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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 perspectives 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 deposit occurs as filling of a karst structure that is currently exposed. We investigated the distribution of the archaeological and paleontological assemblage, as well as the distribution of identified taphonomic features, in order to evaluate 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.

Opposed Reviewers:

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C.O. Hunt
Editor,
Journal of Archaeological Science: Reports

Tübingen, May 20, 2016

Dear Mr. Hunt,

I'm pleased to resubmit for publication in *Journal of Archaeological Science: Reports* a revised version of the manuscript entitled *The need for a taphonomic perspective in spatial analysis: formation processes at the Early Pleistocene site of Pirro Nord (P13), Apricena, Italy*, co-authored with M. Arzarello.

We addressed and commented all the key points raised by the reviewers. We strongly believe that they significantly improved the quality of the paper, and we are grateful to the two anonymous reviewers for that.

In particular, we:

- restructured the manuscript adding subsections according to the two main aims of our study. We also added a new section for the vertical distribution analysis of the finds;
- improved our analyses using more functions and tests;
- published a repository of data, code and text.

Please find attached our inline responses (Italic formatted) to the two reviewers' comments.

Yours sincerely,

Domenico Giusti

Ms. Ref. No.: JASREP-D-15-00502

Title: 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

Responses to Reviewers' comments:

Reviewer #1:

* My main concern is not the use of the statistical approach, which is correct, but the inferences derived from such a small area. Spatial statistics are only reliable when spatial samples are representative of a non-confined spatial population. Although the exact dimensions of the area analyzed are not indicated, the figures show a very small area. This is further constrained by the gravity effect. Most spatial statistics used by the authors are applied to bidimensional horizontal non-constrained population spaces. By using vertical distribution, the authors face the effects of gravity in creating inhomogeneous and/or dependent non-Poisson point patterns.

Concerning the size of the sample area, we provide in Section 3 (Spatial data collection and sampling) a fuller description and the exact dimensions of the areas of analysis. We acknowledge in Section 7 (Discussion) the problem derived by the "lack of information about the original characteristics of the [karstic] system and the reduced area of excavation". However, we assume that our sampling window is representative of the karstic fissure P13, at least at the lowest level of generalization. Higher level of generalization (from the observed point pattern to the entire karstic system) is not the target of our inference. In order to account for the spatial boundary condition, we implement Ripley's isotropic edge correction and we clearly describe it in Section 5 (Point pattern analysis).

The vertical distribution of finds is a key factor in the analysis of site formation processes. We restructured the manuscript introducing a new Section (Vertical distribution), where results of our analyses show that there is no evidence for strong gravitational effect in the distribution of finds. As for the distribution of taphonomic features, we acknowledge the small sample of fossils and suggest, considering as well the lithic sample, that "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".

Moreover, we acknowledge in Section 7 (Discussion) the need for considering three-dimensional spaces in the study of site formation processes study and the technical problems that currently limit the analyses of three-dimensional point patterns. Indeed, although the 'spatstat' software provides basic support for three-dimensional point patterns, the required 3D rectangular box for the spatial 'window' of analysis is a strong constraint that does not fit well to our study area, where the three-dimensional space available for the sediment deposition is unconformably shaped by the presence of big blocks of rock.

* Although I praise the authors by their selection of statistical tests, some information, which would reinforce their study, is missing. For instance, only graphic information is provided but not data-based tests. The authors should first determine the nature of their samples prior to applying the tests they use. Determining whether the point pattern is a homogeneous or inhomogeneous Poisson pattern is fundamental. Here, they could have used chi-square, likelihood ratio tests or Cressie-Read test. Subsequently, they should have determined if the point pattern is Poisson (independent) or non-Poisson. This determines if second-order tests are adequate or not. Independence tests (Kolmogorov-Smirnov, Berman's tests, Cramer-von Mises) would also have been a welcome addition. The authors place special emphasis on Ripley's K test and its derivative forms. K

tests assume homogeneity (which has not been proved for the data sets presented); that is the point process should be stationary. If the point process is not stationary, deviations between the empirical and theoretical estimates should not be taken as evidence of point inter-dependence or interaction, since they may be simply attributed to variations in point density as is common in inhomogeneous point patterns. Showing in a better way is the point process is stationary/homogeneous or not would have provided more support for the K tests used.

In order to determine the nature of the process responsible for the distribution of finds, in Section 6.1 (Results - Formation processes) we re-investigated the point patterns of finds, taking into account the Reviewer's suggestions. Specifically, non-parametric estimation of the intensity is performed by a Gaussian smoothing kernel. Berman's Z₂ test of dependence on a covariate and Receiver Operating Characteristic (ROC) curve are used to exclude the discriminatory power of the x coordinate. The main critique of the quadrat test is the lack of information: the alternative hypothesis is simply the negation of CSR. A point process may fail to be a homogeneous Poisson process either because it fails to have homogeneous intensity, or because it violates the property of independence between points. Moreover, tests using quadrat count are weak when dealing with processes that could be whether stationary and clustered, or spatially inhomogeneous but not clustered.

"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 F(r) functions provide further methods for the interpretation of the distributions" (Section 5.1, Point pattern analysis - Formation processes). Given the geological setting of the site, and the results of our analyses, we determined that the distributions of finds is the results of cluster homogeneous processes.

* The R library spatstat used by the authors is a great resource and contains the function "allstats" which would have provided four different tests dealing with correlation (inter-dependence) and spacing: The G and F functions or the L function (which is a centred version of the K function). A combination of correlation and spacing is found in the J function.

If the authors had previously well determined if they are dealing with homogeneous or inhomogeneous point processes, they could apply standard or corrected functions: Kaplan-Meier for the G and F functions, for instance. Given the inhomogeneous appearance of their samples, the authors could have attempted splitting the material spatial distribution by type (lithic and fauna separately) and fitting inhomogeneous Cox and Cluster models. If preserving the cross-type analysis, a greater display of the multitype K-G-F or J functions would also have contributed to the strength of their analysis.

Following the Reviewer's suggestion, F(r) and G(r) functions have been applied, together with the K(r) function, to the study of the distribution of finds.

* Some suggested modifications follow:
"the earliest-dated locality with human evidence currently known in Western Europe". This is an overstatement.

We have toned-down this statement, re-wording the relevant passage: "making P13 one of the most ancient locality with human evidence currently known in Western Europe {Lopez-Garcia2015}".

* First, other sites with better identified depositional histories (such as Sime Elefante in Atapuerca or Fuentenueva 3 and Barranco del León in the Venta Micena-Orce) are either equally old or even older. In addition, this site has been controversial and if a claim of its ancient status is going to be made, this section should include a much more extensive description and information on its geology and dating. The biostratigraphic date provided is unsecure.

The aim of our study is not to assess or discuss the biochronological dating of the site; therefore, we do not provide a more extensive description and information on the geology ad dating of the site. Other published works (cited in this manuscript) have discussed the dating of the site and its position in the European context.

* Given that P13 is a fissure in a dynamic karstic system, it is very likely that re-elaboration and re-sedimentation processes may account for vertical displacement of microfaunal remains. By no means the associated biostratigraphic date and the lithic materials are secure because taphonomically no direct association exist between them. Re-elaboration/re-sedimentation can put in stratigraphic contact materials from diverse provenience.

We do recognize, instead, that "reworking/re-deposition processes could put in stratigraphic contact materials from diverse provenience" (Section 1, 1.89). Indeed, the aim of our study is to use spatial statistics in order to 1) evaluate the stratigraphic association of finds and 2) identify possible post-depositional reworking of the faunal and lithic assemblage.

Reviewer #2:

* The paper contains a large number of different analysis and results that are presented very often in a confusing way. Part of this is due to a stylistic issue (sentences tend be too long), but I think the main problem is that the link between research question, methods, results, and interpretations are poorly structured. I suggest the authors to be more explicit when they introduce their research questions (i.e. what are the hypotheses? what are the expected results of the spatial analysis for each of them?) and use sub-sections to separate specific research questions/analysis to facilitate the navigation through their findings, as well as make better use of cross-references (e.g. pointing out to specific figures of analysis output in the discussion section), and perhaps lists or tables with the main outputs. As it stands some portions of the text is almost unreadable (e.g. lines 390 to 438 is a single paragraph).

We definitely agree with the Reviewer; thus, we restructured the manuscript adding subsections in Section 5 (Point pattern analysis), 6 (Results) and 7 (Discussion) according to the two main aims of the study, which have been introduced and discussed in Section 1 (Introduction) in a more explicit way (using a numeric list). We also added Section 4 (Vertical distribution) in order to clearly present results of the vertical distribution analysis, which was previously blurry integrated with the spatial point pattern analysis. Moreover, we made a better use of paragraphs and cross-references between the results of our analysis, the figures and the discussions.

* In other parts the paper reads almost like a lab-report where new methods, analysis, and questions are suddenly introduced. For example, at lines 329-331 (in the Results section) the three-dimensional empty space function is introduced, while at lines 302-304 an ordinal classification of the lithics is presented. Both should be in the Material and Method section.

According to the restructured sections of the manuscript, the taphonomical data pertaining the faunal and lithic assemblages have been fully described in subsections 2.1 (Taphonomy of macro vertebrate fossils) and 2.2 (Taphonomy of lithic artifacts). As for the methods, we introduced all the statistics that we applied in subsections 5.1 (Formation processes) and 5.2 (Post-depositional processes).

* Section 2 presents introduce part of data and the background, but never really specify a research question. The subsequent sections and paragraphs describes details of the data (lines 132-160) and a review of PPA (lines 164-206), and we find an more or less explicit hypothesis phrased only at the paragraph starting

at line 207. I understand the authors wanted to use a specific jargon (CSR) to better explain their null hypothesis, but I think the link between analyses and research question should be presented earlier, perhaps as a small paragraph at the end of sections 2.1 and 2.2. To further augment my point with an example, the separation between "cases" and "controls" (line 226) its far easier to grasp in relation to the data if presented when the distinction between TR1 vs TR2&TR3 are presented at lines 79-80.

As noted above, we clarified our research questions in Section 1 (Introduction, l.74). Section 2 (Background) is intended to introduce previous taphonomic studies on the lithic and faunal assemblages. However, the Reviewer is right pointing out that this Section offers as well an overview and description of part of the data used in our analyses. Thus, as suggested, we added paragraphs at the end of subsections 2.1 (l.130-140) and 2.2 (l.170-178). Here we linked the rationale, the research questions and the assumptions of our analyses.

We introduced the separation between 'cases' and 'controls' in subsection 5.2 (Point pattern analysis - Post-depositional processes), because this distinction is more related to the method used to analyze the data, then to the sample materials that we used. However, as suggested by the Reviewer, we better described these categories in relation to the data and the methods (l.393).

* Presumably lines 223 to 242 is intended as the pivotal point of the paper where key research questions are presented with the appropriate formalism of PPA and the link to specific method is illustrated. The presentation, however, is a bit vague, and there is not explanations of why a specific analysis is chosen, and more crucially, what we should expect to observe for a given hypothesis. For example, in line 228 the authors state they would explore the spatial relationship between the case and the controls with a cross-K function, but do specify why is this being done and what should we expect to observe. The subsequent sentence hints something but this it is all to blurry.

In accordance with the Reviewer's comment, in Section 5 (Point pattern analysis) we first provided a general introduction to PPA methods. Thus, in Subsections 5.1 and 5.2 we described the specific PPA methods used in order to respectively tackle our two main goals. Research questions, hypotheses, methods and expected results have been properly described in these subsections.

* Similarly at lines 291-293 the author states that they conducted a cross-K function by random labelling. They then state that their aim is to "assess whether the post-depositional fractures are the result of impacts and/or frictions with rocks already present in the matrix", but again they do not specify what we should expect if the fractures were indeed caused by these rocks or not. After showing that they failed to reject their null-hypothesis they state that "stochastic post-depositional processes are most probably accountable of the [...] distribution of the fractures". I found this unsatisfying, as it does not truly answer whether the rocks caused these fractures or not.

As commented above, we agree with the Reviewer and we provided better descriptions and links between research questions, methods and expected results, discussion.

As for the spatial analysis of fractured lithic artifacts, we removed it from the manuscript. We restricted the analysis of taphonomic features to the distribution of Fe-Mn oxids. We believe that this is the most representative feature in regards to the hypothesis of possible karstic water flows. The presence of Fe-Mn oxides is also the only feature we could compare between lithics and fossils. Thus, we decided to remove the analysis of the fractures from the manuscript, which we believe is now more fluid.

* First of all, I am strong advocate of open-data and reproducible research, so R scripts and raw data should be deposited either as an electronic supplement material or on some online data/code repository. This is my personal view, but I

think when possible this should be compulsory, as it facilitates the reviewing process, but it also enable more people to use similar method to their data. The authors do provide a fairly good description of the methods they used, but this sometime not sufficient, as some details (e.g. the choice of the edge correction formula) might not be specified.

We totally agree with the Reviewer. Consequently, we published a compendium of data, source code and text in an online repository (DOI:).

Regarding the edge correction method, as commented earlier, we implemented Ripley's isotropic edge correction and we clearly described it in Section 5 (Point pattern analysis, 1.332-335).

* In terms of actual analysis, I was a bit surprised by the small number of Monte-Carlo simulations ($n=99$) they used in their analysis. Given the deviation from the confidence envelope seems quite large, I don't think the results will change much but I would increase this for at least one order of magnitude.

Indeed, for pointwise envelopes, this test has exact significance level $\alpha = 2 * nrank/(1 + nsim)$. Thus, in order to have a small significance level (0.01) with 1 rank, we raised the number of Monte Carlo simulations to 199.

* I did appreciate the authors attempt to apply 3-dimensional analysis in archaeological data, but I don't think the assumptions of the standard 3D K function holds here. The problem is that "horizontal" and "vertical" dimensions are part of distinct processes that are nonetheless treated equally, as in the 3D K function distances are measured together. To put in simpler terms 3d K function equally assesses pairs of objects that are 20 cm apart horizontally (which might be the result of the same depositional event) from pairs that are 20 cm apart vertically (which might be more likely the result of two distinct events. Taphonomy, deposition rate, and the morphology of terrain further complicates things, but clearly a spherical buffer is not appropriate, nor a 3d homogenous Poisson a valid null hypothesis in my opinion.

On this point: "horizontal" and "vertical" dimensions are part of distinct processes, we think that it is unlike that a process (depositional or post-depositional) would work only on two of the three spatial dimensions. Splitting the space in planes is indeed analytical convenient, but I think any process is more likely working on 3D space. For example, a water flow in a karstic system would eventually unburied and move fossils from the place A to B, according to the direction of the flow. The locations of A and B could significantly differ in the 3-dimensional space. Thus, I believe 3D spatial analysis should be applied whenever possible. Unfortunately, as we acknowledge in Section 7 (Discussion, 1.660) and commented earlier, "spatial point pattern statistics are at the moment not fully equipped to analyze three-dimensional patterns".

* Given that the central point of the paper is not this analysis, I would just remove everything pertaining the 3d K-function. On a related note, the authors state on line 271 that they "extruded from subsequent analyses the covariate effect of the third coordinate". I am not sure what they mean by this.

As commented above, the vertical distribution of finds and Fe-Mn oxides has been analyzed in detail and presented in the added Section 4 (Vertical distribution). The 'nearly normal' vertical distributions do not suggest strong gravitational effects. Thus, we could proceed analysing the two dimensional point patterns, excluding the covariate influence of the third coordinate.

Regarding the 3D analysis of taphorecords, given the technical limitations of the software and the very small sample of TR1, we removed from the manuscript the spatial point pattern analysis of the three groups of fossils.

* The authors use extensively the bivariate version of the K function using the random labelling (in contrast to the alternative random shift) null model. This is a moot point, but I see random labelling as situations where positions are

fixed but attributes can change, and random shift as positions can change but attributes are fixed. In this case I think the former is more appropriate, but I would like to know why the author choose one over the other.

As for the random labeling model, we first introduced it in Section 5 as a method that assumes "the same process in determining the pattern for different types" (l.328). Thus, in order to clearly introduce the 'random labelling' hypothesis in the context of our study, we added the following paragraph in subsection 5.2 (Point pattern analysis - Post-depositional processes): "Like in applications of point pattern analysis in spatial epidemiology {Diggle2003,Gatrell1996}, 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 controls 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. [...] 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".

* In several points across the paper (e.g. lines 327, 400, 424-425, 443-444) the authors interpret their failing in rejecting their null hypothesis as a support for the null hypothesis. This is incorrect. The fact the empirical K-function is within the confidence envelope does not mean that the pattern is random. It simply means that we cannot state that it is not random, which is very different. If randomness, or better put a homogenous Poisson process is a candidate hypothesis that they wish to select over alternative explanations, they should use an alternative inferential framework (i.e. information-criteria based model-selection, see Eve and Crema 2014, which the authors cite, for an example).

In agreement with the Reviewer's comment, we properly introduced the null hypotheses (Section 5, l.343) and accordingly presented and discussed the results of the analyses (Section 6 and 7).

***Highlights (for review)**

Highlights

- * We stressed the need for a taphonomic perspective in spatial analyses of archaeological sites.
- * Point pattern analysis offers new analytical opportunities for the study of site formation processes.
- * Point pattern analysis is applied to the lithic and faunal assemblage of the biochronologically dated site of Pirro Nord 13.
- * Results support the stratigraphic integrity of the site.

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 perspectives 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 deposit occurs as filling of a karst structure that is currently exposed. We investigated the distribution of the archaeological and paleontological assemblage, as well as the distribution of identified taphonomic features, in order to evaluate 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.

Keywords: Spatial analysis, Point pattern analysis, Site formation processes,

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1. Introduction

2 Studies of site formation processes and spatial analyses have long recognized
3 the role of post-depositional factors in affecting the integrity of archaeological
4 assemblages (Hodder and Orton, 1976; Petraglia and Nash, 1987; Schick, 1984,
5 1986; Schiffer, 1972, 1983, 1987; Wood and Johnson, 1978). More recently, a
6 number of scholars have stressed the importance of establishing the degree of
7 disturbance to archaeological deposits to fully comprehend the archaeological
8 record (Dibble et al., 1997; Djindjian, 1999; Texier, 2000).

9 Beside geoarchaeological techniques, several archaeological and paleontolog-
10 ical methods are widely applied to characterize the processes involved in the
11 formation of an archaeological site and to assess any post-depositional ‘back-
12 ground noise’. Taphonomy moves from its original definition (Efremov, 1940)
13 to a wider conceptual framework, targeting vertebrate assemblages, as well as
14 taphonomic entities produced by human behaviour (Domínguez-Rodrigo et al.,
15 2011). Moreover and often in joint effort, from different spatial perspectives,
16 fabric analysis (Benito-Calvo and de la Torre, 2011; Bernatchez, 2010; Bertran
17 et al., 1997; Bertran and Texier, 1995; Domínguez-Rodrigo et al., 2014c; Leno-
18 ble and Bertran, 2004; McPherron, 2005; de la Torre and Benito-Calvo, 2013);
19 refitting analysis (López-Ortega et al., 2011; Sisk and Shea, 2008; Villa, 1982);
20 vertical (Anderson and Burke, 2008) and size distribution analysis (Bertran
21 et al., 2006, 2012; Petraglia and Potts, 1994) offer meaningful contributions in
22 the unraveling of site formation and modification processes.

23 The importance of spatial statistics in the interpretation of archaeological
24 sites has long been recognized (Hodder and Orton, 1976; Whallon, 1974). How-
25 ever, studies of spatial patterning mostly focus on the behaviour of past popula-
26 tions, assuming that scatters of material culture (if not disturbed) are reflections
27 of prehistoric activities. Moreover, distribution maps still rely mainly on visual
28 examinations and subjective interpretations (Bevan et al., 2013). On the other

29 hand, quantitative methods, adopted from neighbor disciplines since the early
30 1970s (see Hodder and Orton (1976); Orton (1982); and references therein),
31 continue to promote new impulses to archaeological spatial analyses and allow
32 for the characterization of spatial patterns by adopting a more formal, induc-
33 tive approach. Recent studies (Bevan and Conolly, 2006, 2009, 2013; Bevan
34 et al., 2013; Bevan and Wilson, 2013; Crema, 2015; Crema et al., 2010; Crema
35 and Bianchi, 2013; Eve and Crema, 2014; Orton, 2004), even acknowledging
36 post-depositional effects or research biases, have continued to adopt at different
37 scales (from intra-site to regional scales) improvements in spatial statistics to
38 unravel past human behaviors from scatters of material culture. Yet, only a
39 relatively limited number of scholars have applied spatial statistics to site for-
40 mation and modification processes analysis (Carrer, 2015; Domínguez-Rodrigo
41 et al., 2014b,a).

42 In this paper, we adopt a taphonomic perspective to spatial point pattern
43 analysis of the lithic and faunal assemblages from the Early Pleistocene site of
44 Pirro Nord 13, Italy (Arzarello et al., 2007, 2009, 2012; Arzarello and Peretto,
45 2010).

46 The site (P13) provides important contributions to the ongoing debate about
47 the first hominin occurrence in Europe (Carbonell et al., 2008; Crochet et al.,
48 2009; Despriée et al., 2006, 2009, 2010; Lumley et al., 1988; Parés et al., 2006;
49 Toro-Moyano et al., 2011, 2009, 2013). A ‘Mode 1’ lithic assemblage has been
50 identified in stratigraphic association with late Villafranchian/early Biharian
51 paleontological remains. Furthermore, the presence of the Arvicoline species
52 *Allophaiomys ruffoi* correlated to the *Mymomis savini* - *Mymomis pusillus* bio-
53 zone, allows for a biochronologically refined age of between 1.3 and 1.6 Ma,
54 making P13 one of the most ancient locality with human evidence currently
55 known in Western Europe (Lopez-García et al., 2015).

56 The paleontological and archaeological remains are preserved inside a com-
57 plex karst system, exposed and partially destroyed by mining activities of a
58 Mesozoic limestone quarry. The fissure P13 is a vertical fracture located at
59 the stratigraphic boundary between the Mesozoic limestone and the Pleistocene

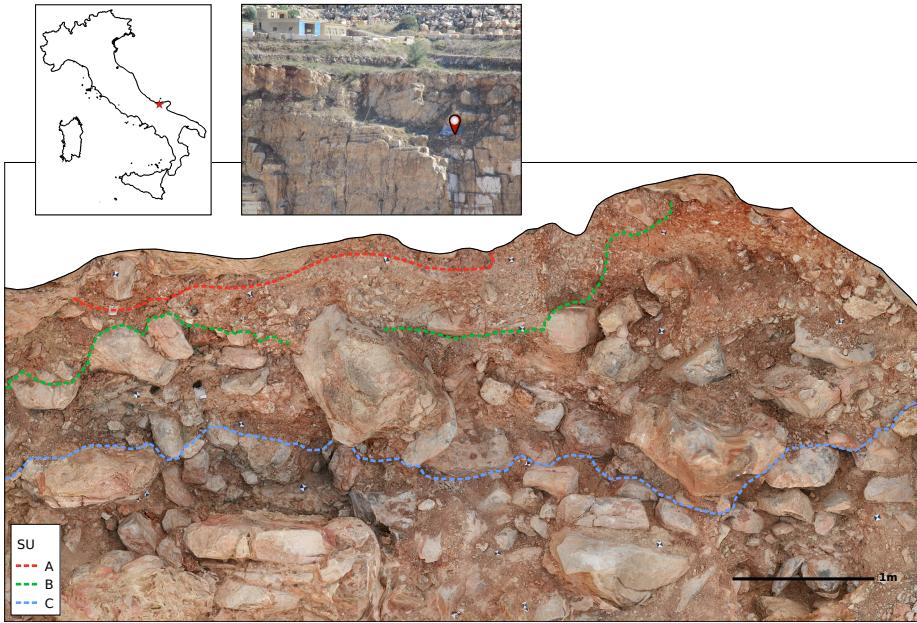


Figure 1: Location of the Pirro Nord (P13) site inside the Cave Dell'Erba quarry and view of the excavated area (2013), with marked sedimentary units.

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

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

⁷⁴ site.

⁷⁵ The main goal of our study is to use a taphonomic perspective in spatial
⁷⁶ data analysis, in order to evaluate degree and reliability of the spatial asso-
⁷⁷ ciation of the lithic artifacts with the faunal remains that were used for the
⁷⁸ biochronological dating of the site.

⁷⁹ By applying point pattern analysis of the spatial distribution of the lithic
⁸⁰ and faunal assemblages, we aim to

⁸¹ 1. investigate the processes involved in the formation of the Pirro Nord (P13)
⁸² deposit.

⁸³ A positive spatial association of the two types of find whould support the as-
⁸⁴ sumption, base on field observations, that the deposition of the archaeological
⁸⁵ and paleontological materials occured simultaneously, as result of subsequent
⁸⁶ mass wasting events.

⁸⁷ With the application of point pattern analysis to identified taphonomic fea-
⁸⁸ tures on the lithic and faunal assemblages, our ultimate objective is to

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

⁹⁰ Indeed, reworking and re-deposition processes could put in stratigraphic contact
⁹¹ materials from diverse provenience. The identification of taphonomic spatial
⁹² patterns allow us to model the spatial processes that produced them and thus
⁹³ propose a reconstruction of the agents involved in the formation and modifica-
⁹⁴ tion of the deposit.

⁹⁵ 2. Background

⁹⁶ With the authors' permission, we integrate in our study unpublished (Bag-
⁹⁷ nus, 2011) and published (Arzarello et al., 2012, 2014) data from previous tapho-
⁹⁸ nomic studies. A brief report is presented here.

⁹⁹ 2.1. *Taphonomy of macro vertebrate fossils*

¹⁰⁰ Taphonomic analysis (Bagnus, 2011) on macro vertebrate fossils evaluated
¹⁰¹ biostratinomic and diagenic processes and grouped faunal remains into different

102 sub-categories: three main taphorecords (TR's, *sensu* Fernández-López, 1987)
103 are defined according to different stages of bone surface modifications by phys-
104 ical and chemical agents (Tab. 1). Grouping was based mainly on weathering
105 (Behrensmeyer, 1978; Díez et al., 1999; Kos, 2003; Torres et al., 2003), abra-
106 sion (Behrensmeyer, 1991) and oxidation (Hill, 1982; López-González et al.,
107 2006; White, 1976; White et al., 2009), because these alterations prevail and are
108 widespread across all the sedimentary units.

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

117 Therefore, a hypothetical model of site formation processes has been pro-
118 posed: animals died close to the karst sinkhole and the action of heavy rains
119 transports sediments and partially articulated carcasses into the fissure. The
120 rapid burial of fossils is confirmed by the general low degree of weathering. Karst
121 erosional processes are responsible for the very large percentage of fractured fos-
122 sils, as a result of the collapse of rock blocks from the vault. The TR1 group of
123 fossils points to internal water-flows, reworking and transportation of already
124 fossilized bones. Finally, manganese oxides that give the external widespread
125 black color to all the fossils, stones and part of the lithic artifacts are products
126 of the freatic water fluctuation.

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

131 Taking into account the inherent spatial properties of taphonomic processes,
132 we assume that taphogenic products (*sensu* Fernández-López, 2000) in space are

Table 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

¹³³ not mutually independent and that entities which are close to each other, are
¹³⁴ likely to have followed the same genesis.

¹³⁵ Thus, in order to tackle our second objective, we analyze the spatial distribution
¹³⁶ of Fe-Mn oxides on the fossils, since the cause of their formation may derive
¹³⁷ from the action of circulating waters. Three ordinal degrees of oxidation (low,
¹³⁸ medium and high) are recognized, based on its aspect, intensity and extension.
¹³⁹ We assume that spatial aggregation of heavily-coated faunal remains (and con-
¹⁴⁰ sequently segregation from non-oxidized ones) is an indication of interactions
¹⁴¹ with karst water flow.

¹⁴² 2.2. *Taphonomy of lithic artifacts*

¹⁴³ The degree of natural alterations (thermal, tribological and chemical) of the
¹⁴⁴ lithic artifact surface, as a result of contact with the sediments, is a valuable
¹⁴⁵ index of integrity of the depositional context and it can usefully support spatial
¹⁴⁶ analysis in reconstructing both the past environmental conditions and the site
¹⁴⁷ formation processes (Burroni et al., 2002).

¹⁴⁸ According to a recent review of preliminary technological analyses (Arzarello
¹⁴⁹ et al., 2012, 2014), the lithic assemblage shows a general good state of preserva-
¹⁵⁰ tion. If we consider the degree of patination as a good indicator of the intensity,
¹⁵¹ and not necessary of the duration, of chemical processes to which the deposit
¹⁵² has been subjected (Burroni et al., 2002), artifacts undergo non-homogeneous
¹⁵³ interactions with chemical agents. Besides fresh artifacts, many of the speci-
¹⁵⁴ ments (35%) bear Fe-Mn coatings (Fig. 2a). Iron-manganese, as well as white

155 superficial patina (5%), seems to equally affect artifacts of different flint raw
156 materials, more readily on those with a porous structure (Fig. 2b).

157 Macroscopic observations of tribological features on the assemblage reveal
158 mint to sharp, not rounded, artifact ridges and edges. Post-depositional frac-
159 tures affect 20% of the lithic material (Fig. 2c).

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

162 As particle size distribution of lithic assemblages has great implications in
163 interpreting site formation processes (Bertran et al., 2012), systematic screen-
164 washing of sediments was carried out in order to guarantee recovery of lithic
165 debris, even though a very low percentage of small-size specimens has been
166 noted. This result can be preliminary explained either as a function of the
167 mode of knapping, which did not produce a lot of debris, or is more likely due
168 to natural post depositional processes (washed-out effect of low energy agents),
169 prior to final burial, possibly outside the karst fissure. Moreover, the dimensional
170 analysis of the complete lithic assemblage (Fig. 2d) does not show sorting effects.

171 We analyse the spatial distribution of taphonomic features on the lithic
172 assemblage, considering that various natural mechanisms, disturbing the spa-
173 tial arrangement of artifacts and sediments, will produce distinctive combina-
174 tions of wear features on the surfaces of lithic artifacts (Burroni et al., 2002).

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

180 3. Spatial data collection and sampling

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

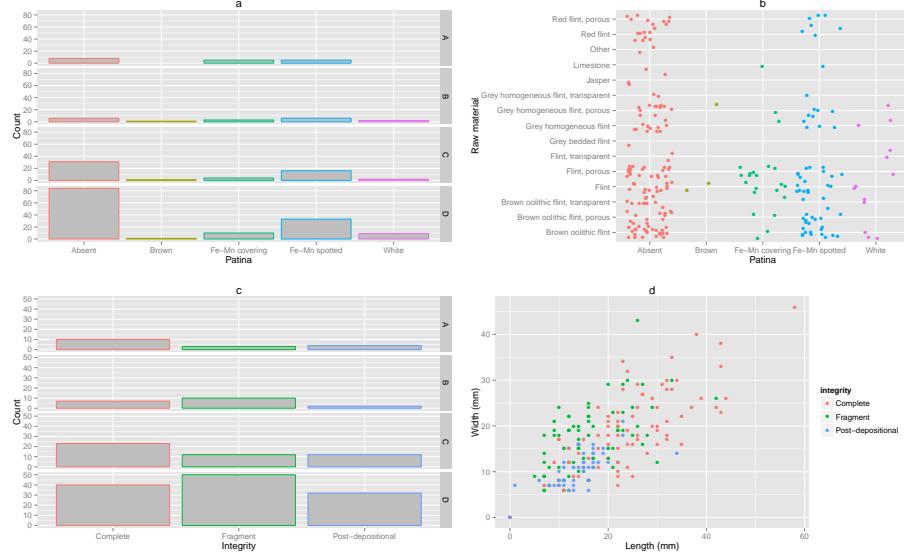


Figure 2: Frequency of patinae on the lithic assemblage (a) and their distribution on raw materials (b); frequency of fractures (c); scatterplot of artifact dimensions (d).

184 From the first excavation season, a grid of 1 square meter units has been set.
 185 Since 2010, the three-dimensional coordinates of the finds are recorded with a
 186 Total Station, which replaced the use of a water level. Orientation (dip and
 187 strike) of coordinated faunal remains (length ≥ 2 cm), geological clasts (length
 188 ≥ 5 cm) and all the lithic artifacts is estimated with a 45 degree of accuracy,
 189 which is not precise enough for detailed fabric analysis.

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

194 Focusing on SU's C and D, we scale the windows of analysis according to
 195 the extension of excavated areas for each SU, excluding the presence of the
 196 large blocks of rock. We reduce in this way the impact of the Modifiable Area
 197 Unit Problem (MAUP) in point pattern analysis (Openshaw, 1996), especially
 198 insidious in this study due to the particular geological setting of the site. The

¹⁹⁹ analyzed areas of SU's C and D are respectively 4.34 m^2 and 5.82 m^2 .
²⁰⁰ During 6 years of excavations, more than 1600 of 2152 macro vertebrate
²⁰¹ fossils have been spatially recorded: 471 from SU C and 916 from SU D. How-
²⁰² ever, Bagnus (2011) conducted taphonomical analysis on fossils recovered dur-
²⁰³ing the 2007 to 2010 field seasons and only 593 of these are classified in one
²⁰⁴of the three taphorecords (Tab. 1). Our sample includes 135 coordinated el-
²⁰⁵ements of the 282 analyzed fossils from SU C. From the total number of 366
²⁰⁶lithic artifacts collected until the 2014 field season, 147 have been recorded with
²⁰⁷three-dimensional coordinates. Our sample includes 34 lithics from SU C and
²⁰⁸84 from SU D. From the micro mammal assemblage, we include in this study
²⁰⁹only the *Allophaiomys ruffoi* species. Of the 53 arvicoline teeth collected from
²¹⁰the screen-washed sediments, 49 have secure provenance attribution from SU B
²¹¹($n = 2$), C ($n = 14$) and D ($n = 33$) (Lopez-García et al., 2015). However, the
²¹²*A. ruffoi* point pattern does not represent the exact distribution of the remains.
²¹³Indeed, we randomly displaced ($r = 0.5$) each point indicating the provenience
²¹⁴of the sieved sediment.

²¹⁵ 4. Vertical distribution

²¹⁶ The vertical distribution of finds is a key factor in the analysis of site forma-
²¹⁷tion processes. Many processes can be well approximated by a ‘nearly’ normal
²¹⁸distribution. However, testing the appropriateness of this assumption is an es-
²¹⁹sential step in spatial data analysis. Strongly right skewed distribution would
²²⁰occur in case of a non-uniform vertical distribution of finds; thus requiring the
²²¹analysis to acknowledge the covariate effect of gravity in the observed spatial
²²²pattern.

²²³ The vertical distribution of finds within SU C is globally unimodal, roughly
²²⁴symmetric (slightly left skewed), in spite of some outliers (Fig. 3a). It ‘nearly’
²²⁵approximates the maximum-likelihood fitting of a normal curve (red line) with
²²⁶mean (μ) = -1.53 m and standard deviation (σ) = 0.27 m . However the Shapiro-
²²⁷Wilk normality test reject the null hypothesis of a gaussian distribution ($p -$

228 value = 0.0005213). On the other hand, the Q-Q plot (Fig. 3b) shows deviations
229 from the theoretical normal distribution (red line) between one (68.27% of the
230 sample) and two (95.45%) standard deviations from the mean. The S-shaped
231 empirical distribution recalls its left skew.

232 The global vertical distribution of finds resemble that of the faunal assem-
233 blage, due to the weight of the latter on the sample data ($n = 471$). The
234 distribution of the lithic artifacts is more left skewed, while the small sample
235 of micromammals follows a multimodal distribution with a prominent peaks
236 at -1.2 m (Fig. 3a). Although the difference in size of the two samples, it is
237 worth notice that the mean value of the vertical distribution of the *A. ruffoi*
238 species is very close to that of the lithic artifacts (Welch Two Sample t-test
239 $p - value = 0.5803$).

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

248 Compared with the global distribution, the vertical distribution of lithic
249 artifacts slightly skews to the right. Nevertheless, the Shapiro-Wilk test fails
250 to reject the normality hypothesis ($p - value = 0.2742$). On the other hand,
251 the micromammals distribution is multimodal and slightly shifted to the right
252 (Fig. 3c). Its mean (-2.284 m) is quite close to the mean of the lithic sample
253 (-2.423 m). However, the Welch t-test rejects the hypothesis of two equal sam-
254 ple means ($p - value = 0.01414$). If we cannot state that the two distributions
255 have the same mean, we remark the highest density of both the assemblages at
256 around -2.5 m.

257 As for the vertical distribution of the identified taphonomic features on the
258 lithic and faunal assemblages, figures 4a,b illustrate the overall distribution of

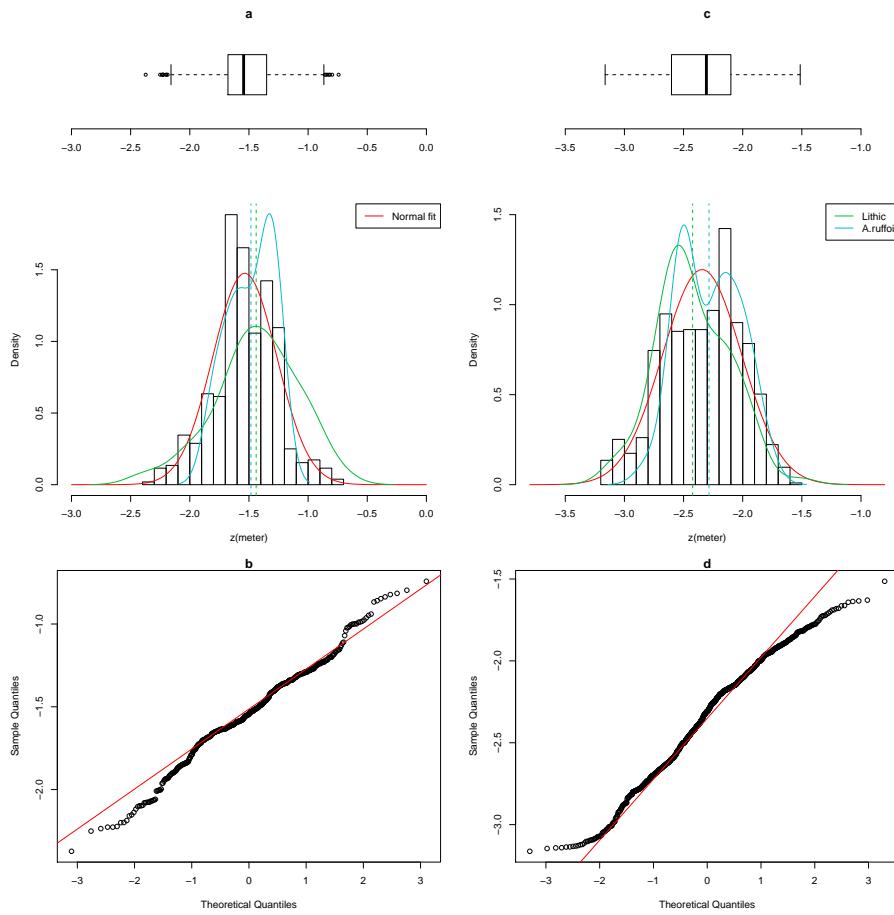


Figure 3: Vertical distribution of finds in SU's C (a,b) and D (c,d).

259 patinae on the lithic artifacts, across SU's C and D. The histogram shows the
260 increasing number of finds between the two sedimentary units. This trend is
261 reflected as well in the rise of Fe-Mn patinated artifacts (41% in SU C and 45% in
262 SU D), compared to non-patinated ones (respectively 50% and 48%). The kernel
263 density estimation (blue and green lines) shows a slightly higher occurrence of
264 patinated artifacts at the lower part of the sequence (below -2.5 m), whereas in
265 SU C (up to -2 m) there is no evident preference in the vertical distribution of
266 patinae. The higher density of patinated artifacts, linked to the concentration
267 of lithics observed in figure 3c at about -2.5 m, can be localized in a restricted
268 spot at the bottom right corner of the excavated area (Fig. 4a).

269 Restricting the analysis to SU C, the vertical distribution of coordinated
270 macro vertebrate fossils analized by Bagnus (2011) spans 71% of the elevation
271 range of the complete assemblage from the same SU. However, beeing only the
272 29% of the population, we acknowledge that our sample cannot be considered
273 representative.

274 The densities of the low and medium rate of oxides resemble the general dis-
275 tribution (Fig. 4c,b). Low values follow a 'nearly' normal distribution (Shapiro-
276 Wilk normality test $p-values = 0.2186$). The density of high oxidized remains
277 (54% of the sample) draws a left skewed distribution, with a peak at about
278 -1.3 m; whereas fossils with a medium degree of oxides are skewed to the right.
279 However there is no clear preference for oxides to occur deeper in the sequence.
280 The mean values are very close to each other and lower values of oxides are
281 more dense at the bottom of the SU.

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

286 Although our study is constrained by the small sample of fossils and by its
287 limited spatial extension to SU C, the analysis of the vertical distribution of Fe-
288 Mn oxides in the faunal and lithic assemblages does not show any clear global
289 pattern. Indeed, even taking into account the localized cluster of artifacts at the

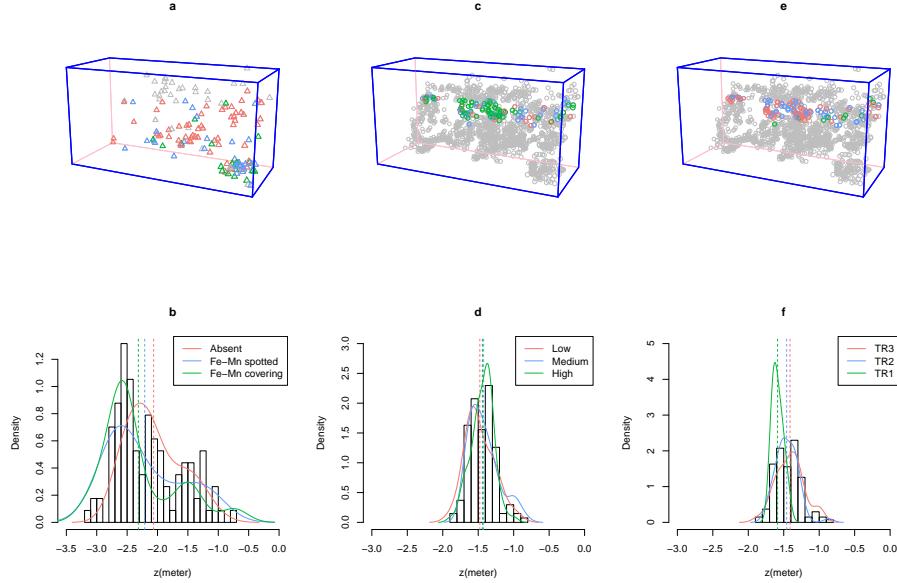


Figure 4: 3D and vertical distributions of Fe-Mn patinae on the lithic assemblage from SU's C and D (a,b); oxides (c,d) and taphorecords (e,f) from the faunal sample.

very bottom of SU D (Fig. 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 SU's 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.

5. Point pattern analysis

The observed patterns of the archaeological and paleontological remains within SU's 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

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

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

318 Multiple scales of second-order patterning and the probability of a stochastic
319 occurrence are explored by the Ripley's K summary function (Ripley, 1976,
320 1977) and derivates, for both univariate and bivariate point patterns. The K
321 function is designed to identify the relative aggregation and segregation of point
322 data at different scales. The univariate $K(r)$ function measures the expected
323 number of events found up to a given distance r around an arbitrary event.
324 By comparing the estimated value $\hat{K}(r)$ to its theoretical Complete Spatial
325 Randomness (CSR) value, it is possible to assess what kind of interaction exists
326 between events. The bivariate function, or cross-type $K_{ij}(r)$ function seeks to
327 evaluate, at each distance r , the spatial relation between two types ij of observed
328 events. In this case, the definition of the null hypothesis uses a randomization
329 technique of either the location of one of the types (random shift hypothesis),
330 or the type itself of the event at each point, preserving the original location
331 (random labeling hypothesis) (Goreaud and Pélissier, 2003). The former aims to
332 evaluate the spatial relationship between patterns of two independent processes,
333 while the latter assumes the same process in determining the pattern for different

334 types.

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

339 Monte Carlo simulations (Robert and Casella, 2004) are used to generate
340 pointwise critical envelopes of random expected values for the null hypothe-
341 ses, providing an adequate level of statistical significance. We choose a small
342 significance level ($\alpha = 0.01$ obtained with 199 simulations), due to the higher
343 possibility to commit a Type 1 error by testing our hypotheses. Values of the em-
344 pirical distribution (black solid line) are plotted against the theoretical Poisson
345 distribution (red dotted line) and the simulated global envelope of significance
346 (grey area). For $K(r)$, when the solid line of the observed distribution is above
347 or below the shaded grey area, the pattern is significantly clustered (points are
348 closer together than would be expected for a complete random pattern) or dis-
349 persed. For $K_{ij}(r)$, the benchmark value πr^2 is consistent with independence
350 between the points of type i and j , and does not imply a Poisson distribution.

351 *5.1. Formation processes*

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

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

362 The intensity of the lithic and faunal assemblages is non-parametrically es-
363 timated by first performing a Gaussian smoothing kernel of their distributions,

364 for both SU's. Likelihood cross-validation bandwidth, which assumes an in-
365 homogeneous process, is selected for each pattern. Edge correction is applied
366 using the method of Diggle (1985). Then, Berman's Z_2 test is used to deter-
367 mine whether or not the intensity depends on a spatial covariate Z , assuming
368 that the spatially varying (inhomogeneous) intensity is a function of Z . Thus,
369 in order to measure the strength of dependence on the covariate, we use the
370 Receiver Operating Characteristic (ROC) curve. Spatially adaptive smoothing,
371 nearest-neighbour density and scan tests have been used in order to assess for the
372 evidence of hot spots in the intensities of the unmarked point patterns. Estima-
373 tions of the $K(r)$ and the Kaplan-Meier corrected empty-space $F(r)$ functions
374 provide further methods for the interpretation of the distributions.

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

389 *5.2. Post-depositional processes*

390 In order to evaluate the degree of post-depositional disturbance of the de-
391 posit, the spatial dependence of observed taphonomic features is assumed to
392 be the expression of a related diagenetic process. Measured phenomena that
393 are closer together in space, tend to be more related than those further apart

394 (Tobler, 1970).

395 Like in applications of point pattern analysis in spatial epidemiology (Diggle,
396 2003; Gatrell et al., 1996), we distinguish between *cases* and *controls*. The
397 distribution of cases of a certain taphonomic alteration can be regarded as the
398 realization of a diagenetic point process, whereas controls points refer to non-
399 altered remains. In a conditional analysis of a spatial case-control study the
400 locations are fixed covariates, and the taphonomic status is treated as a random
401 variable. The simplest null model (*random labelling*) is that the taphonomic
402 status of each find is random, independent and with constant risk of occurrence.

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

414 All the spatial analyses were performed using the *spatstat* package (Baddeley
415 et al., 2015) in R statistical software (R Core Team, 2015).

416 A repository containing a compendium of data, source code and text is
417 archived at the DOI: 10.5281/zenodo.51764

418 **6. Results**

419 *6.1. Formation processes*

420 Figures 5c,d show the smoothing kernel estimation of the faunal assemblage
421 intensity respectively in SU's C and D. Lithic artifacts and micromammals re-
422 mains of the *A. ruffoi* species are superimposed on it. The visual assessment of

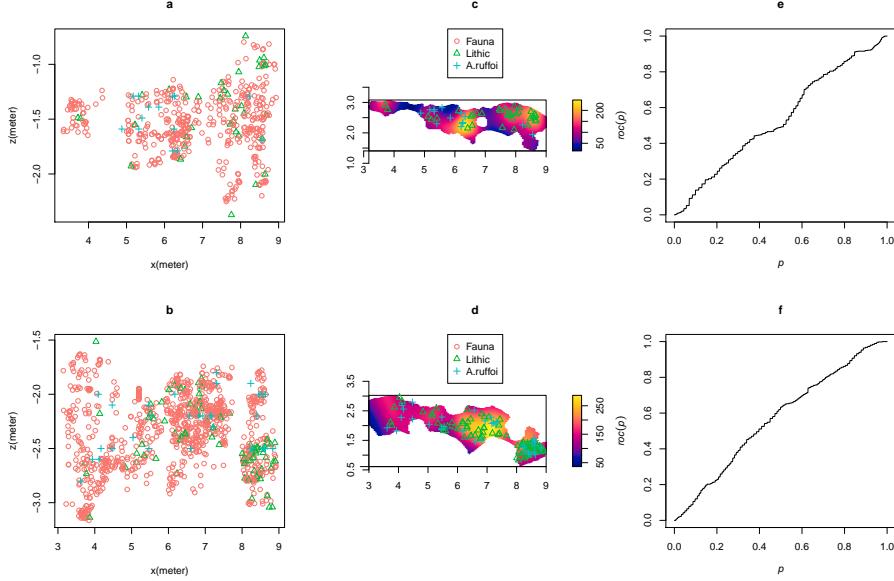


Figure 5: Scatterplot of finds from SU's C (a) and D (b); Smooth density estimation of the faunal assemblage and distribution of lithic artifacts and *A.ruffoi* remains in SU's C (c) and D (d); ROC curves for the covariate x coordinate in SU's C (e) and D (f).

423 the plot suggests positive spatial association between the three types of finds.
 424 Higher intensities in the distributions are evident at specific values of the x co-
 425 ordinate ($6 < x < 7$ and $8 < x < 9$), in both the sedimentary units. Yet,
 426 a concentration of artifacts, already observed in figure 3c and 4a,b, is evident
 427 at the lower right corner of SU D (Fig. 5e). Such higher densities of finds
 428 are clearly showed as well in the scatterplots of the projected third coordinate
 429 (Fig. 5a,b). Notably, the thickness of the sedimentary unit cannot be accounted
 430 to be responsible for those hot spots with higher density of finds. Neither the
 431 apparent inhomogeneous intensities along the x axes is supported by the ROC
 432 curves (Fig. 5e,f). Even if Bermans's Z_2 tests suggest significant evidence of de-
 433 pendence on the x covariate, the ROC curves show that it does not have strong
 434 discriminatory power.

435 Figures 6a,d show the resulting p-values of likelihood ratio scan test statistic.
 436 The test detects differences in the densities of the distributions, showing zones

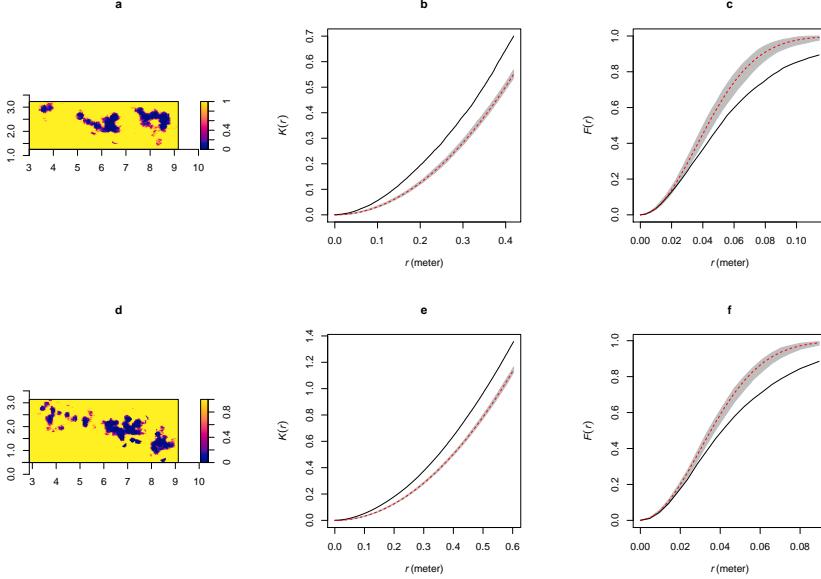


Figure 6: p-values of the likelihood ratio scan test, with logarithmic colour scale, for SU's C (a) and D (d); pointwise envelopes of the homogeneous $K(r)$ and $F(r)$ functions for unmarked finds from SU's C (b,c) and D (e,f).

437 with high abundance of finds. The estimated homogeneous $\hat{K}(r)$ and $\hat{F}(r)$
 438 functions are consistent with this result. For both SU's C (Fig. 6b,c) and D
 439 (Fig. 6e,f) they suggest strong deviation from the null hypothesis of CSR towards
 440 aggregation, at any scale.

441 In analysing a point pattern, it is confounding and it may be impossible
 442 to distinguish between clustering and spatial inhomogeneity (Baddeley et al.,
 443 2015). Given the context of the site, and the results of our non-parametric
 444 analyses, we proceed considering the distributions of finds as the results of clus-
 445 ter homogeneous processes. The bivariate version of the homogeneous $K_{ij}(r)$
 446 and $G_{ij}(r)$ function allow us to statistically test the hypothesis of aggregation
 447 between the types of remains.

448 In figure 7, the top line of panels (a,b,c) shows the ordinary estimations of
 449 the K function for the three types of finds (Fauna, Lithic and *A. ruffoi*) from
 450 SU C. Panel 7a resembles figure 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.

The middle and bottom lines of panels in figures 7 show estimations of the homogeneous cross-type K and G functions for all pairs of type i and j . Interestingly, figure 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. 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 suggest that any artifacts 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. 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 figure 8 (a,b,c) shows estimations of the $K(r)$ function for the three types of finds from SU D. Panel 8a confirms the same clustering trend of the faunal assemblage. Analogous to the distribution of finds from SU C, the global pattern is mostly weighed on the faunal assemblage (Fig. 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 $K_{ij}(r)$

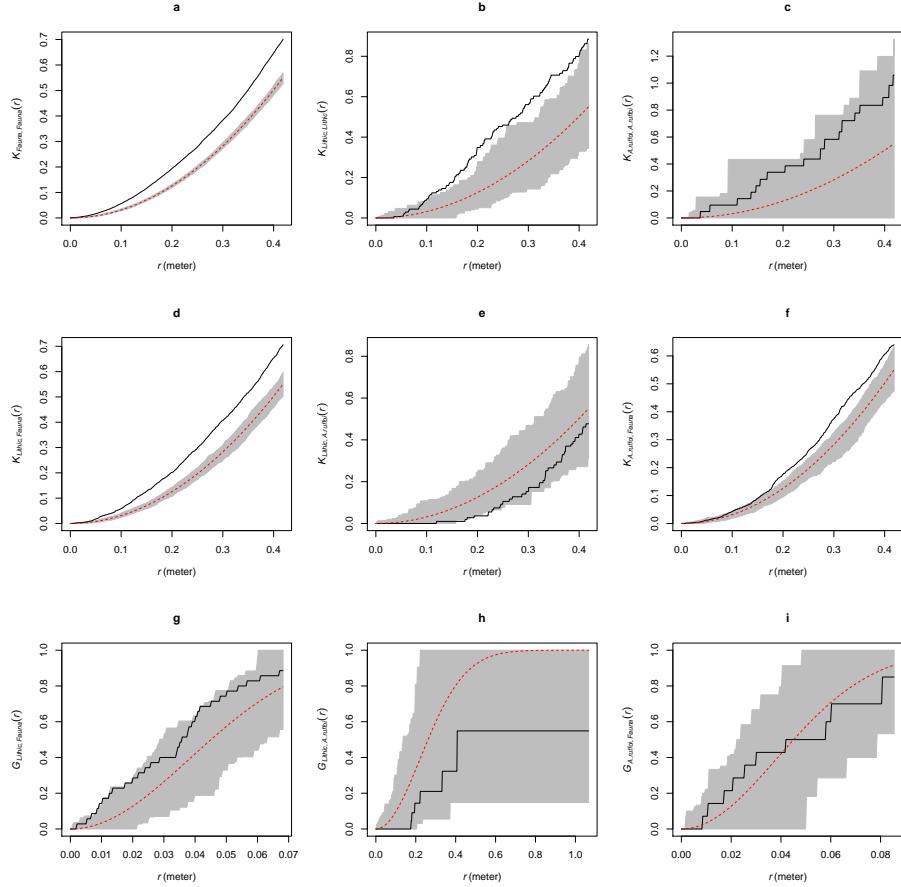


Figure 7: Pointwise envelopes of the homogeneous cross-type $K_{ij}(r)$ and $G_{ij}(r)$ functions for all pair of type i and j in SU C.

482 function support significant positive correlation between the lithic artifacts and
483 the *A. ruffoi* remains (Fig. 8e). Thus, they occur closer than expected in the
484 case of independent distributions. Panel 8f shows the same positive correlation
485 also between micro and macro mammals for $r > 0.2$. The panels 8d,g show
486 as well significant positive aggregation between lithics and fossils for values of
487 $r > 0.1$. In addition, the estimated $\hat{G}_{ij}(r)$ function offers a closer view of the
488 distribution. For values of $r < 0.1$, it fails to reject the hypothesis of indepen-
489 dence.

490 *6.2. Post-depositional processes*

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

496 Figure 4a does not suggest segregation of patinated and non-patinated lithics.
497 If we perform random labeling of the presence of Fe-Mn (spotted and covering)
498 with its absence in both the stratigraphic units, the outputs of the cross-type
499 function (Fig. 9a, b) show that the observed altered artifacts are, with a 0.01
500 level of significance, randomly and independently located in SU C. The pos-
501 tive discrepancy between the estimated $\hat{K}_{ij}(r)$ and the benchmark πr^2 indicate
502 aggregation of cases and controls, but it lies within the grey envelope of the
503 *random labeling* hypothesis. Conversely, patinated and non-patinated lithics in
504 SU D appear to be closest to each other than expected for the null hypothesis.
505 In this unit the observed $\hat{K}_{ij}(r)$ function over-exceeds the envelope at values of
506 $r > 0.4m$, hence it indicates statistically significant aggregation. Such pattern
507 statistically confirms the visual assessment of figure 4a. Consequently, oxidized
508 and non-oxidized artifacts most probably occur in SU D well aggregated in
509 space, while their aggregation is not statistically significant in the above unit.

510 We could not compare the oxidation patterns between lithics and fossils from
511 SU D, because the taphonomic analysis of Bagnus (2011) did not include fossils

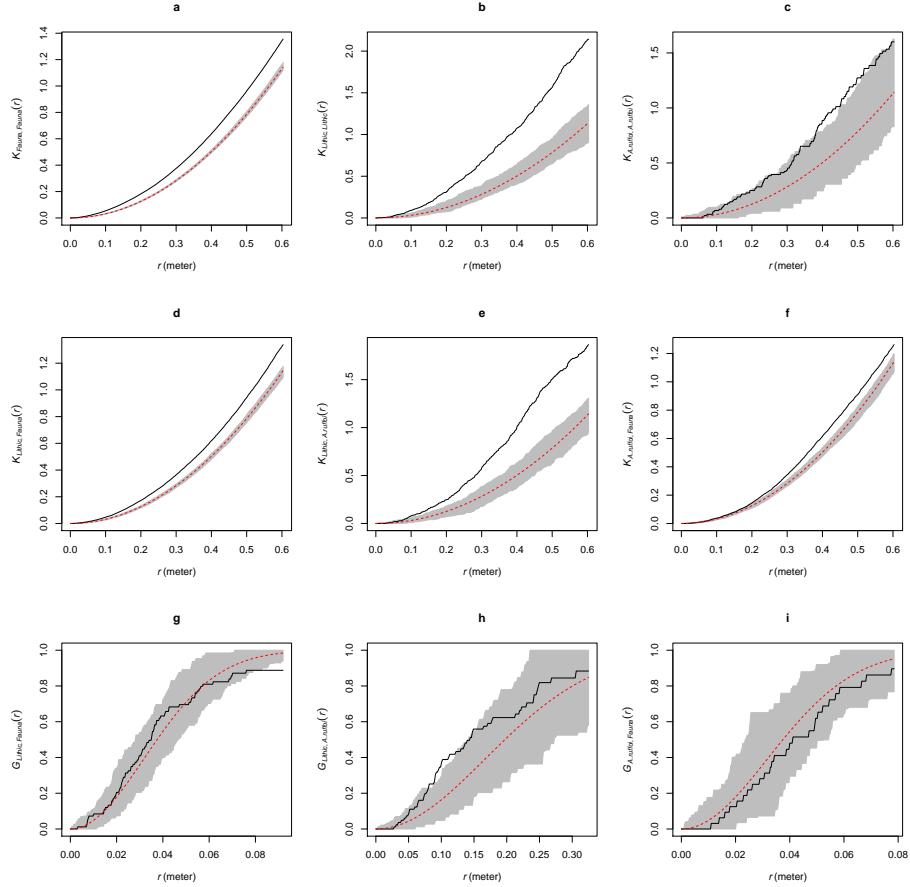


Figure 8: Pointwise envelopes of the homogeneous cross-type $K_{ij}(r)$ and $G_{ij}(r)$ functions for all pair of type i and j in SU D.

512 from this unit. Thus, we focused our analysis on SU C.

513 The distribution map (Fig. 4c) does not suggest any evident pattern. When
514 we apply random labelling of the absence of oxidation with the medium and high
515 degrees of its presence, the output of the bivariate $K_{ij}(r)$ function shows a seg-
516 regation tendency between them, but it is not statistically significant. (Fig. 9c).
517 A random and independent distribution of oxides is more plausible.

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

528 7. Discussion

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

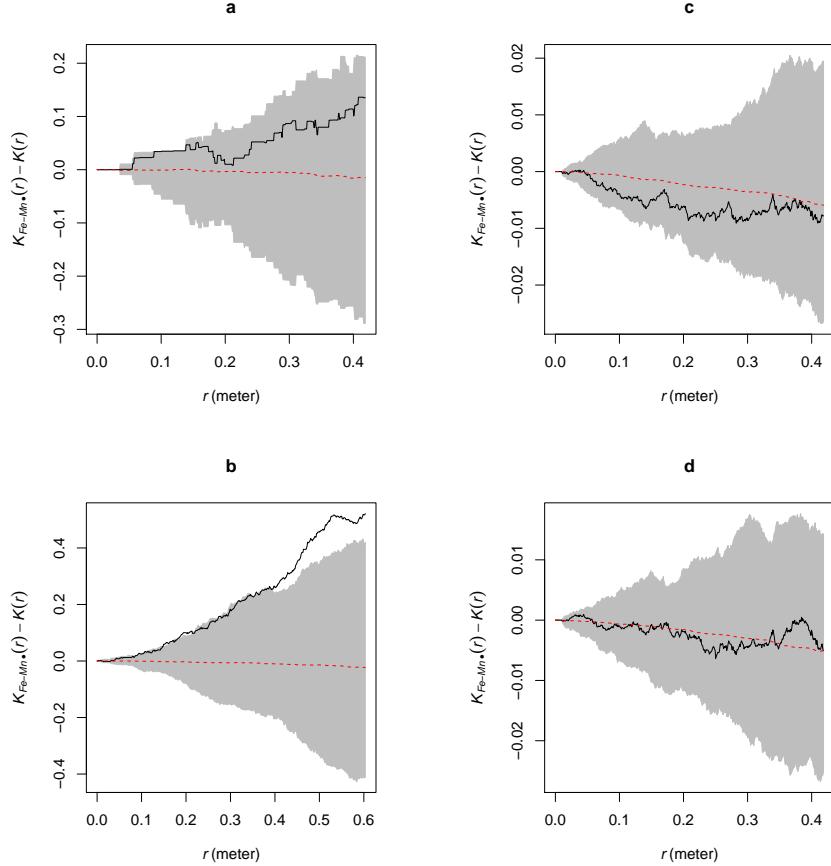


Figure 9: Pointwise envelopes of the homogeneous bivariate $K_{ij}(r)$ function, random labeling cases/*controls* of patinated lithics in SU's C (a) and D (b); oxidized fossils in SU C (c); Fe-Mn oxides on the lithic and the faunal assemblage from SU C (d).

539 *7.1. Formation processes*

540 Non-parametric analyses have been carried out in order to characterize the
541 processes responsible for the formation of the deposit. Then, we accounted for
542 the relative spatial pattern of the different types of finds.

543 The vertical distribution of the archaeological and paleontological assem-
544 blages does not appear to be affected by strong gravitational effects. On the
545 other hand, it resemble a 'nearly' normal distribution and suggests a very close
546 mean occurrence of lithic artifacts and *A. ruffoi* remains, despite the small sam-
547 ple of micromammals (Fig. 3). A visual interpretation of the projected third
548 coordinate (Fig. 5a,b) also suggests that the intensity of finds is not a function
549 of the covariate z . Moreover, higher densities are not linked to the thickness of
550 the stratigraphic units. They are clearly localized at values of $6 < x < 7$ and
551 $8 < x < 9$ in both the SU's, as showed also by figures 5c,d and 6a,d. Indeed,
552 the Berman's Z_2 test for the dependence of the point process on the spatial co-
553 variate x failed to reject the null hypothesis for SU C ($p-value = 0.00445$) and
554 D ($p-value = 1.913e - 14$). However, even if it suggests significant evidence
555 that the intensity depends on some covariate, the effect of that covariate could
556 still be weak. ROC curves (Fig. 5e,f) indicate that the x coordinate does not
557 have discriminatory power.

558 Bartlett (1963) showed that it is possible to formulate a point pattern which
559 can be equally interpreted as a Poisson inhomogeneous process, or a homoge-
560 neous cluster process. According to our non-parametric analyses, we proceeded
561 under the assumption that the processes involved in the formation of the Pirro
562 Nord (P13) deposit are homogeneous and clustered. The scan tests in figures
563 6a,d show hot spots of points, mostly localized between $6 < x < 7$ and $8 < x < 9$.
564 The cluster correlation between all the finds is significantly confirmed by the
565 estimations of the K and F functions (Fig. 6). The first lines of panels in figures
566 7 and 8 offer a type-based view of these patterns. Indeed, the estimated $\hat{K}(r)$
567 functions of the faunal assemblage (Fig. 7a and 8a), which constitute the big-
568 ger part of the analyzed sample of data, resemble the results for the complete
569 populations (Fig. 6b,e). The lithic assemblage also show significat aggregation;

⁵⁷⁰ while the small sample of *A. ruffoi* falls inside the envelope of CSR.

⁵⁷¹ Faunal remains and lithic artifacts show some overlapping when evaluated
⁵⁷² by means of Gaussian smoothing kernel (Fig. 5c,d). Positive spatial association
⁵⁷³ between fossils and lithics is statistically confirmed by the cross-type *K* and *G*
⁵⁷⁴ functions for the examined SU's (Fig. 7 and 8). Fossils and artifacts tend
⁵⁷⁵ then to occur aggregated with each other (they are closest than expected for
⁵⁷⁶ a independent process). Significant spatial proximity is also showed between
⁵⁷⁷ artifacts and micromammal remains, especially in SU D.

⁵⁷⁸ According to the results of our analyses, the stratigraphic and spatial as-
⁵⁷⁹ sociation between the types of remains should be considered as the result of
⁵⁸⁰ the same formation process. Finds occur in the clayey-sand sediment together
⁵⁸¹ with a high number of angular to sub-rounded gravels and boulder-sized rock
⁵⁸² clasts. Such a stratigraphic setting suggests repeated mass-wasting processes
⁵⁸³ (at least two events, represented by SU's C and D, which were included in this
⁵⁸⁴ study) with low degree of reworking in a relatively short span of time (Arzarello
⁵⁸⁵ et al., 2012). Rapid-moving and chaotic water-laden masses, such as mud-flows
⁵⁸⁶ or earth-flows, of soilwash and rock rubble with fossils and artifacts (Butzer,
⁵⁸⁷ 1982, p. 46), could have been triggered by intense rainfalls and trapped in the
⁵⁸⁸ karst sink-hole directly opening to the outside. Sedimentary filling would have
⁵⁸⁹ derived from the top, by gravity, directed into the empty space between the
⁵⁹⁰ large limestone blocks that made up the internal structure of the fissure. The
⁵⁹¹ thickness of the layers is likely correlated to the intensity of such events.

⁵⁹² On the other hand, the clustered distribution of all the finds cannot be linked
⁵⁹³ to the thickness of the statigraphic units. The big blocks of calcarenite, which in
⁵⁹⁴ some places transect the stratigraphic units (Fig. 1), created a complex internal
⁵⁹⁵ structure and might have influenced the direction of sediment accumulation.
⁵⁹⁶ However, sedimentation rate, driven by the rugged topography of the site, does
⁵⁹⁷ not seem to be spatially associated with the localized hot spots (Fig. 6a,d).
⁵⁹⁸ Thus, clustering might have been a correlated effect of the formation process.

⁵⁹⁹ The presence of partially articulated vertebrate skeletal elements and their
⁶⁰⁰ general low degree of weathering indicate fast burial and transport of bones from

601 nearby locations (Bagnus, 2011). A close spatial proximity between the original
602 location of the finds and the karst fissure, as well as a relatively fast burial, is
603 also corroborated by the unrounded ridges and edges of the lithic artifacts and
604 by the technological consistency of the assemblage (Arzarello et al., 2014).

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

607 *7.2. Post-depositional processes*

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

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

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

625 By applying a set of spatial statistics (namely cross-type $K_{ij}(r)$ function)
626 to the archaeological and paleontological remains, we searched for evidence of
627 localized areas, which might have been subjected to the presence of water, es-
628 pecially water-flows.

629 In SU C, the spatial distribution of Fe-Mn patinas on lithics and fossils
630 is, with a certain degree of significance, the result of independent processes

631 (Fig. 9a,c,d). We cannot state that there is aggregation (spatial proximity)
632 between oxidized finds and fresh ones. Neither the results of the bivariate K
633 function, random labeling the cases/controls of Fe-Mn coating, show segreg-
634 ation, which indicative of spatially defined diagenetic processes. In contrast, in
635 SU D (Fig. 9b), patinated and fresh artifacts occur significantly spatially aggre-
636 gated to each other for values of $r > 0.4m$. They occur closer than expected by
637 an independent process at bigger scale. However, the pattern is, with a certain
638 confidence level, independent.

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

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

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

655 Due to the small sample size, we did not apply spatial analysis to the distri-
656 bution of the three taphorecords. However, figure 4e,f suggests that fossils from
657 the TR1 group occur spatially aggregated with fossils from the TR2 and TR3
658 groups. Considering the distribution of Fe-Mn oxides on the lithic and faunal
659 assemblages, the re-elaborated TR1 (*sensu* Fernández-López, 1991, 2007, 2011)
660 might not be associated with the reworking action of water-flows and might
661 be more likely correlated to random and limited rearrangement of parts of the

662 sedimentary matrix.

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

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

677 Moreover, karst site formation processes are highly dependent on the struc-
678 ture and extension of the overall karsic system, as well on the surrounding
679 environment. The lack of information about the original characteristics of the
680 system and the reduced area of excavation strongly limit the analysis.

681 Furthermore, although the need for considering three dimensional distribu-
682 tions in site formation processes study, spatial point pattern statistics are at
683 the moment not fully equipped to analyze three-dimensional patterns, espe-
684 cially when the study-area corresponds to a three-dimensional volume with a
685 complex shape such as a karsic structure.

686 On the other hand, "one must look to non-spatial evidence to corroborate or
687 disprove theories about spatial processes" (Hodder and Orton, 1976, p. 8). The
688 integration with other taphonomic disciplines reinforces the results of spatial
689 analyses and outline new opportunities for point pattern analyses. As recently
690 remarked (Cobo-Sánchez et al., 2014), taphonomic research should be multi-
691 variate (Domínguez-Rodrigo and Pickering, 2010) and it should include spatial
692 analysis as a heuristic tool in the interpretation of site integrity. This is espe-

⁶⁹³ cially demanding when the research questions deal with past human behaviour
⁶⁹⁴ and even more so when site dating is based on the stratigraphic association of
⁶⁹⁵ artifacts and fossils.

⁶⁹⁶ **8. Conclusions**

⁶⁹⁷ The Early Pleistocene site of Pirro Nord 13 provides evidence of the earliest
⁶⁹⁸ human presence in Western Europe. Lithic artifacts have been found in a karst
⁶⁹⁹ fissure filling, together with late Villafranchian/early Biharian paleontological
⁷⁰⁰ remains.

⁷⁰¹ The main goals of our study were:

- ⁷⁰² 1. to investigate the depositional processes involved in the formation of the
⁷⁰³ deposit and
- ⁷⁰⁴ 2. to assess the degree of any potential post-depositional reworking of the
⁷⁰⁵ archaeological and paleontological remains.

⁷⁰⁶ The integration of spatial point pattern analyses with previous taphonomic
⁷⁰⁷ studies on the faunal and lithic assemblages allowed us to test different hypothe-
⁷⁰⁸ ses of site formation and modification processes.

⁷⁰⁹ On the basis of our analyses,

- ⁷¹⁰ 1. we consider the deposit as the result of subsequent events of some type of
⁷¹¹ mass-wasting process, such as a mud-flow or earth-flow, carrying rock rub-
⁷¹² ble with fossils and artifacts. The applied set of spatial analyses confirm,
⁷¹³ with an adequate level of statistical significance, this assumption, based
⁷¹⁴ on field observations, regarding the spatial association between the finds.
- ⁷¹⁵ 2. Based on our taphonomic point pattern analyses of several diagenetic fea-
⁷¹⁶ tures on the lithic and faunal assemblages, we reject the hypothesis of a
⁷¹⁷ substantial post-depositional reworking and mixture of the sedimentary
⁷¹⁸ deposit and we corroborate the stratigraphic integrity of the Pirro Nord
⁷¹⁹ 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 multiscalar 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.

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