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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

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ABSTRACT

Over the past twenty years, early hominin behavioral models have increasingly abandoned social inferences of the behaviors that created the earliest archaeological record. Behavioral reconstructions have focused mostly on the subsistence strategies that conditioned the selection of specific *loci* (i.e., central-places) and the manipulation and consumption of resources therein (i.e., raw material transport and use and carcass acquisition and processing). Part of the reason why the social component of these behaviors has been marginalized lies in the lack of proper modern analogs and also in a lack of analytical tools to link social organization to subsistence. Spatial analysis of the debris patterns generated by modern foragers (depending on their social organizations) is a potentially useful tool to understand behavior in the past. The application of statistical spatial analyses to the distribution of stone tools and bones provides an insightful approach to understand socio-economic behavior at any given site, provided a significant part of the archaeological record of a large paleo-surface has been exposed through excavation. This is the case of FLK Zinj and PTK I. A statistical spatial analysis of these sites shows a spatial interdependence between tools and bones. It also shows that the single dense cluster pattern at these sites is not a preservation issue or a sampling artifact, but the result of a socio-economic organization by early humans that differed from those currently documented among *H. sapiens* foragers.

1. Introduction

One of the main objectives of palaeoanthropological research is the identification of the socio-reproductive organization and subsistence strategies that created human behavior. During the 1970s and 1980s several models emerged to interpret socio-economic behaviors of early hominins through the analysis of the African Early Pleistocene archaeological record. Some models emphasized socio-economic behaviors that resembled those of some modern foraging populations (e.g., Leakey's [1971] "living-floors"; Isaac's [1978] "home base" or "food-sharing" models). Subsequent revisionist models, produced during the 1980s with a concern for site formation processes, were ethologically informed and argued that hominins had social behaviors that were more similar to those of other non-human primates. These include the marginal or obligate scavenger (Binford, 1981) or the passive scavenger (Blumenschine, 1986) models, the stone-cache model (Potts, 1988), the "chimpanzee-nesting" model (Sept et al., 1992), or the "refuge" model (Blumenschine et al., 1991).

In the past 30 years, scholars have abandoned social and functional interpretations of early sites, largely due to the information gap between the reconstruction of site formation, through taphonomic analyses of archaeological materials, and the hominin socio-economic organization required to sustain any of the above models. Isaac's (1983) "central-place foraging" model de-emphasized social aspects of his previous model and Cavallo (1998) managed to reconcile it with passive scavenging models. Shick's (1987) "favored place" model did not include any significant social components and stressed that sites could simply be created by unintentional re-use of certain spaces, and may have served as secondary sources of raw material (Plummer, 2004). The "near-kill location" model (O'Connell, 1997) or the "male display" (O'Connell et al., 2002) model did not emphasize any specific social organization, despite depicting sites as carcass obtainment *loci* created through confrontational scavenging to increase male mating fitness. Even though some authors suggested a modified ethological approach to explain early sites (e.g., the "resource-defense" model (Rose and Marshall, 1996)), most models produced during the past three decades have approached Early Pleistocene hominin behavior by making it similar to those of other primates in an increasingly dehumanizing trend. One of the most recent models produced, the "obligate carnivory" model (Ferraro, 2007), intentionally avoided any interpretation of the

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social behavior of hominins or of the functionality of sites beyond their reconstruction as places where hominins ate substantial amounts of meat. Thus, we have reached a stage which enters in contradiction with the most emblematic contribution of the archaeology of the human origins during the 1980s: archaeologists no longer address early site functionality, and when doing so they detach the social component from their behavioral modeling, which has become mostly dietary. This avoidance of hominin social organization is surprising, since in ethology and behavioral ecology it is widely known that any given subsistence behavior is strongly dependent on specific types of social organizational structures (Brooks and McLennan, 1991). The application of taphonomy to the study of the Early Pleistocene record also unveiled fewer anthropogenic sites than previously thought and showed that a substantial amount of early sites were palimpsests, where hominin behavior was either difficult to detect, marginal or non-existent (Domínguez-Rodrigo et al., 2007).

Where do we stand now? Although there is a substantial amount of information available about the subsistence of hominins at a small number of Early Pleistocene sites, it is fair to state that we know very little about early site functionality and about hominins' general behavior or social organization. In addition, there is potential confusion among the large diversity of interpretations of hominin subsistence, as observed in the array of behavioral models produced. How can their heuristics be empirically tested? This diversity of interpretations may actually be due to the controversial nature of an insufficient archaeological record and/or to flawed theoretical framing of these models.

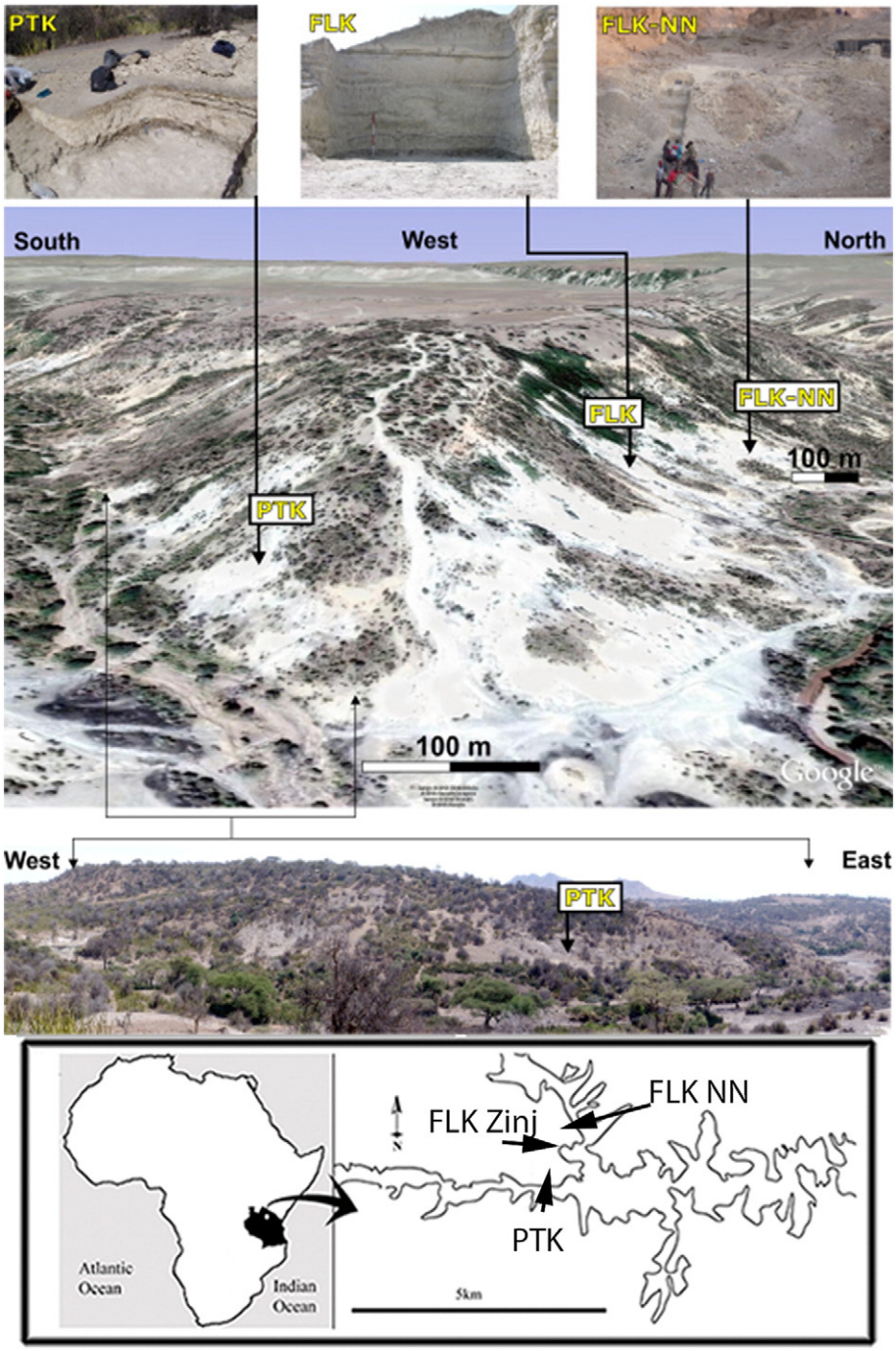

Fig. 1. Location of Olduvai Gorge (inset map) and the Bed I sites underlying Tuff IC.

Table 1
Different types of regressions used and their variants.

Regression type	Formula	Variants
Linear	R0 < − ppm(man ~ marks)	
Logistic regression	R1 < − ppm(man ~ marks,method = "logi")	
Additional linear	R2 < − ppm(man ~ marks + x + y)	With x or y alone
Additional quadratic	R3 < − ppm(man ~ polynom(x,y,2) + marks)	With x or y alone
Quadratic with interaction	R4 < − ppm(man ~ polynom(x,y,2) * marks)	With x or y alone
Additional cubic	R5 < − ppm(man ~ polynom(x,y,3) + marks)	With x or y alone
Cubic with interaction	R6 < − ppm(man ~ polynom(x,y,3) * marks)	With x or y alone

The best AIC estimate was obtained with R6 (including both x and y).

Ethnoarchaeological research has shown that there is a link between social behavior and spatial distribution of material debris (e.g. Gargett and Hayden, 1991; Kroll and Price, 1991; Yellen, 1977). Therefore, spatial analysis has a great potential in providing information of the social behavior displayed by bone and stone tool discarding prehistoric humans. FLK Zinj was one of the Early Pleistocene sites where spatial analysis was initially applied (Kroll, 1994; Kroll and Isaac, 1984; Ohel, 1977). Although some authors pioneered a statistical approach to spatial analysis (e.g. Whallon, 1974, Whallon, 1973), most spatial interpretations remained visually based even after the boom of ethnoarchaeological approaches during the 1970s and 1980s. The original spatial properties of archaeological materials (as reflecting the socio-economic behaviors that created them) can be taphonomically resilient, since patterns may be post-depositionally altered, but not to a point in which the structure is significantly modified by decomposition processes, except for the intervention of high-energy water flows (Yellen, 1977). A simulation of decomposition processes on one of the camps reported by Yellen (1977) showed that "the original spatial organization of a human site may be maintained in large part, though probably with some generalization or loss of resolution, through the relatively extensive attrition and physical disturbance that may occur during the process of its transformation into an archaeological location" (Gregg et al., 1991, p. 195). The use of simple statistical tools like k-means, non-hierarchical clustering and sum-square-error documented objectively the potential preservation of the spatial properties of archaeological assemblages. Twenty five years later there are far more powerful statistical tools used in spatial analyses in epidemiology, ecology and econometrics, which open new windows to the potential use of statistical spatial analysis in archaeology (Bivand, 2010; Dray et al., 2012; Pebesma, 2004; Roger et al., 2013). Through these analyses, it is possible to determine objectively if there are spatial interdependences of different types of archaeological materials and how this dependence is expressed (e.g., regularly or clustering). These tools also incorporate powerful algorithms that enable predictive simulation and sites can be studied not only within the excavated areas but also in broader (commonly unexcavated) contexts (e.g., Domínguez-Rodrigo et al., 2017). Multiple regression methods enable predictions that can be formulated as null hypotheses that subsequent excavations can test. However, for many of these effective methods the spatial sample must be as broad as possible and in archaeology this implies large open excavations.

The famous FLK Zinj (level 22) site remains one of the biggest excavations of an Early Pleistocene site anywhere (almost 300 m^2) (Leakey, 1971) (Fig. 1). It is situated under Tuff IC (1.84 Ma), the same as FLK NN, and has been extensively studied over 50 years. It has been the focus of models on early human hunting and scavenging (see review in Domínguez-Rodrigo et al., 2007; Domínguez-Rodrigo et al., 2014a, b). The site is situated on the upper section of a thin clay deposit on a paleosol that can be traced laterally extensively (representing an old paleolandscape) and that contains other archaeological sites (Uribelarrea et al., 2014). PTK (Philip Tobias Korongo) is located ~500 m south of FLK Zinj site at the junction of the main and secondary branches of Olduvai Gorge (Domínguez-Rodrigo et al., 2015). It was recently discovered by TOPPP (The Olduvai Paleoanthropology and Paleoecology Project) in 2012. It contains three archaeological discrete layers, the densest of which (level I) occurs on the same paleosurface as the FLK Zinj, and is also overlain by Tuff IC (Deino, 2012). Excavations at PTK of the 'upper Zinj' and 'lower Zinj' levels on the same clay stratum as FLK Zinj (as well as of a third archaeological layer underlying these which has yielded a modern human-like hand bone) are ongoing (Domínguez-Rodrigo et al., 2015). The excavated area of around 80 m^2 exhibits a dense concentration of stone tools and fossil bones. Preliminary studies of the assemblage suggest a significant degree of hominin carcass butchery behavior and stone tool use. Green-broken bones are abundant, and the amount of axial remains is substantial, which could be explained by a small impact of carnivore damage. PTK

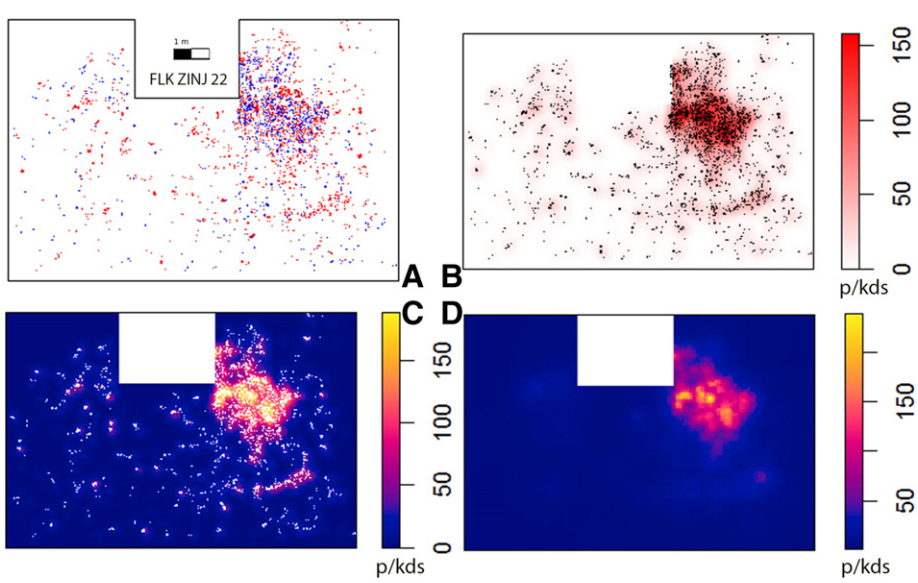

Fig. 2. A, spatial distribution of bones (red) and stone tools (blue) at FLK Zinj level 22; scale = 1 m. B, density of archaeological remains at FLK Zinj using a sigma value based on a likelihood method adjusted to the inhomogeneous Poisson process; C, sharpening of data to show hot spots (high intensity areas); D, hot spot delineated by the Dirichelet-Voronoi estimator. Bar scales = p/kds (estimated pieces per kernel density surface).

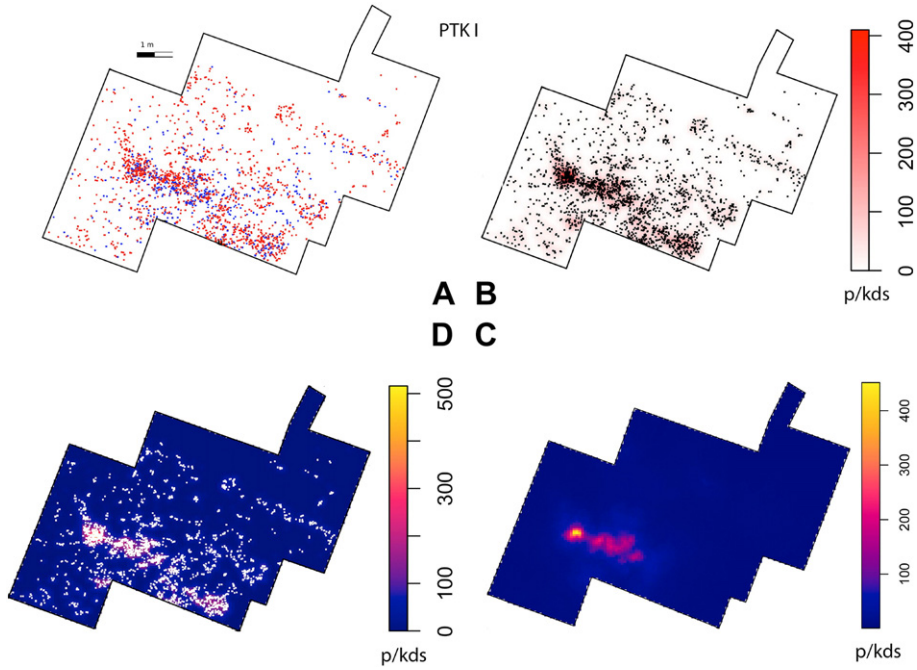

Fig. 3. A, spatial distribution of bones (red) and stone tools (blue) at PTK level I; scale = 1 m. B, density of archaeological remains at PTK using a sigma value based on a likelihood method adjusted to the inhomogeneous Poisson process; C, sharpening of data to show hot spots (high intensity areas); D, hot spot delineated by the Dirichelet-Voronoi estimator. Bar scales = p/kds (estimated pieces per kernel density surface).

will most likely be of great interest for the study of early human behavior once its excavation and analysis are completed. The discovery at PTK of a single dense cluster shows that the spatial pattern documented at FLK Zinj was not an exception and that there were other single high-density bone patches on the Zinj paleolandscape that contrast significantly with the low-density scatters in the surrounding environment (Uribelarrea et al., 2014).

The distribution of materials over such big windows as FLK Zinj and PTK allows testing if stone tool and fossil bone distribution is inter-dependent (and thus, functionally related) or stochastically distributed. It is also possible to document how different taphonomic processes affect lithics and bones differentially from a spatial point of view, further contributing to a broader understanding of site formation. Ultimately, the spatial structure of these sites can be determined to be of anthropogenic origin and/or post-depositionally disturbed. In the case of anthropogenic spatial patterns, it is finally possible to address whether specific spatial patterns reflect specific socio-economic behaviors. It is with this goal that we present here a spatial analysis of FLK Zinj (level 22) and PTK (level I). If anthropogenic (as supported by taphonomic research), the spatial patterns documented at both sites will allow to bring back social interpretations to the behaviors that explain how hominins processed and consumed several carcasses repeatedly at these spots.

The middle-range theory which will sustain our interpretation is the abundant ethno-archaeological literature of hunter-gatherer camp structure. Despite their diversity, most modern human forager camps are structured in multi-cluster units corresponding each cluster to a family unit (i.e., household) plus commonly used special-activity areas (e.g., Yellen, 1977; Gould, 1980; Gould and Yellen, 1987; Gregg et al., 1991; Bartram et al., 1991; Gargett and Hayden, 1991; Kroll and Price, 1991). Dimensional (radial) properties of these clusters may vary according to group size and predatory risks, but the multi-cluster nature of these sites is a direct reflection of individual nucleate (familiar) delimitation of within camp communal space. If hominins had a multiple-household social structure, similar to modern human foragers, regardless of its type (monogamous or polygyneous), we would expect early sites to show multi-cluster distributions as documented in modern human forager camps. The presence of huts, different technology and even fire should not play a role in how these multi-clusters are spatially distributed. They may condition the dimensional properties but not the structural patchy nature of debris discard and accumulation. Each cluster in modern forager camps represents individually nuclear (familiar) consumption areas. In the absence of fire, we will assume that if the familiar structure of modern humans existed, these multiple consumption spots would also have been present at early sites. If anything, the beginning of the use of fire would have disrupted this pattern because it might have been more energy-efficient to create a single

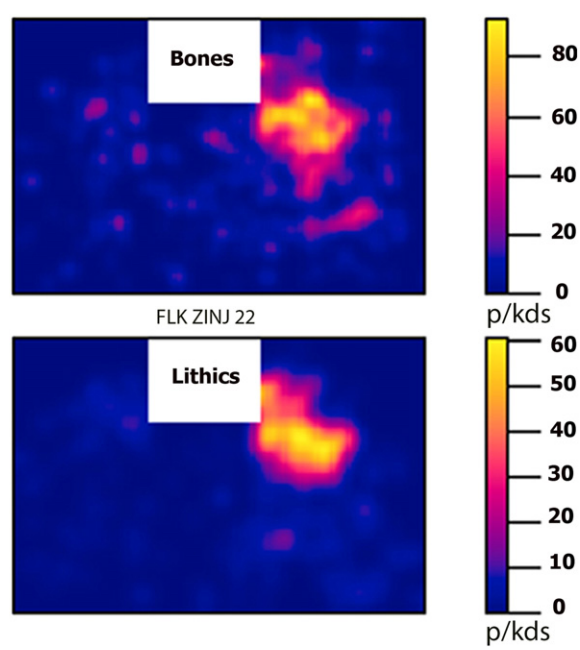

Fig. 4. Cross-type density maps of the distribution of fossils bones and lithic tools at FLK Zinj level 22 using a sigma value based on a likelihood method adjusted to the inhomogeneous Poisson process. Scale = density of remains per measuring unit. Bar scales = p/kds (estimated pieces per kernel density surface).

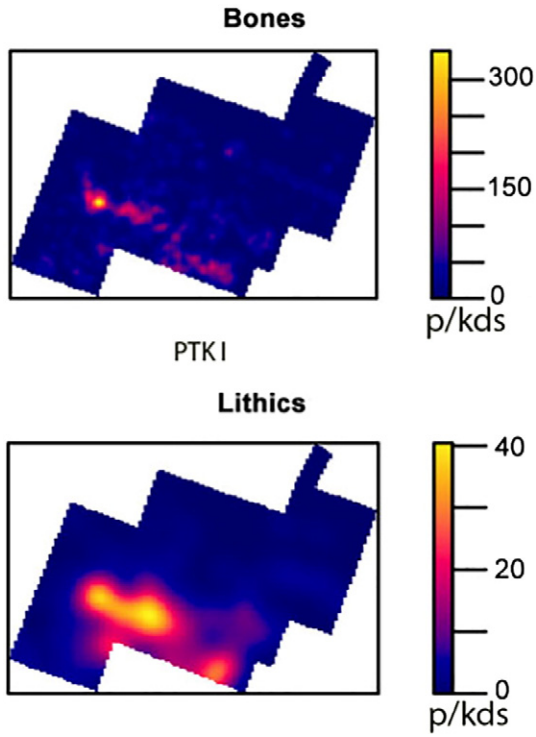

Fig. 5. Cross-type density maps of the distribution of fossils bones and lithic tools at PTK level I using a sigma value based on a likelihood method adjusted to the inhomogeneous Poisson process. Scale = density of remains per measuring unit. Bar scales = p/kds (estimated pieces per kernel density surface).

hearth and a communal consumption spot instead of several. However this is not documented among modern human foragers, which stresses the importance of socio-reproductive organization in the social use of the space. Therefore, the main questions addressed in this paper will be: were early sites organized in multi-cluster of single-cluster patterns? How does that inform us about early human social behavior?

2. Methods

2.1. Measuring spatial inter-dependence of stone tools and bones

Initially, all points (lithics and bones from FLK Zinj 22 and PTK I) were considered together to study the overall spatial point process. Subsequently, given that points were marked, a cross-type approach was implemented by splitting the point patterns by mark type.

Density maps were made by using bandwidths selected by sigma values, which control the degree of smoothing. To select the optimal bandwidth, Diggle and Berman's mean square error cross-validation method and the likelihood cross-validation method were used (Berman and Diggle, 1989). Diggle and Berman's method assumes a Cox process. The likelihood method assumes an inhomogeneous Poisson point pattern. All mapping methods took into account corrections for edge effects. Given the high density of points, a spatial approach to hot zones (i.e., areas with specially elevated intensity) was also used. This was made by using sharpening methods involving likelihood methods, as well as by using a Dirichelet-Voronoi estimator via an adaptive density approach (Baddeley et al., 2015). This involved using 30 repetitions of a specified fraction (f = 0.1–0.5) of randomly selected points used to create a Dirichelet tesselation.

Complete Spatial Randomness (CSR) was measured through a power divergence test statistic (Cressie and Read, 1984). Since the pattern was visually inhomogeneous, the χ^2 would not be reliable for retaining or rejecting the CSR null hypothesis. So, both the Freeman-Tukey statistic and the Neyman's modified statistic were used for this purpose. These tests were applied via multiple Monte Carlo simulations (n = 39) also when testing the alternative hypothesis of clustering. Since these divergence tests are based on variations of the χ^2 tests, the window was gridded so that no grid square had fewer than five objects, since tests conducted with square units containing fewer counts yield unreliable estimates. This implied using a 5 × 4 grid. Clustering was also measured through the Clark-Evans test, which provides K values (Clark and Evans, 1954). When K < 1, the point process indicates clustering. This test was made using correction methods, where the p-value for the test is computed by Monte Carlo simulation of n processes of Complete Spatial Randomness conditional on the observed number of

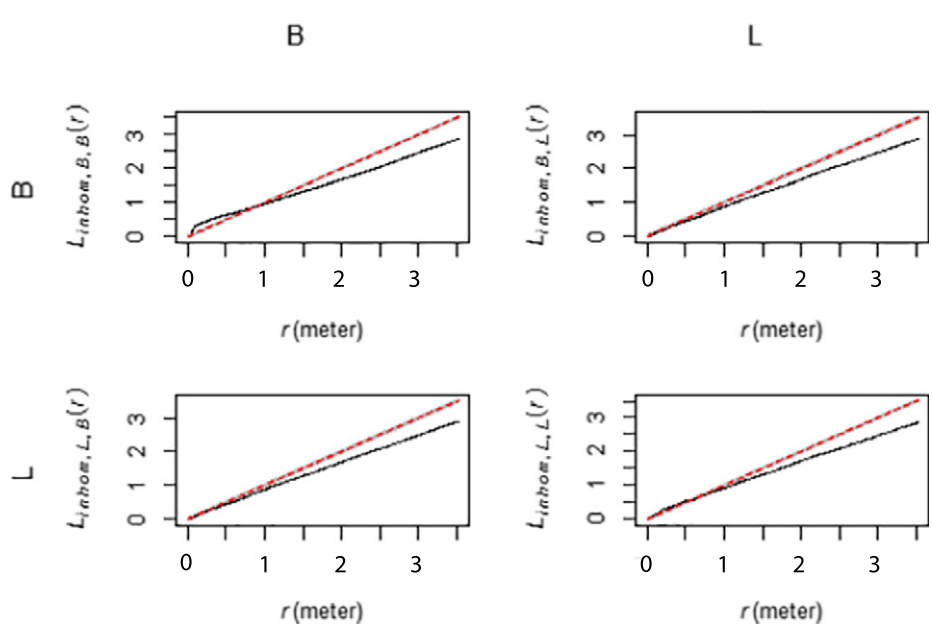

Fig. 6. Inhomogeneous L-function comparing all types of associations (L-L, B-B and L-B), displaying the observed distribution (solid black line), the theoretical distribution (dotted red line) and the confidence envelope (gray area) at FLK Zinj. B, bone; L, lithic.

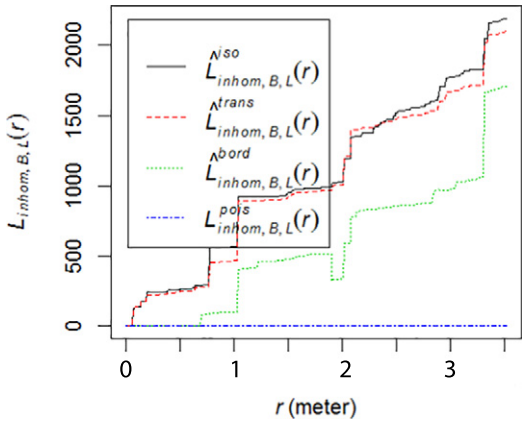

Fig. 7. Inhomogeneous L-function applied to the unmarked point process at FLK Zinj, showing the strong clustering process of lithics and bones, compared to the theoretical random Poisson process. Iso, Ripley's isotropic correction estimate of L: trans, translation-corrected estimate of L; border, border-corrected estimate of L; theo, theoretical Poisson L.

points. The correction methods used was "cdf" (Cumulative Distribution Function). This method evaluates the nearest neighbour distance distribution function G(r) of the stationary point process using the Kaplan-Meier type edge correction. Then the mean of the distribution is calculated from the cdf.

The univariate K(r)-L(r) functions measure the expected number of points in a given distance r around an arbitrary point. By comparing the resulting values to their theoretical CSR values, it is possible to determine the type of spatial point process (i.e., regular, random or clustering). Similarly conceived, the cross-type $K_{ij}(r)$-$L_{ij}(r)$ functions intent to evaluate the spatial relationships between two types ij of points at each selected distance r. When using any of these functions, the null hypothesis tested is Complete Spatial Randomness and Independence (CSRI). To provide certainty, envelopes representing confidence intervals, are used. These envelopes are derived through Monte Carlo simulations involving permutation and resampling. Here, both for the $K_{ij}(r)$-$L_{ij}(r)$ and the $K_i\cdot(r)$ function (see below) critical envelopes of random expected values for the null hypothesis were made combining simulation (n = 69) and random labeling through permutation. The statistical significance selected for hypothesis testing was small to minimize type I errors (alpha < 0.01).

Given the lack of depth values for each of the archaeological objects, no topographic covariate could be used at FLK Zinj. To determine if the spatial distribution of lithics and bones is correlated or inter-dependent, several tests were made. First, a nearest-neighbour correlation (NNC) was made. This provides an "unnormalized" and a "normalized" estimate. The former represents the probability that a typical point and its nearest neighbour belong to the same type. The latter represents the probability that a random mark value has the same probability as another mark value. NNC is a robust method and can be applied to stationary and non-stationary processes.

A second test of point inter-dependence applied in the present study was a random labeling test (using the $K_{ij}(r)$ function). This consists of assuming that each point is determined at random, with independence from other points. A permutation test done through Monte Carlo sampling of (n = 69) randomly relabeled versions of the original data marks, contrasts the null hypothesis that the randomly labeled data are similar to the original data. When using envelopes, the "dot" functions are the most accurate (Baddeley et al., 2015). The i-to-any $K_i\cdot(r)$ function is preferred for interpreting the accuracy in testing or rejecting the null hypothesis of CSRI. This function (in contrast to the $K_{ij}(r)$ function) analyzes the expected number of points of any type situated within a distance r of a typical point i (Baddeley et al., 2015). Values of the empirical distribution (black solid line) are shown in comparison with the theoretical Poisson distribution (red dotted line) and the simulated envelope of significance (gray area). When the black line of the observed distribution is above or below the envelope, the pattern is significantly clustered or dispersed and in both cases a relationship of points of different marks is confirmed.

A I-function test was also used to measure dependence of points of different types. If the point patterns with different marks are independent, then the I-function is equal to 0. Deviations indicate positive or negative association between types (Baddeley et al., 2015).

A further test for the independence of components was made using Stoyan's mark correlation k[*mm*](r) for the point pattern (Stoyan and Stoyan, 1994). This test measures the dependence between the types of two points lying at a distance r (Baddeley et al., 2015). The test

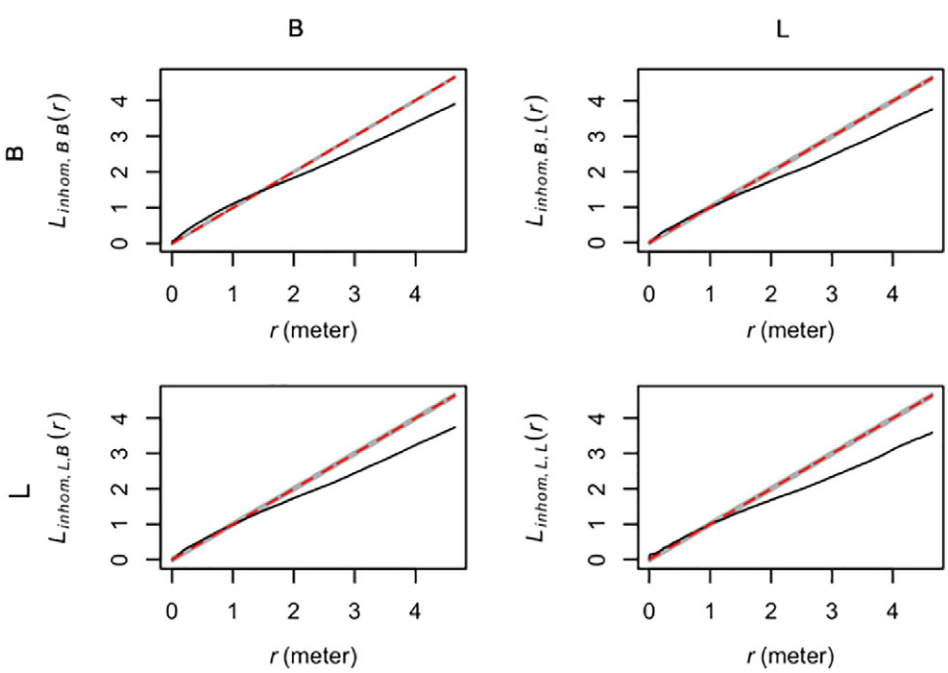

Fig. 8. Inhomogeneous L-function comparing all types of associations (L-L, B-B and L-B), displaying the observed distribution (solid black line), the theoretical distribution (dotted red line) and the confidence envelope (gray area) at PTK. B, bone; L, lithic.

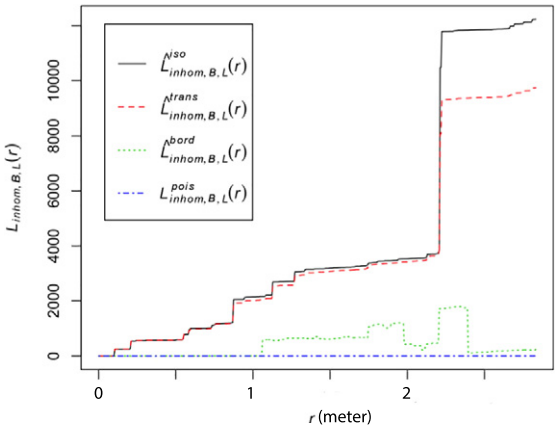

Fig. 9. Inhomogeneous L-function applied to the unmarked point process at PTK I, showing the strong clustering process of lithics and bones, compared to the theoretical random Poisson process. Iso, Ripley's isotropic correction estimate of L: trans, translation-corrected estimate of L; border, border-corrected estimate of L; theo, theoretical Poisson L.

function f is any function f(m1,m2) with two arguments which are possible marks of the pattern, and which returns a nonnegative real value. The value 1 suggests "lack of correlation": if the marks attached to the points of X are independent and identically distributed, then k[*f*](r) = 1. If the marks are a factor (i.e. if X is a multitype point pattern) then f yields the value 0 when the two marks are unequal (points are different types). For f values > 1 the points belong to the same type. Dependence is documented when values are <1.

2.2. Modeling spatial distributions of lithics and bones in the areas surrounding FLK Zinj and PTK

After the spatial relationship of bones and stone tools was properly understood, then regression models were applied to create a foundation for simulation of clustering and scattering processes surrounding the site. A series of linear and polynomial, quadratic, and cubic regressions were made, combining both additional and interactive regressions with element type (Table 1). Non-stationary Poisson models can be fitted via a polynomial regression, which uses a log-quadratic intensity model. In some cases, inhomogeneous models can be fitted with intensity estimates that are proportional to covariates. This is referred to as a baseline model and logarithmic transformations are required. This regression type creates models with offsets. When dependence of points is either suspected or documented, such a positive dependence leading to clustering can be best approached via Cox and Cluster models. These models are modifications of the Poisson process by incorporating random effects, which enable inhomogeneous and inter-dependent point processes. The most optimal regression was selected through the AIC (Aikike Criterion) test. This regression was the base for the simulation carried out. The fitted model was subsequently reproduced inside the excavated Zinj window (modeling how lithics and bones would be best distributed compared to the real pattern). Subsequently, the selected regression was used for modeling the distribution of materials inside unexcavated windows that were expanded from the original Leakey's excavation. The last step was the testing of the model through selective excavation of trenches inside the virtual window.

For this purpose, a new virtual window (21 × 14 m) was created to the East of the Leakey's excavation at FLK Zinj. This rectangular window was used to make predictions about a broader spatial point pattern

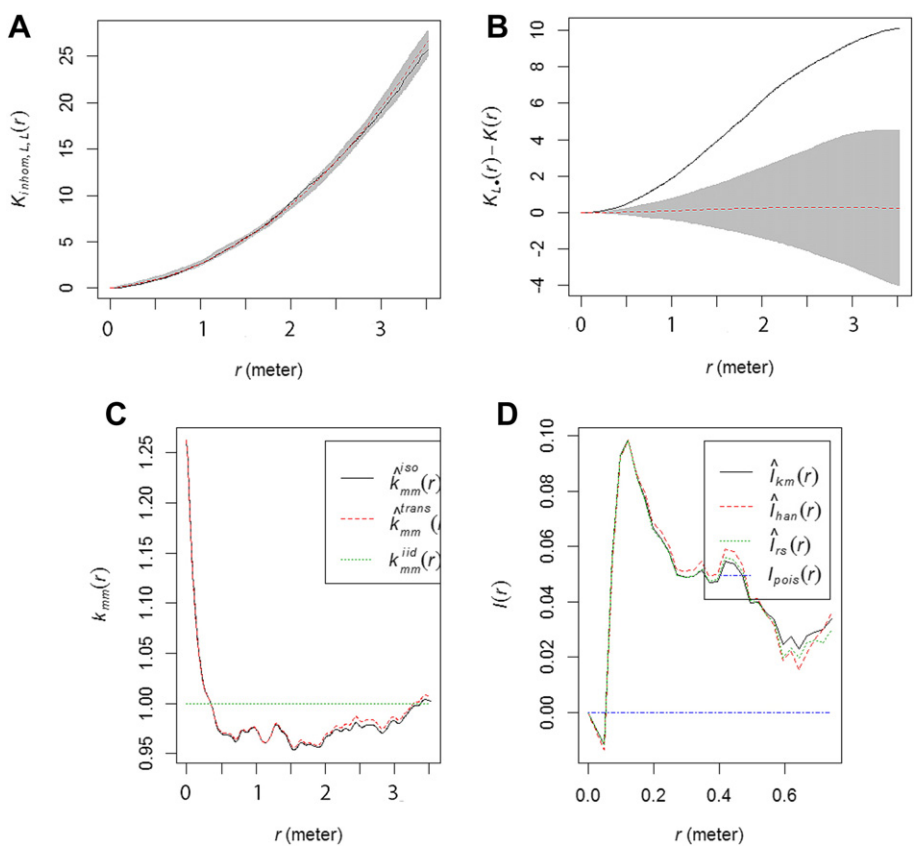

Fig. 10. Functions applied to FLK Zinj. A, Kij(r) function. B, Ki(dot)(r) function. Both show the theoretical Poisson distribution (red dotted line), the observed distribution (black line) and the confidence envelope (gray area). C, Stoyan's correlation test with the different correction methods. Key: r, distance argument; theo, theoretical value (independent marks) for k; trans, translation-corrected estimate of k; iso, Ripley's isotropic correction estimate of k. D. I-function. Key: r, distance argument; theo, theoretical Poisson I(r); rs, border corrected estimate of I(r); han, Hanisch-style estimate of I(r); km, Kaplan-Meier estimate of I(r).

trend than that documented within the excavated window. To test the fitted model, four trenches were excavated inside this virtual window: T1 (12 m^2), T6 (2 m^2), T10 (2 m^2) and S1 (1 m^2). Using a different regression, we produced an alternative fitted model within another bigger virtual window that embodied trenches 4, 5, 7 and 8 as reported in previous work in the FLK gully (Uribelarrea et al., 2014). This bigger virtual window enabled a broader framework in which the issue of FLK Zinj as a very intense bone and lithic cluster could be addressed either as a continuation of a highly productive landscape (Blumenschine et al., 2012) or as an anomaly caused by anthropogenic behavior (Domínguez-Rodrigo et al., 2010; Uribelarrea et al., 2014).

Depth values were available for all archaeological objects at PTK. Thus, in contrast to FLK Zinj, we could test if the distribution of stone tools and bones was correlated to the paleosurface topography. The relationship between the point process intensity and the continuous topographic covariate was estimated via a Kolmogorov-Smirnov test, and via the "rhohat" function, which estimates the parameter probability of density (p) using a resource selection function and a nonparametric smoothing method (Baddeley et al., 2012). With the objective of selecting a good regression model that could be used to simulate clustering and scattering processes outside the excavated window at PTK, several types of regressions were run. In addition to the models used for the spatial point process at FLK Zinj, further regression models were made that included the effect of the topography, which we expected to be significant. Subsequently, the AIC test was applied to select the best regression, which was used to predict the trend of the distribution of bones and lithics in the surrounding areas of the excavation. For this purpose, we selected a new virtual window (30 × 24 m) surrounding the excavated area of PTK. Four trenches were made in this window outside the main excavation area: Trench A (4 m^2), Trench B (1 m^2), Trench C (15 m^2) and Trench D (1 m^2).

The inhomogeneous nature of the Zinj and PTK point patterns suggested that the points were not independent (as required by Poisson process modeling). Bones and stone tools seemed functionally associated, and therefore, their spatial distribution is not independent, as supported by the inter-dependence tests described above. The inferred degree of dependency suggested that regressions should consider cluster processes, which could include point inter-dependence. For this reason Cox-Cluster regression models (via the "kppm" function of the "spatstat" R library) were used. These models were the baseline for a series of simulations following the regression results. These simulations were made using two methods: Thomas and Log Gaussian Cox Process (LGCP). Cluster processes using the Thomas method focus on cluster formation and this is simulated by a two-step process. In the first step, a pattern of "parent" points are generated. Subsequently, each "parent" point generates a random pattern of "offspring" points. Only the latter is examined (Baddeley et al., 2015). In the Thomas cluster process, the offspring clusters following an isotropic Gaussian density pattern. The Thomas process is "a Cox process, with random driving intensity A(u) equal to the superposition of Gaussian densities centred at each of the parent points" (Baddeley et al., 2015: p.463).

A LGCP is a Cox process based on random fields, where intensity is measured by:

A(u) = expG(u), where A(u) is the driving intensity, G(u) is a Gaussian random field.

These random fields are simulated processes with spatially varying intensity, yielding hot (dense) and cold (scatter) point areas. Given the combination of cluster-scatter point patterns replicated and

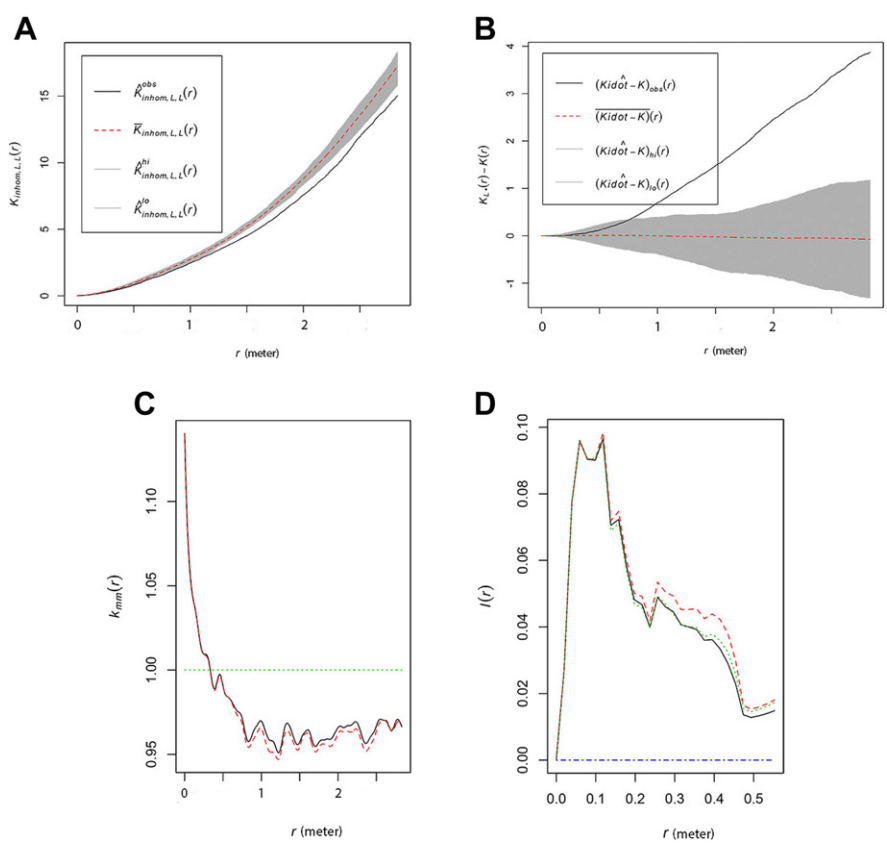

Fig. 11. Functions applied to PTK. A, Kij(r) function. B, Ki(dot)(r) function. Both show the theoretical Poisson distribution (red dotted line), the observed distribution (black line) and the confidence envelope (gray area). C, Stoyan's correlation test with the different correction methods. Key: r, distance argument; theo, theoretical value (independent marks) for k; trans, translation-corrected estimate of k; iso, Ripley's isotropic correction estimate of k. D. I-function. Key: r, distance argument; theo, theoretical Poisson I(r); rs, border corrected estimate of I(r); han, Hanisch-style estimate of I(r); km, Kaplan-Meier estimate of I(r).

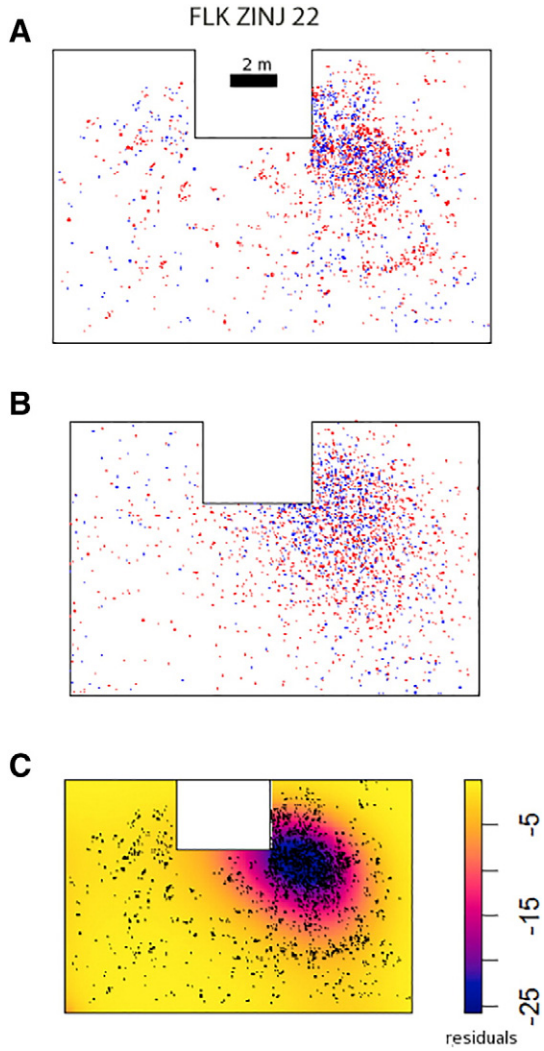

Fig. 12. A, spatial distribution of fossils bones (red) and stone tools (blue) at the excavated area of FLK Zinj; scale = 2 m. B, simulated distribution of fossils bones (red) and stone tools (blue) at FLK Zinj, using the polynomial cubic regression with interaction (with both types of marks: bones and lithics), which yielded the best degree of accuracy as tallied by AIC. C, spatial representation of the residuals yielded by the polynomial cubic regression (B), showing a high degree of accuracy in fitting the estimates to the data in all the area but the main cluster. Bar scale = residual difference between predicted and observed densities.

simulated in the random fields, this method is more realistically reproducing point pattern models that one may find in random spatial distribution of archaeological points.

Both the Thomas and LGCP simulation processes operate with intensity ranges and spatial distributions as observed in the sample used for elaborating the model. The higher degree of clustering and scattering (depending on the method) takes the original sample distribution and size into consideration to project the simulated sample in similar terms either inside the original window or in any other window, where the same spatial patterning is reproduced. Thus, a projection of predicted spatial intensity within a new window does not intend to faithfully reproduce the net real intensities in that window, but their spatial trend, provided the original window from which the model is obtained is representative of the intensity trend within a broader framework.

For the application of the LGCP simulation process to the FLK Zinj and PTK, the selected regression (with the best AIC estimate) was unmarked, since the random field functions have not implemented the use of marked patterns.

3. Results

3.1. Are stone tools and fossils bones at FLK Zinj and PTK I inter-dependent from a spatial point of view?

Visually, the distribution of stone tools and fossils bones at FLK Zinj and at PTK show that most archaeological materials overlap in a cluster (Figs. 2a, 3a). It is clear that there is a decreasing density of stone tools and bones as one moves away from the cluster core (Figs. 2b, 3b). The cluster is extremely dense (hot zone) and it sharply contrasts with the surrounding space (Figs. 2c, d, 3c, d). When density maps are split according to material type (bones and lithics), the discrete spatial concentration of stone tools in the form of a hot spot is more marked than that documented for fossil bones (Figs. 4, 5). This implies that although bone-butchering activities took place in most of the excavated area (in the absence of bone dispersal caused by post-depositional processes), stone tools were discarded and accumulated in a very small portion of the space.

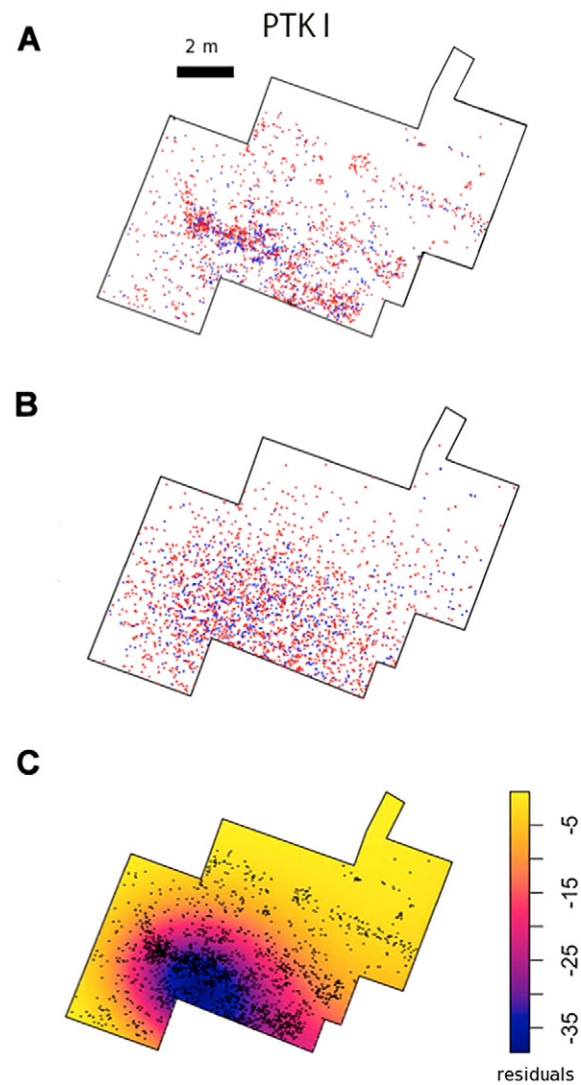

Fig. 13. A, spatial distribution of fossils bones (red) and stone tools (blue) at the excavated area of PTK level I. B, simulated distribution of fossils bones (red) and stone tools (blue) at PTK level I, using the polynomial cubic regression with interaction (with both types of marks: bones and lithics), which yielded the best degree of accuracy as tallied by AIC; scale = 2 m. C, spatial representation of the residuals yielded by the polynomial cubic regression (B), showing a high degree of accuracy in fitting the estimates to the data in all the area but the main cluster. Bar scale = residual difference between predicted and observed densities.

The overlap in clustering of fossils and stone tools would be suggestive of a functional association between both types of materials, caused by the butchering of carcasses to which hominins had a primary access, as has been widely supported by taphonomic studies (Domínguez-Rodrigo, 2015; Domínguez-Rodrigo et al., 2014a, b; Domínguez-Rodrigo and Barba, 2005). A spatial statistical analysis can shed further light on this interpretation. Cressie and Read's power divergence test showed that the point processes were non-stationary: Freeman-Tukey's T^2 statistic (FLK Zinj: $T^2 = 2702$, df = 19, p-value < 0.00; PTK: $T^2 = 2047$, df = 14, p-value < 0.00), Neyman's modified χ^2 statistic NM^2 (FLK Zinj: $NM^2 = 4002$, p-value = 0.05; PTK: $NM^2 = 8170$, df = 14, p-value < 0.00) and a marked χ^2 test (FLK Zinj: $\chi^2 = 5876$, df = 38, p-value < 0.00; PTK: $\chi^2 = 4929$, df = 205, p-value < 0.00) also showed the high probability of inhomogeneity. A Clark-Evans test (with the alternative hypothesis = clustered point process) also supported that the spatial point pattern is clustered (FLK Zinj: R = 0.66, PTK: 0.57). Subsequently, inhomogeneous versions of the $K_{ij}(r)$-$L_{ij}(r)$ functions were selected.

For FLK Zinj, the L function showed that bones were clustered in short distances (up to 1 m) and then they tended to show a progressive regular pattern as would be expected from decreased intensity from a hot spot (Fig. 6, diagonal, upper left). Lithics, in contrast, showed a random pattern in short distances, just to adopt an increasingly regular pattern after 1 m (Fig. 6, diagonal, lower right). When comparing the distributional relationship of both lithics and bones, the pattern documented is random in the short distances (suggesting independence) and then increasingly regular, as expected if moving gradually away from a highly intense zone. The inhomogeneous L-function applied to the complete point process (without differentiating marks) shows that both lithics and bones show a strong tendency to cluster (Fig. 7). The same interpretations can be made about PTK (Figs. 8, 9). It is really surprising that even the same distances in the spatial patterns apply to bones and lithics in both sites.

The nearest neighbour correlation test yields ambiguous results. The unnormalized test (FLK Zinj: 0.6; PTK: 0.7) clearly indicates inter-dependence between bones and lithics. The normalized test (FLK Zinj: 1.1; PTK: 1.2) suggests spatial independence. A comparison between the $K_{ij}(r)$ and the $K_i \cdot (r)$ functions, using random labels, also shows some disagreement. The $K_{ij}(r)$ function suggests that the marks are independent. In contrast, the $K_i \cdot (r)$ function shows that marks are strongly dependent and that lithics are strongly clustered with bones (Figs. 10a, b, 11a, b). A more adequate set of tests for multi-type point processes where there are only two types (like here: bones and lithics) are Stoyan's mark correlation test and the I-function. The correlation tests applied to FLK Zinj and to PTK show that in distances of <0.5 m, bones are more likely to have bones as the nearest neighbours. However, in distances >0.5 m, the nearest neighbours of random bone specimens are lithics. The extensive negative trend along the space suggests that there is a spatial inter-dependence of tools and bones (Figs. 10c, 11c). This interpretation is further supported by the I-function. Taking into account that if point processes (i.e., different types of points) are independent, then the function is equal to 0. Deviations from 0 indicate positive or negative association between types. The I-function for FLK Zinj shows that in very short distances (<0.3 m), there is a negative association between lithics and bones. However, after that distance the spatial dependence of lithic and bones is very strong and prolonged, indicating that both types of materials are

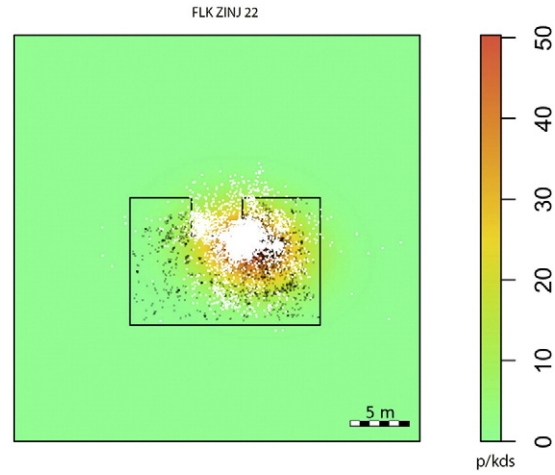

Fig. 15. Expansion of the predictive polynomial regression model applied to FLK Zinj level 22 (white dots are predicted material intensity; black dots are actual materials) over all the surrounding landscape of the excavated window. Green window shows the sampled area. Bar scale = p/kds (estimated pieces per kernel density surface). Horizontal scale = 1 m.

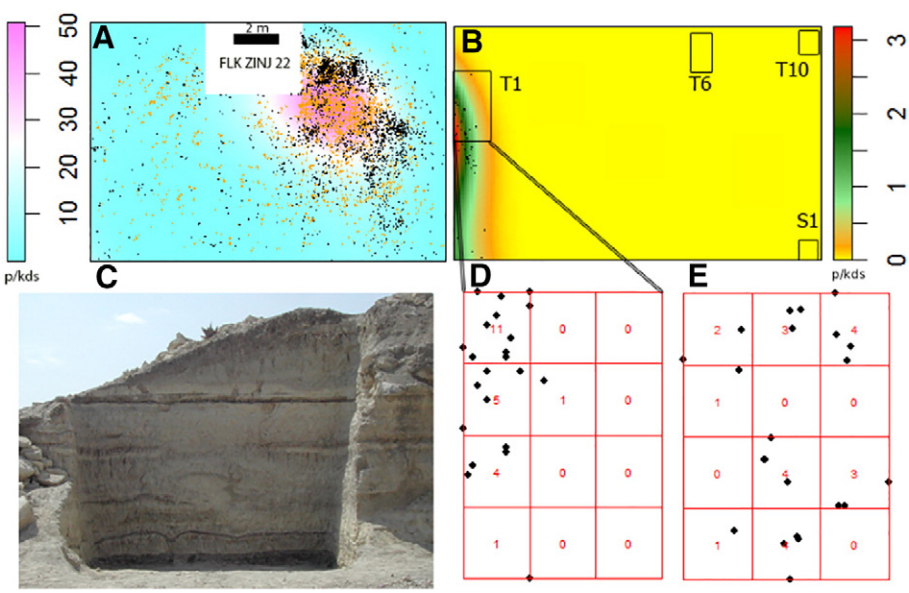

Fig. 14. A, distribution of the simulated fitted model (black dots) superimposed on the archaeological materials (orange dots) at FLK Zinj level 22; scale = 2 m. Bar scale = p/kds (estimated pieces per kernel density surface). B, extension of the virtual window to the East of the excavated site showing the predicted density of materials using the polynomial cubic regression. Notice the sharp contrast in density decrease and the virtual emptiness of the window. C, Trench 1, the biggest test to the predicted model. D, density and spatial distribution of materials predicted by the fitted model. E, density and spatial distribution of materials at Trench 1. Scale = predicted density of materials per measuring unit.

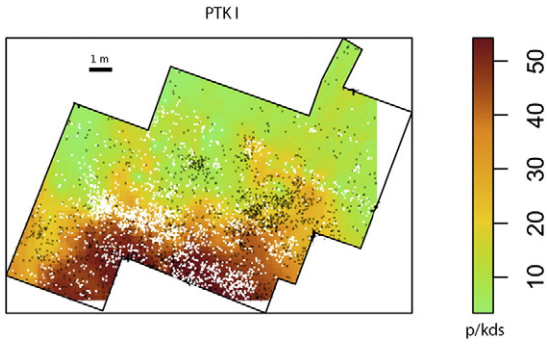

Fig. 16. Polynomial regression fitted model of intensity predicted (black dots) and documented (white dots) at PTK level I depending on the paleotopography of the site. Horizontal scale = predicted density of materials per measuring unit. Bar scale = p/kds (estimated pieces per kernel density surface).

spatially dependent (Fig. 10d). This supports Stoyan's correlation test, which indicated that bones were much more clustered in small distances, and that they are spatially associated in the rest of the area. The I-function for PTK also indicates that there is a positive association between stone tools and bones (Fig. 11d).

These tests are supportive of spatial inter-dependence between stone tools and bones, which further reinforces previous taphonomic interpretations made in this regard, especially with regard to FLK Zinj (Domínguez-Rodrigo, 2015; Domínguez-Rodrigo et al., 2014a, b; Domínguez-Rodrigo and Barba, 2005).

3.2. How big are FLK Zinj and PTK I? Modeling the site outside the excavated area

The distributions of stone tools and bones at FLK Zinj and at PTK, although similar, show an important difference: bones show the highest intensity at the main cluster and decrease radially and gradually from there until the edge of the site. In contrast, lithics show a sharp contrast of their intensity at the main cluster and their virtual marginal representation in the surrounding area, with no gradual decrease as one moves away from the cluster (Figs. 4, 5, 12a, 13a).

From all the regressions applied to the spatial point processes of FLK Zinj and PTK (linear, polynomial quadratic and cubic) (Table 1), with or without addition or interaction, the best AIC estimate was yielded by the polynomial cubic regression with interaction with mark types (lithic and bones) and both coordinates. This regression was tested by simulating a spatial distribution of stone tools and bones using the fitted values of the regression. The resulting spatial pattern is surprisingly very similar to the original one (Figs. 12a, b, 13a, b). The final result overestimates the density of lithics and bones at the clusters, which can be seen at the high values of the negative residuals at the main cluster area. In contrast, the regression virtually reproduces with minimal distortion the overall scattering pattern surrounding the main cluster (notice the small values of residuals) (Figs. 12c, 13c). This is a good guarantee that when applying the fitted model to simulate lithic and bone distribution in a bigger window than the excavated area, the results may be closer to reality than alternative regression estimates.

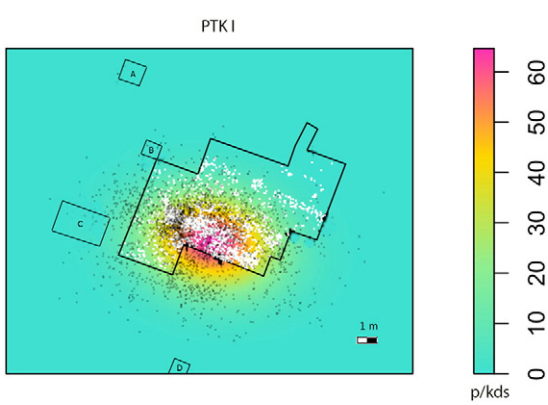

Fig. 17. Expansion of the predictive polynomial regression model applied to PTK level I (black dots are predicted material intensity; white dots are documented materials) over all the surrounding landscape of the excavated window. Peripheral trenches (A–D) are also shown. Scale = predicted density of materials per measuring unit. Bar scale = p/kds (estimated pieces per kernel density surface).

A simulation model applied to FLK Zinj using random fields over a window that was twice the size of the currently excavated area showed the expected distribution of materials to the east of the current site (Fig. 14). Initially, we had selected this area because the scattering pattern documented to the west seemed visually less promising than that to the east, which was denser and showed that the main cluster was closer to the eastern wall of the site than to the western one. Our initial hypothesis was that the eastern side of the site was a continuation of the decreasing scattering pattern documented around the main cluster area. The simulated model, in contrast, showed that if the spatial inter-dependence of lithic and bones was statistically justified at Leakey's excavated site, then material density would immediately decay as one moved away towards the east. Virtually, the only "concentration" of materials would appear adjacent to the southeasternmost part of the main cluster. The remaining virtual window would remain almost empty.

To our surprise, the 4 trenches opened within the virtual window (of the same dimensions as the excavated FLK Zinj), reflected this virtual prediction with perfection (Fig. 14). The two easternmost trenches (T10 and S1) were empty. T6 only contained 2 small bone fragments. T6a (not included here because of erosive problems), originally adjacent to T6, was also empty (Domínguez-Rodrigo et al., 2010). Trench 1, adjacent to the eastern wall of Leakey's excavation contained a total of 23 items (combining bones and stone tools) over 12 m^2 (Fig. 14e). It may be total coincidence, but the simulation produced by the polynomial regression predicted 22 items in that area. Although the shape of the distribution is different between the model and the excavated trench, it is interesting to note that the intensity at the trench was almost exactly predicted by the model. A confirmation of this prediction lies not only in the virtual absence of materials in the other trenches excavated inside the virtual new window, but also in trenches situated to the south and north of it that also showed almost no material (Uribelarrea et al., 2014). A quadratic regression over a much larger area surrounding the site on all orientations show that the perimetral landscape should be devoid of fauna and lithics as is virtually the case (Fig. 15).

Regarding PTK, a Kolmogorov-Smirnov test ($D = 0.306$, p-value < 0.00) suggested that the paleosurface topography had a significant effect on the distribution of archaeological material at this site. This was confirmed by the smoothed kernel p estimator, which further showed the tendency of the intensity of materials to increase on higher elevation (Fig. 16). Polynomial quadratic and cubic regressions that take the effect of the paleosurface topography into account therefore fitted the documented distribution of materials better. This indicates that the higher intensity in the elevated ground is to be attributed to behavior and not just to the paleotopography; otherwise, the pattern would be reversed: paleotopography would influence material distribution on the lower sections, probably caused by a combination of factors among which gravity and post-depositional disturbance would be the most important ones. These models could not be used to create simulations of the materials outside the excavated area, since depth values were only available for the excavated window. A polynomial regression taking into account the coordinates showed that PTK should be a dense cluster with decreasing intensity as one moves away from it in any direction (Fig. 17). Work at the site is still ongoing and although it is premature to produce information of the trenches under excavation, overall, the intensity documented so far tends to agree with this model. Four small trenches made in the peripheral area of the main excavation produced

very low densities of bone fragments and no stone tools. Trench A yielded 15 very small bone fragments (slightly 2 fragments per m^2). Trench B yielded 2 bones (3 were predicted by the fitted model). Trench C yielded 27 specimens (1.8 fragments per m^2). Trench D was empty (as predicted by the model). These preliminary results show accordance with the fitted model.

4. Discussion

The 1.8 Ma FLK Zinj site from Olduvai Gorge (Tanzania) has been at the epicenter of all debates regarding early site functionality and hominin behavior (see extensive references in Domínguez-Rodrigo et al., 2007). Leakey interpreted it originally as a perfect case of a living floor (Leakey, 1971). Sites similar to FLK Zinj discovered at Koobi Fora (Kenya) served as the basis for Isaac's "home base" model, in which he proposed that Plio-Pleistocene hominins selected specific locations for toolmaking, butchery, and food consumption activities (Isaac, 1978). Hominins would repeatedly use these sites, transporting food from the original procurement locations and intentionally sharing it with others at the home base. This model presumed that hominins had sufficient (i.e. primary) access to meat. This assumption was challenged by Binford, who reinterpreted Leakey's original, preliminary faunal list to form a radically different conclusion: Plio-Pleistocene hominins, he proposed, were the last and most marginal of scavengers upon the local meat supply (Binford, 1981). At the same time, Bunn (1983, 1982) was also comparing the FLK Zinj assemblage against referential frameworks that he developed based on carnivore dens, as well as on modern hunter-gatherer home bases. Bunn's taphonomic analysis of the site led him to conclude that hominids at the FLK Zinj site had primary access to meat through hunting or power scavenging (Bunn, 2001). Taphonomic research over the past 20 years has increasingly added support to Isaac's and Bunn's ideas of hominins having primary access to carcasses consumed at some of these sites (see extensive discussion in Domínguez-Rodrigo, 2015; Domínguez-Rodrigo et al., 2007). This empirical evidence was used by Isaac to revise his "home-base" model and propose a new one borrowed from ethology: "central-place" foraging, in which he claimed hominids selected specific spots in the landscape to which they repeatedly brought raw materials that they turned into stone tools to process food resources, which were also collectively transported and shared (Isaac, 1983). The concept of "central-place foraging" refers to the repeated use of a place for food transport and consumption (see review in Lupo, 2007). A "central-place" is not necessarily a "home base". Isaac (1983) adopted the term for modeling early site function only because the social component of the "home base" model could not be archaeologically tested.

Modern hunter-gatherers show a spatial organization in their home bases structured around a particular socio-economic organization based on nuclear families, which create household clusters (e.g., Yellen, 1977; Bartram et al., 1991). This fact determines that material debris is accumulated in patches or clusters: some patches belong to household units and other patches belong to communal-use areas (e.g., special processing places). Material discard in home bases can be continuous or discontinuous, but it is characterized by clusters of high-density materials and scatters of low-density materials. Yellen (1977) differentiated among various types of debris accumulations in foragers' camps. He applied the term "absolute limit of scatter" (ALS) to the area that includes all the material discarded by foragers in their camp. These areas typically can be very large and are almost never uncovered archaeologically. To distinguish the area where most of the materials are concentrated from more external scatters, Yellen used the "Limit of most of the Scatter" (LMS), comprising the "limit of the nuclear area total" (LNA), which consists of all the accumulations of materials generated by multiple "nuclear areas". A more delimited, spatially-discrete and patchy distribution of materials occurs in the "scatters" within each "nuclear area" (LS). These LS patches would in theory be the most easy to detect archaeologically since they occupy a small area (usually >9 m^2) and would be informative of more specific activities, mostly related to food consumption.

Almost 300 m^2 were excavated at Zinj. This still remains one of the largest excavations in any Plio-Pleistocene site in Africa. If Yellen's scheme is applied to FLK Zinj, several features can be documented. The excavation unearthed a dense cluster of bones and stone tools, which could comprise an area similar to several of Yellen's LNAs (limit of nuclear area) including LS (Limit of scatters) of these areas. A single patch is documented at Zinj. There are no more high-density patches on the Zinj surface. As a matter of fact, density of material decreases with distance from the patch. As it stands, FLK Zinj would be a single high-density scatter site quite dissimilar from the multi-scatter nature of most modern foragers' home bases. Quite a similar interpretation could be derived from the spatial analysis of PTK: The site has a dense cluster with decreasing intensity as one moves away from it and lithics are more densely concentrated than bones. The pattern is highly informative because these two sites are the oldest anthropogenic sites composed of a vertically-discrete horizons resting on the same paleo-surface (which implies a limited amount of time in their formation). The similarity is even more surprising when comparing the similar spatial dimensions of both clusters. This cannot be random and must certainly reflect socio-economic behaviors ultimately conditioned by group size.

The fitted model presented here supports that FLK Zinj and PTK were composed of a single dense cluster of lithic and bones surrounded by a buffering scatter area of bones and, to a much lesser degree, of stone tools. It also shows that, contrary to previous assertions that FLK Zinj was a representation of a landscape that was naturally highly productive of carcass remains (Blumenschine et al., 2012), it supports the interpretation that the site was an anomaly: a very intense spot surrounded by moderate to low density bone scatters (Domínguez-Rodrigo et al., 2010). Also contrary to previous assertions that the site underwent significant post-depositional disturbance (Benito-Calvo and de la Torre, 2011), the tight (statistically-supported) spatial association between lithics and bones indicates that the original anthropogenic spatial properties of the lithic and bone assemblages have been preserved (Domínguez-Rodrigo et al., 2012; Domínguez-Rodrigo et al., 2014a, b). This is especially relevant because stone tools and bones have very different physical properties when exposed to hydraulic processes (Shick, 1987).

This brings up the issue of what does the single dense cluster of PTK and FLK Zinj really represent in terms of hominin subsistence and social behavior. Highly intense single-cluster sites are not typical of modern hunter-gatherers´ sites, regardless of site functionality (Bartram et al., 1991; Kroll and Price, 1991; Yellen, 1977). As mentioned above, modern human forager camps are characterized by a multi-cluster spatial pattern, which corresponds to each of the nuclear families integrating any given site (Yellen, 1977). Hunter-gatherers collectively bring food to camps, which is subsequently redistributed among nuclear families. This behavior accounts for the within-site dispersal and multiple spots of concentration of remains. Given that FLK Zinj is similarly sized to some of the camps reported for modern foragers, the presence of a single highly-intense cluster which comprise remains of dozens of carcasses, contrasts with the modern forager pattern and attest to a different form of social consumption of carcasses, further documented at PTK too. The limited scattering of bone remains away from the cluster and the repeated use of the same spot for consuming animals is suggestive of a collective consumption of animal food at such spots. No clear cut marks attributed to disarticulation (Galán and Domínguez-Rodrigo, 2013) have been documented at FLK Zinj. As a matter of fact, Leakey (1971) reported the presence some articulated elements. This would support that carcass parts were not intensively disarticulated once they entered the "central-place", as is commonly the case in modern foragers´ camps to distribute remains among households. The interpretation of group consumption of carcasses on the same spot is further reinforced by the even more intense concentration of lithic remains inside the cluster areas of both sites (Figs. 4 and 5). The broader scatter of

bones when compared to lithics could be reflecting either hominin butchering behaviors on the whole area or, more likely, bone dispersal caused by the post-depositional intervention of carnivores, which tend to scatter materials from clusters (Camarós et al., 2013). It could be argued that the spatial pattern documented at PTK and FLK Zinj could be artificially conditioned by the presence of a tree and the sites having acted as mere refuge spots within fairly open-vegetation habitats. However, phytoliths show uncontroversial evidence of an abundance of trees at FLK Zinj (Ashley et al., 2010) as well as a continuous wooded habitat, alternating with mosaic grassland, on the platform from FLK Zinj to PTK and beyond (Uribelarrea et al., 2014). Without any indications of an ecological constriction conditioning material discard at these spots, both sites preserve direct evidence of hominin behavior through the analysis of the spatial pattern of the discarded materials.

The repeated spatial pattern documented at FLK Zinj and PTK would, thus, indicate that nuclear families as social entities clearly demarcated from the social group had not yet appeared in human evolution. The cooperative and food-sharing behavior exhibited at that time through central-place provisioning (Marlowe, 2006) must have been based on a different social structure, which emphasized group dynamics (probably based on kin) over separated reproductive units.

Whether FLK Zinj and PTK I represent the socio-economic behavior of early humans or are simply a part of their behavioral repertoire remains to be tested through the extensive excavation of more anthropogenic sites. Other Olduvai Bed I and II sites have been taphonomically interpreted as either palimpsests or as sites with marginal hominin input (Domínguez-Rodrigo et al., 2007; Egeland and Domínguez-Rodrigo, 2008). Such sites could not be used to reflect hominin socio-economic behaviors, because spatial properties of the materials (especially bones) are mostly the result of other agencies. Most Koobi Fora early sites are generally poorly preserved to determine if there is a predominantly anthropogenic component to their formation (Isaac, 1997). There is a virtual lack of large open excavations that have exposed a window large enough to compare to modern foragers´ sites. In some cases, large excavations like Kanjera are deposits with extensive vertical projection of materials, instead of discrete accumulations on a paleosurface (Ferraro et al., 2013; Plummer et al., 2009). Such deposits may have limited resolution and integrity since they represent vast time spans of multiple depositional events and probably by more than one agent.

5. Conclusions

Two different Early Pleistocene anthropogenic sites (FLK Zinj and PTK I) display the same spatial pattern in the accumulation of bones and stone tools. Statistical tests show that there is intense interdependence between both types of materials in their spatial distribution and intensity. This further supports that the assemblages preserve high integrity and resolution and offer a unique opportunity to understand socio-economic behaviors through the preserved spatial patterning. The high-density single clusters characterizing these sites would suggest repeated communal use of the same spot for processing and consuming animal carcasses. This does not support the presence of individual nuclear families, which in modern foragers are responsible for the multi-cluster nature of assemblages formed in camps.

Regression models applied to FLK Zinj and PTK have also provided predictive models, which were tested through excavation for FLK Zinj and testing for PTK is ongoing. This enables broadening spatial perspectives beyond the excavated windows. For these models to be efficient, large excavations must exist to provide enough spatial information to model spatial trends beyond the excavated areas. This new tool is powerful to understand site functionality better.

The ideal testing background of social models through spatial patterns is large excavations of anthropogenic assemblages with minimal post-depositional disturbance accumulated during short time periods on the same paleosurface. So far, for the early African Pleistocene this applies only to FLK Zinj and PTK. Until now, evidence shows that these two sites indicate that a cooperative and food-sharing behavior (as inferred taphonomically) was sustained on a social structure different from the pattern of modern foraging human social groups based on the interaction of nuclear families. When this modern human pattern emerged remains one of the crucial questions in human evolutionary studies.

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