Gran de Santa Linya, Pre-Pyrenees, Spain: their relevance for archaeological fabrics of the Upper–Middle Paleolithic assemblages. *Journal of Archaeological Science* 38.12, 3652–3661. DOI: [10.1016/j.jas.2011.08.036](https://doi.org/10.1016/j.jas.2011.08.036).
- Benito-Calvo A, Martínez-Moreno J, Pardo JFJ, de la Torre I, and Torcal RM. 2009. Sedimentological and archaeological fabrics in Palaeolithic levels of the South-Eastern Pyrenees: Cova Gran and Roca del Bous Sites (Lleida, Spain). *Journal of Archaeological Science* 36.11, 2566–2577. DOI: [10.1016/j.jas.2009.07.012](https://doi.org/10.1016/j.jas.2009.07.012).
- Benn D. 1994. Fabric shape and the interpretation of sedimentary fabric data. *Journal of Sedimentary Research* 64.4a, 910–915. DOI: [10.1306/D4267F05-2B26-11D7-8648000102C1865D](https://doi.org/10.1306/D4267F05-2B26-11D7-8648000102C1865D).
- Benvenuti M and Martini IP. 2002. Analysis of Terrestrial Hyperconcentrated Flows and their Deposit. In: *Flood and Megaflood Processes and Deposits*. Ed. by IP Martini, VR Baker, and G Garzón. Vol. 32. Special Publication of the International Association of Sedimentologists. Blackwell Publishing Ltd., 167–193. DOI: [10.1002/9781444304299.ch10](https://doi.org/10.1002/9781444304299.ch10).
- Berman M. 1986. Testing for spatial association between a point process and another stochastic process. *Applied Statistics* 35, 54–62.
- Bernatchez JA. 2010. Taphonomic implications of orientation of plotted finds from Pinnacle Point 13B (Mossel Bay, Western Cape Province, South Africa). *Journal of Human Evolution* 59.3–4, 274–288. DOI: [10.1016/j.jhevol.2010.07.005](https://doi.org/10.1016/j.jhevol.2010.07.005).
- Bertran P, Hetù B, Texier JP, and Steijn HV. 1997. Fabric characteristics of subaerial slope deposits. *Sedimentology* 44.1, 1–16. DOI: [10.1111/j.1365-3091.1997.tb00421.x](https://doi.org/10.1111/j.1365-3091.1997.tb00421.x).
- Bertran P and Texier JP. 1995. Fabric Analysis: Application to Paleolithic Sites. *Journal of Archaeological Science* 22.4, 521–535. DOI: [10.1006/jasc.1995.0050](https://doi.org/10.1006/jasc.1995.0050).
- Bevan A, Crema E, Li X, and Palmisano A. 2013. Intensities, Interactions, and Uncertainties: Some New Approaches to Archaeological Distributions. In: *Computational Approaches to Archaeological Spaces*. Ed. by A Bevan and M Lake. Walnut Creek: Left Coast Press, 27–52.
- Binford LR. 1981. Behavioral Archaeology and the "Pompeii Premise". *Journal of Anthropological Research* 37.3, 195–208.
- Boschian G and Saccà D. 2010. Ambiguities in human and elephant interactions? Stories of bones, sand and water from Castel di Guido (Italy). *Quaternary International* 214.1–2, 3–16. DOI: [10.1016/j.quaint.2009.10.016](https://doi.org/10.1016/j.quaint.2009.10.016).

- Brantingham PJ, Surovell TA, and Waguespack NM. 2007. Modeling post-depositional mixing of archaeological deposits. *Journal of Anthropological Archaeology* 26.4, 517–540. DOI: [10.1016/j.jaa.2007.08.003](https://doi.org/10.1016/j.jaa.2007.08.003).
- Carrer F. 2015. Interpreting Intra-site Spatial Patterns in Seasonal Contexts: an Ethnoarchaeological Case Study from the Western Alps. *Journal of Archaeological Method and Theory*, 1–25. DOI: [10.1007/s10816-015-9268-5](https://doi.org/10.1007/s10816-015-9268-5).
- Cobo-Sánchez L, Aramendi J, and Domínguez-Rodrigo M. 2014. Orientation patterns of wildebeest bones on the lake Masek floodplain (Serengeti, Tanzania) and their relevance to interpret anisotropy in the Olduvai lacustrine floodplain. *Quaternary International* 322–323.0, 277–284. DOI: [10.1016/j.quaint.2013.07.130](https://doi.org/10.1016/j.quaint.2013.07.130).
- De la Torre I and Benito-Calvo A. 2013. Application of GIS methods to retrieve orientation patterns from imagery; a case study from Beds I and II, Olduvai Gorge (Tanzania). *Journal of Archaeological Science* 40.5, 2446–2457. DOI: [10.1016/j.jas.2013.01.004](https://doi.org/10.1016/j.jas.2013.01.004).
- Dibble HL, Chase PG, McPherron SJP, and Tuffreau A. 1997. Testing the Reality of a "Living Floor" with Archaeological Data. *American Antiquity* 62.4, 629–651. DOI: [10.2307/281882](https://doi.org/10.2307/281882).
- Diggle PJ. 1985. A kernel method for smoothing point process data. *Applied Statistics (Journal of the Royal Statistical Society, Series C)* 34, 138–147.
- Domínguez-Rodrigo M, Bunn H, Mabulla A, Baquedano E, UribeArrea D, Pérez-González A, Gidna A, Yravedra J, Diez-Martin F, Egeland C, Barba R, Arriaza M, Organista E, and Ansón M. 2014a. On meat eating and human evolution: A taphonomic analysis of BK4b (Upper Bed II, Olduvai Gorge, Tanzania), and its bearing on hominin megafaunal consumption. *Quaternary International* 322–323, 129–152. DOI: [10.1016/j.quaint.2013.08.015](https://doi.org/10.1016/j.quaint.2013.08.015).
- Domínguez-Rodrigo M, Bunn H, Pickering T, Mabulla A, Musiba C, Baquedano E, Ashley G, Diez-Martin F, Santonja M, UribeArrea D, Barba R, Yravedra J, Barboni D, Arriaza C, and Gidna A. 2012. Autochthony and orientation patterns in Olduvai Bed I: a re-examination of the status of post-depositional biasing of archaeological assemblages from FLK North (FLKN). *Journal of Archaeological Science* 39.7, 2116–2127. DOI: [10.1016/j.jas.2012.02.027](https://doi.org/10.1016/j.jas.2012.02.027).
- Domínguez-Rodrigo M, Cobo-Sánchez L, Yravedra J, UribeArrea D, Arriaza CC, Organista E, and Baquedano E. 2017. Fluvial spatial taphonomy: a new method for the study of post-depositional processes. *Archaeological and Anthropological Sciences*. DOI: [10.1007/s12520-017-0497-2](https://doi.org/10.1007/s12520-017-0497-2).
- Domínguez-Rodrigo M, Diez-Martín F, Yravedra J, Barba R, Mabulla A, Baquedano E, UribeArrea D, Sánchez P, and Eren MI. 2014b. Study of the SHK Main Site faunal assemblage, Olduvai Gorge, Tanzania: Implications for Bed II taphonomy, paleoecology, and hominin utilization of megafauna. *Quaternary International* 322–323, 153–166. DOI: <http://dx.doi.org/10.1016/j.quaint.2013.09.025>.

- Domínguez-Rodrigo M and García-Pérez A. 2013. Testing the Accuracy of Different A-Axis Types for Measuring the Orientation of Bones in the Archaeological and Paleontological Record. *PLoS ONE* 8.7, e68955. DOI: [10.1371/journal.pone.0068955](https://doi.org/10.1371/journal.pone.0068955).
- Domínguez-Rodrigo M, UribeArrea D, Santonja M, Bunn HT, García-Pérez A, Pérez-González A, Panera J, Rubio-Jara S, Mabulla A, Baquedano E, Yravedra J, and Díez-Martín F. 2014c. Autochthonous anisotropy of archaeological materials by the action of water: experimental and archaeological reassessment of the orientation patterns at the Olduvai sites. *Journal of Archaeological Science* 41, 44–68. DOI: [10.1016/j.jas.2013.07.025](https://doi.org/10.1016/j.jas.2013.07.025).
- Eberth DA, Rogers RR, and Fiorillo AR. 2007. A Practical Approach to the Study of Bonebeds. In: *Bonebeds. Genesis, Analysis, and Paleobiological Significance*. Ed. by RR Rogers, DA Eberth, and AR Fiorillo. The University of Chicago Press, 265–332.
- Enloe JG. 2006. Geological processes and site structure: assessing integrity at a Late Paleolithic open-air site in northern France. *Geoarchaeology* 21.6, 523–540. DOI: [10.1002/gea.20122](https://doi.org/10.1002/gea.20122).
- Eren MI, Durant A, Neudorf C, Haslam M, Shipton C, Bora J, Korisettar R, and Petraglia M. 2010. Experimental examination of animal trampling effects on artifact movement in dry and water saturated substrates: a test case from South India. *Journal of Archaeological Science* 37.12, 3010–3021. DOI: [10.1016/j.jas.2010.06.024](https://doi.org/10.1016/j.jas.2010.06.024).
- Fernández-López RS. 1991. Taphonomic concepts for a theoretical biochronology. *Revista Española de Paleontología* 6, 37–49.
- Fiorillo AR. 1991. Taphonomy and depositional setting of Careless Creek Quarry (Judith River Formation), Wheatland County, Montana, U.S.A. *Palaeogeography, Palaeoclimatology, Palaeoecology* 81.3, 281–311. DOI: [10.1016/0031-0182\(91\)90151-g](https://doi.org/10.1016/0031-0182(91)90151-g).
- Frison GC and Todd LC. 1986. *The Colby Mammoth Site: Taphonomy and Archaeology of a Clovis Kill in Northern Wyoming*. Albuquerque: University of New Mexico Press.
- García-Moreno A, Smith GM, Kindler L, Pop E, Roebroeks W, Gaudzinski-Windheuser S, and Klinkenberg V. 2016. Evaluating the incidence of hydrological processes during site formation through orientation analysis. A case study of the middle Palaeolithic Lakeland site of Neumark-Nord 2 (Germany). *Journal of Archaeological Science: Reports* 6, 82–93. DOI: [10.1016/j.jasrep.2016.01.023](https://doi.org/10.1016/j.jasrep.2016.01.023).
- Giusti D and Arzarello M. 2016. The need for a taphonomic perspective in spatial analysis: Formation processes at the Early Pleistocene site of Pirro Nord (P13), Apricena, Italy. *Journal of Archaeological Science: Reports* 8, 235–249. DOI: [10.1016/j.jasrep.2016.06.014](https://doi.org/10.1016/j.jasrep.2016.06.014).
- Harvati K, Panagopoulou E, Tourloukis V, Thompson N, Karkanas P, Athanasiou A, Konidaris GE, Tsartsidou G, and Giusti D. 2016. New Middle Pleis-

- tocene elephant butchering site from Greece. In: *Paleoanthropology Society Meeting*. Atlanta, Georgia, A14–A15.
- Hivernel F and Hodder I. 1984. Analysis of artifact distribution at Ngenym (Kenya): depositional and postdepositional effects. In: *Intrasite Spatial Analysis in Archaeology*. Ed. by H Hietala and P Larson. Cambridge University Press. Chap. 7, 97–115.
- Hodder I and Orton C. 1976. *Spatial Analysis in Archaeology*. New Studies in Archaeology. Cambridge: Cambridge University Press.
- Hovers E, Ekshtain R, Greenbaum N, Malinsky-Buller A, Nir N, and Yeshurun R. 2014. Islands in a stream? Reconstructing site formation processes in the late Middle Paleolithic site of 'Ein Qashish, northern Israel. *Quaternary International* 331, 216–233. DOI: [10.1016/j.quaint.2014.01.028](https://doi.org/10.1016/j.quaint.2014.01.028).
- Isaac GL. 1967. Towards the interpretation of occupation debris: Some experiments and observations. *Kroeber Anthropological Society Papers* 37.37, 31–57.
- Jammalamadaka S, Sengupta A, and Sengupta A. 2001. *Topics in Circular Statistics*. Series on multivariate analysis. World Scientific.
- Karkanis P, Tourloukis V, Thompson N, Giusti D, Panagopoulou E, and Harvati K. In press. Sedimentology and micromorphology of the Lower Palaeolithic lakeshore site Marathousa 1, Megalopolis basin, Greece. *Quaternary International* in press.
- Klusens SL. 1990. *Orientation and density analysis of stone artefacts at Combe-Capelle Bas, Périgord, France*. MA thesis. Philadelphia: University of Pennsylvania.
- Konidaris GE, Athanassiou A, Tourloukis V, Thompson N, Giusti D, Panagopoulou E, and Harvati K. In press. The skeleton of a straight-tusked elephant (*Palaeoloxodon antiquus*) and other large mammals from the Middle Pleistocene locality Marathousa 1 (Megalopolis Basin, Greece): preliminary results. *Quaternary International*. DOI: doi.org/10.1016/j.quaint.2017.12.001.
- Krumbein WC. 1941. Measurement and geological significance of shape and roundness of sedimentary particles. *Journal of Sedimentary Research* 11.2, 64–72. DOI: [10.1306/D42690F3-2B26-11D7-8648000102C1865D](https://doi.org/10.1306/D42690F3-2B26-11D7-8648000102C1865D).
- Kuiper. 1960. Tests concerning random points on a circle. *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen, Series A* 63, 38–47.
- Lenoble A and Bertran P. 2004. Fabric of Palaeolithic levels: methods and implications for site formation processes. *Journal of Archaeological Science* 31.4, 457–469. DOI: [10.1016/j.jas.2003.09.013](https://doi.org/10.1016/j.jas.2003.09.013).
- Lenoble A, Bertran P, and Lacrampe F. 2008. Solifluction-induced modifications of archaeological levels: simulation based on experimental data from a modern periglacial slope and application to French Palaeolithic sites. *Journal of Archaeological Science* 35.1, 99–110. DOI: [10.1016/j.jas.2007.02.011](https://doi.org/10.1016/j.jas.2007.02.011).


- Lindsay JF. 1968. The development of clast fabric in mudflows. *Journal of Sedimentary Research* 38.4, 1242–1253. DOI: [10.1306/74D71B40-2B21-11D7-8648000102C1865D](https://doi.org/10.1306/74D71B40-2B21-11D7-8648000102C1865D).
- Macdonald DIM and Jefferson TH. 1985. Orientation studies of waterlogged wood; a paleocurrent indicator? *Journal of Sedimentary Research* 55.2, 235–239. DOI: [10.1306/212F867F-2B24-11D7-8648000102C1865D](https://doi.org/10.1306/212F867F-2B24-11D7-8648000102C1865D).
- Malinsky-Buller A, Hovers E, and Marder O. 2011. Making time: ‘Living floors’, ‘palimpsests’ and site formation processes – A perspective from the open-air Lower Paleolithic site of Revadim Quarry, Israel. *Journal of Anthropological Archaeology* 30.2, 89–101. DOI: [10.1016/j.jaa.2010.11.002](https://doi.org/10.1016/j.jaa.2010.11.002).
- Marwick B. 2017. Computational Reproducibility in Archaeological Research: Basic Principles and a Case Study of Their Implementation. *Journal of Archaeological Method and Theory* 24.2, 424–450. DOI: [10.1007/s10816-015-9272-9](https://doi.org/10.1007/s10816-015-9272-9).
- Marwick B, d’Alpoim Guedes J, Barton CM, Bates LA, Baxter M, Beavan A, Bollwerk EA, Bocinsky RK, Brughams T, Carter AK, Conrad C, Contreras DA, Costa S, Crema ER, Daggett A, Davies B, Drake BL, Dye TS, France P, Fullager R, Giusti D, Graham S, Harris MD, Hawks J, Heath S, Huffer D, Kansa EC, Kansa SW, Madsen ME, Melcher J, Negre J, Neiman FD, Opitz R, Orton DC, Przystupa P, Raviele M, Riel-Salvatore J, Riris P, Romanowska I, Smith J, Strupler N, Ullah II, Vlack HGV, VanValkenberg N, Watrall EC, Webster C, Wells J, Winters J, and Wren CD. 2017. Open Science in Archaeology. *SAA Archaeological Record* 17.4, 8–14.
- McPherron SJP. 2005. Artifact orientations and site formation processes from total station proveniences. *Journal of Archaeological Science* 32.7, 1003–1014. DOI: [10.1016/j.jas.2005.01.015](https://doi.org/10.1016/j.jas.2005.01.015).
- McPherron SJP, Dibble HL, and Goldberg P. 2005. *Z. Geoarchaeology* 20.3, 243–262. DOI: [10.1002/gea.20048](https://doi.org/10.1002/gea.20048).
- Morton AGT. 2004. *Archaeological Site Formation: Understanding Lake Margin Contexts*. Vol. 1211. International Series. Oxford: British Archaeological Reports.
- Nickel B, Riegel W, Schonherr T, and Velitzelos E. 1996. Environments of coal formation in the Pleistocene lignite at Megalopolis, Peloponnesus (Greece) - reconstruction from palynological and petrological investigations. *N. Jb. Geol. Palaont. A*. 200, 201–220.
- Ohser J. 1983. On estimators for the reduced second moment measure of point processes. *Mathematische Operationsforschung und Statistik, series Statistics* 14, 63–71.
- Organista E, Domínguez-Rodrigo M, Yravedra J, Uribelarrea D, Arriaza MC, Ortega MC, Mabulla A, Gidna A, and Baquedano E. 2017. Biotic and abiotic processes affecting the formation of BK Level 4c (Bed II, Olduvai Gorge) and their bearing on hominin behavior at the site. *Palaeogeography, Palaeoclimatology, Palaeoecology* (in press). DOI: [10.1016/j.palaeo.2017.03.001](https://doi.org/10.1016/j.palaeo.2017.03.001).

- Orton CR. 1982. Stochastic process and archaeological mechanism in spatial analysis. *Journal of Archaeological Science* 9.1, 1–23. DOI: [10.1016/0305-4403\(82\)90002-4](https://doi.org/10.1016/0305-4403(82)90002-4).
- Panagopoulou E, Tourloukis V, Thompson N, Athanassiou A, Tsartsidou G, Konidaris G, Giusti D, Karkanis P, and Harvati K. 2015. Marathousa 1: a new Middle Pleistocene archaeological site from Greece. *Antiquity* Project Gallery 89.343. DOI: [10.15496/publikation-5878](https://doi.org/10.15496/publikation-5878).
- Petraglia MD and Nash DT. 1987. The impact of fluvial processes on experimental sites. In: *Natural formation processes and the archaeological record*. Ed. by DT Nash and MD Petraglia. Vol. 352. International Series. Oxford: British Archaeological Reports, 108–130.
- Petraglia MD and Potts R. 1994. Water Flow and the Formation of Early Pleistocene Artifact Sites in Olduvai Gorge, Tanzania. *Journal of Anthropological Archaeology* 13.3, 228–254. DOI: [10.1006/jaar.1994.1014](https://doi.org/10.1006/jaar.1994.1014).
- Pewsey A, Neuhauser M, and Ruxton GD. 2013. *Circular Statistics in R*. Oxford University Press. 208 pp.
- Pierson TC. 2005. *Distinguishing between debris flows and floods from field evidence in small watersheds*. USGS Numbered Series. U.S. Geological Survey.
- R Core Team. 2017. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria.
- Ripley BD. 1976. The second-order analysis of stationary point processes. *Journal of Applied Probability* 13.2, 255–266. DOI: [10.2307/3212829](https://doi.org/10.2307/3212829).
- Ripley BD. 1977. Modelling spatial patterns. *Journal of the Royal Statistical Society, series B* 39, 172–212.
- Ripley BD. 1981. *Spatial Statistics*. New York: John Wiley and Sons.
- Ripley BD. 1988. *Statistical inference for spatial processes*. Cambridge University Press. DOI: [10.1017/CB09780511624131](https://doi.org/10.1017/CB09780511624131).
- Sánchez-Romero L, Benito-Calvo A, Pérez-González A, and Santonja M. 2016. Assessment of Accumulation Processes at the Middle Pleistocene Site of Ambrona (Soria, Spain). Density and Orientation Patterns in Spatial Datasets Derived from Excavations Conducted from the 1960s to the Present. *PLOS ONE* 11.12, 1–27. DOI: [10.1371/journal.pone.0167595](https://doi.org/10.1371/journal.pone.0167595).
- Schick KD. 1984. *Processes of Paleolithic site formation: an experimental study*. PhD thesis. US: University of California, Berkeley.
- Schick KD. 1986. *Stone Age sites in the making: experiments in the formation and transformation of archaeological occurrences*. Vol. 319. International Series. Oxford: British Archaeological Reports.
- Schick KD. 1987. Modeling the formation of Early Stone Age artifact concentrations. *Journal of Human Evolution* 16, 789–807.
- Schiffer MB. 1972. Archaeological Context and Systemic Context. *American Antiquity* 37.2, 156–165.
- Schiffer MB. 1983. Toward the identification of formation processes. *American Antiquity* 48.4, 675–706.

- Schiffer MB. 1987. *Formation processes of the archaeological record*. Albuquerque: University of New Mexico Press.
- Shackley ML. 1978. The behaviour of artefacts as sedimentary particles in a fluvial environment. *Archaeometry* 20.1, 55–61. DOI: [10.1111/j.1475-4754.1978.tb00212.x](https://doi.org/10.1111/j.1475-4754.1978.tb00212.x).
- Texier JP. 2000. A propos des processus de formation des sites préhistoriques / About prehistoric site formation processes. fr. *Paléo* 12.1, 379–386. DOI: [10.3406/pal.2000.1610](https://doi.org/10.3406/pal.2000.1610).
- Toots H. 1965. Orientation and distribution of fossils as environmental indicators. In: *Nineteenth Field Conference of the Wyoming Geological Association*, 219–292.
- Tourloukis V, Thompson N, Panagopoulou E, Giusti D, Konidaris GE, Karkanis P, and Harvati K. In press. Lithic artifacts and bone tools from the Lower Palaeolithic site of Marathousa 1, Megalopolis, Greece: preliminary results. *Quaternary International*.
- Van Vugt N, de Bruijn H, van Kolfschoten M, and Langereis CG. 2000. Magneto- and cyclostratigraphy and mammal-fauna's of the Pleistocene lacustrine Megalopolis Basin, Peloponnesos, Greece. *Geologica Ultrajectina* 189, 69–92.
- Vaquero M, Chacón MG, García-Antón MD, de Soler BG, Martínez K, and Cuartero F. 2012. Time and space in the formation of lithic assemblages: The example of Abric Romaní Level J. *Quaternary International* 247.0, 162–181. DOI: [10.1016/j.quaint.2010.12.015](https://doi.org/10.1016/j.quaint.2010.12.015).
- Villa P. 2004. Taphonomy and stratigraphy in European prehistory. *Before Farming* 2004.1, 1–20. DOI: [10.3828/bfarm.2004.1.1](https://doi.org/10.3828/bfarm.2004.1.1).
- Voorhies M. 1969. Taphonomy and population dynamics of an early Pliocene vertebrate fauna, Knox County, Nebraska. *Contributions to Geology, University of Wyoming Special Paper* 1, 1–69. DOI: [10.2113/gsrocky.8.special_paper_1.1](https://doi.org/10.2113/gsrocky.8.special_paper_1.1).
- Walter MJ and Trauth MH. 2013. A MATLAB based orientation analysis of Acheulean handaxe accumulations in Olorgesailie and Kariandusi, Kenya Rift. *Journal of Human Evolution* 64.6, 569–581. DOI: [10.1016/j.jhevol.2013.02.011](https://doi.org/10.1016/j.jhevol.2013.02.011).
- Watson. 1961. Goodness-Of-Fit Tests on a Circle. *Biometrika* 48 (1/2), 109–114.
- Wood RW and Johnson DL. 1978. A survey of disturbance processes in archaeological site formation. In: *Advances in archaeological method and theory*. Ed. by MB Schiffer. Vol. 1. New York: Academic Press. Chap. 9, 315–381.
- Woodcock NH and Naylor M. 1983. Randomness testing in three-dimensional orientation data. *Journal of Structural Geology* 5.5, 539–548. DOI: [10.1016/0191-8141\(83\)90058-5](https://doi.org/10.1016/0191-8141(83)90058-5).

Recursive anisotropy: A spatial taphonomic study of the Late Villafranchian vertebrate assemblage of Tsiotra Vryssi, Mygdonia Basin, Greece

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Abstract

Spatial taphonomy complements the traditional taphonomic approach. By applying advanced spatial statistical methods, it aims to investigate the multiscale and multilevel spatial properties of biotratynomic and diagenetic processes. In this study, we elaborate on a specific aspect - spatial anisotropy - of taphonomic processes. Circular statistics are used for the fabric analysis of elongated elements; geostatistics (directional variograms), wavelet and point pattern analyses are applied for detecting anisotropy at the assemblage level. The main aim is to unravel the taphonomic history of the Late Villafranchian vertebrate assemblage Tsiotra Vryssi (Mygdonia Basin, Macedonia, Greece), with respect to the specific depositional environment, the number of depositional events (single or multiple) and the degree of transportation of the fossil record (autochthonous vs. allochthonous assemblage). The results of our multiscale and multilevel analysis of anisotropy, integrated with preliminary remarks about the differential preservation of skeletal elements and with sedimentological observations, suggest multiple dispersion events and recurrent spatial re-arrangement of a lag, (peri)autochthonous assemblage, consistent with the cyclical lateral switching of a braided fluvial system. Spatial taphonomy enhances our understanding of taphonomic modification processes, in turn with consequences for palaeoecological reconstructions and biochronological estimates. Furthermore, this study offers an important contribution to the building of a spatial taphonomic referential framework for the interpretation of other fossil vertebrate assemblages, including archaeo-palaeontological ones.

C.1 Introduction

Since the first definition of taphonomy as “the study of the transition (in all its details) of animal remains from the biosphere into the lithosphere” (Efremov, 1940), the spatial properties of taphonomic processes received special attention. Concerned about thanatocoenosis, Efremov (1940) indicated as chief part of a taphonomic study, among others, the analysis of “the spatial distribution of animal remains and their distribution relatively to the planes of stratification”. More recent research on early hominid evolution (Behrensmeyer, 1975a; Boaz and Behrensmeyer, 1976; Hill, 1976) extended the original definition of taphonomy beyond its role as a “new branch of paleontology” (Efremov, 1940) to include also formation and modification processes of the archaeological record. Despite some misrepresentations in the archaeological adaptation of the original concept (e.g., the ontological difference between natural and cultural formation processes; Domínguez-Rodrigo et al., 2011; Lyman, 2010), in the last decades taphonomy has widened its theoretical and methodological framework towards an integrative and multidisciplinary investigation that aims to reconstruct the past in all its details, incorporating any signal of the processes, both natural and cultural, that modified the original properties of the organic and inorganic components (Domínguez-Rodrigo et al., 2011).

If taphonomy evolved towards an evolutionary and systemic approach that embraces multiple taphonomic levels of organisation (i.e., basic taphonomic elements, taphonomic groups [taphons], taphonomic populations and taphoclades; Fernández-López, 2006), likewise, the study of the spatial properties of taphonomic processes extended from the analysis of the spatial distribution of animal remains in relation to the stratigraphic setting, towards a multilevel quantitative investigation of the spatial behaviour of different taphonomic entities (*sensu* Fernández-López, 2006). Therefore, spatial taphonomy, formally defined by Domínguez-Rodrigo et al. (2017), encompasses the spatial properties of basic entities (i.e., taphonomic elements, constituting the fossil record), as well as higher level en-

titles (e.g., taphonomic groups or populations). Indeed, at multiple scales and levels of organisation, the spatial patterns observed in any palaeontological or archaeological assemblage retain valuable information about taphonomic accumulation and re-elaboration processes (*sensu* [Fernández-López et al., 2002](#)). Spatial taphonomic data, appropriately recorded, can be quantitatively analysed within a statistical framework in order to reliably draw inferences about taphonomic processes, in turn with consequences for palaeoecological reconstructions ([Fernández-Jalvo et al., 2011](#)), biochronological estimates and the interpretation of past human behaviours.

In this study, we elaborate on a specific aspect - anisotropy - of the spatial properties of taphonomic entities, with implications for the interpretation of taphonomic processes. Anisotropy, as opposed to isotropy, is generally defined as the property of a process of being directionally dependent. Spatial anisotropic patterns can be seen as products of physical anisotropic processes, such as fluvial or eolian processes, which modified at multiple scales and levels of organisation the original spatial properties of taphonomic entities.

At the level of basic taphonomic elements, anisotropy, expressed as preferential orientation of fossils or artefacts, is among the key variables used for interpreting site formation and modification processes. Especially in terrestrial alluvial environments, anisotropy is one of the proxies traditionally used to discriminate autochthonous vs. allochthonous assemblages ([Petraglia and Nash, 1987](#); [Petraglia and Potts, 1994](#); [Schick, 1987](#); [Toots, 1965](#); [Voorhies, 1969](#), among others). The orientation of elongated elements, prone to preferentially align along the flow direction, would eventually indicate the action of water-flows and suggest substantial transport prior to burial. Nevertheless, anisotropy has been equally documented in autochthonous assemblages subjected to low-energy water-flows ([Cobo-Sánchez et al., 2014](#); [Domínguez-Rodrigo et al., 2012, 2014d](#)); hence, it can be a necessary but not sufficient condition to differentiate allochthony from autochthony ([Lenoble and Bertran, 2004](#)). Moreover, besides water-flow processes, anisotropy has been as well observed in association with a wide range of other biostratinomic

processes, such as slope processes (Bertran and Texier, 1995) and trampling (Benito-Calvo et al., 2011).

Although the anisotropy of basic taphonomic elements have been long studied, the anisotropy of higher level taphonomic entities received by far less attention (see Markofsky and Bevan, 2012 for a directional analysis of archaeological surface distributions). Here we address this research gap and conduct a spatial taphonomic study of anisotropy both at the level of fossil specimens and at the assemblage level. The present study uses a comprehensive set of spatial statistics (fabric analysis, geostatistics, wavelet analysis, point pattern analysis) in order to identify directional trends that may not be readily apparent. Indeed, beyond the traditional approach of eye-spotting spatial patterns, spatial statistics allow one to adopt a more formal, quantitative approach.

Therefore, integrating the results of our multiscale and multi-level analysis of anisotropy with preliminary remarks about differential taphonomic preservation, we aim to disentangle the taphonomic history of the fossiliferous locality Tsiotra Vryssi (Mygdonia Basin, Macedonia, Greece; Konidaris et al., 2015).

Finally, this study offers an important contribution to the building of a spatial taphonomic referential framework for the interpretation of other fossil vertebrate assemblages, including archaeo-palaeontological ones (Domínguez-Rodrigo et al., 2017).

C.2 The palaeontological site of Tsiotra Vryssi (TSR)

The locality Tsiotra Vryssi (TSR) is located in the Mygdonia Basin (Macedonia, Greece), about 90 km southeast of Thessaloniki (Fig. C.1). TSR was discovered in 2014 by a joint research team from the Aristotle University of Thessaloniki and the Eberhard Karls University of Tübingen during systematic field surveys in the basin. After the first collection of fossils from the exposed natural section and the test excavation carried out in 2014, systematic excavation of the site

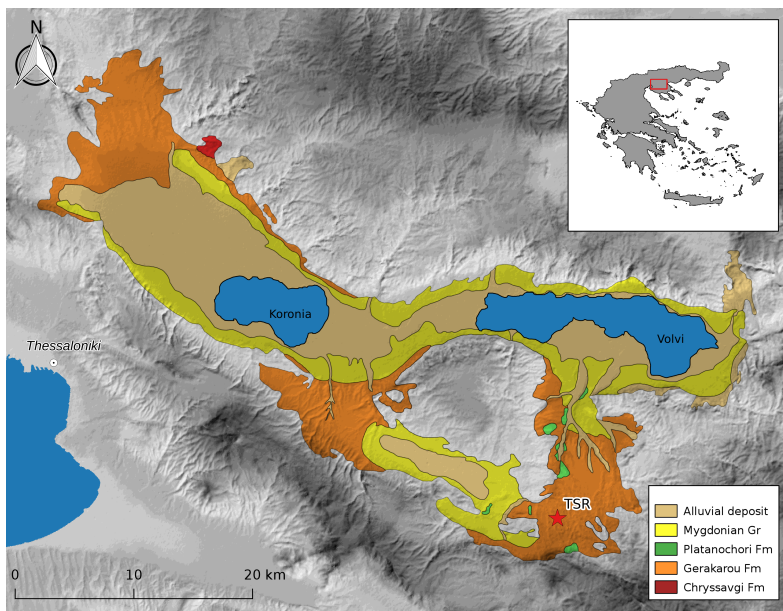


Figure C.1: Geological setting of the Mygdonia Basin (Macedonia, Greece) showing the Quaternary lithostratigraphic units and the location of Tsiotra Vryssi (TSR), modified after [Koufos et al. \(1995\)](#)

took place in 2015 and is still ongoing (Fig. C.2a).

To date, the excavation covers an about 10 m-thick stratigraphic interval from the upper Gerakarou Formation (Fig. C.1), a suite of continental clastic deposits of mainly fluvial origin and interlayered palaeosols ([Konidaris et al., 2015](#); [Koufos et al., 1995](#)). The TSR fauna occurs mainly within a c. 1 m-thick interval of silts (uppermost part of Geo2, see Fig C.3) and comprises several mammalian taxa, as well as some birds and reptiles, whose preliminary biochronological correlation is consistent with a late Villafranchian (Early Pleistocene) age ([Konidaris et al., 2016, 2015](#)).



Figure C.2: Panoramic view (2017) of the excavation area at Tsiotra Vryssi (a). Picture of Geo 2a, North section (b). Details of a cluster of bones (c, f, g) and articulated specimens (d, e).

The sedimentary character of the excavated deposits allows identifying two main depositional units (Geo 1 and Geo 2, from younger to older; Fig. C.3). The fossiliferous unit Geo 2 begins with about 1.5 m (Geo 2b in Fig. C.3) of cross-stratified gravelly sands organised into dm-thick beds with a range of planar to trough-cross laminations. Above a sharp contact, a few tens of cm of well-sorted, structureless fine sands follow, which rapidly grade upward into the deposit forming the matrix of the main TSR fossil finding (Geo 2a in Fig. C.3). This is represented by about 1 m of poorly sorted silts (moderately rich in mica grains), which are locally intercalated by cm-thick lenses of medium to coarse sands and become relatively more clayey in their topmost 30 cm. Apart for alignment of isolated granule-grade clasts and some crude parallel lamination in coarse lenses, the deposits appear overall structureless. Noteworthy, Geo 2b can be followed laterally for at least 150m in a E-W direction, suggesting an extensive setting of deposition. Geo 1 begins with an up to 2 m-thick bed set of cross-stratified gravelly sands and gravels, similar to those observed in Geo 2b (Geo 1b in Fig. C.3). It down-cuts deeply into the underlying Geo 2a and shallows toward the W. In the same direction component beds of Geo 1b tend to be thinner, finer grained and less extensive laterally, suggesting less energetic hydrodynamic conditions. Though poorly exposed, the younger Geo 1a is represented by a monotonous 3 m-thick section of poorly silty sands devoid of coarse intercalations, which rapidly grades into clayey silts of a distinctive pale brown colour (Fig. C.3).

Overall, the stratigraphic position of TSR in the fluvio-terrestrial Gerakarou Formation (Koufos et al., 1995) and the specific sedimentary sequence of the site indicate that TSR was formed in a fluvial environment. A preliminary visual inspection of the vertical and horizontal distribution of the fossil finds (Fig. C.4) suggests a densely preserved association of fossils (about 24 elements/m²), homogeneously distributed within the study area. Apparent anisotropy is also suggested at assemblage level.

In such a fluvial depositional context, questions arise with respect to the specific character of the TSR fossil assemblage, the

The palaeontological site of Tsiotra Vryssi (TSR)

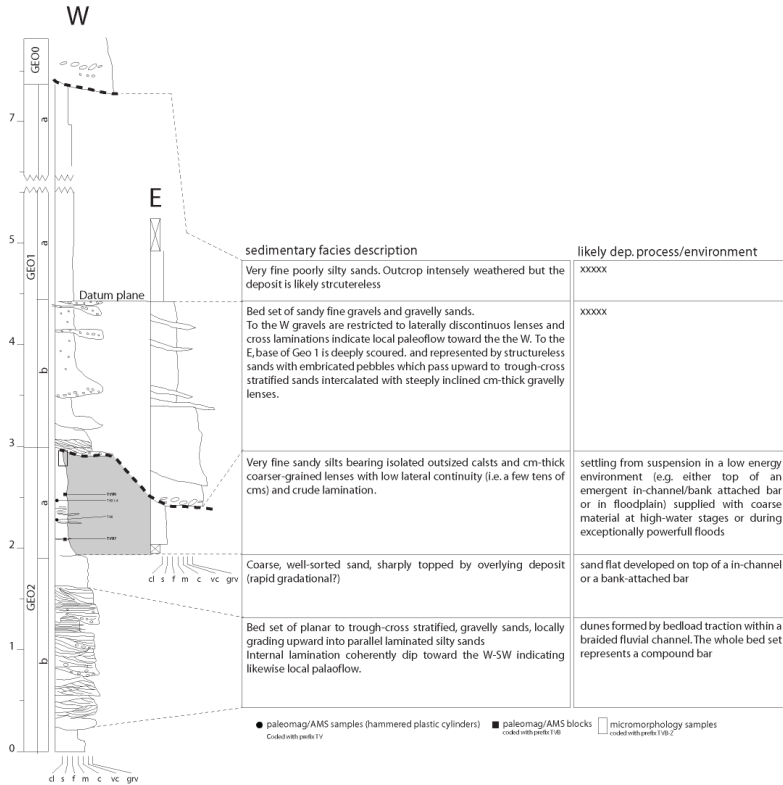


Figure C.3: Stratigraphic log of the Tsiotra Vryssi locality.

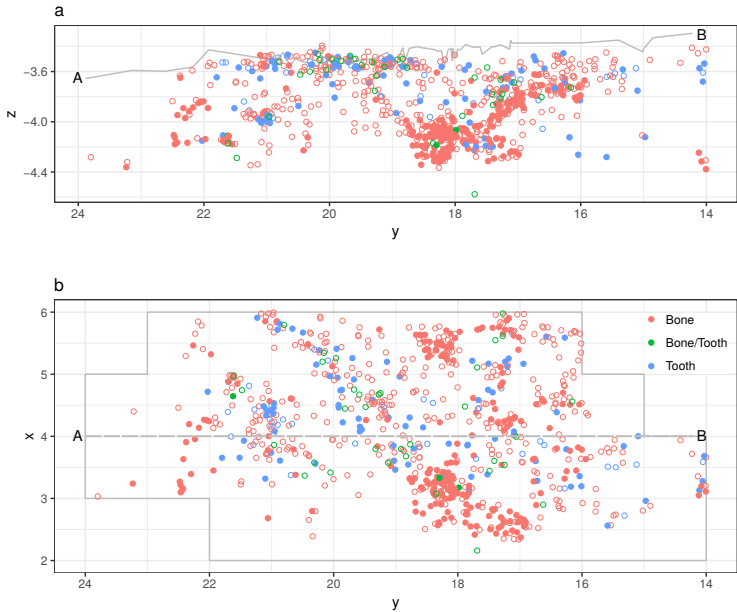


Figure C.4: Vertical (a) and horizontal (b) distribution of the sampled fossil specimens from Tsiotra Vryssi (excavations 2015-2017). Filled circles mark complete specimens, hollow circles mark fragmented ones. Grey continuous line in a) marks the Geo 1/2 erosional contact, as recorded at the AB transect marked in b).

number of depositional events (single or multiple) and the degree of transportation of the fossil record (autochthonous vs. allochthonous assemblage).

C.3 Material and methods

C.3.1 Data collection and subsetting

Since 2015 a grid of 1 m² units was set up and a total station was used in order to record the spatial provenience of collected (i.e., diagnostic bones and teeth, and carnivore modified bones) and not collected remains (i.e., not diagnostic bone fragments with length ≥ 50 mm; Fig. C.2a). Not diagnostic, or not carnivore modified bone fragments with length < 50 mm were not recorded. This dimensional threshold was chosen because small bone fragments show more random orientations than longer specimens (Domínguez-Rodrigo et al., 2014d). Orientation (plunge and bearing) of clearly elongated specimens (i.e., specimens with length at least twice the width) was measured with a 1 degree accuracy, using a compass and inclinometer (Eberth et al., 2007; Fiorillo, 1991; Voorhies, 1969, among others). Strike and dip measurements were taken along the symmetrical longitudinal a-axis (SLA) of the specimens (Domínguez-Rodrigo and García-Pérez, 2013), using the lowest endpoint of the a-axis as an indicator of the vector direction. The dimensions (length and maximum width) of the recorded finds were measured on-site with a millimetric measuring tape.

The present spatial taphonomic study analysed a sample of stratified specimens ($n = 797$) from the fossiliferous layer Geo 2a, whose spatial coordinates were recorded with the total station. The area of analysis concerns the 34 m² excavated from 2015 until 2017. The sample included mostly macromammal remains ($n = 707$, 89%), undetermined isolated bone fragments ($n = 70$), birds ($n = 12$) and turtle ($n = 8$) remains. A sub-sample ($n = 249$) was further subset for the fabric analysis described below. Stratified specimens from Geo 2a collected during the test excavation of 2014, or subsequently

found in plaster-jackets with concentration of bones during the lab preparation were excluded due to the lack of precise spatial coordinates. The very small sample ($n = 4$) of micromammal remains was also not included in the spatial and faunal analyses. Faunal analysis was conducted on a sub-sample of complete or fragmented, isolated or articulated macromammal remains ($n = 707$). Further subsetting strategies are described below.

C.3.2 Spatial anisotropy

Different methods have been developed in neighbouring disciplines to detect spatial anisotropy. Here we use circular statistics for the fabric analysis of taphonomic elements; geostatistics (directional variograms), wavelet analysis and point pattern analysis for detecting anisotropy at the assemblage level. AMS for the fabric analysis of magnetic minerals.

Fabric analysis

The first controlled experiments and analyses of the orientation and dispersal of disarticulated mammal bones as indicators of the depositional context, carried out by [Toots \(1965\)](#) and [Voorhies \(1969\)](#), led to an increasing number of studies of the effects of water flows on natural and anthropogenic faunal assemblages ([Aramendi et al., 2017](#); [Benito-Calvo and de la Torre, 2011](#); [Cobo-Sánchez et al., 2014](#); [de la Torre and Benito-Calvo, 2013](#); [Domínguez-Rodrigo et al., 2014b, 2012, 2014d](#); [Fiorillo, 1991](#); [Nash and Petraglia, 1987](#); [Organista et al., 2017](#); [Petraglia and Nash, 1987](#); [Petraglia and Potts, 1994](#); [Schick, 1987](#), among others).

Whereas most of these studies have been conducted on disarticulated elongated bones or bone fragments - which were observed to preferentially align their a-axes along the direction of the flow - relatively few have investigated the hydraulic behaviour of articulated skeletal elements. Flume experiments conducted by [Coard and Denell \(1995\)](#) and [Coard \(1999\)](#) demonstrated that articulated bones

display a greater transport potential than disarticulated ones when the articulated elements align themselves. However, they also noted that skeletal parts with a higher number of articulated elements, such as complete limbs, may show weak preferential orientation when assuming disorganised spatial configuration, i.e., when not aligned. Therefore, articulated bones, although relatively common in TSR (Fig. C.2c,d,e), were not included in the fabric analysis.

In this study we applied circular statistics to a subset of 249 non-articulated, elongated bone specimens, having length ≥ 20 mm (Domínguez-Rodrigo et al., 2014d). No distinction of skeletal elements was made, due to the high percentage (91%, $n = 227$) of fragmented remains in the analysed sample - mostly appendicular ($n = 122$), undetermined ($n = 93$), axial and cranial ($n = 12$) fragments - and due to the low percentage (9%, $n = 22$) of complete bones - 17 limb bones, 4 scapulae and a rib.

We applied Rayleigh and omnibus tests of uniformity, such as Kuiper, Watson and Rao (Jammalamadaka et al., 2001), to test the isotropic orientation of the fossil specimens. Whereas the Rayleigh test assumes a unimodal distribution and assess the significance of the sample mean resultant length (\bar{R}), the omnibus tests detect multimodal departures from the null hypothesis of circular isotropy.

Rose and equal area Schmidt diagrams were used as exploratory data analysis tools to visualise the sample distribution. Compared to the widely used rose diagrams, which plot the circular distribution of the bearing values, the Schmidt equal area diagram informs about the distribution of the three-dimensional orientation (plunge and bearing) of the elements (Fiorillo, 1988). Points plotting at the margin of the globe indicate planar fabric, whereas points towards the centre have higher dip angles.

The Woodcock diagram (Woodcock and Naylor, 1983), based on three ordered normalised eigenvalues (S_1 , S_2 , S_3), was used to discriminate between linear (cluster), planar (girdle) and isotropic distributions. In the Woodcock diagram, the C parameter ($C = \ln(S_1/S_3)$) expresses the strength of the preferential orientation, and its significance is evaluated against critical values from simulated

random samples of different sizes. A perfect isotropic distribution would plot at the origin, with equal eigenvalues ($S_1 = S_2 = S_3 = 1/3$). On the other hand, the K parameter ($K = \frac{\ln(S_1/S_2)}{\ln(S_2/S_3)}$) expresses the shape of the distribution, and it ranges from zero (uni-axial girdles) to infinite (uni-axial clusters).

In a fluvio-lacustrine environment a cluster distribution would suggest a strong preferential orientation of the sample, such as in the case of channelised water flows (Petraglia and Potts, 1994), whereas a girdle distribution a weaker preferential orientation, spread over a wider range of directions. Overland flows have been interpreted to produce such a pattern (Organista et al., 2017). On the other hand, a isotropic distribution would suggest that post-depositional disturbance by water flows was not strong enough to preferentially orient the assemblage (Domínguez-Rodrigo et al., 2014b). However, a variety of taphonomic processes can produce similar patterns. Fabric analysis, although very informative, has low power by itself. In order to overcome the intrinsic limitations of the fabric analysis, a multivariate approach to site formation and modification processes should be employed (Lenoble and Bertran, 2004).

Geostatistics

Geostatistics refer to a body of concepts and methods typically applied to a limited sample of observations of a continuous variable, such as environmental variables. Geostatistics thus aim to estimate the variance and spatial correlation of known observations and predict, using interpolation methods such as Kriging, unknown values of the variable at non-observed locations. Moreover, by using directional variograms, geostatistics enable the identification of spatial anisotropy (i.e., directional patterns). Since the vast majority of spatial statistics assume stationarity and isotropy, it is well understood that a misinterpretation of spatial anisotropy may result in inaccurate spatial modelling and prediction.

Although well known in ecological studies, only a relatively small number of studies have explicitly applied geostatistics to the study

of site formation and modification processes, using directional variograms to investigate the specimens size spatial distributions (Domínguez-Rodrigo et al., 2014b,c), or to specifically detect spatial anisotropy of archaeological assemblages (Bevan and Conolly, 2009; Markofsky and Bevan, 2012).

In order to investigate spatial anisotropy in the distribution of the TSR fossil assemblage and identify spatial continuity in some directions more than others, we used directional variograms and variogram maps. The studied sample includes 797 recorded specimens (isolated or articulated, complete or fragmented bones and teeth) unearthed from Geo 2a and included in the 34 m² window of analysis (Fig. C.4). The same sample was used for the wavelet and point pattern analyses.

Specifically, plotting the semi-variance between the variable values of sampled point pairs as a function of distance (spatial lag) between these pairs, directional variograms are used to model the spatial variation at multiple scales and different directions. Three parameters (*nugget*, *range* and *sill*) are estimated from an experimental variogram to fit a theoretical omnidirectional variogram. The *nugget* is used to account for spatial variability at very short distances. The *range* indicates the maximal distance up to which there is spatial correlation. At longer distances the semi-variance levels off forming the *sill*, indicating independence between pairs of sample separated by that minimum distance (Dale and Fortin, 2014; Lloyd and Atkinson, 2004). Thus, we plotted the experimental directional variogram against the theoretical omnidirectional variogram. A directional semi-variance lower than the fitted omnidirectional variogram indicates continuity in the analysed direction. We selected for our analysis the N-S (0°), E-W (90°), NE-SW (45°) and NW-SE (135°) geographical directions. In addition to the directional variograms, variogram maps are visual representations of the semi-variance: the anisotropy is represented by an ellipse, its axes being proportional to the variation expected in each direction. Thus, the direction of maximum anisotropy corresponds with the major axis of the ellipse (Legendre and Legendre, 2012).

Wavelet analysis

As a second method for the detection of spatial anisotropy at the assemblage level we used the wavelet analysis. Wavelet analysis, commonly applied in mathematics for signal processing, has relatively wide application in palaeoclimatology and palaeoecology, but is seldom used in site formation processes studies (Markofsky and Bevan, 2012).

Differently from the geostatistic approach to the analysis of spatial anisotropy, which is based on a transformation of point values into a continuous surface, the wavelet approach does not apply any transformation, but identifies the elements (points) of a pattern merely by their location. In this regard, the wavelet analysis does not suffer from the arbitrary choice of a surface smooth parameter, as in the case of geostatistics.

For each specific point of the pattern, a wheel of 360 sectors of 1° is used to measure the average variance in the angles between point pairs (Rosenberg, 2004). The significance of the wavelet analysis is evaluated against 199 Monte Carlo simulations of the observed pattern under the null hypothesis of randomness. The variance is plotted as a function of angle measurements. Direction is measured anti-clockwise from East (i.e., 0° is East, 90° is North). When the distribution of the observed values (dashed line) wanders above the simulated values (continuous line), the pattern shows significant anisotropy in that direction.

Point pattern analysis

A spatial point pattern is the outcome of a random spatial point process. Any natural phenomenon which results in a spatial point pattern, such as a distribution pattern of fossils, can be viewed as a point process (Baddeley et al., 2015). Therefore, the analysis of a spatial point pattern ultimately addresses the nature of the point process that generated the pattern. Point pattern analysis has been specifically applied to the study of site formation and modification pro-

cesses by a relatively small number of studies (Domínguez-Rodrigo et al., 2014b, 2017, 2014c; Giusti and Arzarello, 2016; Giusti et al., In press; Lenoble et al., 2008; Organista et al., 2017). However, this analytical method has never been used to detect anisotropy in the distribution patterns of archaeological or palaeontological assemblages. Nevertheless, detecting anisotropy is an essential part of any spatial analysis. Standard statistical tools in spatial point pattern analysis rely on crucial assumptions about the point process itself: a point process is assumed to be stationary and/or isotropic if its statistical properties are not affected by shifting and/or rotating the point process.

In order to further assess the presence of anisotropy in the distribution pattern of the TSR assemblage, we specifically applied the point pair distribution function ($O_{r1,r2}(\Phi)$; Baddeley et al., 2015). The function estimates the probability distribution of the directions of vectors joining pairs of points that lie more than $r1$ and less than $r2$ units apart. With selected different distances $r1$ and $r2$, the function estimates the multiscale variation of anisotropy. Results are visualised in rose diagrams, where the direction is measured counter-clockwise from East (0°).

At the supra-element assemblage level, spatial anisotropy is expected to be detected in a fluvial depositional environment, and most likely to share the same preferential orientation with taphonomic elements. Characteristic elongated lag deposits are typical patterns observed in association with water-flows dragging materials in one direction, the same as the main orientation of the elements (Domínguez-Rodrigo et al., 2012).

C.3.3 Differential preservation

Differential preservation, or taphonomic survival, refers to the proportion of taphonomic elements being preserved after the action of environmental factors (Fernández-López, 2006). Selective preservation arises from the differential modification of taphonomic entities, by interaction of inherent properties of the entities with the exter-

nal environmental factors. Skeletal part representation is among the key variables potentially indicative of the selective action of water-flows (Behrensmeyer, 1975b; Kaufmann et al., 2011; Voorhies, 1969, among others). Other variables, not considered in this preliminary study, include breakage patterns, disarticulation patterns and bone surface modifications.

The pioneering flume experiments by Voorhies (1969) on disarticulated, complete sheep and coyote bones resulted in a three-group classification of fluvial transport susceptibility of skeletal elements, subsequently elaborated by Behrensmeyer (1975b). Since shape and structural density have been found to influence the transportability of skeletal elements (Behrensmeyer, 1975b; Boaz, 1982), assemblages subject to moderate to high-energy water-flows typically show an under-represented number of smaller, less dense bones. The Voorhies Groups I (rib, vertebra, sacrum, sternum) is the most easily affected by fluvial transport; thus its presence or absence in the fossil assemblage informs about the degree of disturbance by water-flows. In turn, the proportion between the represented Voorhies Groups provides evidence for the degree of preservation of the assemblage (Behrensmeyer, 1975b). We included in the Voorhies groups only complete, non-articulated macromammal bones (plus rami of mandibles, and maxillae) of adult individuals - the very few specimens of juvenile individuals, having different hydraulic behaviour, were excluded. Our grouping criteria followed the classification reported in Lyman (1994, Tab.6.5). Carpals, tarsals and sesamoids were included in Voorhies Group I/II, as the phalanges; maxillae in Group II/III, as the mandibular rami. The studied sample included 147 specimens of Perissodactyla ($n = 59$), Artiodactyla ($n = 41$), Carnivora ($n = 12$) and yet indeterminate taxa ($n = 35$). The distribution of determinate Voorhies Groups was further categorised in 5 size classes, following the body mass (BM) classification of Palombo (2010, 2016), modified for *Ursus etruscus* after Koufos et al. (In press). The first group (BM1), not present so far in our collection, includes mammals whose weight is less than 10 kg; BM2 ranges from 10 to 59 kg (*Canis etruscus*); BM3 from 60 to 249 kg

(*Ursus etruscus*, medium-sized Cervidae); BM4 from 250 to 1000 kg (*Equus*, *Bison*, *Praemegaceros*). We excluded from the Voorhies Groups specimens attributed to BM5, that includes very large mammals over 1000 kg weight (Rhinocerotidae and Elephantidae). Nevertheless, their skeletal element representation was analysed following the Fluvial Transport Index (FTI) classification of [Frison and Todd \(1986\)](#). Undetermined taxa or BM classes (named NA) were also included in the analysis.

Closely related to the Voorhies Groups, the ratio of complete isolated teeth/vertebrae (T/V) is another indicator of the depositional environment ([Behrensmeyer, 1975b](#)). High-energy fluvial deposits, such as channel-fills and -lag deposits, tend to have high T/V ratio, whereas a low T/V ratio characterises low-energy fluvial deposits, such as that of floodplain deltaic and lacustrine settings ([Lyman, 1994](#)).

Complimentary to the hydraulic behaviour of complete, isolated faunal remains classified in the Voorhies Groups, the skeletal part representation of fragmented bones provides another indication of the degree of preservation of the assemblage ([Domínguez-Rodrigo et al., 2017, 2014d; Pante and Blumenschine, 2010](#)). Vertebrae and ribs, being mostly cancellous, fragile and comparatively low-dense bones, are more susceptible to fragmentation and transportation, even in low-energy conditions, with respect to cranial and appendicular elements, which are more dense and likely to survive in lag assemblages ([Domínguez-Rodrigo et al., 2017](#)). In order to integrate the Voorhies Groups, we analysed a subsample of 400 isolated macromammal specimens, composed of 315 bone and tooth fragments, 78 complete teeth, 1 antler, and 6 appendicular bones of juvenile or BM5 specimens.

Finally, the distribution of articulated bones was analysed by anatomical regions. A sub-sample of 50 articulated macromammal units of 154 bone elements were classified as axial (vertebrae, ribs, scapulae and pelvis) or appendicular (humeri, femura, radii, tibiae, metapodials, carpals/tarsals and phalanges) units.

C.3.4 Reproducible research

The subset of the raw data collected for this study, necessary to reproduce the reported results, is licensed, except where otherwise specified, under the CC-BY license and publicly available on an open-access repository. The repository includes in addition metadata description and the code used to process and reduce the dataset. The analyses were performed in R: a language and environment for statistical computing (R Core Team, 2017); except for the wavelet analysis, performed using the PASSaGE software, version 2 (Rosenberg and Anderson, 2011). The commented R code needed to reproduce the reported analyses is released under the MIT license in the same repository. We provide as well a detailed description of the procedure used in PASSaGE.

C.4 Results

C.4.1 Anisotropy of basic taphonomic elements

Circular statistics were applied for the fabric analysis of basic taphonomic elements, i.e., isolated, not articulated elongated complete bone specimens or bone fragments. Tab. C.1 summarises the results of the circular uniformity tests. The Rayleigh test, which assumes a unimodal distribution, confirmed (p -value = 0.001) the significance of the sample mean resultant length ($\bar{R} = 0.165$). The value of \bar{R} close to 0 indicates that the data are evenly spread around the mean direction ($\bar{\theta} = 148^\circ$, SE), with relatively high standard deviation ($\hat{\sigma} = 1.89$) and angular variance ($V = 48^\circ$). On the other hand, the Schmidt and rose diagrams (Fig. C.5a) showed a multimodal distribution, mostly concentrated in the SE quadrant and with secondary peaks to the N and SW. Accordingly, the Kuiper, Watson and Rao omnibus tests, all rejected the null hypothesis of uniformity at the 99% confidence level, thus suggesting a significant anisotropic multimodal distribution of the fossil sample. Moreover, the Schmidt diagram (Fig. C.5a) showed a planar fabric of the sam-

Table C.1: Values and p – values of circular uniformity test statistics.

Sample n	mean dir.	Rayleigh		Kuiper		Watson		Rao	
		R	p	V_n	p	U^2	p	U	p
249	148°	0.165	0.001	2.3791	<0.01	0.3957	<0.01	186.5181	<0.001

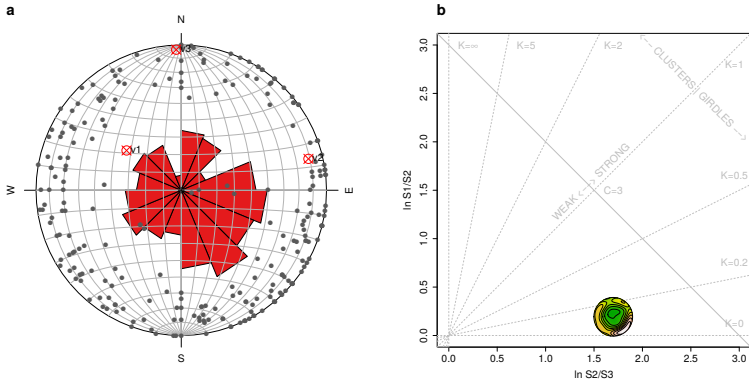


Figure C.5: Rose and equal area Schimdt diagrams (a). Woodcock diagram (b).

ple distribution, with points plotting predominantly on the edge of the equal area hemisphere, thus indicating 0-to-low degree of dip (mean plunge=12°; variance=1.5°).

In the Woodcock diagram (Fig. C.5b), the C value (1.89) is higher than the critical $S1/S3$ test value (1.44) for $N=300$ at 99% confidence level. Thus, the data sample significantly rejects the hypothesis of randomness in favour of a strong organised sample. The K value (0.11) plots the data sample close to $K = 0$, indicating uniaxial girdles (planar fabric).

C.4.2 Anisotropy of the taphonomic population

Geostatistics (directional variograms and variogram map), wavelet and point pattern analyses were used for detecting anisotropy at the assemblage level. Fig. C.6a shows the kernel smooth density estimation ($\sigma = 0.17$) of the sample distribution in the study area. A preliminary visual examination suggests a NW-SE oriented clustering of the assemblage, although interfered with secondary NE-SW oriented dispersion. Fig. C.6b shows the variograms in the four main geographical directions (N-S, E-W, NE-SW, NW-SE), plotted against the omnidirectional fitted variogram. As a rule of thumb, in order to determine the spatial structure of the sampled data, only the first two-thirds of the variogram are interpreted (Dale and Fortin, 2014). The omnidirectional variogram (red line) indicates that at short distance lags, the semi-variances are close to zero, indicating very strong spatial structure (correlation). With longest distance lags, the semi-variance rise to a plateau (*sill*) of lack of spatial correlation. The semi-variance of the NW-SE (135°) direction is lower than in the omnidirectional variogram, starting well before the *sill*, thus indicating continuity (spatial correlation) in that direction. Minor directional trends are also detected in the N-S (0°), and to a lesser extent in the NE-SW (45°) directions. This result is clearly confirmed by the diagonal striping in the variogram map (Fig. C.6c). The map shows a major ellipse oriented NW-SE, with minor parallel structures.

As for the wavelet analysis, Fig. C.7 plots the variance as function of the direction, ranging anti-clockwise from 0° (E) to 180° (W). A major peak is evident at 135° (NW), wandering way above the expected values for a random (isotropic) pattern. A secondary significant peaks, although of much less intensity, is present at 85° (N). In accordance with the directional variograms, the wavelet analysis indicates a significant anisotropy in the NW-SE direction. Moreover, it suggests minor occurrence of points (specimens) in the N-S direction, as also indicated by the geostatistics analysis. However, in contrast with the directional variograms, the angular wavelet graph

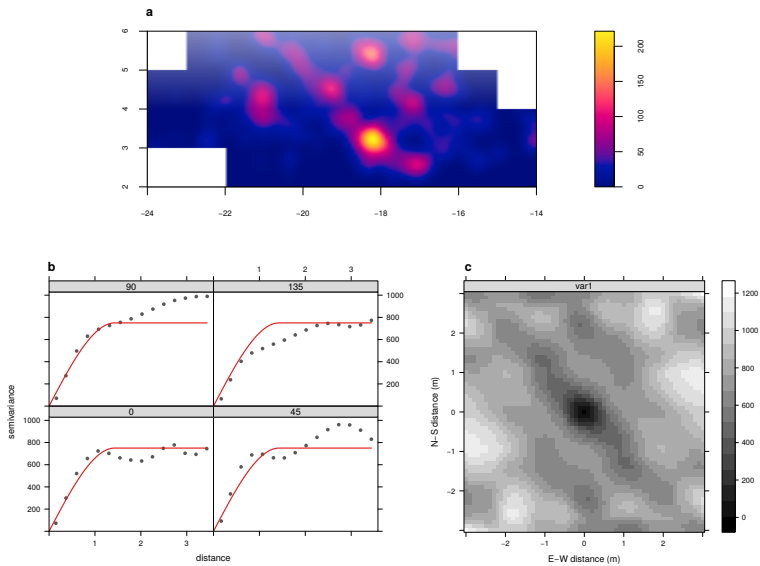


Figure C.6: Kernel smoothed intensity function of the fossil assemblage (a). Directional variograms (4 clockwise directions from N-S, 0°) shown as grey points alongside the fitted omnidirectional variogram shown as a continuous red line (b) and variogram map (c).

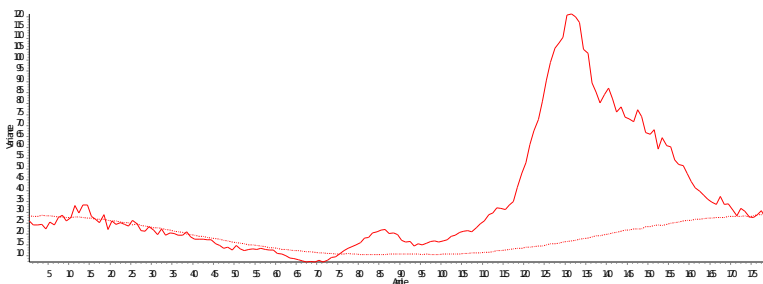


Figure C.7: Angular wavelet graph. Angles range from 0° (E) to 180° (W). Peaks of variance (continuous line) indicate the direction of maximum anisotropy. Dashed line marks the Monte Carlo simulated null hypothesis of isotropy.

does not support significant preferential orientation in the NE range (angles between 0° and 90°).

Fig. C.8 shows the results of our point pattern analysis and specifically the point pair distribution function $O_{r_1, r_2}(\Phi)$ for a range of distances $r_1 = 0.01$ m and $0.25 < r_2 < 1.5$ m. The plot illustrates the multiscale variation of anisotropy, from a uniform, isotropic pattern (for $r_2 = 0.25$ m), to increased anisotropy in the NW-SE direction. The maximum anisotropy is observed for $r_2 = 1$ m, as elements at a maximum distance of 1 m show the strongest directional pattern. With increased distances of $r_2 > 1$ m, the rose diagrams suggest the addition of a second orthogonal NE-SW directional trend, which reflects the parallel alternation of NW-SE bands in the assemblage distribution.

C.4.3 Differential preservation

Fig. C.9a shows the distribution at the family level of the whole sampled material. Determined taxa included Perissodactyla, Artiodactyla, Carnivora and Proboscidea, together with a number of un-

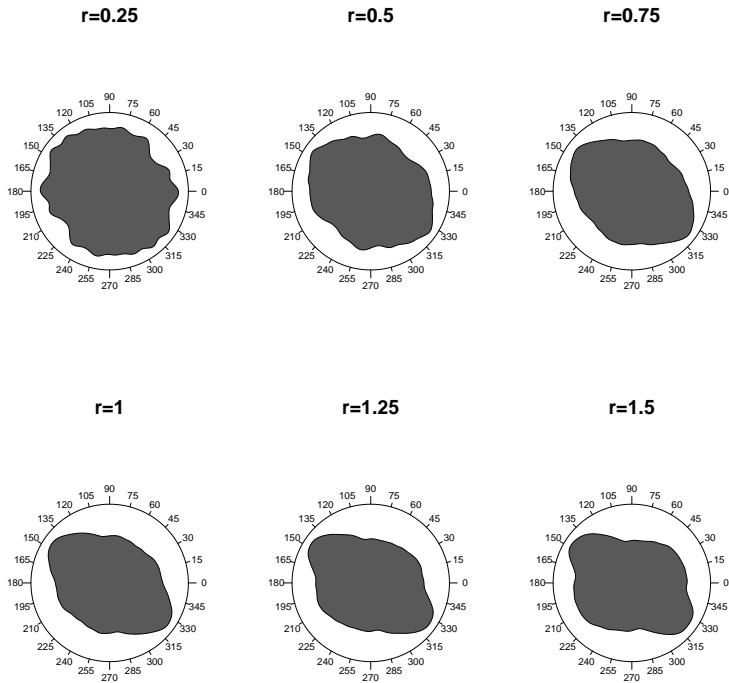


Figure C.8: Rose diagrams of the point pair distribution function for a range of distances ($0.25 < r_2 < 1.5\text{m}$). Direction is measured counter-clockwise from East (0°).

determined bone fragments (44%). The histogram shows the prominent presence of Equidae over other taxa (27%), followed by Bovidae (11%) and Cervidae (5%). However, it is worth noting the presence of very large mammals (body mass class BM5), such as Elephantidae and the rhinocerotid *Stephanorhinus* sp., and to a less extent, of carnivores, such as the *Canis etruscus* and *Ursus etruscus*.

The distribution of the Voorhies Groups plotted by body mass classes is shown in Fig. C.9b. BM1 is so far not present in the TSR assemblage, while BM2 includes the *C. etruscus*, BM3 includes the medium-sized Cervidae and *Ursus etruscus*, BM4 the medium- and large-sized *Equus* sp., *Bison* sp. and the large-sized cervid *Praemegaceros* sp. Notably, the Voorhies Group III is represented in Fig. C.9b only by the crania of the carnivores *Canis* and *Ursus*. Moreover, the fossil record of *U. etruscus* included maxilla fragments (Voorhies Group II/III), isolated teeth, 2 articulated vertebrae and an ulna fragment. Specimens from the BM4 grouped mostly in II/III, II, I/II and showed lack of Voorhies Group I and III. On the other hand, the bulk of undetermined BM specimens plotted in Voorhies Group I/II, with some occurrence in Group I, II, and to a less extent in Group II/III.

Fig. C.9c shows the side-by-side distribution of complete and fragmented isolated macromammal skeletal elements. Firstly, the skeletal element distribution of complete specimens suggests a very high teeth/vertebra ratio (7.8). The ratio (3) is lower, but still relatively high when considering isolated, fragmented specimens. Limb bone and undetermined fragments represent the majority of the fragmented, isolated specimens, as compared to axial skeletal parts.

Accordingly, the prominent presence of appendicular skeletal elements over axial is also showed in the distribution of articulated specimens (Fig. C.9d), which account for 22% of the sampled assemblage. Articulated lower limb elements (metapodes, carpals/tarsals, phalanges) represent the majority of bones, often articulated to fragmented upper elements (radii, tibiae, humeri, femora). Interestingly, some of the latter elements bear carnivore gnawing marks (Fig. C.2e).

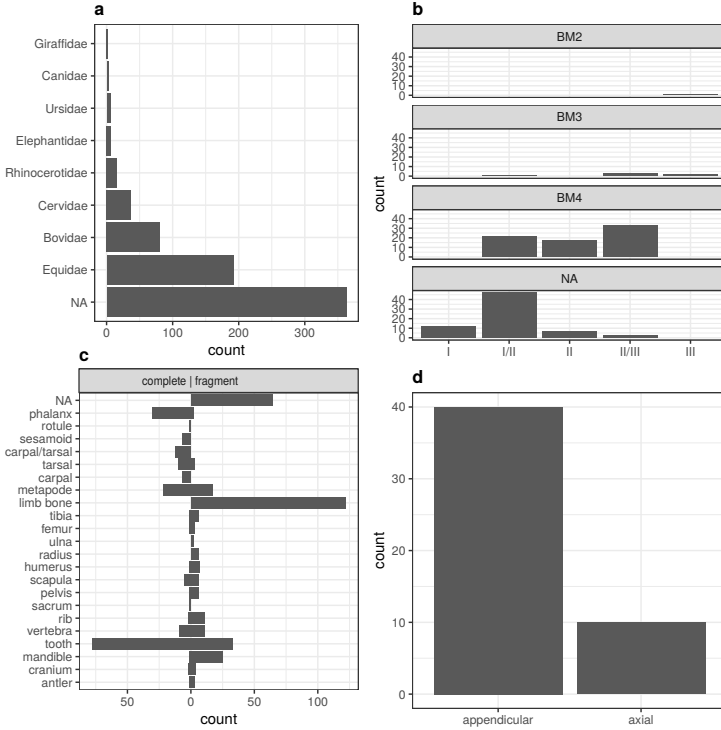


Figure C.9: Distribution at the family level of the whole sampled material (a). Voorhies Groups distribution of the complete, isolated macromammal bones (plus rami of mandible and maxillae) by body mass (BM) (b). Side-by-side distribution of complete/fragmented isolated macromammal skeletal elements (c). Skeletal region distribution of articulated macromammal specimens (d).

C.5 Discussion

Spatial taphonomy recently emerged as new methodological framework complement to the traditional taphonomic approach (Domínguez-Rodrigo et al., 2017; Giusti and Arzarello, 2016; Giusti et al., In press). By using spatial statistical methods, spatial taphonomy aims to investigate the multiscale and multilevel spatial properties of different taphonomic entities (*sensu* Fernández-López, 2006). Indeed, taphonomic alteration processes work simultaneously, at different scales, on entities of different level of organisation, from the basic taphonomic elements (bone specimens), to higher level taphonomic groups (taphons) or populations (assemblages). For example, dispersion processes of taphonomic elements may modify their spatial location, orientation and removal degree. At the same time, dispersion of taphonomic elements may also cause changes in the density, spatial distribution and representatives of elements of each taphon or taphonic population (Fernández-López, 2006). Thus, beside the traditional taphonomic approach, the results of spatial taphonomy are of great importance for investigating the natural or cultural processes of dispersal and accumulation of faunal or cultural remains, in turn with consequences for palaeoecological reconstructions, biochronological estimates and past human behavioural inferences.

In this regard, this study offers an initial contribution to the development of a so far non-existent referential framework for the spatial taphonomic interpretation of palaeontological or archaeological assemblages (Domínguez-Rodrigo et al., 2017). Indeed, the taphonomic study of non-human related bone assemblages has great importance for archaeological research as well. As an example, water-flow processes are recognised to be among the most important natural processes in the formation and modification of a significant percentage of the vertebrate fossil and archaeological sites alike (Behrensmeyer, 1975a, 1982, 1988; Coard, 1999; Coard and Dennell, 1995; Petraglia and Nash, 1987; Petraglia and Potts, 1994; Schiffer, 1987; Voorhies, 1969, among others). Under the effect of water-flows, assemblages may adopt a variety of forms, ranging from

(peri)autochthonous rearranged assemblages and biased lag assemblages to transported, allochthonous assemblages (Behrensmeier, 1988; Domínguez-Rodrigo and García-Pérez, 2013). One fundamental assumption behind reliable inferences on past human behaviour is the pristine preservation of the depositional context. Therefore, it is essential, in order to fully comprehend the archaeological record, to test within a referential framework alternative taphonomic hypotheses.

In this study, taphonomic dispersion and accumulation processes were analysed focusing on a specific aspect - anisotropy - of the spatial properties of taphonomic entities. A multilevel analysis of anisotropy was conducted at the level of basic taphonomic elements and at the assemblage level. Anisotropy, defined as the preferential orientation of skeletal elements, constitutes a fundamental part of any taphonomic study (Aramendi et al., 2017; Benito-Calvo and de la Torre, 2011; Cobo-Sánchez et al., 2014; de la Torre and Benito-Calvo, 2013; Domínguez-Rodrigo et al., 2014b, 2012, 2014d; Fiorillo, 1991; Nash and Petraglia, 1987; Organista et al., 2017; Petraglia and Nash, 1987; Petraglia and Potts, 1994; Schick, 1987; Toots, 1965; Voorhies, 1969, among others). However, spatial anisotropy at supra-element level of taphons or assemblages is an often neglected taphonomic criterion that should be reconsidered, especially in spatial taphonomic analyses of fluvial dispersion and accumulation processes. Moreover, it must be considered that standard spatial statistics rely on crucial assumptions about the isotropy of the spatial processes responsible for the observed spatial pattern (Baddeley et al., 2015).

We investigated the multilevel spatial anisotropy and selective composition of the fossiliferous deposit of Tsiotra Vryssi, from the fluvial Gerakarou Formation of the Mygdonia Basin, Greece. Specific research questions regarded the character and number of depositional processes and the degree of re-elaboration of the fossil record. Specific aspects of our results are discussed below.

C.5.1 Recursive anisotropy

Recursive anisotropy emerged at the level of basic taphonomic elements and at the assemblage level. Fabric analysis, geostatistics, wavelet and point pattern analyses all pointed to a preferential NW-SE orientation of the assemblage and the sub-sample of elongated bone specimens.

Fabric analysis, or the analysis of the orientation (plunge and bearing) of elongated elements, can provide valuable insight into taphonomic processes, allowing discrimination between different orientation patterns (isotropic, linear or planar). We analysed a sub-sample of not articulated, clearly elongated bone specimens, mostly limb bone fragments. Articulated units were excluded from the fabric analysis since experimental studies by [Coard and Dennell \(1995\)](#) and [Coard \(1999\)](#) reported that articulated units with a higher number of elements, such as complete limbs, may show weak preferential orientation when not aligned, as they often occur at TSR (Fig. [C.2c,d,e](#)). Otherwise, the authors concluded that articulated bones showed a greater than expected hydraulic transport potential. Thus, their conspicuous presence in the TSR fossil record (about 22%) would not necessarily suggest an autochthonous deposit.

The results of the circular uniformity test statistics (Tab. [C.1](#)) agreed upon rejecting the null hypothesis of uniformity, suggesting a significant anisotropic distribution of the fossil sample. The Schimdt and Woodcock diagrams in Fig. [C.5](#) indicated planar fabric (0-to-low degree of dip) and a girdle pattern, with preferential orientation towards the SE. In girdle distribution elements orient over a wider sector of angles than cluster distributions, yet showing higher anisotropy than random distributions. Whereas cluster, linear patterns are associated with channelised water-flows ([Petraglia and Potts, 1994](#)), girdle, planar patterns have been interpreted as products of overland flows (runoff; [Organista et al., 2017](#)). The preferential orientation of the sampled elongated bones suggests that the TSR fossil deposit most likely underwent relatively high-energy, but non-channelised NW-SE water-flows. It is also worth noting that

characteristic channel features were not identified in the excavation area. However, anisotropy does not itself discriminate between allochthonous and autochthonous deposits. Autochthonous lag assemblages undergoing minimal re-sedimentation could also exhibit significant anisotropic spatial patterns (Domínguez-Rodrigo et al., 2014a, 2012, 2017, 2014c). Since a wide range of different taphonomic processes can produce similar patterns, an unequivocal discrimination based only on fabric observations is seldom possible, and other taphonomic criteria should be considered (Lenoble and Bertran, 2004).

Geostatistics, wavelet and point pattern analyses were applied in order to detect anisotropy of the TSR fossil assemblage. All these different methods agreed on identifying a preferentially NW-SE oriented distribution. Four directional variograms and a variogram map (Fig. C.6b,c) were calculated from a kernel density estimation of the assemblage spatial distribution (Fig. C.6a). Small, dense clusters of fossils, although occurring at different elevations in the 1m-thick vertical distribution (Fig. C.4a), concatenate along a prevailing NW-SE direction, in a series of 3 recognisable bands with less dense areas between them. Secondary minor directions (N-S and NE-SW) were identified in the directional variograms (Fig. C.6b). In the same manner, the wavelet graph (Fig. C.7) and the rose diagrams (Fig. C.8) also detected a strong preferential NW-SE directional distribution. Similar elongated lag deposits are typically associated with water-flows dragging material in one direction (Domínguez-Rodrigo et al., 2012).

These observations are in agreement with AMS results, in that the mean K1 axis (maximum axis of anisotropy) is oriented along a NW-SE direction (Fig. XC) suggesting likewise local paleoflow.

Thus, the observed recursive multilevel anisotropy patterns most probably points to the action of NW-SE oriented water-flows, at the specific location of the TSR site. However, both analyses of isotropy at element level (fabric analysis) and assemblage level (geostatistics, wavelet and point pattern analyses) suggested some degree of noise in the prevalent NW-SE distributions toward other directions, espe-

cially to the orthogonal NE-SW direction. Whereas long bones can roll orthogonally to the main direction of the flow (Voorhies, 1969), noise in the main directional trend at assemblage level may indicate multiple depositional processes, or secondary reworking post-depositional processes. Moreover, the relatively high average density of preserved elements ($24/\text{m}^2$) occur in small, well defined clusters (Figs. C.2f,e, C.4 and C.6a). Such spatial aggregation of taphonomic elements may be the result of a combination or the sum of different taphonomic processes (Fernández-López et al., 2002). On the other hand, the formation of gaps in the spatial distribution and clusters of elements in correspondence with topographic depression may as well be associated with lag deposits (Petraglia and Potts, 1994).

C.5.2 Differential preservation

According to the evolutionary and systemic theory of taphonomy, taphonomic alteration is not only conceived as a destructive process, but it also has positive effects with the preservation and creation of new taphonomic groups. In this sense, the differential destruction (or taphonomic sieve) of taphonomic entities is just a particular case of taphonomic alteration, as it is the differential modification that gives rise to selective preservation (Fernández-López, 2006). Intrinsic and extrinsic taphonomic factors determine the differential preservation of taphonomic entities. In this study we integrated our spatial taphonomic approach with a preliminary study of the differential preservation of fossil elements.

In the BM4 class of mammals, the relatively high abundance of skeletal elements belonging to the Voorhies Groups I/II, II and II/III (Fig. C.9b) suggests minor winnowing of the assemblage, with preservation of the densest elements that are above the threshold of transportability (Behrensmeier, 1988). Indeed, skeletal elements in the Voorhies Group I (ribs, vertebrae, sacrum, sternum) tend to be transported more easily by saltation or flotation in relatively low-energy currents (Voorhies, 1969). The under-representation of the Voorhies Group III (crania and complete mandibles) in the BM4

class is balanced by the high occurrence of cranial elements in the Group II/III (rami of mandibles and maxilla fragments). Thus, the distribution in Fig. C.9b suggests, more than the taphonomic sieve of the Voorhies Group III, a higher fragmentation rate of cranial elements in the BM4 class of mammals (*Equus*, *Bison*, *Praemegaceros*). On the other hand, the Voorhies Group III is better represented in the BM classes 2 and 3, which include smaller mammals, i.e., *C. etruscus*, *U. etruscus* and medium-sized cervids. The presence of better preserved carnivore cranial elements, as well as the presence of a partial articulated skeleton of a wolf-sized carnivore, would suggest an autochthonous or para-autochthonous assemblage (Behrensmeyer, 1988).

Although excluded from the Voorhies Group analysis, it is worth noting the presence of several skeletal elements of Elephantidae (a complete scapula, a complete radius/fibula, a limb bone fragment and several articulated carpals) with different FTI values, comparable to elements of the Voorhies Group II and III (Frison and Todd, 1986). Their distribution suggests that the assemblage was winnowed of the elements with highest FTI, which are comparable to elements of the Voorhies Group I. This is also the case for the other excluded megaherbivore, the rhinocerotid *Stephanorhinus*, which is represented by several teeth and limb bones.

Overall, the very high teeth/vertebra ratio (7.8) also supports the hypothesis of a lag, winnowed assemblage. Moreover, the actual presence of a high number of limb and undetermined bone fragments, together with complete appendicular and axial elements (Fig. C.9c) supports also some degree of sorting (taphonomic sieve) of the smallest, cancellous fragments. Segregation of axial elements from epiphyses and shafts has been observed even in low-energy fluvial environments (Domínguez-Rodrigo et al., 2017).

On the other hand, as noted earlier, the conspicuous presence of articulated specimens in the TSR fossil assemblage does not necessarily suggest an autochthonous deposition, since articulated bones may as well show a great hydraulic transport potential (Coard, 1999; Coard and Dennell, 1995). Nevertheless, it is worth noting that the

distribution of articulated units in TSR shows a significant presence of appendicular elements over axial ones (Fig. C.9d). Thus, the under-representation of articulated axial elements also indicates a winnowed, lag assemblage formed by the densest and most resilient elements, with sieve and transport of part of the lighter and more cancellous elements. However, carnivore ravaging alike tends to eliminate or at least lead to underrepresentation of those skeletal elements (the less dense, axial elements) in the transport group most prone to be transported by water (Domínguez-Rodrigo et al., 2012; Voorhies, 1969). Interestingly, a preliminary analysis of the bone breakage patterns suggests that carnivores had some active role in the modification and possibly in the accumulation of bones at TSR (Fig. C.2e; Konidaris et al., 2015).

In conclusion, considering the results of our spatial taphonomic analysis, processes of taphonomic dispersion, such as fluvial accumulation processes, would have likely separated and disseminated the most cancellous taphonomic elements, favouring the persistence of Carnivores could have likely been active accumulation agents. The recursive anisotropic spatial patterns, at the level of taphonomic elements and at the assemblage level, as well as the clustering pattern in relatively small, dense, aggregations of elements aligned in parallel NW-SE oriented bands, suggest that the TSR deposit resulted from multiple taphonomic dispersion events, with winnowing of less dense, lighter elements and spatial anisotropic re-arrangement of a lag, autochthonous assemblage accumulated over the migrating banks of a NW-SE oriented fluvial system. As suggested by Organista et al. (2017), it is likely for secondary overbank flows to aggregate bones dispersed over the bank surface into topographic depressions, where they accumulate and acquire greater stability.

Noteworthy, both Geo 1 and Geo 2 show fining upward trends and facies sequences similar to those typical of braided rivers (Miall, 1977). In such a sequence, the lower coarser-grained part would represent one or more sets of sinuous-crested medium-scale bedforms (i.e. small dunes) forming by bedload traction in the deeper reaches of channels, whereas the upper muddy part is dominantly deposited

by decantation either on top of in-channel or bank-attached emerging bars or in floodplains, occasionally provided with coarse material at high-water stages (Miall, 1982). Therefore, the excavated section can be viewed as the product of cyclical lateral switching of a braided fluvial system.

C.6 Conclusions

Spatial taphonomy is the systemic, multiscale and multilevel study of the spatial properties of taphonomic processes. Indeed, taphonomic alteration processes work simultaneously, at different scales, on entities of different levels of organisation, from the basic taphonomic elements (bone specimens), to higher level taphonomic groups (taphons) or populations (assemblages). In this study we elaborated on a specific aspect - anisotropy - of the spatial properties of taphonomic processes, investigating an often neglected aspect of the spatial distribution of taphonomic populations.

A multilevel analysis of anisotropy was conducted for the Early Pleistocene fossiliferous locality Tsiotra Vryssi, from the fluvial Gerakarou Formation of the Mygdonia Basin, Greece. Differential preservation of skeletal elements was also analysed in order to unravel the character and number of depositional processes and the degree of re-elaboration of the TSR fossil record. The results of the analyses suggested repeated taphonomic dispersion processes, with winnowing of less dense, lighter elements and spatial anisotropic re-arrangement of a lag, autochthonous assemblage possibly accumulated over the migrating banks of a NW-SE oriented fluvial system.

We believe that this study contributes towards the development of a referential framework for the spatial taphonomic interpretation of other palaeontological, as well as archaeological, localities.

References

- Aramendi J, Uribelarrea D, Arriaza MC, Arráiz H, Barboni D, Yravedra J, Ortega MC, Gidna A, Mabulla A, Baquedano E, and Domínguez-Rodrigo M. 2017. The paleoecology and taphonomy of AMK (Bed I, Olduvai Gorge) and its contributions to the understanding of the “Zinj” paleolandscape. *Palaeogeography, Palaeoclimatology, Palaeoecology* (in press). DOI: [10.1016/j.palaeo.2017.02.036](https://doi.org/10.1016/j.palaeo.2017.02.036).
- Baddeley A, Rubak E, and Turner R. 2015. *Spatial Point Patterns: Methodology and Applications with R*. London: Chapman and Hall/CRC.
- Behrensmeyer AK. 1975a. Taphonomy and paleoecology in the hominid fossil record. *Yearbook of Physical Anthropology* 19, 36–50.
- Behrensmeyer AK. 1975b. The taphonomy and paleoecology of Plio-Pleistocene vertebrate assemblages East of Lake Rudolf, Kenya. *Bulletin of the Museum of Comparative Zoology* 146, 473–578.
- Behrensmeyer AK. 1982. Time resolution in fluvial vertebrate assemblages. *Paleobiology* 8.3, 211–227. DOI: [10.1017/s0094837300006941](https://doi.org/10.1017/s0094837300006941).
- Behrensmeyer AK. 1988. Vertebrate preservation in fluvial channels. *Palaeogeography, Palaeoclimatology, Palaeoecology* 63.1, 183–199. DOI: [10.1016/0031-0182\(88\)90096-X](https://doi.org/10.1016/0031-0182(88)90096-X).
- Benito-Calvo A and de la Torre I. 2011. Analysis of orientation patterns in Olduvai Bed I assemblages using GIS techniques: Implications for site formation processes. *Journal of Human Evolution* 61.1, 50–60. DOI: [10.1016/j.jhevol.2011.02.011](https://doi.org/10.1016/j.jhevol.2011.02.011).
- Benito-Calvo A, Martínez-Moreno J, Mora R, Roy M, and Roda X. 2011. Trampling experiments at Cova Gran de Santa Linya, Pre-Pyrenees, Spain: their relevance for archaeological fabrics of the Upper–Middle Paleolithic assemblages. *Journal of Archaeological Science* 38.12, 3652–3661. DOI: [10.1016/j.jas.2011.08.036](https://doi.org/10.1016/j.jas.2011.08.036).
- Bertran P and Texier JP. 1995. Fabric Analysis: Application to Paleolithic Sites. *Journal of Archaeological Science* 22.4, 521–535. DOI: [10.1006/jasc.1995.0050](https://doi.org/10.1006/jasc.1995.0050).
- Bevan A and Conolly J. 2009. Modelling spatial heterogeneity and nonstationarity in artifact-rich landscapes. *Journal of Archaeological Science* 36.4, 956–964. DOI: [10.1016/j.jas.2008.11.023](https://doi.org/10.1016/j.jas.2008.11.023).
- Boaz DD. 1982. *Modern riverine taphonomy: its relevance to the interpretation of Plio-Pleistocene hominid paleoecology in the Omo basin, Ethiopia*. PhD thesis. University of California, Berkeley.
- Boaz NT and Behrensmeyer AK. 1976. Hominid taphonomy: Transport of human skeletal parts in an artificial fluvial environment. *American Journal of Physical Anthropology* 45.1, 53–60. DOI: [10.1002/ajpa.1330450107](https://doi.org/10.1002/ajpa.1330450107).

- Coard R. 1999. One Bone, Two Bones, Wet Bones, Dry Bones: Transport Potentials Under Experimental Conditions. *Journal of Archaeological Science* 26.11, 1369–1375. DOI: <https://doi.org/10.1006/jasc.1999.0438>.
- Coard R and Dennell R. 1995. Taphonomy of Some Articulated Skeletal Remains: Transport Potential in an Artificial Environment. *Journal of Archaeological Science* 22.3, 441–448. DOI: <https://doi.org/10.1006/jasc.1995.0043>.
- Cobo-Sánchez L, Aramendi J, and Domínguez-Rodrigo M. 2014. Orientation patterns of wildebeest bones on the lake Masek floodplain (Serengeti, Tanzania) and their relevance to interpret anisotropy in the Olduvai lacustrine floodplain. *Quaternary International* 322–323.0, 277–284. DOI: [10.1016/j.quaint.2013.07.130](https://doi.org/10.1016/j.quaint.2013.07.130).
- Dale M and Fortin M. 2014. *Spatial Analysis: A Guide for Ecologists*. Second Edition. Cambridge University Press.
- De la Torre I and Benito-Calvo A. 2013. Application of GIS methods to retrieve orientation patterns from imagery; a case study from Beds I and II, Olduvai Gorge (Tanzania). *Journal of Archaeological Science* 40.5, 2446–2457. DOI: [10.1016/j.jas.2013.01.004](https://doi.org/10.1016/j.jas.2013.01.004).
- Domínguez-Rodrigo M, Bunn HT, and Yravedra J. 2014a. A critical re-evaluation of bone surface modification models for inferring fossil hominin and carnivore interactions through a multivariate approach: Application to the FLK Zinj archaeofaunal assemblage (Olduvai Gorge, Tanzania). *Quaternary International* 322–323.0. The Evolution of Hominin Behavior during the Oldowan-Acheulian Transition: Recent Evidence from Olduvai Gorge and Peninj (Tanzania), 32–43. DOI: <http://dx.doi.org/10.1016/j.quaint.2013.09.042>.
- Domínguez-Rodrigo M, Bunn H, Mabulla A, Baquedano E, Uribelarrea D, Pérez-González A, Gidna A, Yravedra J, Diez-Martin F, Egeland C, Barba R, Arriaza M, Organista E, and Ansón M. 2014b. On meat eating and human evolution: A taphonomic analysis of BK4b (Upper Bed II, Olduvai Gorge, Tanzania), and its bearing on hominin megafaunal consumption. *Quaternary International* 322–323, 129–152. DOI: [10.1016/j.quaint.2013.08.015](https://doi.org/10.1016/j.quaint.2013.08.015).
- Domínguez-Rodrigo M, Bunn H, Pickering T, Mabulla A, Musiba C, Baquedano E, Ashley G, Diez-Martin F, Santonja M, Uribelarrea D, Barba R, Yravedra J, Barboni D, Arriaza C, and Gidna A. 2012. Autochthony and orientation patterns in Olduvai Bed I: a re-examination of the status of post-depositional biasing of archaeological assemblages from FLK North (FLKN). *Journal of Archaeological Science* 39.7, 2116–2127. DOI: [10.1016/j.jas.2012.02.027](https://doi.org/10.1016/j.jas.2012.02.027).
- Domínguez-Rodrigo M, Cobo-Sánchez L, Yravedra J, Uribelarrea D, Arriaza CC, Organista E, and Baquedano E. 2017. Fluvial spatial taphonomy: a new method for the study of post-depositional processes. *Archaeological and Anthropological Sciences*. DOI: [10.1007/s12520-017-0497-2](https://doi.org/10.1007/s12520-017-0497-2).
- Domínguez-Rodrigo M, Diez-Martín F, Yravedra J, Barba R, Mabulla A, Baquedano E, Uribelarrea D, Sánchez P, and Eren MI. 2014c. Study of the SHK

- Main Site faunal assemblage, Olduvai Gorge, Tanzania: Implications for Bed II taphonomy, paleoecology, and hominin utilization of megafauna. *Quaternary International* 322–323, 153–166. DOI: <http://dx.doi.org/10.1016/j.quaint.2013.09.025>.
- Domínguez-Rodrigo M, Fernández-López S, and Alcalá L. 2011. How Can Taphonomy Be Defined in the XXI Century? *Journal of Taphonomy* 9.1, 1–13.
- Domínguez-Rodrigo M and García-Pérez A. 2013. Testing the Accuracy of Different A-Axis Types for Measuring the Orientation of Bones in the Archaeological and Paleontological Record. *PLoS ONE* 8.7, e68955. DOI: [10.1371/journal.pone.0068955](https://doi.org/10.1371/journal.pone.0068955).
- Domínguez-Rodrigo M, Uribelarrea D, Santonja M, Bunn HT, García-Pérez A, Pérez-González A, Panera J, Rubio-Jara S, Mabulla A, Baquedano E, Yravedra J, and Díez-Martín F. 2014d. Autochthonous anisotropy of archaeological materials by the action of water: experimental and archaeological reassessment of the orientation patterns at the Olduvai sites. *Journal of Archaeological Science* 41, 44–68. DOI: [10.1016/j.jas.2013.07.025](https://doi.org/10.1016/j.jas.2013.07.025).
- Eberth DA, Rogers RR, and Fiorillo AR. 2007. A Practical Approach to the Study of Bonebeds. In: *Bonebeds. Genesis, Analysis, and Paleobiological Significance*. Ed. by RR Rogers, DA Eberth, and AR Fiorillo. The University of Chicago Press, 265–332.
- Efremov IA. 1940. Taphonomy: a new branch of paleontology. *Pan American Geologist* 74, 81–93.
- Fernández-Jalvo Y, Scott L, and Andrews P. 2011. Taphonomy in palaeoecological interpretations. *Quaternary Science Reviews* 30.11, 1296–1302. DOI: [10.1016/j.quascirev.2010.07.022](https://doi.org/10.1016/j.quascirev.2010.07.022).
- Fernández-López RS. 2006. Taphonomic Alteration and Evolutionary Taphonomy. *Journal of Taphonomy* 4.3, 111–142.
- Fernández-López RS, Fernández-Jalvo Y, and Alcalá L. 2002. Accumulation: taphonomic concept and other palaeontological uses. In: *Current Topics on Taphonomy and Fossilization*. International Conference Taphos 2002. Ed. by MD Renzi, MP Alonso, M Belinchón, E Peñalver, P Montoya, and A Márquez-Aliaga. Valencia, 37–47.
- Fiorillo AR. 1988. A proposal for graphic presentation of orientation data from fossils. *Contributions to Geology* 26.1, 1–4.
- Fiorillo AR. 1991. Taphonomy and depositional setting of Careless Creek Quarry (Judith River Formation), Wheatland County, Montana, U.S.A. *Palaeogeography, Palaeoclimatology, Palaeoecology* 81.3, 281–311. DOI: [10.1016/0031-0182\(91\)90151-g](https://doi.org/10.1016/0031-0182(91)90151-g).
- Frison GC and Todd LC. 1986. *The Colby Mammoth Site: Taphonomy and Archaeology of a Clovis Kill in Northern Wyoming*. Albuquerque: University of New Mexico Press.

- Giusti D and Arzarello M. 2016. The need for a taphonomic perspective in spatial analysis: Formation processes at the Early Pleistocene site of Pirro Nord (P13), Apricena, Italy. *Journal of Archaeological Science: Reports* 8, 235–249. DOI: [10.1016/j.jasrep.2016.06.014](https://doi.org/10.1016/j.jasrep.2016.06.014).
- Giusti D, Tourloukis V, Konidaris GE, Thompson N, Karkanas P, Panagopoulou E, and Harvati K. In press. Beyond maps: Patterns of formation processes at the Middle Pleistocene open-air site of Marathousa 1, Megalopolis basin, Greece. *Quaternary International*. DOI: <https://doi.org/10.1016/j.quaint.2018.01.041>.
- Hill A. 1976. On carnivore and weathering damage to bone. *Current Anthropology* 17, 335–336. DOI: [10.1086/201732](https://doi.org/10.1086/201732).
- Jammalamadaka S, Sengupta A, and Sengupta A. 2001. *Topics in Circular Statistics*. Series on multivariate analysis. World Scientific.
- Kaufmann C, Gutiérrez MA, Álvarez MC, González ME, and Massigoge A. 2011. Fluvial dispersal potential of guanaco bones (Lama guanicoe) under controlled experimental conditions: the influence of age classes to the hydrodynamic behavior. *Journal of Archaeological Science* 38.2, 334–344. DOI: <https://doi.org/10.1016/j.jas.2010.09.010>.
- Konidaris GE, Kostopoulos D, Koufos GD, Tourloukis V, and Harvati K. 2016. Tsiotra Vryssi: a new vertebrate locality from the Early Pleistocene of Mygdonia Basin (Macedonia, Greece). In: *XIV Annual Meeting of the European Association of Vertebrate Palaeontologists*. Haarlem, The Netherlands: Koninklijke Nederlandse Akademie Van Wetenschappen, 37.
- Konidaris GE, Tourloukis V, Kostopoulos DS, Thompson N, Giusti D, Michailidis D, Koufos GD, and Harvati K. 2015. Two new vertebrate localities from the Early Pleistocene of Mygdonia Basin (Macedonia, Greece): Preliminary results. *Comptes Rendus Palevol* 14.5, 353–362. DOI: <http://doi.org/10.1016/j.crpv.2015.05.004>.
- Koufos GD, Konidaris GE, and Harvati K. In press. Revisiting *Ursus etruscus* (Carnivora, Mammalia) from the Early Pleistocene of Greece with description of new material. *Quaternary International*. In press. DOI: <https://doi.org/10.1016/j.quaint.2017.09.043>.
- Koufos GD, Syrides GE, Kostopoulos DS, and Koliadimou KK. 1995. Preliminary results about the stratigraphy and the palaeoenvironment of Mygdonia Basin, Macedonia, Greece. *Geobios* 28. Supplement 1. First European Palaeontological Congress, 243–249. DOI: [10.1016/S0016-6995\(95\)80171-5](https://doi.org/10.1016/S0016-6995(95)80171-5).
- Legendre P and Legendre L. 2012. *Numerical Ecology*. Developments in Environmental Modelling. Elsevier Science.
- Lenoble A and Bertran P. 2004. Fabric of Palaeolithic levels: methods and implications for site formation processes. *Journal of Archaeological Science* 31.4, 457–469. DOI: [10.1016/j.jas.2003.09.013](https://doi.org/10.1016/j.jas.2003.09.013).
- Lenoble A, Bertran P, and Lacrampe F. 2008. Solifluction-induced modifications of archaeological levels: simulation based on experimental data from a mod-

- ern periglacial slope and application to French Palaeolithic sites. *Journal of Archaeological Science* 35.1, 99–110. DOI: [10.1016/j.jas.2007.02.011](https://doi.org/10.1016/j.jas.2007.02.011).
- Lloyd C and Atkinson P. 2004. Archaeology and geostatistics. *Journal of Archaeological Science* 31.2, 151–165. DOI: [10.1016/j.jas.2003.07.004](https://doi.org/10.1016/j.jas.2003.07.004).
- Lyman RL. 1994. *Vertebrate Taphonomy*. Cambridge Manuals in Archaeology. Cambridge University Press.
- Lyman RL. 2010. What Taphonomy Is, What it Isn't, and Why Taphonomists Should Care about the Difference. *Journal of Taphonomy* 8.1, 1–16.
- Markofsky S and Bevan A. 2012. Directional analysis of surface artefact distributions: a case study from the Murghab Delta, Turkmenistan. *Journal of Archaeological Science* 39.2, 428–439. DOI: [10.1016/j.jas.2011.09.031](https://doi.org/10.1016/j.jas.2011.09.031).
- Miall AD. 1977. Lithofacies Types and Vertical Profile Models in Braided River Deposits: A Summary. In: *Fluvial Sedimentology*. Ed. by AD Miall. Vol. Memoir 5. Calgary: Canadian Society of Petroleum Geologists, 597–604.
- Miall AD. 1982. *Analysis of fluvial depositional systems*. Tulsa, Okla: AAPG.
- Nash DT and Petraglia MD, eds. 1987. *Natural formation processes and the archaeological record*. Vol. 352. International Series. Oxford: British Archaeological Reports.
- Organista E, Domínguez-Rodrigo M, Yravedra J, Uribelarrea D, Arriaza MC, Ortega MC, Mabulla A, Gidna A, and Baquedano E. 2017. Biotic and abiotic processes affecting the formation of BK Level 4c (Bed II, Olduvai Gorge) and their bearing on hominin behavior at the site. *Palaeogeography, Palaeoclimatology, Palaeoecology* (in press). DOI: [10.1016/j.palaeo.2017.03.001](https://doi.org/10.1016/j.palaeo.2017.03.001).
- Palombo MR. 2010. A scenario of human dispersal in the northwestern Mediterranean throughout the Early to Middle Pleistocene. *Quaternary International* 223–224.0, 179–194. DOI: [10.1016/j.quaint.2009.11.016](https://doi.org/10.1016/j.quaint.2009.11.016).
- Palombo MR. 2016. To what extent could functional diversity be a useful tool in inferring ecosystem responses to past climate changes? *Quaternary International* 413.Part B, 15–31. DOI: <https://doi.org/10.1016/j.quaint.2015.07.069>.
- Pante MC and Blumenschine RJ. 2010. Fluvial transport of bovid long bones fragmented by the feeding activities of hominins and carnivores. *Journal of Archaeological Science* 37.4, 846–854. DOI: <https://doi.org/10.1016/j.jas.2009.11.014>.
- Petraglia MD and Nash DT. 1987. The impact of fluvial processes on experimental sites. In: *Natural formation processes and the archaeological record*. Ed. by DT Nash and MD Petraglia. Vol. 352. International Series. Oxford: British Archaeological Reports, 108–130.
- Petraglia MD and Potts R. 1994. Water Flow and the Formation of Early Pleistocene Artifact Sites in Olduvai Gorge, Tanzania. *Journal of Anthropological Archaeology* 13.3, 228–254. DOI: [10.1006/jaar.1994.1014](https://doi.org/10.1006/jaar.1994.1014).
- R Core Team. 2017. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria.

- Rosenberg MS. 2004. Wavelet analysis for detecting anisotropy in point patterns. *Journal of Vegetation Science* 15.2, 277–284. DOI: [10.1111/j.1654-1103.2004.tb02262.x](https://doi.org/10.1111/j.1654-1103.2004.tb02262.x).
- Rosenberg MS and Anderson C. 2011. PASSaGE: Pattern Analysis, Spatial Statistics and Geographic Exegesis. Version 2. *Methods in Ecology and Evolution* 2.3, 229–232. DOI: [10.1111/j.2041-210x.2010.00081.x](https://doi.org/10.1111/j.2041-210x.2010.00081.x).
- Schick KD. 1987. Experimentally-derived criteria for assessing hydrologic disturbance of archaeological sites. In: *Natural formation processes and the archaeological record*. Ed. by DT Nash and MD Petraglia. Vol. 352. International Series. Oxford: British Archaeological Reports, 86–107.
- Schiffer MB. 1987. *Formation processes of the archaeological record*. Albuquerque: University of New Mexico Press.
- Toots H. 1965. Orientation and distribution of fossils as environmental indicators. In: *Nineteenth Field Conference of the Wyoming Geological Association*, 219–292.
- Voorhies M. 1969. Taphonomy and population dynamics of an early Pliocene vertebrate fauna, Knox County, Nebraska. *Contributions to Geology, University of Wyoming* Special Paper 1, 1–69. DOI: [10.2113/gsrocky.8.special_paper_1.1](https://doi.org/10.2113/gsrocky.8.special_paper_1.1).
- Woodcock NH and Naylor M. 1983. Randomness testing in three-dimensional orientation data. *Journal of Structural Geology* 5.5, 539–548. DOI: [10.1016/0191-8141\(83\)90058-5](https://doi.org/10.1016/0191-8141(83)90058-5).

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Journal articles

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- Karkanas P., V. Tourloukis, N. Thompson, **D. Giusti**, E. Panagopoulou, K. Harvati. (*In press*). Sedimentology and micromorphology of the Lower Palaeolithic lakeshore site Marathousa 1, Megalopolis basin, Greece. *Quaternary International*. DOI: [10.1016/j.quaint.2018.02.037](https://doi.org/10.1016/j.quaint.2018.02.037).
- Konidaris G., A. Athanassiou, V. Tourloukis, N. Thompson, **D. Giusti**, E. Panagopoulou, K. Harvati. (*In press*). The skeleton of a straight-tusked elephant (*Palaeoloxodon antiquus*) and other large mammals from the Middle Pleistocene locality Marathousa 1 (Megalopolis Basin, Greece): preliminary results. *Quaternary International*. DOI: [10.1016/j.quaint.2017.12.001](https://doi.org/10.1016/j.quaint.2017.12.001).
- Marwik B., J. d'Alpoim Guedes, C. M. Barton, L. A. Bates, M. Baxter, A. Bevan, E. A. Bollwerk, R. K. Bocinsky, T. Brughams, A. K. Carter, C. Conrad, D. A. Contreras, S. Costa, E. R. Crema, A. Daggett, B. Davies, B. L. Drake, T. S. Dye, P. France, R. Fullager, **D. Giusti**, S. Graham, M. D. Harris, J. Hawks, S. Heath, D. Huffer, E. C. Kansa, S. W. Kansa, M. E. Madsen, J. Melcher, J. Negre, F. D. Neiman, R. Opitz, D. C. Orton, P. Przystupa, M. Raviele, J. Riel-Salvatore, P. Riris, I. Romanowska, J. Smith, N. Strupler, I. I. Ullah, H. G. V. Vlack, N. vanValkenberg, E. C. Watrall, C. Webster, J. Wells, J. Wintersand C. D. Wren. 2017. Open Science in Archaeology. *SAA Archaeological Record* 17, 8–14. DOI: [10.17605/OSF.IO/3D6XX](https://doi.org/10.17605/OSF.IO/3D6XX)
- **Giusti D.** and M. Arzarello. 2016. The need for a taphonomic perspective in spatial analysis: Formation processes at the Early Pleis-

tocene site of Pirro Nord (P13), Apricena, Italy. *Journal of Archaeological Science: Reports* 8, 235–249. DOI: [10.1016/j.jasrep.2016.06.014](https://doi.org/10.1016/j.jasrep.2016.06.014).

- Konidaris G., V. Tourloukis, D. S. Kostopoulos, N. Thompson, **D. Giusti**, D. Michailidis, G. Koufos, K. Harvati. 2015. Two new vertebrate localities from the Early Pleistocene of Mygdonia Basin (Macedonia, Greece): Preliminary results. *C.R.Palevol* 14, 353–362. DOI: [10.1016/j.crpv.2015.05.004](https://doi.org/10.1016/j.crpv.2015.05.004).
- Panagopoulou E., V. Tourloukis, N. Thompson, A. Athanassiou, G. Tsartsidou, G. E. Konidaris, **D. Giusti**, P. Karkanias, K. Harvati. 2015. Marathousa 1: a new Middle Pleistocene archaeological site from Greece. *Antiquity Project Gallery* 89(343). DOI: [10.15496/publikation-5878](https://doi.org/10.15496/publikation-5878).

Book chapters

- Menéndez L. P., **D. Giusti**. (*In press*). Global and local trends of craniofacial variation in southern South America. In: *New Perspectives on the Peopling of the Americas*. Ed. by K. Harvati, G. Jaeger and H. Reyes-Centeno. Tuebingen: Kerns Verlag.

Published conference abstracts

- **Giusti D.**, V. Tourloukis, G. E. Konidaris, N. Thompson, P. Karkanias, E. Panagopoulou, K. Harvati. 2017. Beyond maps: Patterns of formation processes at the Middle Pleistocene open-air site of Marathousa 1, Megalopolis Basin, Greece. In: *Proceedings of the European Society for the Study of Human Evolution* 6, 74. Leiden.
- Harvati K., E. Panagopoulou, V. Tourloukis, N. Thompson, P. Karkanias, G. E. Konidaris, A. Athanassiou, G. Tsartsidou, **D. Giusti**. 2017. Marathousa 1: New Lower Paleolithic elephant butchering site from the Megalopolis basin, Greece. In: *Proceedings of the European Society for the Study of Human Evolution* 6, 84. Leiden.
- Konidaris G. E., A. Athanassiou, V. Tourloukis, N. Thompson, **D. Giusti**, E. Panagopoulou, K. Harvati. 2017. The *Elephas (Palaeoloxodon)*

Publication list

antiquus skeleton and other large mammals from the Lower Palaeolithic locality Marathousa 1 (Megalopolis Basin, Greece): preliminary results. In: *Proceedings of the European Society for the Study of Human Evolution* 6, 104. Leiden.

- Tourloukis V., N. Thompson, E. Panagopoulou, G. E. Konidaris, **D. Giusti**, A. Athanassiou, G. Tsartsidou, P. Karkanas, K. Harvati. 2017. The lithic assemblage and bone tools from the Lower Palaeolithic site of Marathousa 1, Megalopolis, Greece: first results. In: *Proceedings of the European Society for the Study of Human Evolution* 6, 202. Leiden.
- Harvati K., E. Panagopoulou, V. Tourloukis, N. Thompson, P. Karkanas, A. Athanassiou, G. E. Konidaris, G. Tsartsidou, **D. Giusti**. 2016. New Middle Pleistocene elephant butchering site from Greece. In: *Abstracts of the Paleoanthropology Society 2016 Meeting*. PaleoAnthropology, A14–A15.
- **Giusti D.** 2013. A GIS approach to the Paleolithic site of Pirro Nord, Italy: From data management to spatial analysis through a Wiki documentation. In: *Proceedings of the European Society for the Study of Human Evolution* 2, 98. Vienna.