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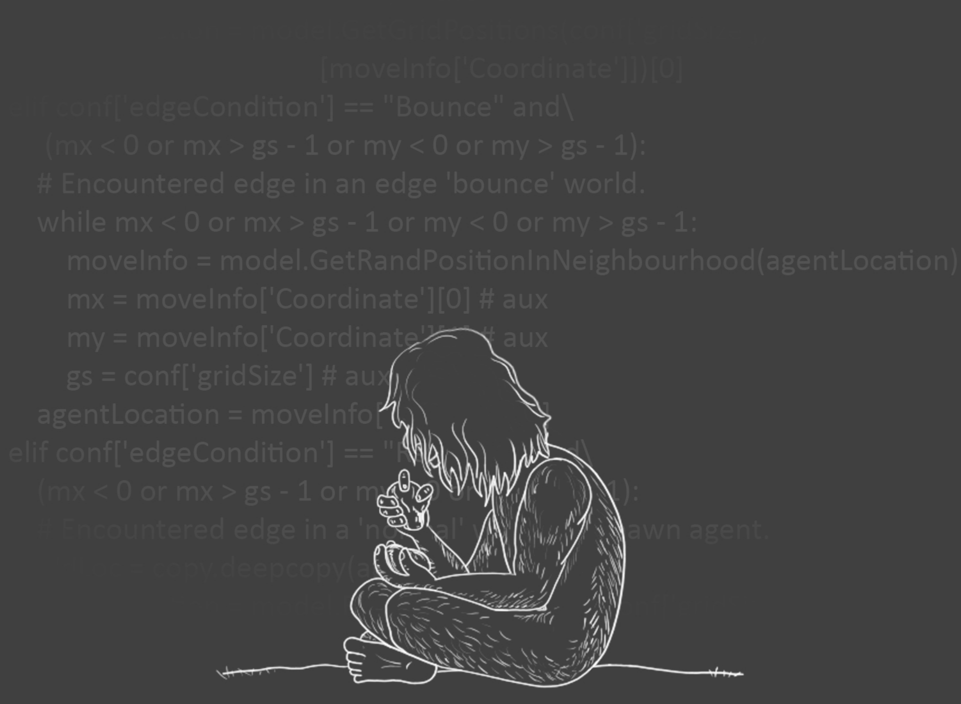

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Interpreting lithic raw material variability in Middle Palaeolithic contexts:

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(Southeastern France)

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Cover design: Background photo by C. Pop, showing parts of the region studied in this thesis as seen from the top of Mount Ventoux. Drawings courtesy of Andrea Strusievici.

For Valentina and Theodora.

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Chapter One
Introduction

1 Rationale and Goals

Lithic artifacts constitute ubiquitous and often sole surviving evidence of past human activities for much of the evolutionary history of our genus. They thus provide comparable vectors of analysis across a wide range of environmental and temporal contexts, revealing key aspects of past adaptations. The raw materials from which such artifacts were manufactured can often be traced to specific natural deposits, enabling important insights into factors such as procurement costs that would have shaped past lithic resource management decisions and consequently the variability observable in archaeological assemblages (e.g., Dibble 1991; Kuhn 1995; Andrefsky 2008 and references therein); they also provide crucial clues regarding overall land use strategies at different scales (e.g., Féblot-Augustins 2009; Frahm et al. 2016; Turq et al. 2017). It is for these reasons that lithic provenance studies have long been considered important in elucidating key aspects of human/environment interactions in prehistory. Notwithstanding their potential, there are two major challenges that provenance studies face. The first consists of identifying and characterizing original procurement locations accurately and with meaningful precision across landscapes that may have changed substantially both during and since the initial deposition of the investigated assemblages (e.g., Dibble 1991; Turq 2005). Much progress has been made in this regard over the last few decades, both in terms of the identification and cataloguing of exploitable naturally occurring raw material deposits (e.g. Biró 2009; Fernandes 2013; Pereira et al. 2016), and in terms of the development of novel characterization and classification techniques for materials used in prehistory, including chert (e.g. Fernandes et al. 2007; Parish 2011; Olofsson and Rodushkin 2011; Brandl et al. 2018) and obsidian (see Kuzmin et al. 2020). Nevertheless, sourcing archaeological lithics continues to be a very resource-intensive task that often comes short of providing conclusive answers regarding specific procurement locations.

A second challenge, and one which is the focus of this thesis, pertains to the interpretation of the provenance data: even if we could identify the procurement location of all stone artifacts with perfect accuracy and precision, we would still face the daunting task of interpreting static archaeological frequencies in terms of dynamic human behaviours. Lithic artifacts are a versatile component of wider organizational systems and could have been used in multiple contexts, and for multiple purposes, throughout complex life histories (e.g., Andrefsky 2008). Inferring behaviours and their determinants from palimpsests of discarded, lost, or abandoned end products is therefore difficult, and it is particularly so in the case of assemblages created through the agency of different hominin species, where the fundamental cognitive processes and abilities underpinning observed variability may not have been the same as those that underlie our own practices. As a consequence, most explanations of raw material variability in Middle Palaeolithic contexts incorporate, out of necessity, a series of assumptions that have not been rigorously tested.

Agent-based modelling has great potential for addressing this problem because it enables the systemic effects of different assumptions to be examined in detail. However, the most promising applications so far have employed abstract units as well as abstract definitions of space and time (e.g., Brantingham 2003; Barton and Riel-Salvatore 2014), and it is difficult to evaluate whether the simplifying assumptions underpinning such abstractions are valid. Consequently, a primary goal pursued in this thesis is the development of a minimally realistic agent-based methodology for inferring one aspect of past adaptations, namely land use, on the basis of archaeological raw material variability. Specifically, the approach pursued here aims to be as simple as possible while being spatially and temporally explicit and employing real and well-defined units (e.g., grams of stone) as well as behavioural rules that make sense for a given temporal and geographic context. A parallel goal is the development of a resource selection model that can be easily integrated into such agent-based framework, one built strictly on the basis of archaeological observations and which can account equally well for both exploited and unutilized raw material sources. While these goals are met using data from a specific site, namely the Bau de l'Aubesier (southeastern France), the resulting methods are expected to be broadly applicable in other contexts as well.

What follows is an overview of the specific research questions this thesis seeks to answer, contextualized by means of a background discussion of stone procurement studies in Middle Palaeolithic contexts. I then provide a general summary of the methods and data I use, outlining the process through brief summaries of the chapters that are included in this work.

2 Research questions

The research questions pursued in this thesis reflect an overall concern with letting provenance data speak for themselves rather than forcing a fit to models developed using other lines of evidence (e.g., ethnographic analogy). They can be summarized as follows:

1. What can be learned from re-evaluating a neutral model of lithic procurement (Brantingham 2003) in terms of developing an alternative, agent-based framework for interpreting provenance data?
2. Can we determine the likely extents of the territories over which lithic resources were locally exploited by Middle Palaeolithic hominins without relying on untested and possibly untestable assumptions?
3. Can we determine the extent of the likely home ranges of Middle Palaeolithic individuals and groups based solely on lithic provenance data and a minimal and clearly justified set of assumptions?
4. What, if anything, can provenance data tell us of how Neanderthals may have conceptualized stone resources and, more broadly, about the cognitive processes underpinning their use?

3 Background

3.1 The European Middle Palaeolithic

The term Middle Palaeolithic refers to a phase of development in techno-economic organization that is traditionally characterized by a focus on flake tools produced through lithic reduction sequences that employ prepared core techniques, most notably Levallois (e.g., Burkitt and Childe 1932; Clark 1969; Adler et al. 2014; Soriano and Villa 2017), and more broadly by a suite of innovations (e.g., Fontana et al. 2013; Hérisson et al. 2016) implying increasingly greater behavioural and executive flexibility, planning complexity, and control (e.g., White et al. 2011; Kuhn 2013; see also Malinsky-Buller 2016). In Europe, it is chronologically constrained between the onset of MIS 8 and 3, or roughly 300-250kya (e.g., White et al. 2011; di Modica et al. 2016; Hérisson et al. 2016; Soriano and Villa 2017) and the appearance of early Upper Palaeolithic or transitional technocomplexes such as the Châtelperronian between ca. 50-40kya (e.g., Hublin et al. 2012; Richter 2016). It spanned variable areas from the Mediterranean to roughly 55° North (see Nielsen et al. 2017 for a discussion) and the entire longitude of the continent, depending on prevailing climatic conditions (e.g., Roebroeks et al. 2011). Lastly, it is associated with Neanderthals (e.g., Roebroeks and Soressi 2016; but see e.g., Harvati et al. 2019).

Kuhn (2013) has argued that true innovations in the Middle Palaeolithic were few (see also Stiner 2013), amounting to hafting, pyrotechnology, and the use of pigments, the rest of the technological systems representing a reorganization of an already existing repertoire. While other inventions presaging the eventual onset of the Upper Palaeolithic, such as specialized bone tools (e.g. Soressi et al. 2013), cave art and other forms of symbolic material culture (e.g., Zilhão, 2012; Radovčić et al. 2015; Hoffmann et al. 2018a; Hoffmann et al. 2018b) are also sporadically evidenced in Middle Palaeolithic contexts, behavioural plasticity, reflected in variable technological and organizational responses to circumstances, is increasingly considered to be a hallmark. Indeed, the apparent simplicity of Middle Palaeolithic artifacts, which consist mostly of processing tools such as scrapers, notches, and denticulates (e.g., Richter 2016; Ruebens and Wragg Sykes 2016) betrays a great deal of tactical and strategic sophistication in their procurement, manufacture, and use (e.g. Kuhn 2013; Turq et al. 2013; Locht et al. 2016; Picin 2018), as well as pronounced regional differences, particularly in the case of younger assemblages (e.g. Ruebens and Wragg Sykes 2016; see also Richter 2016; cf. Daujeard et al. 2016).

Novel landscape utilization strategies emerging during the Middle Palaeolithic are evidenced by various proxies indicative of increased and varied mobility patterns as well as sophisticated regional-scale organization and scheduling of activities (cf. Binford 1989). These proxies include seasonal and possibly logistic (*sensu* Binford 1980) utilization of sites (e.g., Daujeard and Moncel 2010; Delagnes and Rendu 2011; Ashton and Scott 2016), which in some cases attest to monospecific hunting strategies (e.g., Daujeard and Moncel 2010; Richter 2016), substantial fragmentation of reduction sequences and differential processing and transport of raw materials (e.g., Delagnes and Rendu 2011; Raynal et al. 2013; Turq et al. 2013; Ruebens and Wragg Sykes 2016), a widespread negative correlation between retouch intensity and artifact densities (see Kuhn 2013 and references therein), and the general diversification of lithic reduction methods to fit different, situationally specific mobility requirements (e.g., Turq et al. 2017).

The behavioural flexibility characteristic of Middle Palaeolithic adaptation seems to have been underpinned by an excellent knowledge of resources over relatively large areas (e.g., Raynal et al. 2012) and overall exploitation strategies aimed at optimization. Beyond that, however, it is likely that explanations for specific adaptations (e.g., the use of specific tool types, specific reduction methods for specific raw materials, tasks, and situations, or regional trends in raw material management) can only be provided for specific contexts, without generalizing to the entire Middle Palaeolithic record (see Eixea 2018). For instance, temporal trends are evidenced in some regions such as Britain (e.g., Ruebens and Wragg Sykes 2016) and the Aquitaine Basin (e.g., Turq 2013) but seem absent in others (e.g., Spain – de la Torre et al. 2013; SE France – Daujeard and Moncel 2010). Similarly, stone management in the Aquitaine (e.g., Turq 2013) appears to be quite different from what is evidenced in southeastern France (e.g., Raynal et al. 2013). Overall, there is a growing consensus that the Middle Palaeolithic cannot be viewed as a homogeneous, static entity.

3.2 Stone resources and the Middle Palaeolithic record

As the preceding discussion has already hinted, much of our understanding of Middle Palaeolithic lifeways derives from evidence preserved in stone. Indeed, owing to their durability and varied uses, lithic materials are ubiquitous in Middle Palaeolithic assemblages, providing comparable and sometimes only vectors of analysis between sites that may otherwise be quite dissimilar in terms of geographic and temporal context, preservation potential, and resource availability or use. Stone artifacts have therefore been used to draw inferences at a variety of scales, ranging from the cognitive processes reflected in the manufacture of individual pieces (e.g., Stout 2011; Muller 2017), to the land use strategies employed by hominins (see above and section 1.3.3.2 below). It is clear that, combined with other lines of evidence, lithics have the potential to inform us of many aspects of Middle Palaeolithic adaptations. However, it is important to recognize that there are some fundamental differences between toolstone and other resources that hominins regularly exploited, and that the distinguishing characteristics of lithic materials must be considered carefully before incorporating lithic data into more comprehensive explanatory frameworks, as they may inform us of potentially very different processes and behaviours, operating at different spatial and temporal scales (e.g., Vaquero et al. 2017).

Some of the distinguishing characteristics of lithic resources are as follows:

a) Raw material sources are essentially static when considered at human timescales. Consequently, the costs of procurement are highly predictable provided an area has been inhabited long enough for resource distribution and topography to be known.
b) The nature of the raw materials (e.g., knappability, durability, ease of extraction) can vary substantially between sources, but such differences, when viewed at human timescales, tend to be fixed. The benefits afforded by different procurement alternatives are therefore also highly predictable if a region is well-known.
c) Good quality raw materials occur over a limited exposure. Often, though not always, usable materials are found in spatially constrained settings (e.g., a discrete outcrop or secondary deposit) which can theoretically be identified from archaeological pieces based on structural, chemical, and physical signatures resulting from unique geological histories (see e.g., Luedtke 1992; Malyk-Selivanova 1998; Fernandes et al. 2007).
d) Most lithic raw materials are a non-renewable resource when considered at human time scales. This may be important to consider when investigating the long-term exploitation of primary sources (see, e.g., Dibble 1991).
e) As attested by use-wear studies, traces left on other materials (e.g., cutmarks on bone), and their very ubiquity, lithic raw materials were, throughout the Palaeolithic, an essential part of adaptation for members of our genus, both for the extraction and processing of resources for consumption, and for the creation of other tools.
f) As a consequence of ***c*** and ***d***/***e*** above, and because other resources essential to humans (e.g., food and shelter) are not predictably found at lithic raw material sources, toolstone has to be transported to where it may be needed, resulting in a human-mediated displacement across the landscape.
g) Stones are heavy and may contain flaws that are difficult to identify prior to use. As is both ethnographically (e.g., Sillitoe and Hardy 2003) and archaeologically (e.g., Barkai et al. 2002) documented, it often pays off to process the materials, to some extent at least, prior to transport.

h) Stone tool making is a reductive process, and this has several implications. First, as a piece of stone is worked, it gets progressively smaller, decreasing its usability potential over time. Second, at least parts of the process of manufacture can be reconstructed through refitting and technological studies (see, e.g., Andrefsky 2009 and references therein), thereby giving insights into overall strategies employed, and tactical decisions made, by individual tool makers. Third, as stone is transported, the reduction process may be fragmented across sites (see ***f*** above), thus giving us a glimpse of how a site fit within a wider land use pattern (e.g., Moncel et al. 2014).
i) Finally, lithic implements are durable, and we can reasonably expect them to survive indefinitely in archaeological contexts in the absence of post-depositional processes that would physically remove them from a site. Conversely, their durability, combined with the costs of transport (***f*** above), imply that the potential for lithic materials to have been exposed to multiple episodes of human alteration or agency is high – for instance, materials may have been recycled long after their original discard or abandonment for a very different purpose by a totally unrelated individual (e.g., Turq et al. 2013).

In short, stone was a fundamentally important (e), predictable (a, b) non-renewable (d) but potentially very abundant resource, whose transformations through human agency can be investigated in good detail (h) by virtue of its preservation potential (i). Since transporting rocks necessary for livelihood (e) over great distances comes at a cost (g), the spatial distribution of stone deposits was likely a strong determinant of overall settlement and mobility strategies (e.g., Mellars 1996; see also Doronicheva et al. 2016). However, given the predictability of procurement (a), particularly compared to that of other resources, stone provisioning is unlikely to have been the main determinant of most scheduling activities. On the other hand, some amount of stone is likely to have been carried by individuals to ensure supply when needed (e.g., Kuhn 1995). At a minimum then, and because the geographic origin of toolstone can often be ascertained (c), investigating lithic materials should enable us to elucidate aspects of both group and individual mobility.

3.3 Toolstone procurement studies

3.3.1 Historical considerations

Prehistorians have long recognized that raw material availability and characteristics affect assemblage variability (e.g., Moulin 1903; Dibble 1985; Kuhn 1991; see also references in Turq 2005). Focused, systematic research into the provenance of archaeologically exploited stone has a shorter history, however. Important studies were conducted in the 1960s and 1970s (e.g., Valensi 1960; Renfrew et al. 1965; Renfrew 1969; Kozlowski 1972; Luedtke 1976 – see also Delage 2003 for a more detailed discussion) against a backdrop of shifting theoretical perspectives and increased interdisciplinarity. In terms of theory, archaeology as a whole was moving away from a culture-historical paradigm and towards an emphasis on understanding behaviours and cultural processes (see, e.g., Trigger 2006), with parallel developments in cultural anthropology (e.g., cultural ecology). Within approaches that increasingly saw lithic technology as a dynamic component of wider adaptive systems, understanding toolstone procurement strategies, and as a corollary identifying the location of potential raw material sources, became, at least in principle, critically important (e.g., Sellet 1993; Andrefsky 2008). Increasing interdisciplinary collaboration, on the other hand, exemplified by, for instance, the International Flint Symposium (first held in 1969 – see, e.g., Sieveking and Hart 1986), led to the development of characterization methods that enabled more reliable source attributions for archaeological artifacts, as well as to a good understanding of the distribution and geological context in which sources of usable stone occurred in many regions (e.g., Leonoff 1970; Luedtke 1976; Gramly 1978; Morala 1980).

The 1960s and 1970s were also an important period in terms of developments in hunter-gatherer studies (e.g., Lee and DeVore 1968), which strongly shaped how lithic raw material provenance data would be interpreted in Middle Palaeolithic contexts later on. For instance, the often-noted two-hour-walk foraging radius is attributable to Richard Lee's work among the Ju/'hoansi (Wobst 1978), while many other constructs regularly used in the literature today can be traced, directly or indirectly, to Lewis Binford's work among the Nunamiut. The influence of this body of work on subsequent interpretations of lithic provenance data is difficult to overstate. Binford's idea of embedded procurement, for example, though not new (see Luedtke 1976), provided a theoretical justification for interpreting maximum transfer distances in terms of home range sizes (e.g., Féblot-Augustins 1993, 1999; Kuhn 1995; Mellars 1996), still a common practice today. Similarly, his distinction between residential and logistic mobility has framed many interpretations over the last three decades (e.g., Féblot-Augustins 1993; de Soler et al. 2020). His concept of curation, introduced in the 1970s, continues to be similarly influential, in part because, as Andrefsky (2008) noted, "it linked stone tools to mobility patterns".

Be as it may, by 1980 the necessary basic theoretical and methodological building blocks were in place, and over the following decade provenance studies became a major focus in Palaeolithic research in France and elsewhere in Europe (e.g., Floss 1994; Mellars 1996; Turq 2005; Biro 2009; Feblot-Augustins 2009; see also Delange 2003). The 1980s thus witnessed the creation of the first major lithotheques in France, Hungary, and Switzerland (Biro 2008), as well as a series of publications by a handful of French researchers (e.g., Geneste, Turq, and Demars), working mainly in the Aquitaine Basin, and which would become the basis for later syntheses that continue to influence interpretation today (e.g., Féblot-Augustins 1993, 1999; Mellars 1996).

Among the most enduring contributions of this literature are Geneste's definitions of local, intermediate, and distant procurement zones. As summarized later by Mellars (1996) and others (e.g., Feblot-Augustins 1993), work in southwestern France in the 1980s pointed to a strong reliance (70+% of lithics) on materials collected at up to 4-5 km from camps, discarded or abandoned at all stages of lithic reduction (though seldom in the form of retouched implements), and the frequent (i.e., ca. 80% of cases) presence of small quantities of "terminal products" transferred over distances of up to 100 km from a relatively large array of sources. Diverse raw materials, procured from sources found at intermediary distances (i.e., 5 to 20 km), were also a recurrent characteristic of assemblages from these sites, representing a mix of utilization patterns typical of materials collected at more distant sources and at local ones. For Mellars (1996), some of these later materials, namely those collected from sources located at 6 to 12 km from sites, could have been collected during occasional forays within an "extended foraging radius". The more distant materials (i.e., 20 - 100 km) were typically thought to reflect the mobility of Neanderthal groups over their home ranges. Mellars (1996) noted that a site may have been used by multiple groups exploiting different territories, but many other researchers (e.g., Feblot-Augustins 1993) worked under the assumption that the distribution of distant utilized raw material sources provided insights into the movements of discrete groups, and that maximal transfer distances could be used to provide meaningful estimates of their home range sizes.

Since the late 1990s our understanding of the geographic distribution of usable raw material sources across the Neanderthal range has improved considerably, and many assemblages, covering a wide geographic range, have now been analyzed from the point of view of lithic raw material provenance. Together with important developments in sourcing methodologies that resulted in cheaper and faster data acquisition (e.g., pXRF), improved reliability, and/or greater informational potential (e.g., Fernandes et al. 2007), we now have a substantially expanded dataset on Middle Palaeolithic toolstone procurement. However, there have been relatively few major developments in terms of how data are interpreted; indeed, the frameworks proposed in the 1980s and 1990s on the basis of a handful of sites continue to colour, if not dominate, approaches to the interpretation of Middle Palaeolithic raw material procurement data. There continues to be an overriding concern with the utilization of distant materials, either to elucidate regional patterns of raw material transfers or to assess the possibility of inter-group exchanges, and by and large the problem of raw material procurement continues to be framed in terms of ethnographically-derived models of embedded or direct procurement within the context of logistic or residential mobility.

This is not to say that no important theoretical contributions have been made; there have certainly been exciting new developments in terms of the availability of novel approaches to interpretation, ranging from agent-based modelling (e.g., Brantingham 2003), GIS analyses (e.g., Ekshtain 2016), to more theoretical approaches based on estimates of energy consumption (e.g., Verpoorte 2006). There is also a greater awareness of the potential role the recycling of materials may have in explaining instances of long-distance transport (e.g., Turq et al. 2013), and a greater emphasis has been placed on the development of new methods aimed at understanding resource utilization and land use at smaller scales (e.g., Browne and Wilson 2011; Frahm 2016). However, the impact of these advancements on overall syntheses of Middle Palaeolithic raw material provisioning has been minimal.

3.3.2 An overview of contributions

Raw material procurement studies came to the fore in Middle Palaeolithic research at a time when the planning and organizational abilities of Neanderthals, and more broadly their capacities for symbolic thought and cooperation, were under heavy assault. Provenance studies contributed to debates on Neanderthal abilities in a number of ways. For example, they provided data indicating that Neanderthals did not always employ expedient technologies (e.g., Soressi and Hays 2003; see also Hiscock et al. 2009; Kuhn 2013) and that they had a good knowledge of the environments they inhabited (e.g., Féblot-Augustins 1993; Raynal et al. 2012; Raynal et al. 2013), exploiting them strategically. Such strategic exploitation is thought to be reflected in the directions and distances from which stone resources were brought in, often interpreted in terms of residential mobility in the case of resources not available in the immediate vicinity of the sites at which they were discarded or abandoned (e.g., Feblot-Augustins 1993, 1999). It is also thought to be reflected in the provisioning of sites (*sensu* Kuhn 1995) in cases where the absence of raw materials was known (e.g., di Modica et al. 2016; Malinski-Buller 2016), and more broadly in a strategic adjustment of exploitation strategies based on expected raw material availability (e.g., Braun 2005; Dogandžić and Đuričić 2017 and references therein; Delpiano et al. 2018).

Such studies also revealed Neanderthals were selective in their use of stone resources, often, but not always, preferentially targeting outcrops of higher quality rocks (e.g., Wilson 2007; Eixea 2018) despite being perfectly capable of applying complex reduction techniques (e.g., Levallois) to a wide range of materials with potentially lower access costs, including limestone (e.g., Dogandžić and Đuričić 2017;

Eixea 2018; Eixea et al. 2020), basalt (e.g., Reynal et al. 2013; Santagata et al. 2017), phonolite (e.g., Santagata et al. 2017); quartzite (e.g., Eixea 2018; Eixea et al. 2020), and andesite (e.g., Panagopoulou 2004; see also Daffara et al. 2019). Indeed, raw material provenance data has been used to explore the degree to which different selection criteria were important (e.g., nodule size, knapping quality, functional performance – e.g., Browne and Wilson 2011; Wilson et al. 2018), how these criteria changed through time at individual sites (e.g., Wilson and Browne 2014), and also how raw material selectivity varied across different regions (e.g., Eixea 2018). Overall, research into toolstone procurement has served to highlight the versatility of Neanderthal adaptation, even if more limited than evidenced with anatomically modern humans.

Provenance studies also revealed that in most instances lithic raw materials were transferred over shorter distances during the Middle Palaeolithic than in subsequent periods. As noted by Féblot-Augustins (2009) amongst others, almost all sites appear to have been provisioned with materials typically found within what may be called an 'extended foraging radius' of up to 12 km or so, covering areas reachable through occasional daily forays (e.g., Mellars 1996). Longer transfers, though almost always documented, appear to result from the discard of generally high-quality materials carried by individuals as part of their mobile toolkits, typically retouched implements or flexible matrices (e.g., Meignen 2009; see also Hiscock et al. 2009; Turq et al. 2013; Turq et al. 2017). Such long-distance transfers are also normally restricted to areas that may have corresponded to home ranges of groups or individuals that made use of the sites (see below), as they only exceptionally exceed 100 km (see Feblot-Augustins 2009). While macro-regional differences are attested, reflecting perhaps the underlying differences in the geographic distribution of raw-material-bearing geological formations (Duke and Steele 2010) or resource availability more broadly, the overall data suggests inter-group exchanges *of stone* were uncommon, if they occurred at all. This, in turn, has implications in terms of the complexity of social organization (e.g., size of interaction networks – e.g., Eixea 2018).

The contribution of basic data on hominin-environmental interactions is, of course, useful beyond the relatively narrow scope of debates on the degree of Neanderthal behavioural modernity. As noted above, provenance studies can hint at the *extent* of the territories exploited by Neanderthals at different analytical scales (see below) as well as at the *nature* and *degree* of mobility within those territories (see, e.g., Féblot-Augustins 1993; Fernandez-Laso et al. 2011; Raynal et al. 2013; see also Cole 2002), particularly when combined with other lines of evidence such as stable isotope and faunal studies. Viewed at a regional level and drawing on data from multiple sites, provenance data can further be used to examine connections or mobility corridors between different geographic zones (e.g., Turq et al. 2017; Eixea et al. 2020), and diachronic shifts in the apparent size of the territories have been interpreted by some as signaling transitions in subsistence patterns and socio-economic organization (e.g. Zilhão 2001; Ashton and Scott 2016). Indeed, the ability to provide insights into mobility, and perhaps social interactions, is considered by many to be the most important aspect of provenance studies (e.g., Larick 1986; Takács-Biró 1986; Mellars 1996). The basic picture that has emerged in terms of territorial exploitation to date, and which has not changed substantially since the 1980s, can be summarized as follows:

1. <u>Area within which daily foraging activities occurred</u>: Typically, 5 - 10 km from a site, corresponding to a *maximum* of ca. 80 - 315 km^2 (e.g., Hayden 2012; see also Mellars 1996; Wilson et al. 2018). This estimate is based on considerations of the radius within which the bulk

of the archaeological materials were procured (though further details are often not given), and the close agreement with ethnographic observations (see above; see also e.g., Mellars 1996).

2. Group home ranges: The extent of the territories regularly exploited by the group(s) that spent some time at a site within their system of residential mobility have been discussed based on attested transfer distances as well (e.g., Mellars 1996; Steele 1996; Cole 2002). Typically, transfer distances of between 20 - 100 km are seen as indicating home range sizes, and consequently result in estimates for the latter of at least ca. 1,000 km^2 (e.g., Boyle 1998) and up to more than 10,000 km^2 (e.g., Féblot-Augustins 1993; see also Wilson et al. 2018), depending on how one interprets the often very muddled uses of the concept of "territory" (e.g., Raynal et al. 2012; Turq et al. 2013). These estimates are in line with estimates from some carnivore models (e.g., Walker 2014) and some ethnographic data (e.g., Marlowe 2005), but other lines of evidence suggest these estimates may be too high (see below). The presence of materials from distant sources has been interpreted as indicating a relatively high degree of residential mobility, since lengths of residence must have been shorter than the time spent by materials in mobile toolkits (e.g., Cole 2002), but this aspect is typically discussed in qualitative terms.

3. Individual ranges - landscapes of habit, zones of socioeconomic influence, "tribal" range, or "mating network": Some researchers (e.g., Gamble 1999 and references therein; Pearce and Moutsiou 2014; see also Churchill 2014) interpret maximum transfer distances in terms of territories used by individuals and those with whom these individuals interact in some capacity. It is often difficult to distinguish, based on the usage, whether this is what many authors have in mind when discussing Neanderthal territories, or whether it is group home ranges, or something entirely different.

Beyond this, raw material provenance also supplies critical data for understanding tactical and strategic decisions in the use of stone that directly influenced assemblage variability, and consequently our interpretations of technological organization as well as typology. In essence, the real or anticipated costs of acquiring different raw materials constrained choices, and the properties of the rocks worth getting (e.g., fracture characteristics, nodule sizes and shapes) are typically thought to have affected both tool morphology and the choice of reduction techniques (e.g., Andrefsky 1994; Braun 2005; but see Eren et al. 2014; Garefalakis et al. 2018). Moreover, said costs may also explain the different treatment of materials (e.g., high-quality materials being transferred over longer distances in specific package types); there are indeed many examples where different degrees of mobility are thought to be attested to by different types of implements or reduction strategies (e.g., Turq et al. 2013; Faivre et al. 2014; Ruebens and Wragg Sykes 2016; Turq et al. 2017).

3.3.3 Interpretive challenges

While a substantial corpus of data on Middle Palaeolithic toolstone procurement has now been compiled (see section 1.3.3.1 above), numerous issues hinder its interpretation. Some of the most salient ones are discussed below:

Terminology: Critical terms underpinning both the interpretation and reporting of basic data, such as *local*, *exotic*, *group*, *mobility*, *territory*, or *home range* are in most instances poorly defined, and the theoretical assumptions underpinning their use are seldom explicitly discussed and justified. Consequently, it can be difficult to integrate the results of studies conducted in different regions. A few examples are worth a closer look:

a. *local*: This term, while mostly used to denote materials procurable within 5 km or less, sometimes also refers to materials procurable within 10 km of a site (e.g., Moutsiou 2011; de la Torre 2013; Eixea 2018) or more (e.g., 12 km in Cole 2002; 20 km in Adler et al. 2014), and often it is not defined at all (e.g., Martinez and Rando 2001; Zilhão 2001; Blaser et al. 2002). While the reasoning behind the choice of a cut-off value (if any) to define "local" often makes sense within the context of a specific paper, it can lead to misunderstandings when multiple studies are compared in terms of how materials were procured, and by whom (e.g., by individual site residents in the context of daily foraging activities, or while residing at other nearby sites and then brought in during residential moves). This is not a trivial problem (cf., Mellars 1996) because it has important implications with regards to the scale of Neanderthal activities: do these "local" materials inform us of daily exploitation territories, of the home ranges of one or more groups, or perhaps of something else? Indeed, the lumping together of the typically dominant component of assemblages as "local" also serves to render this local range somewhat of a *terra incognita*, concealing potentially very interesting and highly informative differences and similarities in the utilization of such areas across the Neanderthal range. Few studies (e.g., Frahm et al. 2016) have so far focused squarely on evaluating the use of these "local" areas on the basis of the provenance of stone.

b. *mobility*: Although the potential of sourcing studies to inform us of past mobility patterns is a key perceived contribution (see above), seldom is the term defined or discussed in sufficient detail. Neanderthals may well have been very mobile without getting far from their place of birth (e.g., Verpoorte 2006), or they may have died quite far from it after a lifetime of moving very little. If by mobility we mean the area used by *individuals* over their lifetime, the direct (isotopic) evidence we have for such mobility (e.g., Richards et al. 2008; Moncel et al. 2019; Wißing et al. 2019; Nava et al. 2020) is inconclusive, perhaps simply because mobility differed across different contexts (e.g., at Spy and Goyet, or at Fumane and Riparo Broion – see Wißing et al. 2019 and Nava et al. 2020 respectively). The observed limits on maximum toolstone transfer distances may hint at upper limits to such mobility, but they may just as well reflect instead a limited capacity (or willingness) to carry the same materials for long periods (i.e., may reflect mobile toolkit turnover – see, e.g., Brantingham 2003). If, on the other hand, mobility is considered in terms of the frequency of residential moves, we can say that at times residence appears to have amounted to a few days at most (e.g., Payre level F – Moncel et al. 2019), while at others (e.g., Payre level Gb – Moncel et al. 2019) it seems to have been longer, although what that means in terms of weeks or months is seldom specified. Residence time is nevertheless critical for interpreting long-distance transfers of materials thought to have been carried in mobile toolkits, since it affects the number of residential moves such materials may be expected to survive before discard (see, e.g., Cole 2002).

c. *territory*: Another concept of critical relevance whose meaning is seldom clarified is that of "territory". Whose territory? As already noted above (see section 1.3.3.2), "tribal" and "band" territories are sometimes used almost interchangeably (e.g., Raynal et al. 2012), and there is a widespread and often implicit assumption that archaeological raw materials within a given assemblage reflect the use of the environment by a discrete group of individuals (e.g., Moncel et al. 2019) who do not regularly move to and from other such groups transporting stone. This assumption is not well-supported by ethnographic data (the composition of hunter-gatherer bands is fluid – see, e.g., Haviland et al. 2013), nor is it normally justified on other grounds. Is the presence of distant raw materials informative with regards to the maximal size of band home ranges, mating networks, or perhaps something else?

The problem is not that we lack a universal definition for these terms, or some universal theoretical framework for interpreting the data – the problem is that often the complexities and the challenges these terms pose are not discussed or acknowledged, and that data is typically not reported in a way that enables overcoming these issues.

Data collection and reporting: Data presented in provenance studies is often incomplete. For instance, information is often given on the nearest possible geological source of an archaeologically represented raw material type, but seldom for potential alternatives, the *assumption* being that such nearest sources reflected actual procurement locations. However, this assumption can be wrong if those alternatives differ in terms of properties that would have influenced procurement decisions (e.g., extent of exposure, ease of extraction, nodule shape), or if continued use temporarily depleted the supply of easily collectable rocks at the nearest source (see, e.g., Luedtke 1976). Many studies (e.g., Spinapolice 2012) also focus on maximum procurement distances, and consequently under-report the location and characteristics of potential sources located closer to the site, often simply stating that certain percentages of materials are “local” or “semi-local.” This effectively reduces the resolution of the data, making it very difficult to apply or explore alternative interpretive frameworks.

Inescapable outdated interpretive frameworks: The under-reporting of basic provenance data and the problematic use of key terminology have made it difficult to move beyond the earliest interpretive frameworks. Thus, predominantly “local” raw material procurement continues to be discussed as a feature of the Middle Palaeolithic record as if no meaningful differences in landscape exploitation exist between sites provisioned exclusively with rocks available within a few meters and those provisioned primarily from sources found only at several kilometers (but less than, say, 12) from a site, despite the presence of workable materials nearby (e.g., the Bau de l’Aubesier, or La Combette, in southeastern France). Provenance data also continues to be discussed in terms of Binford’s binary alternatives (e.g., curated versus expedient technologies, embedded versus direct procurement, collector versus forager settlement systems) as if these exhausted all possibilities. Yet the fact that virtually any assemblage can be made to fit into Binford’s schemas is a weakness, not a strength (see Popper 1963). Aside from this, central-place foraging models (e.g., Kelly 1995) continue to strongly influence interpretation, despite the fact that they were developed on the basis of modern hunter-gatherers whose foraging habits, including division of labour (e.g., Kuhn and Stiner 2006; but see Henry et al. 2014) and the nature of the exploited resources, are likely fundamentally different from those of Neanderthals. For instance, the majority of the evidence points to Neanderthals having had a narrower diet and relying primarily on mobile terrestrial resources (e.g., Stiner 2013; Power 2019), whereas the majority of the food consumed by most ethnographically documented foragers consists of gathered, relatively stationary resources, or are of aquatic origin (e.g., Kelly 1995; Marlowe 2005). In short, few current approaches allow the data to speak for themselves (exceptions include Wilson and Browne 2011; Frahm et al. 2016), and few allow for the possibility that Neanderthals may have processed information just as competently, but differently, from us, without assuming a unilinear development of intelligence and broader cognition.

4 METHODOLOGY

4.1 Agent-based modeling:

The preceding discussion highlights the need to examine and develop alternative frameworks for interpreting provenance data which minimize assumptions, are internally coherent and consistent, employ explicitly and rigorously defined terminology, and are capable of generating hypotheses which can be unambiguously rejected. Agent-based models (ABMs) fit these criteria well. Such models, which have a long history of archaeological application (e.g., Lake 2015), enable the study of complex patterns that emerge from simple and clearly defined low-level interactions between goal-oriented autonomous agents and their environments (e.g., Bonabeau 2002). They require explicit and formal definition of all included behavioural rules and parameters, as well as careful consideration of overall model mechanics. AMBs can be used to study the systemic effects of changes in individual model components, and therefore to formulate a clear set of expectations of what may be expected under modelled conditions, and *why*.

Neutral agent-based models provide a particularly promising starting point in the development of an alternative interpretive framework based on computer simulations because they aim to be as simple as possible both in terms of their underlying assumptions – all modelled processes are either stochastic or constant – and in terms of the number and nature of included variables and parameters. Unfortunately, the quest for ultimate simplicity renders these models highly abstract, and as a result they a) can be difficult to interpret in terms of real-world relevance or applicability, and b) run the risk of unwittingly simulating impossible realities. Moreover, it has long been noted that specifying parameters for such models is notoriously difficult (e.g., Gotelli and McGill 2006) and that fiddling with these can artificially result in patterns that resemble real observations (Enquist et al. 2002). Due partly to this, such models have so far seen very limited adoption and have had minimal impact on provenance studies.

To overcome these issues, in this thesis I propose, implement, and test a minimally realistic agent-based model of raw material management (Chapter 5). As the term is used here (c.f., Plagányi 2007), a minimally realistic model (hereinafter, MRM) is one that seeks to bridge the gap between abstract neutral models and models which aim to emulate the past. In effect, an MRM seeks to be the simplest model (i.e., with the fewest variables or processes) that can generate patterns which are quantitatively comparable and compatible with archaeological observations (i.e., fit within the basic observed constraints such as assemblage size) in the absence of a given mechanism (e.g., selective land use), using real-world units (e.g., grams of stone), and postulating logically consistent behaviours and parameter settings that, based on our current state of knowledge, have a reasonable *a priori* probability of having been true in the target temporal and geographic context, and given the nature of the employed units and chosen modelling scale. Therefore, as envisioned here, an MRM is necessarily both spatially and behaviourally explicit. It should be noted that MRMs are not well-suited for all tasks; they are best seen as virtual laboratories, to borrow a phrase from Premo (e.g., Premo 2010), where assumptions can be tested and aspects of the record which are at present unknowable can be explored so as to generate clear hypotheses about the past.

4.2 Local resource selection: a network model

In this thesis I supplement the MRM approach discussed above with a novel method for investigating raw material resource selection at sites where neutral expectations (e.g., Brantingham 2003 and

Chapter 3) are clearly contradicted by the available data, as is the case with the Bau de l'Aubesier (hereinafter, the Bau - see Chapter 2 and Chapter 4).

Typically, the issue of resource selection is approached, at an assemblage level, through a comparison of environmental resource availability and degrees of archaeological representation, as well as through an examination of technological parameters thought to reflect preferences, such as more intense maintenance or reduction of specific raw material types. At the Bau de l'Aubesier resource selection has been previously investigated by means of a more complex approach based on the application of GLMs, or generalized linear models (Browne and Wilson 2011; Wilson and Browne 2014). The advantage of such models, which have proven to be a fruitful avenue of research not only at the Bau and elsewhere as well (e.g., La Combette – Wilson et al. 2018), is that they enable the relative influence of multiple predictors to be examined simultaneously and in relation to each other. They also allow for the attractiveness of individual resources to be quantified from a perspective that approaches that of the hominins who used them. This, of course, is very helpful in the context of agent-based simulations, since it provides a simple way of specifying relative probabilities of selection for resources an agent may be evaluating as procurement options. However, such models are limited in their ability to incorporate or account for the possible influence of the spatial configuration of sources, shown in Chapter 3 to have a significant effect on their degree of utilization even under an entirely neutral scenario; they are also limited in their ability to explain the lack of exploitation of resources with intermediary attractiveness values.

In this thesis I therefore develop an approach to local resource selection which builds upon previous efforts while addressing some of their limitations. While it is applied specifically to the Bau de l'Aubesier, the proposed method, which enables *testing* of hypotheses premised on cost/benefit optimization, is applicable to other contexts as well. As discussed in detail in Chapter 4, it involves conceptualizing individual raw material sources as nodes in an edge- and node-weighted network of possible procurement alternatives, with edge weights corresponding to minimum travel times between nodes along least-cost paths, and node weights corresponding to a composite measure of source characteristics (e.g., raw material quality, extent of exposure). For each node in this network – that is, from the perspective of each source - the viability of procuring materials from all available alternatives, including the source itself, is determined by quantifying, using selection criteria empirically derived based on a generalized linear model, the caliper of each possible procurement path that passes through a source and ends at the site.

An advantage of this approach is that it allows for the identification of optimal exploitation alternatives for a given site while fully accounting for the presence of competing alternatives, and without assuming that the closest source of a material will have been used. A related advantage is that it allows for the identification of sources expected to have been avoided by virtue of being sub-optimal exploitation targets. This, in turn, allows for the testing of hypotheses pertaining to navigational abilities and degrees of landscape knowledge. Finally, the method provides a unique advantage in the context of an MRM that considers residential mobility (Chapter 5), since it substantially reduces the source dataset for any given site, real or simulated, based solely on archaeologically observed criteria.

5 Data used in this Thesis

5.1 Simulation data:

A substantial portion of this thesis (Chapters 3 and 5) involves the analysis of virtual assemblages generated through computer simulations. These assemblages represent spatial samples of discard records created by simulated agents at a regional scale over timeframes that vary according to the specific research goals being pursued, and which can correspond to either actual archaeological sites or hypothetical ones. They consist of aggregates of raw material units with a known history of procurement, transport, and discard, originally collected at locations that represent either real sources (Chapter 5) or randomly placed hypothetical ones (Chapter 3).

5.2 Archaeological data:

The analyses presented in Chapters 4 and 5 are based on previously published data on lithic resource exploitation at the French Middle Palaeolithic site of the Bau de l'Aubesier (Vaucluse, southeastern France). This rockshelter, hereinafter referred to as "the Bau" and discussed at length in Chapter 2, has yielded a complex and rich archaeological sequence some 13 m thick and deposited over the course of roughly 100,000 years or more (≥200 kya to ≤ 100 kya). It is found in an area of variable topography that has not experienced major geomorphological changes over the last 200,000 years and was never glaciated. The region surrounding the site has also been thoroughly investigated for the purposes of lithic sourcing by Lucy Wilson who, over the course of more than 25 years, has located and systematically documented 350 naturally occurring primary and secondary deposits of knappable rocks available within ca. 40 km of the site, most of which appear to have been unexploited by the site's inhabitants.

The total number of lithics recovered from the partially excavated deposits amounts to at least 85,000 (de Lumley-Woodyear 1969; Texier 2004). Of these, 40,770 pieces originating from throughout the sequence have been analyzed by Wilson for provenance purposes. Although alternation such as patination and burning prevented adequate raw material characterization for most lithics, 15,674 artifacts could nevertheless be matched to a minimum of 17 and a maximum of 101 possible procurement locations (Wilson and Browne 2014). The available evidence indicates that these sourced artifacts are representative of the overall artifact sample, both in terms of the variation in raw material types and in terms of their coverage of the Bau sequence.

Previous studies of the Bau dataset also indicate that materials were selectively procured from sources located within a relatively narrow interval of 8 to 13 km from the site. While this is still within the "extended foraging radius" that may be covered by hunter-gatherers during occasional daily forays (e.g., Mellars 1996), it certainly deviates from the general trend of provisioning sites from sources found within 5 km or so. There are many exceptions to that trend, however, and from a variety of regions and site types: at the nearby La Combette, for instance, 55% of the materials were procured from sources located at more than 18 km from (Wilson et al. 2018). At the Iberian site of Abric Romani (level M), 81% of the materials are reported to have been collected from sources located 5-10 km away (Fernandez-Laso et al. 2011; see also de la Torre et al. 2013), a situation similar to that seen at Payre in France (Daffara et al. 2019; see also Santagata et al. 2017: 476; Moncel et al. 2019). At Axlor (Spain), the majority of lithics are made of stone likely collected at 15-30 km from the site (de la Torre et al. 2013), like at Las Fuentes de San Cristobal, also in Spain, where most of the assemblage consists of lithics procured at 9-25 km (Garcia-Anton et al. 2011). At Karabi Tamchin in Crimea, the predominant use of materials collected at ca. 25 km from the site is also attested (Yevtushenko et al. 2003; Burke 2006), and at Wallertheim (Germany) Adler (2003) documents the dominant use of materials found at 6 km from the site. There are also far more striking examples: at the Italian site of Grotta dei Giganti, for instance, half of the materials were reportedly procured from sources located at more than 100 km (Spinapolice 2012).

Given the above, the Bau was selected for the purposes of this thesis because:

a) the present-day availability of lithic resources in the area is well-known, and it can be considered to be representative of what could have been exploited during the deposition of the Middle Palaeolithic layers at the site (this assumption is tested in Chapter 4).
b) raw material sources are known over an area large enough to allow for a realistic modelling of residential mobility.
c) The available archaeological data is comprehensive and covers a very long time-span, increasing confidence in the proposition that unexploited sources were intentionally ignored or avoided rather than simply unknown or unavailable to hominins inhabiting the site, and therefore allowing for hypotheses regarding landscape knowledge and navigational abilities to be tested (see 1.4.2 above).
d) It provides an opportunity to explore an atypical case of "local" raw material exploitation which could in principle reflect either the regular use of large (i.e., 8 – 13 km) daily exploitation territories or site provisioning in the context of residential mobility within small (i.e., 8 - 13 km) home ranges.

5.3 Geospatial data:

The geospatial data used in this thesis (Chapters 4 and 5) consist of: a) postprocessed Shuttle Radar Topography Mission (SRTM) digital elevation models (DEMs) supplied by the International Center for Tropical Agriculture (Jarvis et al. 2008), and b) point source coordinates for raw material sources supplied by Lucy Wilson. SRTM data are freely available not only for the region but also globally, and their adequacy for the type of route calculations required in the context of this work (Chapter 4) has been demonstrated, comparing favourably with higher resolution datasets available for the targeted area (Browne and Wilson 2013). Point source coordinates, on the other hand, are adequate given the resolution of the SRTM data and the size of the study region, which is defined on the basis of the available sources and covers roughly 100x100 km. Source extents do exceed the size of the raster cells by a factor of up to two in approximately 30% of cases, and a few sources represent linear features, but this is not expected to result in notable inaccuracies.

6 Outline of Thesis Chapters

6.1 Chapter 2: An overview of the French Middle Palaeolithic site of the Bau de l'Aubesier

This chapter presents an overview of the Bau de l'Aubesier based on an extensive review of the available literature. My sole aim in this section is to provide relevant context for the interpretation of the analyses presented in Chapters 4 and 5.

6.2 Chapter 3: Re-examining basic assumptions through a systematic re-evaluation of Brantingham's neutral model of raw material procurement

In 2003 Jeffrey Brantingham published a neutral model of lithic procurement which sought to simulate archaeological raw material variability in the absence of any optimization strategies in the acquisition, use, transport, and discard of lithic materials. On the basis of similarities between model-generated and archaeologically observed patterns, he concluded that said variability may not be informative with regard to past adaptation. Despite being one of the most cited lithic procurement papers from the early 2000s, and despite its profound implications, the third chapter of this thesis provides the first systematic re-assessment of the model. My aim is both to revisit Brantingham's provocative claims, and to explore the limitations and theoretical potential of neutral models more broadly.

While I demonstrate that Brantingham's original model is flawed in that it cannot produce meaningful analogues of the archaeological record, my analyses underscore the promise of agent-based neutral models as alternative starting points for the interpretation of lithic raw material variability and, more generally, as exploratory tools. On the basis of a revised model, Chapter 3 outlines a new set of expectations for what such variability should look like under neutral conditions, and highlights some aspects of provenance data that should be reported so as to maximize inferential potential. On the other hand, my results also underscore the need to maintain a minimal degree of realism in model parameter estimation, simulation lengths, and in the implementation of behaviours that can ensure the survivability of the agents.

6.3 Chapter 4: A network model of local resource selection for evaluating landscape knowledge, navigation, and foraging extents at the Bau de l'Aubesier

This chapter introduces a novel approach for determining the likely extents of the foraging areas around archaeological sites on the basis of lithic provenance data. The approach is designed to test hypotheses of Neanderthal mobility, landscape knowledge, navigational abilities, and resource selection criteria without relying on ethnographic analogies, Neanderthal-specific energetic and/or biomechanical estimates (e.g., Verpoorte 2006), or other lines of evidence aside from the raw material source data themselves. As noted in the methodology section above (see section 1.4.2), this approach is premised on a conceptualization of raw material sources as nodes in an edge- and node-weighted network of plausible procurement alternatives and an evaluation of optimal procurement paths based on archaeologically evidenced selection criteria determined using a generalized linear model (GLM).

The approach is applied to the Bau de l'Aubesier to explain why large majority of available sources appear to have been systematically ignored over a period of some 100,000 years despite many yielding good materials in relatively close proximity to the site. The results demonstrate that the situation at the Bau is not explainable by substantial changes to the lithic resource landscape (see e.g., Dibble 1991) or simple chance; instead, it is consistent with a pragmatic strategy of lithic resource exploitation over a large area extending some 2.5 - 3.5 hours from the site, purposeful but largely embedded in other activities, and underpinned by excellent navigational skills and knowledge of the region. The results are also consistent with a relatively uniform utilization of the landscape by the site's inhabitants.

6.4 Chapter 5: Exploring home ranges and non-local procurement through a minimally realistic model of raw material management at the Bau de l'Aubesier

The impact of residential mobility on archaeological raw material variability is poorly understood, at least in quantitative terms. What percentage of materials found at one site can we expect to have been collected by hominins while residing at other sites? What is the likelihood that these materials were collected from the same geological sources, therefore appearing to be "local"? How many residential moves can we reasonably expect raw materials to have survived in mobile toolkits? Can such transported materials be distinguished from recycled implements transferred between sites by unrelated groups? How does this impact interpretations of territory sizes on the basis of maximum transfer distances? Chapter 5 answers such questions by integrating the local resource procurement model developed in Chapter 4 into a regional-scale agent-based simulation of lithic raw material management. The novel simulation framework introduced in this chapter is minimally realistic (see section 1.4.1 above) and is developed based on insights gained from the re-examination of Brantingham's neutral model discussed in Chapter 3. It is applied to the Bau in order to explore assemblage variability and the extent of the territories where raw material exploitation is consistent with the resource selection criteria evidenced at the site, in order to better understand the scale of mobility and land use strategies employed by hominins who resided there (however briefly).

The results presented in this chapter reaffirm the conclusions of Chapter 4, particularly with regards to the navigational skills, degree of landscape knowledge, and optimizing resource exploitation strategies evidenced in the record preserved at the Bau. Overall, I find that the explanation proposed in Chapter 4 for why a majority of regional sources were not exploited by the inhabitants of the site holds even if the effects of residential mobility are factored in. These results do leave open the possibility that the territories regularly used by hominins while residing at the Bau (i.e., daily exploitation territories) may perhaps not have extended quite as far as 2.5 to 3.5 hours from the site, but they also show that the Bau data are inconsistent with a regular exploitation of territories smaller than seen in modern hunter-gatherers (cf., Verpoorte 2006). Beyond this, the analyses presented in Chapter 5 enable a series of predictions to be made regarding the expected assemblage raw material composition for any contemporaneous site in the region and highlight areas of compatibility with data available from the Bau.

6.5 Chapter 6: Conclusions

This chapter provides a synthetic overview of the main theoretical and practical contributions of this thesis, outlining some promising future research directions.

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Chapter Two

An overview of the French Middle Palaeolithic site of the Bau de l'Aubesier

1 Introduction

The Bau de l'Aubesier (hereinafter, 'the Bau') is a large rockshelter located at the western border of the sub-alpine chain in the department of Vaucluse, southeastern France (Figure 1). It was named by Franki Moulin at the beginning of the 20th century, 'Bau' being, according to Moulin, a Provençal word denoting a steep rock with a generally flat summit (Moulin 1903: 369). Indeed, the site is found today about halfway down the deep gorge of the Nesque river, in steep and challenging terrain below a large plateau (Figure 2). The gorge is carved in Lower Cretaceous (Bedoulian) limestone (see Figure 3), and although the Nesque now runs mostly dry on the surface throughout much of the year, it is the only waterway in the area (Moulin 1904: 427-48), and its surface flow is likely to have been more substantial in the past (e.g., Moulin 1903; Fernandez 2001: 11). Even today the Nesque is sometimes subject to rapid floods (e.g., Texier 2004: 83), and on occasion veritable lakes are known to have formed at the mouth of the gorge (documented, for example, in 1885 and 1900 – Moulin 1903). With easy access to water, three different types of ungulate home ranges (open flats on the plateau, wooded areas near the river, and steep escarpments), and abundant sources of high-quality flint (see Figure 3), the Bau would have thus presented a strategic location for its inhabitants in a region with many known Middle Palaeolithic sites (Figure 1).

The site's deposits are thick (at least 12 m, but the bedrock was not reached during excavations) and extend over more than 250 m^2 (e.g., Lebel et al. 2001: 11097). They form a plateau in the rockshelter proper and appear in more or less horizontal layers down the north-facing slope at its front. They are also very rich in both faunal remains and lithic materials, deposited over a period of some 100,000 years of repeated occupation across the Middle and Upper Pleistocene. The numerous archaeological layers consist primarily of "cryoclastic breccias with variable amounts of matrix and/or cement" (Lucy Wilson, personal communication), and they comprise two main units: an upper one corresponding to the plateau, and lower one corresponding to the slope deposits. Both preserve evidence of repeated occupations. The site is remarkable in several regards, including but not limited to the richness of the horse remains it has yielded (e.g., Fernandez et al. 2006), the evidence for volumetric blade production in layers dated to MIS 7 (see Carmignani et al. 2017: 39-40), the presence hominin remains with pathologies thought to have required conspecific care (Lebel et al. 2001; Lebel and Trinkaus 2001), and the utilization of lithic raw material sources located within a relatively narrow distance interval of roughly 8-13 km from the site, despite the presence of good quality flint closer to the Bau. What follows below is a brief, synthetic overview of the history of research at the Bau and of some important finds. My goal here is not to provide a comprehensive and authoritative overview of the site – for that the reader is directed to Lucy Wilson's upcoming book, "Shades of Laughter, Shades of Life" – but rather to provide some additional context for the analyses and results presented in Chapters 4 and 5.

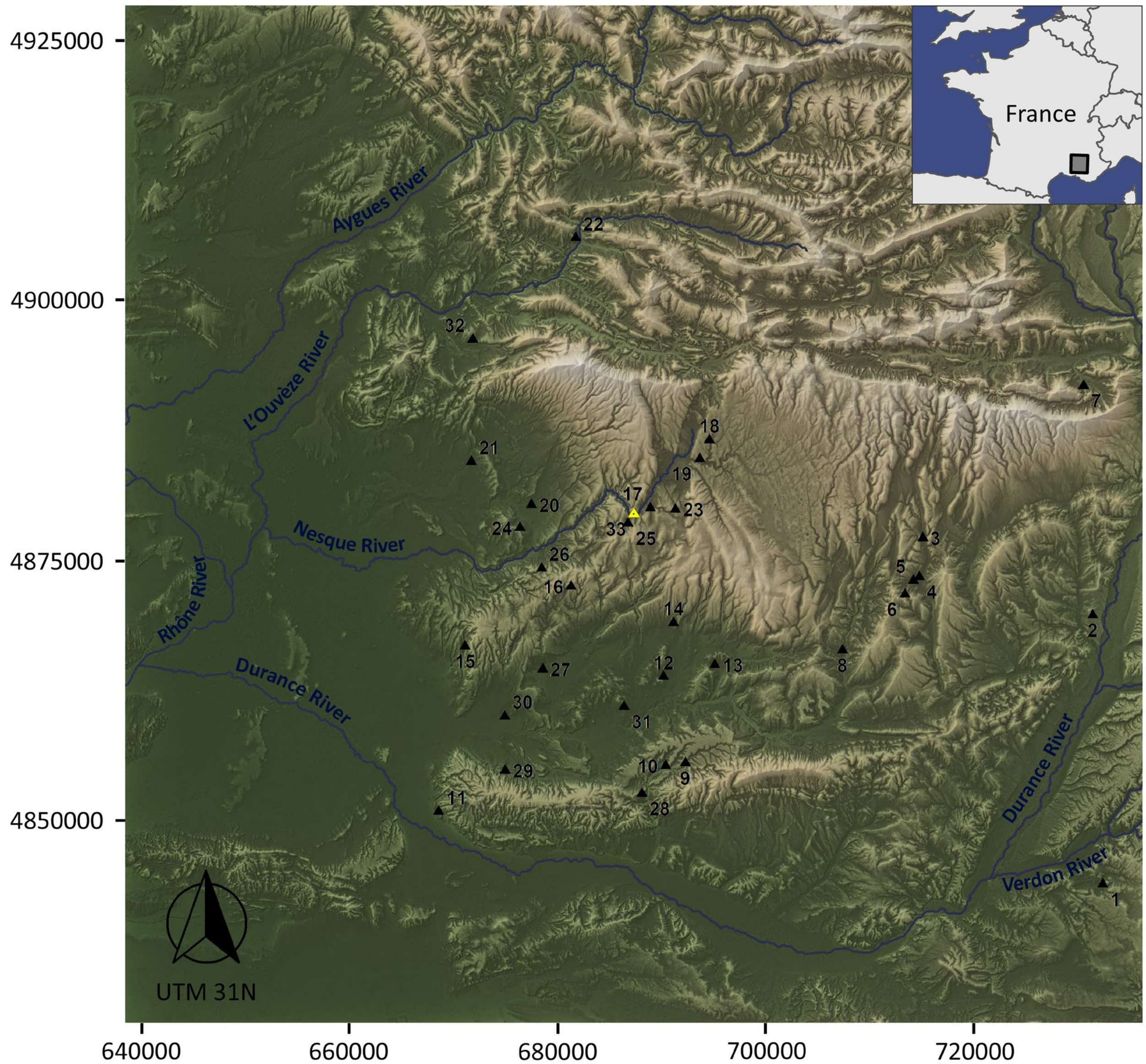

Figure 1: The Bau de l'Aubesier (17) and nearby localities with reported Middle Palaeolithic finds*.* The indicated locations are: 1. Mallavasse; 2. Pic d'Oriou; 3. Grotte du Largue; 4. Plan de Gondran; 5. Le Clos; 6. Saint-Laurent; 7. Grotte de Saint Robert; 8. Pont de la Blaque; 9. Les Peyrards; 10. Baume de Boux; 11. Grotte de la Falaise; 12. Gargas; 13. Les Trecassats; 14. Pont de Redony; 15. Vallescure; 16. Baume Troucade; 17. Bau de l'Aubesier; 18. Deffend de Sault; 19. Pied de Sault; 20. Les Sablons; 21. Coquillade; 22. Bas Guillotte; 23. La Balate; 24. Peyvoullier; 25. Combe de Saume Morte; 26. Faraud; 27. Berigoule; 28. La Combette; 29. Station d'Oppede; 30. Abri des Briquets; 31. Verrieres; 32. Les Argiliers - Malaucene; 33. Grotte de Jarle. Inset shows the location of the region within France, to scale. Location data compiled from de Lumley-Woodyear (1969) and Fernandez (2006). Coordinates are given in UTM zone 31N. Elevation data: SRTMGL1 (NASA JPL). Country border data: Natural Earth. River data: European Environmental Agency.

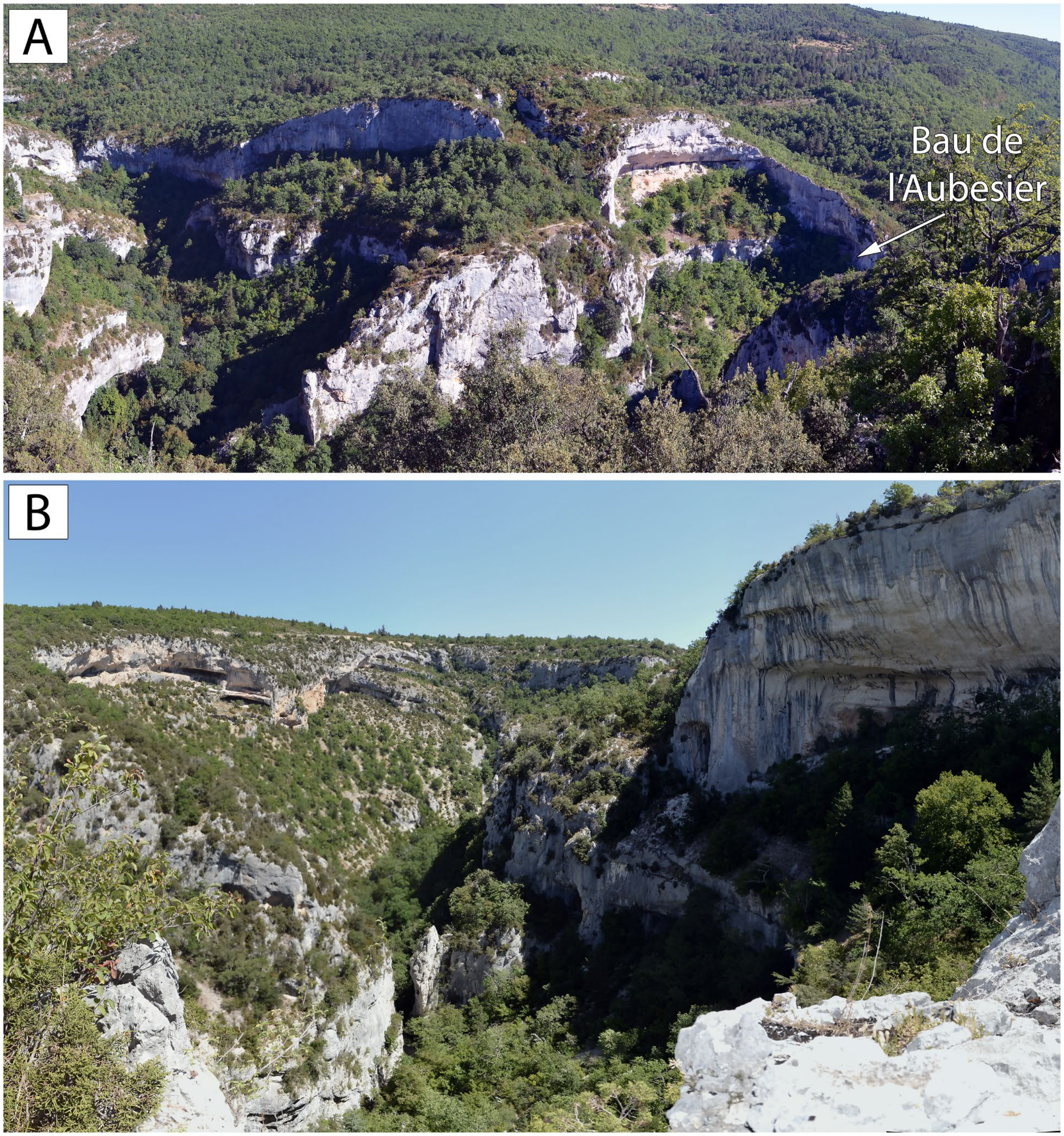

Figure 2: The gorges of the Nesque as seen from the north (A) and south (B) by the Bau. The arrow in figure A indicates the location of the Bau de l'Aubesier, and points at the lower slope excavations; the photograph in B was taken immediately above the site.

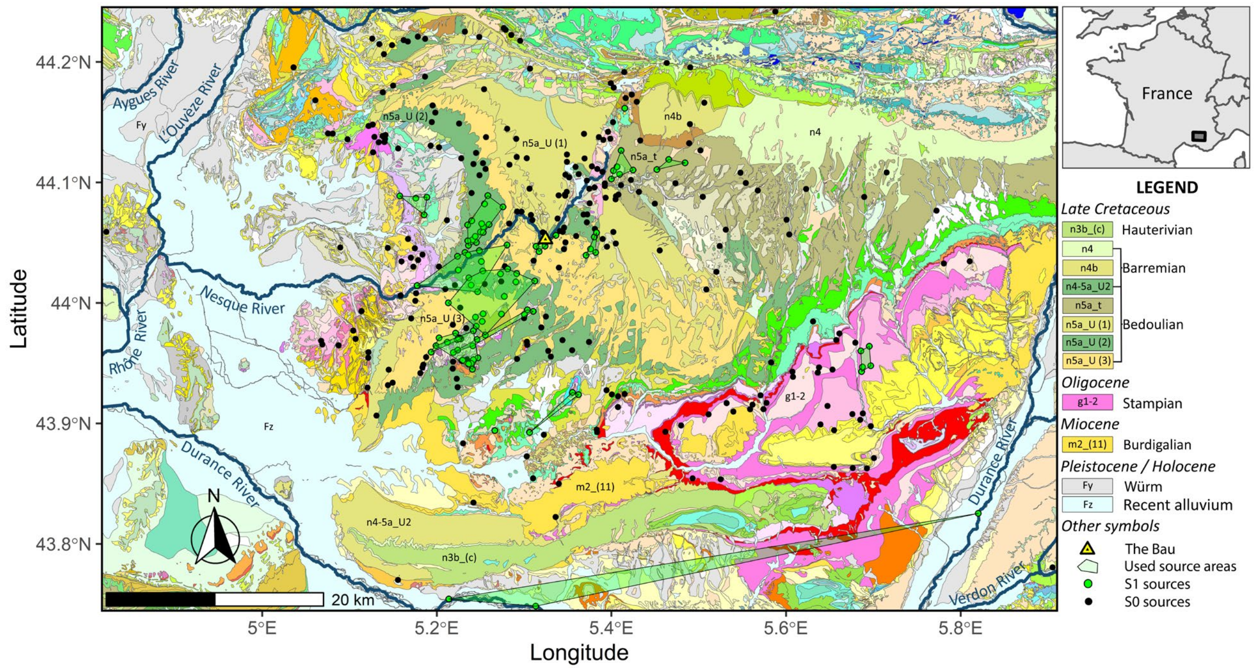

Figure 3: Geological map of the study region and sources of used and unused lithic materials. Geological data supplied by the French Geological Survey (BRGM); river data supplied by the European Environmental Agency.

2 History of research

The first excavations at the site were conducted by Franki Moulin along the western wall of the rockshelter (Figure 4), following a visit to the Bau with M. Bonnefoy in August of 1901 (de Lumley-Woodyear 1969: 384). Moulin excavated until 1903 and published an extensive 90-page report on the site in the same year (Moulin 1903) as well as a short summary in 1904. His 1904 summary included notes on stratigraphy, a one-page description on the lithic materials, which he estimated to include thousands of pieces and which he notes was dominated by points (Moulin 1904: 15), a brief discussion of faunal remains (15 species identified by Depéret), which included a *Homo* upper molar, and brief notes regarding recovered charcoal. As is made clear in the accompanying comments by Raymond and A. de Mortillet, the site was immediately seen as an important Mousterian locality (see Moulin 1904: 19).

Moulin's excavations covered an irregular area up to 16 m long and 6 m wide (see Figure 4a) within the rockshelter where, as noted above, sediments form a plateau (see Figure 7 for reference). Moulin left a section at the south-western limit as stratigraphic witness (Moulin 1903: 392) and described the sediments along two sections (lines 1 and 2 in Figure 4a), both reaching the same stratigraphic horizon consisting of sterile gravels at a depth of 185 cm in the north, closer to the talus, and 228 cm at the south (i.e., at the back of the rockshelter), where the top layers were thicker. He reported that below a thin (ca. 4 cm) earthy layer containing Neolithic pottery (Moulin 1903: 383), a mass constituted primarily of limestone elements of variable sizes contains the traces of habitation overlying the bottom gravels (Moulin 1903: 393). He considered these deposits to have accumulated over a substantial timespan during the Pleistocene (Moulin 1903: 390), and thought the habitation area was for the most part restricted to the investigated western section of the rockshelter, which may have provided, according to him, enhanced protection from winds and rain (Moulin 1903: 394).

Based on both artifact distributions and geological considerations, Moulin (1903: 396; see also Figure 5a) distinguished four distinct stratigraphic zones below a sterile layer he identified as *ab*[1] (ca. 45 cm thick in the northern profile), noting that the archaeological assemblage is perfectly homogeneous both in terms of fauna and tools (Moulin 1903: 394). At the top of the artifact-bearing deposits along the northern profile he identified a heavily agglomerated mass (labeled *ab*[2]), ca. 4 cm thick, which contained a few rare bones and flints. Below, he described a speleothem, denoted B and ca. 40 cm thick, that was rich in bone fragments intermixed with flint tools and abundant flint flakes. Moulin's layer B overlies layer C, constituted by a generally loose, black, dusty mass ca. 10-12 cm thick and very rich in organic residue of animal origin (Moulin 1903: 399) as well as abundant lithics and bone. The nature of fractures on the latter, as well as the arrangement of the former, found here, unlike in the other layers, piled on top of each other and resting on their flat surfaces and having remarkably fresh edges, suggested to Moulin that this layer represented a vast heap of refuse that was later compacted. He also thought this layer was deposited very quickly, perhaps, he speculated, in as little as 12 years (Moulin 1903: 400). Finally, at the top of the bottom gravels Moulin describes layer D, a very hard speleothem ca. 45 cm thick and constituted by a mix of limestone fragments, flint tools and small flakes, as well as faunal remains, although the bones are fewer and less heavily fragmented than in layer B. This layer is distinguished by having a blackish zone about 8-10 cm thick in the middle, denoted d^2 (see Figure 5a) which Moulin considered to reflect a momentary intensification of habitation. Charcoal in the two bottom layers C and D, belonging almost exclusively to a shrub (*Amelanchier*), suggested to Moulin that the vegetation in the immediate vicinity of the site was similar to what exists today (Moulin 1903: 431).

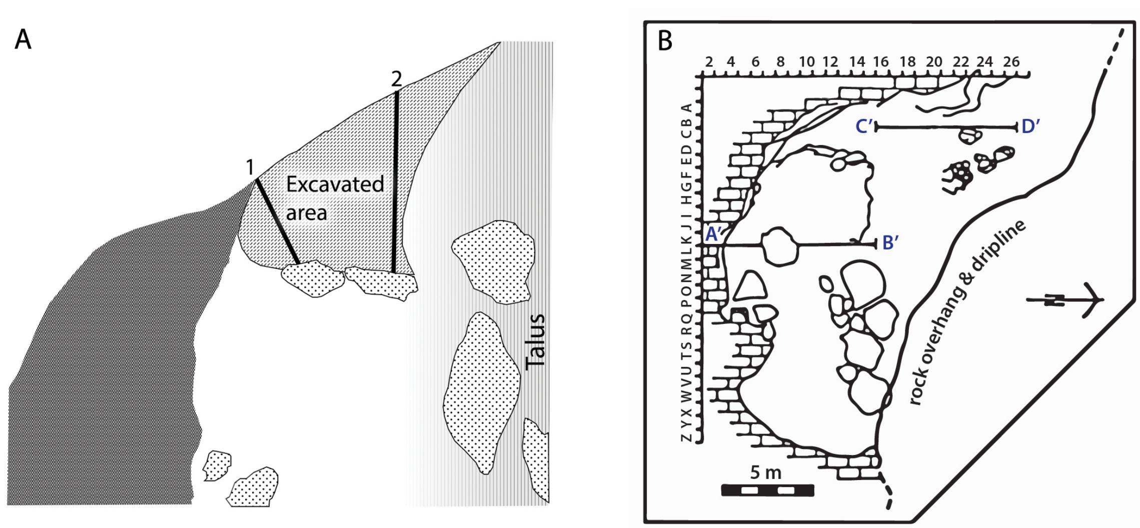

Figure 4: Partial and full plans of the rockshelter. Sub-figure A shows the area excavated by Moulin (16m long and up to 6m wide at 2 according to Moulin) and the location of the stratigraphic profiles (1 and 2) he describes; B shows the location of the stratigraphic profiles for the lower slope (C'-D') and trench L (A'-B') excavations conducted between 1987 and 2000 under the supervision of Serge Lebel. After Moulin (1903: 392) and Lebel (2000: 22; see Carmignani et al. 2017).

Subsequent investigations at the Bau were carried out after the Second World War, in the 1950s and 1960s, by Louis Gauthier, Bertrand Mary, and later de Lumley-Woodyear, who published a stratigraphic profile spanning the entire North/South extent of the site in 1969 together with a detailed description of the lithic assemblage. The stratigraphic profile published by de Lumley-Woodyear in 1969, partially reproduced in Figure 5b, retains Moulin's nomenclature for the uppermost layers but also shows the composition of the topmost sediments down the talus. It is accompanied by a short, half-page discussion. De Lumley-Woodyear considered the thick sequence to have been deposited very quickly at the end of Würm II (MIS 4-3). He thought that the alternating layers with large and smaller cryoclastic blocks reflected deposition under rigorous but variable climatic regimes, with seasonal and daily cycles of thawing and freezing respectively. These layers, he argued, subsequently underwent concretionary processes resulting in what are today very hard brecciated deposits (de Lumley-Woodyear 1969: 385).

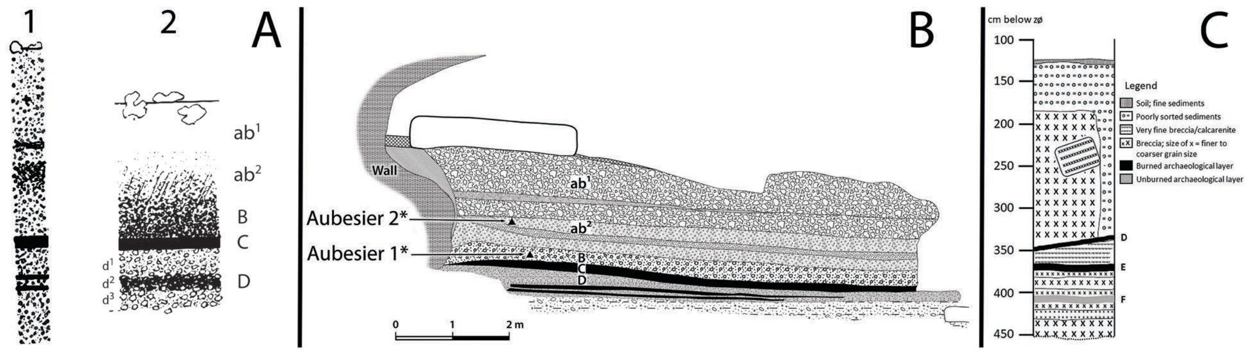

Figure 5: Stratigraphic profiles of the upper ('plateau') deposits. Subfigure A shows the profile published by Franki Moulin in 1903, edited to improve clarity (the numbers refer to the lines in Figure 4); subfigure B shows part of the profile published by de Lumley-Woodyear in 1969, redrawn and modified to correct an error in the attribution of the hominin finds (* the Aubesier 1 and Aubesier 2 labels do not appear in the original); and subfigure C shows a profile drawn in 1995 by Lucy Wilson from the Lebel excavations (personal communication, used with permission).

Most of what is known of the site today, however, comes from the extensive excavations carried out between 1987 and 2000 by a team led by Serge Lebel (two- to three-month seasons - Wilson and Browne 2014: 30). These latter excavations focused on two main zones (see Figure 4b and Figure 6): 1) trench L, in the center of the rockshelter in the upper part of the deposits, mostly excavated up to 2 m (Wilson and Browne 2014: 30); and 2) the lower slope deposits in front of the old Moulin trench, excavated inwards from the base (Wilson and Browne 2014: 30). It is these excavations that form the basis of the stratigraphic overview presented in the next section. Yet, before to discussing stratigraphic observations, it is important to first clarify some aspects of nomenclature.

The layers in the two excavated areas were defined and named according to different criteria by Lebel's team. In the western area, along the side wall, the floor of the old Moulin trench was named F, using alphabetic notation like earlier researchers. Above F, two layers (E and D) were defined early on by Lebel's team based on the archaeological concentrations observed at the bottom of the Moulin trench, and subsequently a layer C when abundant materials were encountered higher up in the deposits (Lucy Wilson, personal communication). It is important to note here that Lebel's layers C and D do not correspond to the layers C and D specified earlier by Moulin and de Lumley-Woodyear (see Figure 5); in fact, the relationship between the earliest stratigraphic descriptions and current ones remains unclear. Below layer F, and starting with the base of G, Lebel's team defined layers based on arbitrary z values, in one-meter depth intervals. When warranted, these layers were then subdivided according to sedimentological or archaeological criteria (Lucy Wilson, personal communication).

In trench L the layers were defined according to archaeological and stratigraphic criteria, as with other layers excavated on the upper plateau (i.e., by the Moulin trench). However, they were named using numerals instead of letters, because the correspondences with layers excavated by the Moulin trench were not known. Indeed, while Lebel undertook some further work at the site in 2006 to clarify how archaeological layers from the two excavated areas are connected to each other, certain aspects still remain unresolved (e.g., Wilson and Browne 2014: 30-31), and consequently different nomenclature continues to be applied to layers from trench L and the Moulin trench. It should also be noted here that Philippe Fernandes (2001: 15) defined a level 4 in his thesis, for the purposes of faunal analysis, which combines several layers from the site, including layer 4.

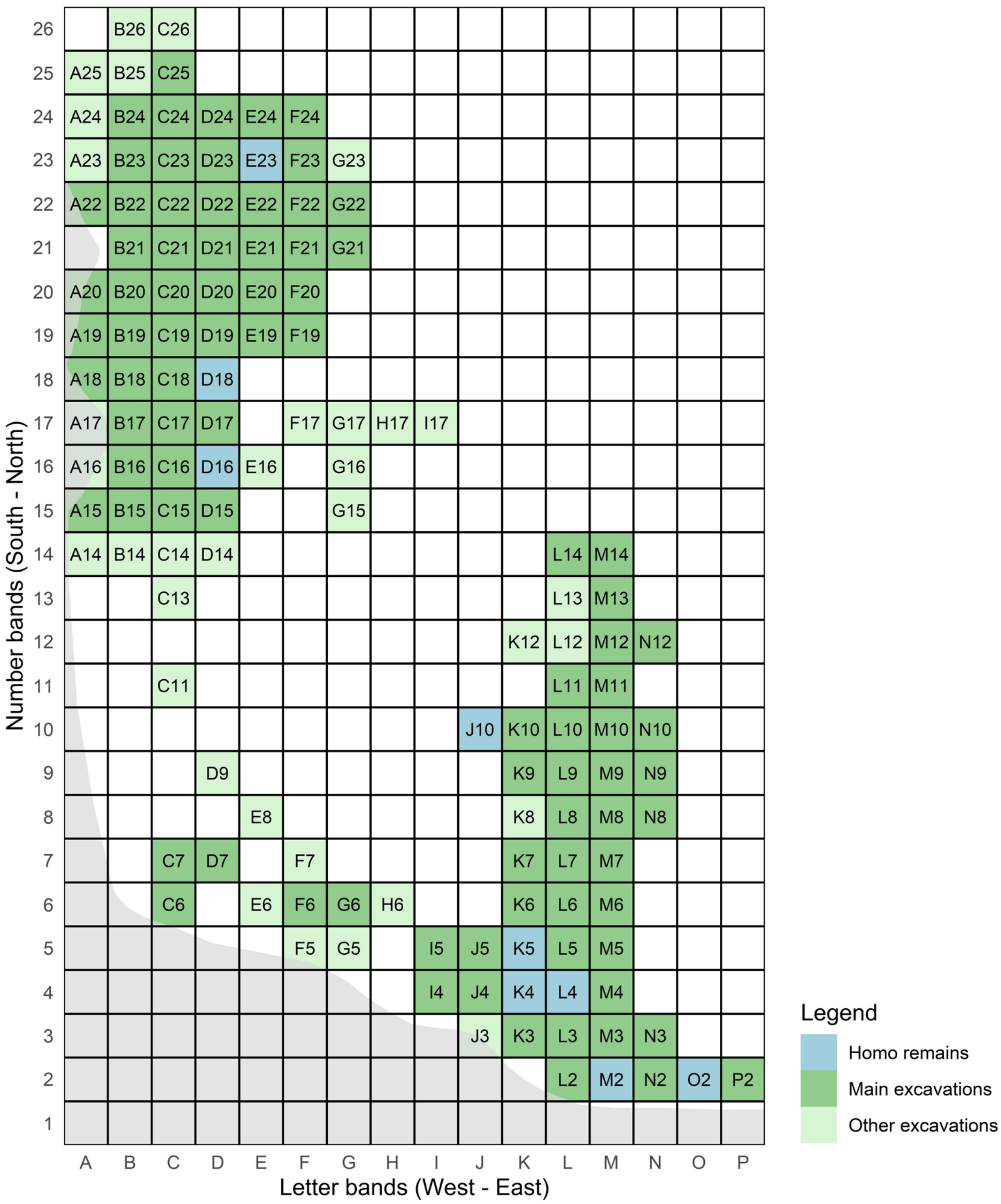

Figure 6: Partial plan of Lebel's excavations. Squares show in dark green denote the main excavated areas, while squares shown in pale green indicate other excavated areas for which I had access to some information; some areas excavated by Lebel's team are likely not included in this figure, nor are the excavations conducted by earlier researchers (e.g., Moulin). Grey denotes the rockshelter wall. Data for the figure were supplied by Lucy Wilson (personal communication).

3 Stratigraphy and the age of the deposits

The oldest known sediments at the Bau were uncovered in a test pit excavated at the north-western margin by Lebel's team (see Figure 7). They were deposited during a cold phase (MIS 8 or earlier) and are sterile (e.g., Fernandez 2006: 14). At the time of their deposition the rockshelter would have been situated lower within the gorge of the Nesque than it is today, since rock fragments detached from the roof and walls by frost-cracking constitute the majority of the sediments at the site. Thus, both the ceiling and the floor of the rockshelter have shifted upward over time, while the rockshelter has become shallower due to a receding overhang (Lucy Wilson, personal communication). Nothing is known of the geological history of the Bau prior to the deposition of these sterile layers, since bedrock was not reached during excavations, but it likely extends back to the opening of the gorge of the Nesque, perhaps more than 5 million years ago (Lucy Wilson, personal communication).

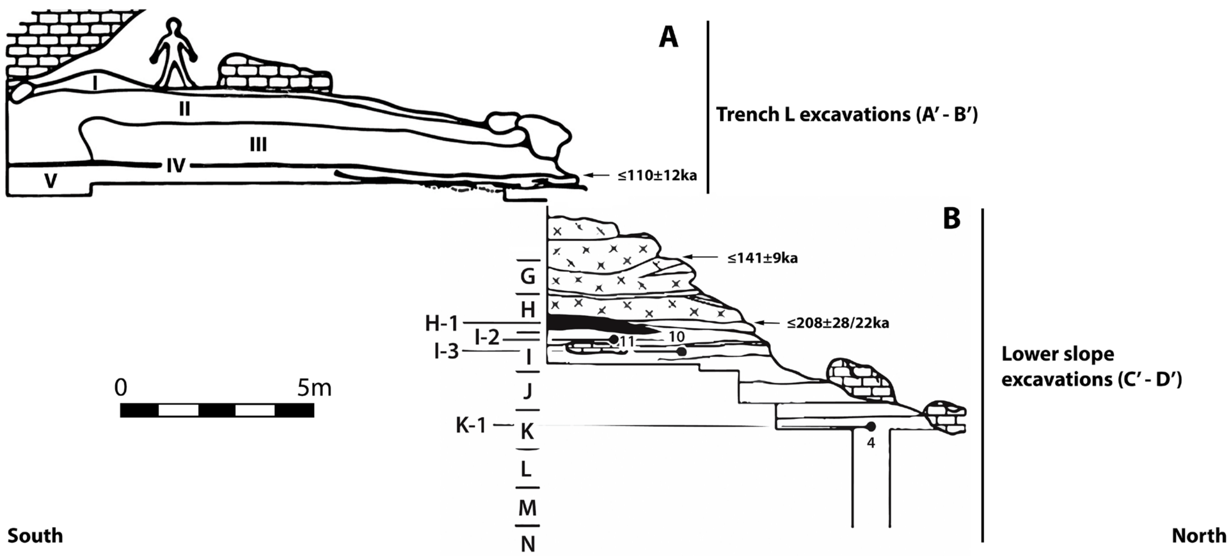

Figure 7: Stratigraphic profile of the Bau de l'Aubesier. The numbers 4, 10, and 11 indicate the locations of the respective Homo finds. Section A shows the trench L profile; section B shows the lower slope profile; refer to Figure 4 for more details. The partial set of dates corresponds to ages determined for speleothems (see main text). After Lebel et al. (2001: 11098), with modifications. Copyright (2001) National Academy of Sciences (original figure).

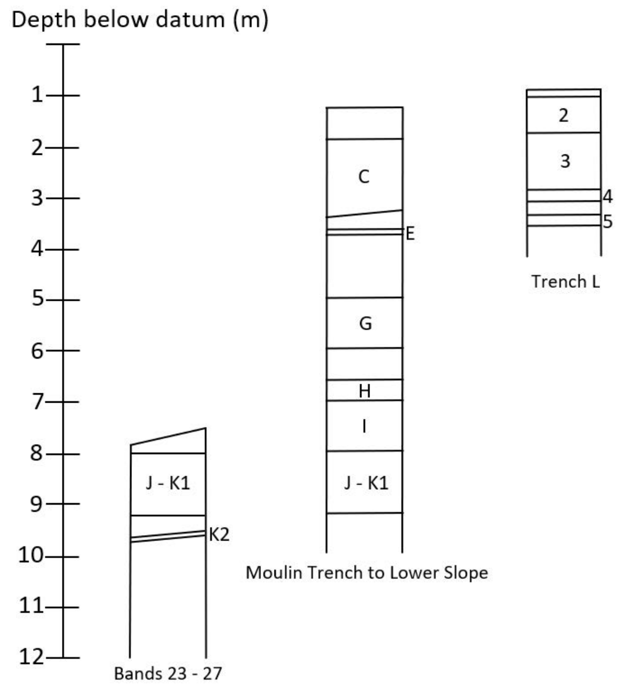

Figure 8: Simplified schematic of the stratigraphy at the Bau. Note that both roman numerals (e.g., Lebel et al. 2001) and Arabic numerals have been used to identify layers from trench L. Reproduced, with permission from Lucy Wilson, from Carmignani et al. (2017).

The earliest known archaeological layer has been named K2 (see Figure 8), and was also excavated by Lebel's team at the north-western margin of the site. It consists of fine-grained sediments that likely accumulated during a temperate phase of MIS 7 (Carmignani et al. 2017: 5) and which yielded abundant lithic and faunal remains. While some of the lithics from this layer are burnt - burned artifacts are a common feature throughout the entire sequence - no hearths were uncovered during excavations (Lucy Wilson, personal communication). Above K2, the second-oldest archaeological layer is J4-K1, a concentration of thousands of lithics and faunal remains that spans both sides of the arbitrary J/K boundary (see preceding section) in uncemented sediments at the northwest of the site. However, only limited information is available on this layer proper because publications have typically considered J and K1 together as a single unit. As a whole, J-K1 consists primarily of uncemented cryoclastic debris that likely accumulated during MIS 6 and perhaps the latter part of MIS 7 (see, e.g., Fernandez 2006: 97). These were later washed and reworked (e.g., Carmignani et al. 2017: 6), showing notable concentrations of artifacts only at the bottom (i.e., J4-K1 – Lucy Wilson, personal communication). Overall, J-K1 attests to the processing of at least 37 animals, mostly large herbivores (see Table 1).

Above layer J, more cryoclastic debris accumulated leading to the formation of the sediments of layer I. These have been divided into four sub-layers, with an indurated to cemented layer I4 at the bottom, and layers I1 and I2 at the top (Lucy Wilson, personal communication). This part of the excavated Bau sequence yielded a large number of faunal remains (MNI of 86 – see Table 1 below), particularly in the unconsolidated sediments found just below layer H (sub-layer I2). It also yielded a more modest (but still substantial) number of lithics, as well as hominin remains consisting of a tooth and a partial mandible (see next section). The faunal remains suggest an accumulation in a cold, dry, and generally open landscape, most likely during MIS 6 (e.g., Fernandez 2006).

The stratigraphy of the sediments that make up the arbitrarily defined layer H is complex, and they evidence changes in climate as well as intriguing behaviours not previously seen at the site, including the accumulation of a large number of unworked cobbles that were transported from the stream below and the intensive and very selective hunting (see Fernandez 2006: 98) of *Capreolus capreolus* (MNI = 8) and *Cervus elaphus* (MNI = 6). These behaviours are attested in the thick (30 – 45 cm), highly burned, and archaeologically very rich section that constitutes sub-layer H1, formed as a result of repeated, discontinuous occupations that were perhaps separated by centuries (Lucy Wilson, personal communication). Some sediments found at the bottom of layer H, and which resemble those found in the preceding layer I, were assigned to sub-layer H2, while above H1 the sediments of H consist of highly cemented breccia containing few artifacts (Lucy Wilson, personal communication). Overall, layer H appears to have accumulated at the end of MIS 6, as suggested by the available absolute dates (see below), and perhaps the beginning of MIS 5, as suggested by the fauna (Fernandez 2006: 97).

Layer H is covered by the thick and strongly cemented breccia of layer G, which marks the top of the slope deposits below the upper plateau. This breccia contains cryoclastic debris, like much of the rest of the sequence, and suggests deposition over a long period and under variable climatic conditions. Absolute dates (see below) obtained on two speleothems point to accumulation during MIS 6, but beyond this the information available on layer G is rather sparse; this section of the deposits received less attention both due to the difficulty of excavating it (it is very hard) and to the paucity of archaeological material it contained (Lucy Wilson, personal communication); indeed, habitation during the deposition of layer G is interpreted as sporadic and very short-term stopovers (e.g., Wilson and Browne 2014: 34) that seem to have involved *in situ* knapping and removal of processed products from the site (Lucy Wilson, personal communication).

The more recent sediments are known from excavations on the plateau. In the western section the information available from Lebel's excavations is relatively limited, since his team focused on trench L at the centre of the rockshelter. Nevertheless, it can be noted that the base of the old Moulin trench constitutes a distinct if poor archaeological layer named F by Lebel's team. The nature of the sediments, cryoclastic fragments mixed with variably indurated finer materials, indicates accumulation during a glacial period, although a more temperate phase than generally attested by layer G (Lucy Wilson, personal communication); moreover, based on the lithic assemblage hominins appear to have visited the site sporadically, if perhaps for slightly longer periods than during the deposition of G. Above F, and above a sterile section ca. 35-40 cm thick, a relatively thin and nearly horizontal layer of soft, burned sediments is found (Lucy Wilson, personal communication). This layer, rich in archaeological materials, was labeled as layer E by Lebel's team, and may correspond to parts of Moulin's layer D. Above Lebel's layer E is a strongly cemented fine-grained breccia 10 to 35 cm thick, on top of which a black layer of soft, fine-grained sediments with abundant archaeological materials accumulated (Lucy Wilson, personal communication). This corresponds to Lebel's layer D, and possibly to Moulin's layer C. Above, more cryoclastic sediments were deposited, reworked, and later cemented into breccia, making up what may be described as the hodgepodge of sub-layers (Lucy Wilson, personal communication) that corresponds to Lebel's layer C.

In the eastern excavated area, along trench L, the picture is clearer. The oldest sediments known in this section are attributed to layer V, located under the same fine-grained breccia that is found above Lebel's layer E in the western sector, although there is no clear equivalence between any of the layers excavated by the Moulin trench and layer V. The sediments are mostly loose, coarse rock fragments mixed with mainly unburned lithics and faunal remains, which overall indicate cool environmental conditions. Above layer V, and above the fine-grained breccia, lies layer IV, which may be the lateral equivalent of Lebel's layer D in the western excavated area, and possibly Moulin's layer C, but the information preserved from Lebel's layer D is insufficient to reach firm conclusions (Lucy Wilson, personal communication). In any case, this ca. 15-20 cm thick layer extends over at least 40 m^2 (Lucy Wilson, personal communication; see also Blackwell et al. 2001: 722) and is dominated by archaeological materials; it is the richest at the site, having yielded ca. half of the lithics recovered by Lebel's team, it is highly burned, and most likely represents a palimpsests of occupational episodes (Lebel, 1994 qtd. in Fernandez 2006).

After the deposition of this very rich layer IV, cold conditions caused frost-cracking of the rockshelter wall and ceiling, leading to the accumulation of cryoclastic fragments that were later cemented into breccia and/or washed during subsequent warmer phase(s) (Lucy Wilson, personal communication). This breccia, named layer III by Lebel's team, has a complex stratigraphy and has yielded relatively few archaeological materials. These have been interpreted as representing palimpsests of multiple occasional, short-term stays, as the lithics seem to mostly reflect toolkit maintenance (Lucy Wilson, personal communication). Above layer III, which may be equivalent to Lebel's layer C in the Moulin trench, the loose cryoclastic sediments of layer II contain scattered but relatively abundant archaeological materials, some of which show clear signs of movement and alteration by free-flowing water (Lucy Wilson, personal communication). Overall, the assemblage from layer II represents a palimpsest of occupations by highly mobile people who brought in materials from distant sources but also used local ones to a greater extent than seen in any other layer at the site (Lucy Wilson, personal communication). Parts of layer II may also correspond to Lebel's layer C (e.g., Wilson and Browne 2014: 30), but this layer may well simply be missing by the Moulin trench (Lucy Wilson, personal communication). Layer II, was covered by a thin deposit of recent sediment and, like in the Moulin trench (e.g., Moulin 1903, 1904) some fragments of pottery were found (Blackwell et al. 2000: 346).

From 1989 onward samples were collected for dating purposes; these included teeth for ESR, recovered from layers IV in trench L and layers D to J4 in the western excavated area (C'-D' in Figure 4b), speleothem samples for $^{230}Th/^{234}U$ dating from layers IV (trench L) to H1, and six flints for TL dating from layer H1 (e.g., Blackwell et al. 2000, 2001; Lebel et al. 2001; see also Richter 2011). Overall, the chronology is somewhat uncertain because no dates are available from the topmost or lowermost layers, multiple scenarios can account for the ESR dates, in part due to the lumpy nature of the sediments (Blackwell et al. 2000: 358), and the speleothem dates likely indicate maximum ages (Blackwell et al. 2001: 738). However, for layer IV the teeth suggest an age of 90±30 ka (assuming linear uptake of U) while $^{230}Th/^{234}U$ dates on a speleothem indicated a maximum age of 109.8 +12.5 / -11.2 ka at 2σ (Blackwell et al. 2001: 742). Moreover, a date of 141±9 ka for a speleothem recovered from the top of layer G brackets layer D, located somewhat lower than layer IV (Blackwell et al. 2001: 721), to an age between 90 and 140 ka (Blackwell et al. 2001: 742). On the other hand, three teeth from the lowermost dated layers, J2-J4, yielded ages that seem to underestimate their true age (the oldest date was 170±37 ka at 1σ), possibly due to secondary diagenesis (Blackwell et al. 2001: 752). Considering the dates obtained for overlying layers, however, Blackwell et al. (2001: 751) suggest layers J2-J4 "should exceed 160-180 ka and might be as old as, or slightly older than, 208+28/-23 ka (Blackwell et al. 2001: 742), an age that is consistent with the TL dates obtained for layer H1, and which range from an average minimum and maximum of 169±17 ka and 191±15 ka respectively (Lebel et al. 2001: 11098). Overall, then, the available dates indicate that the Middle Palaeolithic deposits at the Bau likely accumulated over a timespan of some 100,000 years or more (see also Wilson and Browne 2014: 30-31).

4 THE ARCHAEOLOGICAL EVIDENCE

4.1 Fauna

The first to report on the faunal material from the site was Moulin (1903; 1904), who listed a total of 13 mammalian species as well as some gastropods following determinations by Depéret. A somewhat expanded list appears in de Lumley-Woodyear (1969: 385), who also included qualitative information on their relative abundance. Further analyses of the faunal material were carried out in the late 1980s and 1990s by Faure et al. (see e.g., Fernandez 2006: 18), and subsequently by Fernandez (e.g., Fernandez 2001; Fernandez and Legendre 2003; Fernandez 2006; Fernandez et al. 2006), who assessed, for all ungulate taxa and among other aspects, the degree of preservation of the materials as well as the procurement strategies they evidence. In total, Fernandez (2006: 9) recognized 19 species in the assemblage, of which four belong to the order carnivora. These latter are represented by few remains (NISP = 49), and two (*Canis lupus* and *Lynx lynx*) are reported to occur only in what Fernandez referred to as layer II (Fernandez 2006: 18; Fernandez 2001: 22).

The overall picture that emerges is therefore of a sequence that is very rich in ungulates - over 2700 identifiable ungulate teeth and bone specimens, accounting for a minimum of 241 individuals (see Table 1), are discussed by Fernandez (2006), – and very poor in carnivores. The mortality profiles of the herbivores strongly suggest hunting rather than scavenging as the primary procurement strategy (Fernandez and Legendre 2003: 1584), and there are, generally speaking, very few traces of carnivore activity (see Fernandez 2001: 175 and 178). Conversely, numerous traces of anthropic modification are visible on the cortical surfaces of bones (e.g., Fernandez in Texier 2004: 86) which, at least in layers H1 and IV, were also used as fuel (Fernandez in Texier 2004: 86). Fernandez suggests hunting was likely collective and probably occurred on the plateau above the site or along the rugged escarpments surrounding it (Fernandez in Texier 2004: 86).

The represented ungulate species, often co-occurring in the same layers (Table 1 – see also Fernandez 2001: 262), are characterized by different predator avoidance strategies, different seasonal behaviours, and different types of home ranges, including open flats (e.g., horses, aurochs), rugged and steep terrain (e.g., tahr, ibex), and at least somewhat wooded areas (e.g., medium and small-sized cervids and wild boar). In general, animals appear to have been hunted when most abundant and most vulnerable, using hunting strategies adapted to the different taxa (Fernandez 2001). In certain layers at least, where the season of death can be established for multiple species, the Bau appears to have been inhabited at various times of the year. In layer H1, for example, chamois and tahr were likely hunted from late fall to late winter/spring (Fernandez 2001: 68, 85), horse in the summer and early fall (e.g., Fernandez 2001: 172), and roe deer between March and July (Fernandez 2001: 194); other species, such as auroch and red deer, may have been hunted throughout the year. With several taxa (e.g., horse, tahr, auroch) evidence points to systematic butchering (Fernandez 2001).

The assemblage is richest in horses and aurochs, both well-represented throughout the sequence (Table 1). Selective hunting targeting prime-age individuals characterized the procurement of these large herbivores, likely on the plateau above the shelter (Fernandez 2001). The available evidence suggests that horses were hunted seasonally (ca. July-September) throughout the sequence (based on 25 teeth, mostly from layers H and I), while the total absence of juvenile aurochs teeth indicates slaughter outside the birthing period (most frequently April-June – see Fernandez 2001: 124). Diachronic trends are also evidenced in the Bau sequence, as adult (6-15 year-old) horses attain the highest frequencies in layers H, I, and J, whereas the remains from the upper layers suggest selective hunting of younger and older animals (Fernandez and Legendre 2003: 1585).

It is important to note that the faunal remains have been subject to substantial post-depositional alteration throughout the sequence, but particularly in the basal layers. Such alteration resulted from factors such as exposure to water, episodes of freezing and thawing, intense charring in certain layers, and sediment compression (Fernandez 2001: 58). These factors complicate the identification and interpretation of anthropic alteration, which included fracturing bone (very common) for marrow extraction (e.g., with tahr – Fernandez 2001: 73 – or horse – Fernandez 2001: 178), cutmarks attesting to defleshing and probable removal of tendons (e.g., Fernandez 2001: 254), and using bone as fuel in layers H and IV (e.g., Fernandez 2001: 260). It also complicates the interpretation of carcass processing strategies, as for several taxa (e.g., horse, aurochs) the best represented anatomical parts are those with low nutritional value. Fernandez has argued that this is due to strong differential preservation rather than transport of desirable parts off-site (e.g., Fernandez 2001: 257), but in any case it is clear that the number of individuals recognizable in the assemblage, though large (Table 1), likely substantially underrepresents the true number of animals butchered at the Bau.

Table 1: Summary of faunal data for some of the represented ungulates, by layer. Data compiled from Fernandez (2006). Note: that B3[1] may represent a coding error and refer to 3B (i.e., IIIB) instead (Lucy Wilson, personal communication)**.**

Layer	M. giganteus	D. dama	C. elapus	C. capreolus	Equus	S. scrofa	B. primigenius	R. rupicapra	H. cedrensis	Total
	MNI	MNI	MNI	MNI	MNI	MNI	MNI	MNI	MNI	
I										
II			1	3	1		1	1		7
IIB								1		1
III							1			1
IIIC				1						1
IVA			1				1			2
IVM			1							1
IVP		1	2		2		1			6
IV	1	2	6	2	5	1	5	1		23
V	1	1	1		2		1			6
B3[1]							1			1
C								1		1
C1		1								1
E			1		1		1			3
F			1		1					2
G				1						1
H			1		1					2
H1	2	1	6	8	10		9	2	11	49

H2		1	1	2	3		2	1		10
I			1		2		1			4
I1	1				1	1	2		1	6
I2	2	1	3	2	11	2	8	1	4	34
I3	2	2	3		4	1	11		1	24
I4	1	1			5	1	8	1	1	18
J			1		2		1			4
J1	1				2		5			8
J2		1		1	2		6		1	11
J3					2		2			4
J4				1	3		2	1	1	8
K1					1		1			2
K2										0
Total	11	12	30	21	61	6	70	10	20	241

4.2 *Homo* remains

The human remains recovered from Bau de l'Aubesier, all considered to belong to the Neanderthal lineage with the probable exception of the Aubesier 3 incisor, consist of several isolated deciduous and permanent teeth as well as a partial mandible (e.g., Lebel et al. 2001: 11098; Lebel in Texier 2004: 87). As noted in section 2 above, the first human remains at the site were discovered early on by Moulin at the base of his layer B (Moulin 1903: 417). Unfortunately, the molar in question, a right dm^2 without pathologies and thought to have been shed naturally pre-mortem, by a 10- or 11-year-old child (Moulin 1903: 400, 417-422), is now lost (de Lumley-Woodyear 1969: 385). A second tooth, a left P$_2$, was found in 1964 by Bertrand Mary (de Lumley-Woodley 1969: 385) in what appears to be Moulin's layer ab^2 (see Figure 5). The rest of the human remains were discovered during the 1994 and 2000 excavation seasons (Lebel et al. 2001: 11097). The Aubesier 4 (I^2), 5 (dm^1), 10 (M^1 or M^2), 12 (M^1 or M^2) teeth, as well as the Aubesier 11 mandible were described in detail in a series of publications in the early 2000s (Trinkaus et al. 2000; Trinkaus et al. 2000a; Lebel et al. 2001; Lebel and Trinkaus 2001, 2002a). The other teeth include Aubesier 6 (dc^1, shed post-portem) and 9 (I^2, shed post-mortem), which could possibly belong to the same individual as Aubesier 12 (Lebel and Trinkaus 2002b: 556), Aubesier 7 (dm^2, shed pre-mortem), and Aubesier 8 (dm^1), all recovered from upper layer IV, towards the back of the layer (Lebel in Texier 2004: 87; Lucy Wilson, personal communication).

Lebel et al. (2001: 11098) note that Aubesier 4, 10, and 11 were found in the lower slope excavations (see Figure 7) in layers K-1, I-3, and I-2 respectively, while the rest were recovered from layer IV (Aubesier 3 was found in layer II – Lucy Wilson, personal communication). These remains belong to individuals of various ages, from immature (e.g., Aubesier 1, 5, 6, 8, 9, and perhaps 12) to prime age adults (Aubesier 4, 10), to possibly quite an old individual (Aubesier 11). They are remarkable in that two of the teeth (Aubesier 5 and 12) show evidence of caries, Aubesier 4 at least shows wear consistent with heavy non-masticatory use, and Aubesier 10 shows evidence of some dental care. The partial mandible shows extensive antemortem lesions which occurred some time before death and would have functionally compromised to the point that Lebel et al. (2001) suggested may have required care by other group members.

4.3 The lithic assemblages

Henry de Lumley-Woodyear (1969: 386) published a Bordian analysis of the sizable collection of lithics recovered by Louis Gauthier between 1950 and 1957. Those materials would have originated from the upper deposits first investigated by Moulin. Based on de Lumley-Woodyear's report, the collection included a minimum of ca. 1,340 complete or proximal flakes; however, the total number of examined pieces is unfortunately not specified. He classified the assemblage as Typical Mousterian of Levallois facies rich in scrapers (de Lumley-Woodyear 1969: 396) and suggested a late age, specifically the end of Würm II (i.e., MIS 4-3). To de Lumley-Woodyear it was evident that substantial reduction occurred outside the site and that raw materials were brought in primarily as good quality flakes. Despite this, he notes, cores are abundant, with ca. 12-13 large flakes, and ca. 4 tools per core (figures given as percentages in the original). De Lumley-Woodyear classified most of these cores as atypical (41%), with Levallois ones constituting only ca. 10% of the core total despite the very high Levallois Index (IL) of the assemblage (75.1 – de Lumley-Woodyear 1969: 386). Overall, he considered the lithic assemblage from the entire then-known sequence to be very homogeneous (de Lumley-Woodyear 1969: 386). As Texier (2004: 89) points out, however, the scientific value of de Lumley's conclusions is limited because the stratigraphic provenance of the analyzed materials is uncertain.

Further techno-typological analyses, preliminary in nature (Wilson and Browne 2014: 29), appear in a report on the 1988-2000 excavations presented by Lebel to the French Ministry of Culture and Communication in 2000. This unpublished report, briefly summarized in Wilson and Browne (2014) and also discussed by Texier (2004), included information on 4,118 technologically and typologically identifiable pieces from layers 2 to 5, C, and H to K1 (see Figure 7), including 882 cores (251 Levallois, 631 non-Levallois). Texier (2004: 89-90) notes that the material systematically recovered by Lebel's team amounted to more than 80,000 pieces of debitage, mostly (79-98% depending on the layer) small (1-3 cm), as well as 3,580 cores and shaped tools, with retouch present on 2-20% of blanks depending on the layer (Texier 2004: 91). Many of the lithics - over 44,000 pieces of debitage, mostly <2 cm (Fernandez 2006: 15), and ca. 2000 cores and retouched flakes (essentially all scrapers) - come from layer IV, a layer characterized by a high laminar index, short blades, and an important component of Upper Palaeolithic types (Texier 2004: 90). Layer H1 is also rich, having yielded almost 9,000 lithics (ca. 10% >1 cm) and more cores than layer IV (Texier 2004: 90); Texier (2004: 90) notes that a substantial portion (ca. 30%) of the cores from H1 are Levallois, and that, in general, this layer, the richest in lithics from the lower sequence (i.e., the slope deposits), is similar typologically to layer IV. Overall, the absence of cortical debitage suggests cores were partially reduced at provisioning locations, but their relatively high number in the assemblage, and the large number of small pieces present, is interpreted as indicating on-site reduction (Texier 2004: 90), echoing early observations by Moulin (1903: 408).

Subsequent techno-typological analyses of the lithic materials recovered from Lebel's excavations, as well as of some of the older collections, were conducted by Lucy Wilson and students in 2013 and 2014. These are to be published in Lucy Wilson's upcoming book. More recently, Carmignani et al. (2017) published an analysis of 3,249 lithics from the lower layers J and K. These latter analyses allow for some general observations:

1. Most of the pieces consist of debris, indicating substantial *in situ* flaking. At least for the lower layers J and K, the *in situ* flaking activity has been described as intense (Carmignani et al. 2017: 8). In these lower layers there are, on average, 11 flakes greater than 20 mm per core.

2. Retouch is rare, and at least in the lower layers J and K, it seldom modifies the shape of the blanks when present (Carmignani et al. 2017: 23). Indeed, formal tools in these layers are reported to be rare (Carmignani et al. 2017: 28).
3. Carmignani et al. (2017: 5) report that only a few pieces could be refitted, possibly indicating off-site discard.
4. The material is relatively fresh and not suggestive of displacement or strong crushing (Carmignani et al. 2017: 5).
5. A majority of the lithics were made on flint procured from relatively substantial distances from the site (>5 km) and often brought in as nodules or cores, at least in the lower layers. In these layers Carmignani et al. (2017: 37) note that raw materials from distant sources are well-represented through all stages of the *chaîne opératoire*.
6. Some diachronic changes are evidenced in technological behaviours, at least in the lower layers.

The analyses conducted by Wilson and her students in 2013 and 2014 indicate that substantial *in situ* knapping is characteristic of much of the Bau sequence, not just the lower layers, with at least some raw material types being represented at all stages of the reduction sequence (Lucy Wilson, personal communication). This is despite the fact that only in layer II does the proportion of stone procurable near the Bau exceed 7%, even then representing only 15% of the assemblage total (Lucy Wilson, personal communication). While Wilson's analyses do indicate further changes throughout the rest of the sequence, reflected for instance in the degree to which different raw material types were exploited (Wilson and Browne 2014; see also next section), they also highlight that these changes should be viewed against a background of substantial continuity. Indeed, the same major raw material types were consistently exploited, even if in different proportions and even if some layers reflect a greater diversity of raw materials than others; along the same lines, the proportion of local raw materials remains very low throughout the sequence. Blades and Levallois products continue to be present, the proportion of formal tools remains broadly similar, and burned lithics and bones are a consistent feature of the assemblages despite the lack of other evidence for fire use in some of the layers. In brief, some of the general observations noted above for the lower layers are broadly applicable to the entire sequence. With others (e.g., refitting), the information to which I have access is not detailed enough to allow for further comments. It is important to note, however, that occasional examples of double patina, or partially patinated artifacts, point to at least some degree of recycling (Lucy Wilson, personal communication), and that some aspects of the assemblages indicate tool maintenance and repurposing (Lucy Wilson, personal communication).

5 Lithic raw material procurement at the Bau

The lithic materials used at the Bau are virtually all flint (e.g., Wilson and Browne 2014: 33). Concerns regarding the source of the raw materials used at the site extend back to the very first investigations conducted by Moulin. Indeed, in his 1903 publication he devoted six pages (403-409) to a discussion of flint-bearing formations in the region and the incidence and utilization of sources. Through his investigation of the area surrounding the Bau he identified a potential source for two cores from layer D (1903: 397, 408); these, he suggested, were roughly worked at the source and then reduced at the Bau, as indicated by the abundance of small flakes (408). Such early efforts notwithstanding, it was only with Lucy Wilson's work at end of the 20th century that lithic raw material use at the site became well-known.

In 1987 Lucy Wilson began a survey project aimed at identifying and characterizing potential raw material sources in the region surrounding the Bau (e.g., Wilson 2007a: 389). Over the course of more than two decades Wilson sampled and systematically described 350 primary and secondary raw material deposits, containing mostly Cretaceous and Oligocene flints (see Figure 1). She has also analyzed over 40,000 archaeological pieces of types all sizes from throughout the sequence, including over 23,000 lithics recovered from the upper layers II-V in the trench L excavation, the majority (> 20,000) from layer IV, and ca. 16,000 from layers C to K2 along the western wall (see Figure 7; see also SOM 2 in Wilson and Browne 2014).

Wilson (2007b: 318) reports that geological samples collected at each potential source were characterized primarily by means of macroscopically visible features and through petrographic analyses of thin sections, supplemented by limited geochemical data and focusing on properties such as microfossils that can be used to distinguish materials by age and depositional environments. Archaeological artifacts on the other hand, were classified by Wilson into distinct types based primarily on characteristics "visible to the naked eye or under a hand lens" (Wilson and Browne 2014: 33) and under field conditions (Wilson and Browne 2014: 31). Petrographic analyses of thin sections from the identified types complemented these characterizations (e.g., Wilson and Browne 2014: 33; Browne and Wilson 2011: 599). The artifacts were initially classified into 32 distinct variants with known sources in the region, as well as 7 types whose provenance is undeterminable due to weathering or burning, and 7 types from unknown sources (see Browne and Wilson 2011: 599).

The 32 variants known to occur throughout the region could ultimately be traced to some 101 locations within 17 "source areas" (see Browne and Wilson 2011), with more than one location often containing indistinguishable raw materials and with more than one variant possibly occurring at a given location. In total these variants accounted for only 15,674 artifacts, most lithics being impossible to source due to various types of alteration (see also Texier 2004: 90). The percentage of undeterminable lithics varied by layer, from between ca. 89% in layer E to ca. 31% in layer G with a mean of ca. 60% (see SOM 2 in Wilson and Browne 2014), but there is no evidence of differential alteration across flint types, so the sample of sourced artefacts is considered to be representative (Wilson and Browne 2014: 33). The number of artifacts which were procured from unknown sources, on the other hand, is very small, amounting to only 171 artifacts (Lucy Wilson, personal communication). Overall, the Bau appears to be quite centrally located within its raw material supply zone (see Figure 1), with most artifacts made from raw materials found within 13 km of the site, but seldom closer than 10 km (e.g., Wilson et al. 2018: 96).

The resulting database, which is very large and comprehensive compared to that available for most other Middle Palaeolithic sites, enabled a series of publications that not only elucidated raw material procurement at the Bau, but also made important theoretical and methodological contributions. Thus, in 2007, Wilson examined terrain difficulty (kcal/km) as an explanatory variable for source utilization (Wilson 2007b; see also Wilson 2003) and demonstrated that, at least at the Bau, it affected procurement choices. In the same year she introduced an equation aimed at quantifying the attractiveness of potential raw material sources when considering intrinsic properties (i.e., geological, geographic) alone, and proposed using the resulting values in a gravity model that accounted for distances as well (e.g., between potential sources and sites - see Wilson 2007a: 402). The two-fold goal of this latter publication was to assess the degree of fit between the actual use of sources at the Bau and their calculated attraction values, in order to better understand the human factors (as opposed to physical factors) that shaped procurement, and to present a method of determining areas where specific sources should have been used given the presence of competing neighbours. Wilson demonstrated the utility of the approach considering 11 sources represented in layer IV at the Bau (Wilson 2007a: 400-401).

A subsequent publication with Constance Browne in 2011 aimed to overcome some limitations of the developing approach by considering optimal weighing of the variables included in Wilson's 2007 equation, adding new predictors, assessing different ways of evaluating access costs, expanding the number of considered sources to all for which data was available, and including combined provenance data from multiple layers. This work was based on the formulation and evaluation of generalized linear models that simultaneously considered the influence of the different variables, and treated sources of indistinguishable raw materials together as 'source areas' (110 in total - a number eventually increased to 122 - 17 of which are represented at the Bau; see above, and Browne and Wilson 2011: 600). This latter feature constituted an important deviation from the earlier work, since a representative source, ultimately the one with the highest quality raw materials (Browne and Wilson 2011: 605), had to be selected to describe each source area. Overall, this work indicated that hominins at the Bau were selectively procuring raw materials from sources that were easy to access and contained abundant and easy to find larger (>16 cm), high-quality rocks (see Browne and Wilson 2011: 601, 605), evidencing an optimizing behaviour in line with expectations from optimal foraging theory.

The aforementioned publication also set out plans to apply the model to individual layers within the site, and to other sites in the region (Browne and Wilson 2011: 606). These goals would be addressed a few years later (Wilson and Browne 2014; Wilson et al. 2018), with an intervening publication by Browne and Wilson in 2013 aimed at clarifying the observation that calculating travel costs from sources to the Bau along straight-line routes resulted in better models of source attractiveness, or resource selection, than using least-cost routes computed in ArcGIS (Browne and Wilson 2011: 605). The authors therefore assessed the effects of using different map resolutions and different ways of computing travel paths, and found that, at least at the Bau, models using Shuttle Radar Topography Mission (SRTM) data and straight-line routes indeed provided better results than using higher resolution digital data (provided by SPOT) and/or least-cost paths.

The application to multiple archaeological layers from the upper and lower sequences was reported by Wilson and Browne in 2014. That publication examined diachronic changes in the contribution of included predictors and in the choices of source areas, finding no striking differences in the latter, but identifying an abrupt change in the former: the characteristics of the raw materials themselves (quality, size) appear to have become suddenly more important in the upper layers (II, III, IV, V, and C), deposited after ca. 141 ka ago (see also section 3 above), than in the older, lower layers where terrain variables contributed most to resource selection (Wilson and Browne 2014: 35). Similar albeit more gradual changes were also noted in the faunal and techno-typological lithic data, with the younger deposits evidencing an increasing emphasis on smaller prey and a more intense utilization of the raw materials echoed in lower proportions of cores, tools, and Levallois products (see Wilson and Browne 2014: 36).

Wilson and Browne interpreted the findings in terms of Kuhn's (1995) schema of contrasting provisioning strategies (i.e., of places and individuals). They suggested that the lower layers at the Bau represent longer-term occupations, when the site itself tended to be provisioned with raw materials that were somewhat easier to procure, whereas the upper layers may represent shorter-term occupations by hominins more concerned with the quality of their mobile toolkits. The change, reflecting perhaps a re-organization of the economy, may have been triggered by the harsh climate of late MIS 6, evidenced first in changes to aspects of hominin adaptation that shaped raw material procurement, and then more gradually in prey choice and technological behaviours. An alternative briefly considered by the authors is that the differences reflect two hominin populations, or even species (Wilson and Browne 2014: 36), but as they note there is no need to invoke such explanation. Indeed, it is important to consider the observed trends against a background of substantial continuity throughout the sequence (see section 4.3). It is also important to keep in mind that the abrupt change from the lower to the upper deposits is evidenced in the quantity of pieces ultimately derived from specific source areas rather than their weight, and the number of by-products (e.g., debris) generated with increasing reduction is not proportional to their mass, which complicates interpretation.

More insight into raw material procurement at the Bau came from the comparison ensuing from the first application of the approach to another site, namely La Combette (Wilson et al. 2018). This smaller rockshelter, containing younger (ca. 60-78 ka) and rapidly accumulated deposits (see Wilson et al. 2018: 90), is located in the same region as the Bau but in easier terrain and at the southern fringes of its raw material provisioning zone (Wilson et al. 2018: 88; see also Figure 1). The comparison revealed that while site catchments (*sensu* Higgs, see Bailey and Davidson 1983) were of roughly similar size (ca. 1600-1700 km^2) and display substantial overlap (Wilson et al. 2018: 97), the most intensely exploited sources (>10 artifacts, corresponding perhaps to the site exploitation territories *sensu* Bailey and Davidson 1983: 88) at the Bau occur within a territory that is considerably smaller than at La Combette (223 km^2 at Bau, versus 790 km^2 for La Combette), reflecting perhaps its greater resource richness and/or longer occupations. It also revealed that that most provisioning occurred within a much narrower distance interval, between ca. 8 and 13 km from the site (Wilson et al. 2018: 96). On the other hand, differences in the importance of resource selection predictors at the two sites serve to contextualize some previous interpretations. For instance, the importance of raw material quality in the upper layers at the Bau (see above) contrasts with the relatively lower importance of this variable at La Combette, even though both cases are associated with more mobile groups whose provisioning strategies align more with Kuhn's provisioning of individuals than of places (see Wilson et al. 2018: 88, 96, and Wilson and Browne 2014). Finally, the comparison of La Combette to the Bau also served to highlight the overall theoretical and methodological contributions of the approach developed over the years by Wilson and Browne, by signaling its wider applicability.

6 Summary

The Bau de l'Aubesier contains a rich and complex Middle Palaeolithic sequence that records some 100,000 years of relatively continuous Neanderthal presence in the Vaucluse department of southeastern France. Found in an area of variable topography that has not experienced major geomorphological changes since the deposition of the first known traces of habitation, the site provides one of the most comprehensive and consistent lithic provenance datasets available for a Middle Palaeolithic site. As discussed in section 5 above, this dataset is well-studied, albeit not from a simulation perspective, and documents the extensive use of relatively distant sources despite the availability of suitable raw materials nearby. While questions remain regarding the stratigraphy and dating of the site's deposits, and about the nature and drivers of the typological and technological variability evidenced in the lithic assemblages, the site is, overall, understood quite well.

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Chapter Three

Re-examining basic assumptions through a systematic re-evaluation of Brantingham's neutral model of raw material procurement

Simulating Lithic Raw Material Variability in Archaeological Contexts: A Re-evaluation and Revision of Brantingham's Neutral Model

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Simulating lithic raw material variability in archaeological contexts:

A re-evaluation and revision of Brantingham's neutral model

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Abstract

This paper presents a systematic re-evaluation of Brantingham's (2003) neutral model of raw material procurement. I demonstrate that, in its original form, the model is ill-suited to the identification of archaeologically visible patterns, as it can only simulate processes governing the composition of toolkits and these differ substantially from those influencing the composition of discard records. I discuss and implement a series of modifications, and provide a detailed analysis of discard records produced under revised model definitions. On this basis I argue that qualitative similarities in patterns generated by the neutral model and those evidenced in archaeological contexts cannot be used to prove, or disprove, the adaptive or functional significance of raw material variability (cf. Brantingham 2003). However, I show that the revised model *can* be used to detect deviations from neutral expectations quantitatively and within well-defined error ranges.

I outline a new set of predictions for what archaeological variability should look like under the simplest procurement, transport, and discard behaviours, and argue that deviations from each of these may be traceable to specific behavioural domains (e.g. biased mobility, raw material selectivity). I also demonstrate that: a) archaeological sites or assemblages do not offer an adequate proxy for the average composition of ancient forager toolkits; b) assemblage richness is, by itself, a very poor predictor of occupational histories; and c) that the common practice of calculating expected frequencies from distances to sources is flawed, regardless of how such distances are measured.

Keywords

Lithic sourcing; raw material procurement; neutral model; agent based modeling; archaeological theory

1. Introduction

This paper presents a systematic re-evaluation of Brantingham's (2003) neutral model of lithic raw material procurement. The model, introduced as a radical alternative to traditional approaches, aims to investigate the behavioural significance of archaeological raw material variability on the basis of a minimal and well-defined set of assumptions. In essence, it is an agent-based model which simulates variability under entirely neutral (i.e. random or constant) acquisition, discard, and mobility behaviours. Surprisingly, the patterns generated by the model are qualitatively similar to those evidenced in many archaeological contexts. These similarities suggest, according to Brantingham, that the degree of representation of different raw materials in archaeological assemblages may be of "no functional or adaptive significance whatsoever" (Brantingham 2003: 490).

This argument is currently difficult to accept for at least two reasons. First, neutral explanations (i.e. that variability is the result of stochastic processes) run counter to established theory and, based on the current state of knowledge, they have a low *a priori* probability of being true. Consequently, accepting such explanations on the basis of *qualitative* similarities may be ill-advised. Secondly, Brantingham evaluates patterns evidenced in toolkit states rather than discard records, and it is unclear to what degree these are relevant to understanding archaeological variability in the first place (cf. Brantingham 2003: 493). Nevertheless, the model's ability to replicate archaeologically observable patterns cannot be ignored, and it is likely that Brantingham's work has much more to contribute to archaeological theory than a simple cautionary tale.

Despite being published over a decade ago, however, and despite its continued conceptual or applied use (e.g. Brantingham 2006; Clarkson 2007: 17; Braun et al. 2010; Perreault and Brantingham 2011; Clarkson and Bellas 2014; Lengyel 2015) and profound implications, the model itself as well as Brantingham's analyses and conclusions have yet to be systematically reassessed (cf., e.g. Oestmo et al. 2014; Duke and Steele 2010; Moutsiou 2011: 57). Thus, the goals pursued here are: a) to evaluate the representativeness of Brantingham's results, b) to ascertain the degree to which toolkit states are adequate proxies for discard records, c) to evaluate the model's ability to generate discard records which resemble the archaeological record in a meaningful way, d) to provide a detailed investigation of such discard records, and e) to discuss some of the wider implications of the neutral model.

I begin by providing a brief theoretical background in order to contextualize Brantingham's work and highlight its importance for archaeological research. Next, I assess a fully independent replication of the original model by means of 500 simulations, greatly exceeding the scope of the original study, which considered only a handful of simulations (Brantingham did not report their exact number). Through this assessment I identify a series of potential problems with the original definitions of the model, and show that the processes governing the composition of toolkits are markedly different from those governing the composition of the discard records. Moreover, I show that the original model is incapable of producing discard records that resemble the archaeological record in a meaningful way.

I implement a minimal set of revisions required to overcome the main limitations of the original model, and provide a thorough analysis of the patterns evidenced in the discard records produced by three simulations, each lasting 250 million time-steps and run with different parameters. I re-examine Brantingham's original predictions in light of my results and show that qualitative similarities between model-generated and archaeologically observable patterns cannot be used to accept, or reject, the adaptive or functional significance of raw material variability (cf. Brantingham 2003). However, I also show that the revised model can, theoretically at least, detect deviations from neutral expectations with a relatively high degree of precision and known, well-defined error ranges.

My results do not support some of Brantingham's original predictions, but they do provide a new set of expectations for what variability should look like under the simplest procurement, transport, and discard behaviours. I argue that predictions made on the basis of these expectations may be rejected on an individual basis, and that deviations may be traceable to variables influencing particular behavioural domains (e.g. resource selectivity, mobility). Ultimately, the revised model presented here is also, by necessity, a model for the formation of the archaeological record, and I show that it can be used to investigate issues of fundamental importance for archaeological research, including the relative importance of lithics in past adaptations and the meaning of archaeological sites. I therefore conclude my discussion with a brief examination of the wider theoretical implications of the model.

2. Theoretical background

2.1. Lithic procurement studies in an evolutionary context

Stone is the only resource exploited throughout human history which is both well-represented in most archaeological contexts and whose geographic provenance can be ascertained with some confidence. The representation of different raw materials can therefore be evaluated in terms of the location and characteristics of sources in a given area, allowing for useful information on human/landscape interactions to be recovered at most archaeological sites.

In principle, this information allows for insights into past landscape utilization patterns (e.g. Binford 1979 and Gould and Saggers 1985; Gould 1978; Féblot-Augustins 1993, 1999; Fernandes et al. 2008; Brantingham 2006; Arakawa 2006), social behaviours (e.g. Pearce and Moutsiou 2014; Moutsiou 2011; Gould and Saggers 1985), and even the cognitive abilities of extinct hominins (e.g. Moutsiou 2011; Braun et al. 2009; Braun et al. 2008; Spinapolice 2012 and references therein). Additionally, it allows for more refined interpretations of other aspects of stone tool variability, since it is generally acknowledged that technological choices, the final shape of artifacts, and the use-lives of different tools can be affected, to varying degrees, by the intrinsic properties (e.g. hardness, nodule shape) and the availability of different raw materials (Dibble 1991; Kuhn 1991; Andrefsky 1994, 2009 and references therein; Driscoll 2010).

2.2. Challenges of modeling past procurement behaviours

Procurement studies can play a key role in shaping our understanding of the evolution of the human condition, but only if adequate theoretical frameworks exist for inferring dynamic behaviours from what is in many ways a static record. Building theoretical models of raw material procurement is a difficult task, however, and choosing between alternative explanations is often a challenge. The reasons for this are numerous, but the following deserve some brief consideration:

a. Raw material procurement may have been embedded in other activities (e.g. Binford 1979), potentially unrelated to basic subsistence[1], and in many cases it may be impossible to determine whether, or to what degree, that was the case (Gould and Saggers 1985: 123; cf. Myers 1986: 66-72). Thus raw material variability may have been governed, to varying degrees, by factors unrelated to lithic procurement proper.

b. The spatial range of lithic exploitation need not necessarily correspond to the range over which other resources were procured. This possibility renders inferences about mobility or foraging radii difficult to draw (Cole 2002; cf. Myers 1986: 60-65).

c. We lack adequate ethnoarchaeological information on how lithic resources were managed by foragers who still depended on them in modern times[2]. It is therefore difficult to develop well-grounded theories of how raw materials may have been procured and used in the past, even when investigating traces left by anatomically modern humans.

d. Past choices are difficult to evaluate because both the cost and the benefits of procuring specific raw materials are hard to determine. First, "cost and distance to source are not equivalent" (Kuhn 1991: 78), not least because cost depends on the specifics of spatial practices (i.e. land use, mobility) as well as conceptualizations and perceptions of space (*sensu* Lefebvre 2007). Second, the quality (i.e. flakeability, durability) or benefits afforded by different materials are both contextually-dependent (e.g. what use a tool was put to) and notoriously difficult to quantify (e.g. Woods 2011: 84-99; Pop 2013). Indeed, quality may have been, and likely was, considered from a simple binary perspective: either good enough, or not, for whatever purpose was envisioned at the time.

In practice these difficulties lead to a series of fundamental but hard to evaluate assumptions being built into virtually all current models of raw material procurement. These assumptions can manifest in the choices of variables to be used (e.g. distance to source), in the differentiation between physical and socio-cultural factors (e.g. definitions of 'cost' and 'quality'), in notions of what archaeological sites represent (e.g. periods of continued habitation), and even in our perceptions of the relative importance of lithics in hominin adaptation. The fact that potentially unfounded assumptions are built into our models does not imply, of course, that these models are of no value. On the contrary, such models have significantly enriched our understanding of the past (e.g. Adams and Blades 2009; Yamada and Ono 2014). The inclusion of these assumptions does imply, however, that the reliability of inferences derived

[1] Binford (1979: 259) argued that lithic raw material procurement was embedded in basic subsistence activities, but there is no reason to suspect that it may not also have been embedded in non-subsistence activities which may not be visible archaeologically (e.g. Gould and Saggers 1985: 122).
[2] While there are a series of ethnoarchaeological accounts of lithic procurement (e.g. Binford 1979; Gould and Saggers 1985; see also the review by McCall 2012), the studied populations had access to modern means of transport (e.g. Gould and Saggers 1985: 120), and even in the case of Binford's study of the Nunamiut, which provided the basis for his "embedded procurement" argument, it failed to consider variables that are critical in understanding procurement behaviours (see Cole 2002: 54).

solely on the basis of the provenance of stone is questionable and, moreover, that we are limiting our inquiry to variables that may, ultimately, not be the most significant in explaining past behaviours.

2.3. Brantingham's (2003) neutral model in context

Brantingham's work is valuable in this context because it provides an alternative starting point, constructed on the basis of minimal and explicitly defined assumptions. In essence, it aims to provide insight into what variability should look like, and more importantly perhaps, why, if only the effects of random processes and constant parameters are considered. Briefly, Brantingham's model aims to be:

a. *A neutral model*: Neutral models are similar, but not identical to, null models, of which sometimes they are considered a special case (Gotelli and McGill 2006; cf. Brantingham 2003: 490-491). They are defined by Pearson and Gardner (1997: 215) as "a minimum set of rules required to generate pattern in the absence of a particular process (or set of processes) being studied." In essence, they aim to evaluate the effects of "noise", or those processes which are not relevant to the questions being asked, so as to more reliably detect "signals". In the case of Brantingham's (2003) work these questions pertain to adaptive processes and, consequently, his model seeks to evaluate the effects on non-adaptive behaviours.

b. *An agent-based model:* Agent-based models aim to computationally simulate complex systems on the basis of the local interactions of autonomous, decision-making agents (e.g. Bonabeau 2002; Janssen 2012). They are useful because: a) the emergent, macro-level patterns generated by these low-level interactions are often difficult or impossible to predict through traditional analytical approaches, and b) by modifying the set of behavioural rules each agent is given it becomes possible to study the effects of isolated variables and specific parameters on the behaviour of the overall system.

In following an agent-based approach Brantingham (2003) encodes neutral processes in a set of behavioural rules. Specifically, he simulates a single agent which: a) has a fixed capacity to carry raw materials; b) randomly moves to an adjacent cell or stays in place at every simulation time-step; c) collects as many raw materials as possible upon chance encounters with sources; and d) if possible (i.e. if its toolkit is not empty), discards one raw material unit at random after every move. The landscape with which the agent interacts contains randomly distributed sources of identical quality (however defined) and infinite, uniformly distributed non-lithic resources.

There are many advantages to such agent-based neutral models. These include simplicity, rigorous formal definition, and the ability to: a) detect and understand emergent patterns, b) study the systemic effects of individual variables, and c) provide well-defined null-hypotheses against which archaeological variability can be evaluated. In principle, then, Brantingham's model provides a strong foundation for building bottom-up interpretive frameworks that offer an alternative to traditional top-down approaches.

It must be noted, however, that Brantingham's model is not, strictly speaking, a neutral model: as suggested by Brantingham himself (2003: 504), the modeled behaviours (e.g. random procurement) may have been adaptive, and consequently there is no clear distinction between what constitutes "noise" and "signal". Beyond this, neutral models require specifying parameters which may be impossible to estimate directly (see Gotelli and McGill 2006), and as such are neither assumption-free nor particularly reliable. Indeed, fiddling with parameters can lead to a variety of patterns, including some that may resemble those observed in real contexts (Enquist et al. 2002). Finally, Brantingham's model is only agent-based in a restricted sense, since interactions between agents, or indeed, the effects of simulating multiple agents, are not considered.

2.4. Theoretical implications of the neutral model

Brantingham (2003) argued that the neutral model is capable of replicating a number of commonly observed archaeological patterns. If correct, this has a number of important implications for archaeological theory. The most direct implication, and one which is discussed by Brantingham (2003) in detail, is that raw material variability may not be informative with regard to past adaptation. I consider this conclusion to be overly pessimistic but, if correct, it would imply that our ability to extract useful information from the representation of raw materials in archaeological contexts is severely limited. It would also imply, of course, that many current interpretations are wrong.

The implications of the model extend far beyond the issue of raw material procurement, however. For instance:

a. If the neutral model accurately simulates procurement behaviours we would have to accept the possibility that access to raw materials, and consequently access to stone tools, was far less important in the past than commonly believed[3]. This is because the requirements of random walks are incompatible with the requirements of constant access to lithic sources. Indeed, Brantingham (2003: 494) reports that even in the context of a simulation in which the average distance between raw material sources was but 4% of the maximum distance that the agent could traverse with a full toolkit, said agent spent 25% of simulation time without any access to stone tools.

b. A good correspondence between the model's output and patterns observed in archaeological assemblages also suggests that lithic recycling played at best a very minor role (cf. Amick 2007).

c. Such good correspondence would also imply that sites were never a living space or dwelling of any kind - under the model, assemblages are simply random aggregates of items discarded over time by agents whose probability of remaining at any one location for two consecutive time-steps is only one in nine.

Taken together, and based on our current state of knowledge, these implications suggest, but do not demonstrate, that if it accurately simulates archaeological patterns the neutral model is probably wrong. Insofar as the model is taken to be an exploratory tool rather than a realistic simulation of the past, however, this may be largely inconsequential. Indeed, it would be expected that attempts to

[3] As discussed by Sillitoe and Hardy (2003), there is certainly evidence to suggest that we may be overestimating the "true place [of lithics] within the material culture of which they formed part" (Sillitoe and Hardy 2003: 555).

demonstrate the invalidity or incorrectness of the model would result in productive reassessments of some fundamental assumptions regarding the very nature of the archaeological record.

3. Methods

In order to avoid perpetuating potential errors, I replicated Brantingham's model solely on the basis of the definitions provided in the original publication (Brantingham 2003: 491-494), without examining Brantingham's code or that of alternative implementations (Janssen and Oestmo 2013). I coded the model in Python (v3.4.3) with the aid of the SciPy (v0.15.1) and NumPy (v1.9.1) libraries (van der Walt et al. 2011), relying on SciPy's implementation of the "Mersenne Twister" algorithm (Matsumoto and Nishimura 1998) for the generation of pseudo-random numbers. I tested both the Python code and the simulation outputs for correctness and compliance with the definitions of the model (see Table S2 in Electronic Supplementary Materials [ESM] 1).

I analyzed the outputs of 500 simulations of the original model, focusing on the variability and patterns evidenced across the entire simulation set (c.f. Brantingham 2003). This number was chosen arbitrarily, but it was deemed large enough to offset potential biases resulting from variations in the local density of the randomly placed sources and the expected low degree of coverage attainable by agents in individual simulations. In this regard it should be noted that none of the simulation lengths reported by Brantingham (2003) exceeded 25,000 time-steps, or 10% of the minimum that would be required to achieve complete coverage of the simulated world (a 500x500 grid, containing 250,000 cells). The low degree of coverage, coupled with the random (i.e. non-uniform) placement of sources, renders individual simulations susceptible to biases resulting from local differences in source densities.

My analyses of the replicated model indicated that the termination conditions specified by Brantingham end simulations prematurely, thereby biasing overall results and also preventing the formation of discard records suitable for detailed investigations. I therefore modified the definitions of the model without fundamentally altering it. The algorithm of the revised model is outlined in Figure 1 (cf. Brantingham 2003: 494), and the modifications are summarized below:

a. I removed the condition upon which simulations terminate after agents encounter 200 unique raw material sources. Instead, I define a new, single termination condition whereby simulations end after a pre-defined number of time-steps. This allows for the results of simulations to be interpreted in terms of patterns evidenced within a specified time-span, without having to consider the effects of the variable time required to achieve a specific degree of coverage of the simulated world (e.g. reaching a set number of sources). Thus, this single termination condition allows for easier comparison of simulations run with different mobility, discard, and toolkit size parameters.

b. I modified the behaviour of agents at the edges of the simulated world so as to allow for arbitrarily long simulations. In the revised model agents continue to have an equal probability of moving to one of the adjacent cells or staying put, but only those cells that exist within the confines of the world are considered: thus, four movement options are available to agents at the corners of the grid, six at non-corner edge cells, and nine at any other grid location.

c. I slightly modified the logical sequence of the algorithm so as to allow agents initially placed on a source to fill their toolkit in the first simulation time-step (cf. Brantingham 2003: 494).

d. I optimized the model for running long simulations (hundreds of millions of time-steps), partially by discarding information on toolkit states[4] and retaining only information on the discard record.

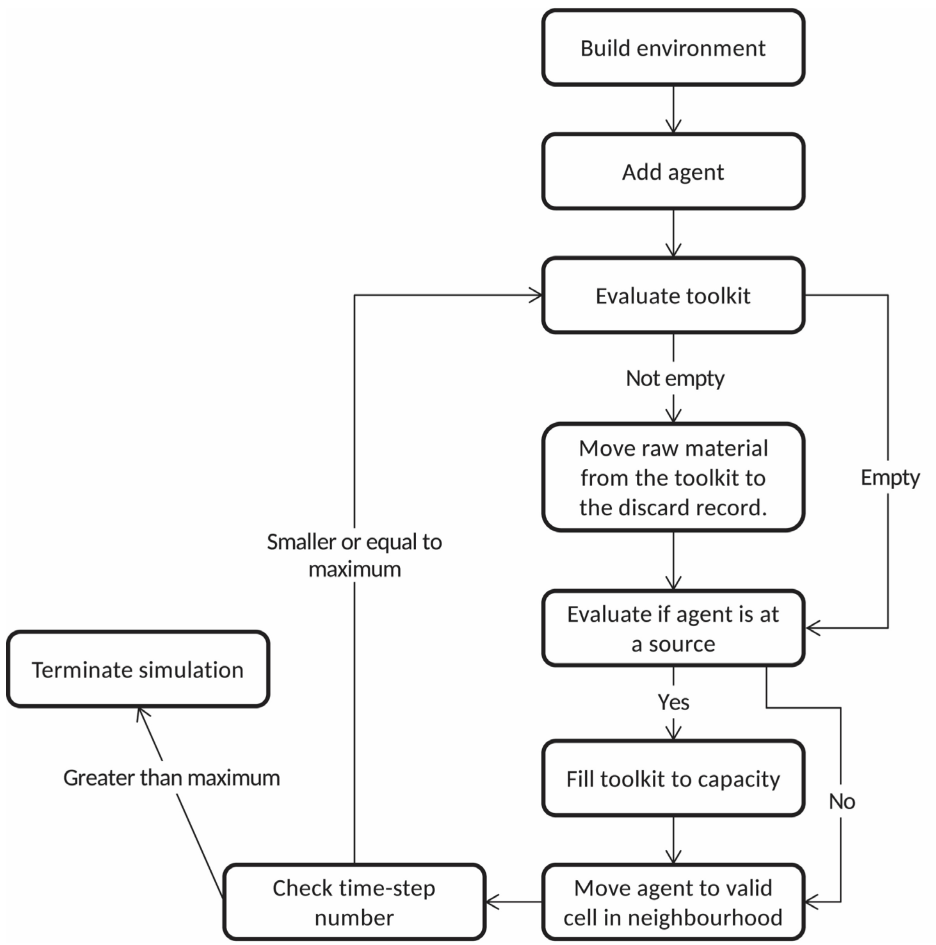

Fig. 1 Flowchart of the revised model's algorithm. Simulations only terminate when a pre-defined maximum number of time-steps has been reached

As with the replicated model, the outputs of all 3 main and 9 auxiliary simulations (250 million time-steps each – see sections 4.2 and 4.2.2.2 for an explanation of the number, and lengths, of simulations) run under revised model definitions were tested prior to analysis. The tests were very similar to those summarized in Table S2 (ESM 1), but differed in two ways: first, due to computational constraints simulations of the revised model only recorded toolkit state data for the initial 200 thousand time-steps,

[4] Information on toolkit states was still recorded for the first 200 thousand time-steps, but only for diagnostic purposes.

and consequently some tests could only be conducted on a small portion of the simulation outputs; secondly, some tests had to be modified to account for differences in model definitions (e.g. termination conditions).

All diagnostic tests and statistical analyses were conducted in R version 3.1.2 (R Core Team 2014) with the aid of RStudio (RStudio 2014) and a number of R packages, namely: nabor version 0.4.3 (Elseberg et al. 2012) for fast KD-Tree nearest neighbour searches, data.table version 1.9.4 (Dowle et al. 2014) for fast manipulation of the large simulation data sets (>4GiB per simulation under revised model definitions), raster version 2.3-33 (Hijmans and van Etten 2012) and rasterVis version 0.35 (Lamigueiro and Hijmans 2014) for the generation, manipulation, and visualization of raster data, spatstat version 1.39-1 (Baddeley and Turner 2005) and sp version 1.0-17 (Bivand et al. 2013) for simplified analysis and manipulation of spatial data, and testit version 0.3 (Xie 2013) for running diagnostic tests on simulation outputs.

The R code for all analyses and plots, as well as the Python code for the revised and replicated models are available under the terms of the GNU General Public License version 2 or later in the Electronic Supplementary Materials (ESM) 2 and at: http://alyanne.net/software/SABM/.

4. Results

4.1. A re-examination of Brantingham's neutral model

4.1.1. General observations on replication results

The general toolkit patterns discussed by Brantingham (2003) were replicated successfully (see Supplementary Electronic Materials [ESM 1] for a full account). However, while all values reported by Brantingham fell within the range of variability evidenced in the outputs of the 500 simulations that I analyzed, they were seldom truly representative. Most of the observed discrepancies are likely explainable by the fact that the lengths and outputs of the simulations are highly variable. This variability, which entails a low probability of observing representative values across all investigated relationships in the context of a single or small number of simulations (Brantingham analyzed only a handful of simulations, but the exact number was not reported), is mainly the result of the arbitrary termination conditions, which cause simulations to end prematurely (see ESM 1 for more details). Some minor discrepancies can also be attributed to problematic aspects of Brantingham's analysis, however. Specifically, linear distances, which are incompatible with the definitions of Brantingham's model, are employed in derivations of foraging radii and maximum expected toolkit richness values; as a consequence, both derivations are incorrect (see ESM 1 for details).

The results of my replication call into question some of Brantingham's conclusions. In particular, I was unable to confirm Brantingham's postulated relationship between modal and maximal transport distances, or that between median/modal transport distances and the sizes of the foraging radii (Brantingham 2003: 498-500; see ESM 1 for more details). This renders Brantingham's analysis of archaeological parallels debatable, because the reported ratios of maximal to modal transfer distances

(2 for the Aquitaine Basin, 4.6 to 6 for the Middle Palaeolithic of Central Europe – see Brantingham 2003: 503) are much lower than the ratio observed in my simulations (approximately 20) [5].

My analyses also confirmed several of Brantingham's conclusions, however. These include: a) the assertion that the neutral model predicts a strong correlation between maximum toolkit richness states and toolkit sizes (Brantingham 2003: 498), b) the observation that modal and median transport distances observed in toolkits are minimally affected by resource densities (Brantingham 2003: 499), and c) the observation that long distance raw material transfers can be explained by very simple behaviours (Brantingham 2003: 503).

4.1.2. Toolkit and discard record patterns

The combined output of the 500 simulations revealed important differences between the patterns evidenced in the simulated toolkits and those observable in the discard records, or the records of the final resting locations (grid cells) of all items removed from the toolkit. These discrepancies, which are discussed in detail below, call into question Brantingham's assertion that "[i]ndividual archaeological assemblages may be treated as repeated random samples of different sizes from the mobile toolkit" (Brantingham 2003: 493)[6], at least insofar as such samples are not spatially constrained[7], and the archive of discard events can be considered a more pertinent analogue for the archaeological record than ephemeral toolkit states. This, in turn, calls into question the relevance of simulated toolkit patterns for understanding archaeological variability.

The most dramatic difference was observed in the relationship between sample size (i.e. the total number of items per cell or toolkit state) and raw material richness (i.e. the number of unique raw materials represented). As shown in Figure 2a, the discard records evidence a clear increase in richness states with increasing sample sizes, with observations most frequently displaying a 1:1 or similar ratio. In the toolkit data set (Figure 2b) a small increase in richness states with increasing sample size can also be observed, but the nature of the overall relationship is much less clear. Importantly, the toolkit data

[5] Note that Brantingham's own reported modal and maximum transport distance values are also inconsistent with his predicted ratio of 3 to 4. Indeed, Brantingham (2003: 499) first argues that "the neutral model predicts that maximum raw material transport distances should be three to four times the *foraging radius d*" (italics mine), but in his discussion of archaeological parallels he states that "[m]aximum transport distances are expected to be three to four times the distance represented by the *internal mode*" (Brantingham 2003: 501; italics mine). It is unclear why Brantingham equates foraging radii with internal modes (Brantingham 2003: 503), given that the foraging radius value he uses is 10 (e.g. Brantingham 2003: 499) and the modal value is 5 (Brantingham 2003: 498). Using the actual modal value he provides, the maximal to modal distance ratio is 8.6, not the 3-4 value used in his analysis of archaeological parallels.

[6] Note that the model provides only one and very weak mechanism for allowing such "random samples of different sizes (Brantingham 2003: 493) to be drawn from the toolkit, namely the 1/9 probability that the agent will remain at the same location for two consecutive time-steps, discarding two items from the same toolkit at the same location. While arbitrarily obtaining toolkit samples larger than one by simply querying it for multiple items is technically possible, doing so would violate the definitions of the model (i.e. discard rates) and would provide meaningless results.

[7] It should be noted that Brantingham discusses patterns evidenced in toolkits states sampled over time, not in space (i.e. at a specific grid coordinate). This is probably because, as shown in the text, the definitions of the model prevent such spatial sampling.

points tend to cluster at high sample size values across all richness states, while in the discard record there appears to be a limit on the *minimum* richness states observable with high item counts; Indeed, no cells containing 24 items or more were found to have less than 3 unique raw material types represented (Figure 2). Moreover, it should be noted that the sample sizes for individual cells are low, never exceeding one third of the size of the mobile toolkit despite the fact that individual simulations of over fifty thousand time-steps were observed, and the cumulative total for all simulations exceeded 8.1 million. Given these differences, it is clear that random samples from the toolkit data set provide only a distorted view of the patterns evidenced in the discard record.

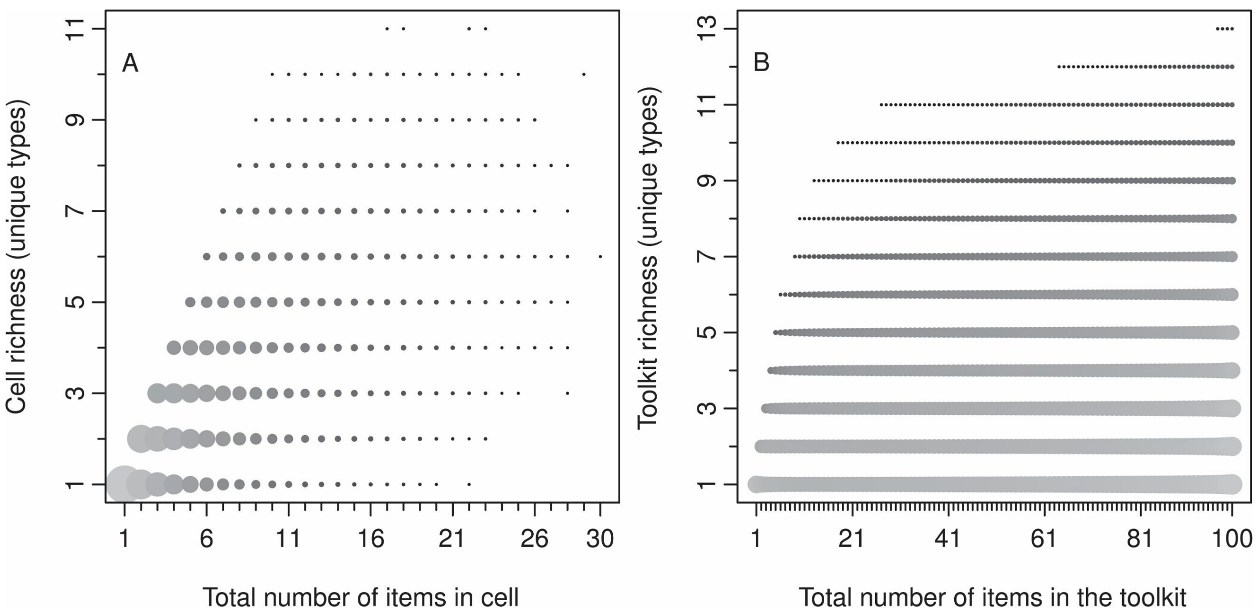

Fig. 2 Relationship between richness state (number of unique raw material types) and sample size in a) the discard record (n=1.92 million), and b) toolkit states (n=8.1 million). Filled circles denote individual variable combinations, while their size and grayscale values represent the number of individual observations. Circle diameters grow with the fourth root of sample size ($n^{1/4}$), so as to permit visualization despite the extreme differences in the frequencies of observation (1 to 700586); colours, on the other hand, are given as the log of sample size transformed to fit in the range of 0 (black) and 0.75 (light gray)

Notable albeit less pronounced differences in transport distance patterns can also be observed. As shown in Figure 3, although the modal transport distance remains the same across both data sets (3 grid cells), the probability of observing it is approximately 15 percent lower in the discard record; at the same time, the probability of observing long transport distances is higher than that recorded in the toolkits despite the considerably lower sample size (5.3 million versus 333.7 million).

These differences may seem surprising given that both data sets encode different aspects of the same information, but they are explainable by two simple facts. First, toolkits are mobile and encode primarily changes over time, while discard locations are fixed and encode mainly changes over space. Consider, for example, a situation in which four sources are placed at an equal distance of five grid cells from a given location *x*, but in different directions (e.g. north, south, east, and west). Because the probabilities of observing transport distances of 5 grid cells or more are high (5 grid cells corresponds to the median transport distance - see ESM 1), we should expect all four sources to be well represented at location *x*, provided that simulations are long enough to allow the agent reasonable coverage of the simulated world. Conversely, the probability of observing all four sources being represented in a single snapshot of the toolkit is low, because the agent would have to continuously carry raw materials over the minimum distance of 20 grid cells that is required to visit all four sources[8]. Thus, all else being equal (e.g. equal sample size), we would expect the raw material richness of the discard record to be higher than that observed in the toolkits.

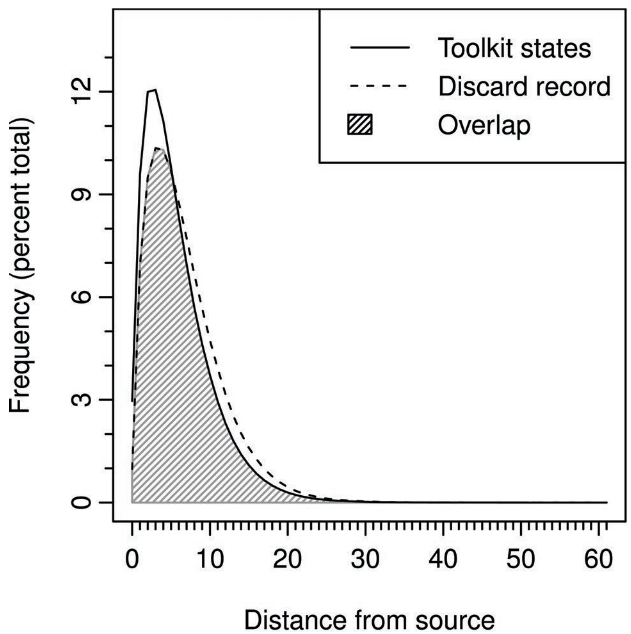

Fig. 3 Comparison of transport distance frequency distributions evidenced in the aggregated toolkit and discard record data sets. Observations on all transported items across the 500 simulations (8.1 million time-steps) are included; these total 333.7 and 5.3 million in the case of toolkit states and discard records respectively. The large differences in sample sizes are due to the fact that only one item may enter the discard record per time-step, while toolkits can and often do contain multiple items at any given point in time. Frequencies are given as percentages of the total number of observations for each data set

A second, compounding factor is that there are no upper limits to the number of items that may enter the discard record at a given location, except those defined by the simulation termination conditions. Input to the toolkit, however, is limited at any given point to its overall carrying capacity of 100 raw material units. Consequently, richness states greater than 100 raw material types could never be observed in the toolkits, even within the context of simulations run with an extreme density parameter of one; In the discard records, on the other hand, such richness states would be expected to be common, because a source density of one implies that 100 distinct raw material sources are always found within a radius of 5 grid cells from any given location, or a distance that corresponds to the

[8] The distance an agent may cover in a given number of time-steps is equal to the number of time-steps, regardless of direction, because diagonal movements carry no penalty; in other words, under the mobility rules stipulated by Brantingham, the hypotenuse of a right triangle is equal in length to the other two sides. Thus, the distance between two sources located at x = ±5 and y = ±5 from each other is 5 grid cells.

median transport distance observed across my simulations (see ESM 1). Toolkits can therefore offer only a biased view of maximum attainable richness states, and indeed richness states in general.

The fill rates of toolkits are also variable, and generally high (1-100 raw material units, depending on how full the toolkit is when a source is encountered), while those of the discard record are constant and low: only one raw material unit may be discarded in any given time-step. These variable fill rates bias the transport distance patterns recorded in the toolkits towards lower values, because up to 100 observations of transport distances of zero may be recorded in a single time-step during source encounters, while only one such observation may be recorded in the discard data. In other words, the relative frequencies of specific transport distance observations at or near to raw material sources is higher in the toolkits than it is in discard records, and this translates to different probability frequency distributions.

In short, the processes governing the composition of toolkits differ from those governing the composition of the discard record, and consequently the former are poor proxies for the latter. The opposite is also true, of course: discard records, and by implication archaeological sites or assemblages, do not and cannot offer, as it is all too often assumed, an adequate proxy for the average composition of ancient forager toolkits. Critically, this observation remains true even if factors such as post-depositional processes and time-averaging could be assumed to have played no role in shaping archaeologically observable patterns.

4.1.3. Limitations of Brantingham's neutral model

As noted in the previous section (see Figure 2a), the maximum number of items discarded at a single location across all 500 simulations is very low (30 raw material items), even relative to the carrying capacity of the simulated agents (100 raw material units). This is primarily a consequence of the arbitrary end conditions stipulated by Brantingham (i.e. encounters with 200 unique sources or with the edges of the world), which prevent the simulated agent from revisiting specific locations a large number of times (a maximum of 40 cell visits were recorded in individual simulations). However, the low rates of discard (one item per time-step), as well as the random mobility of the agents are also contributing factors.

As shown in Figure 4, the maximum number of items discarded at a single location increases non-linearly with simulation length. To assess the exact nature of this relationship I used a Generalized Linear Model (GLM) with Poisson error structure and log link function (McCullagh and Nelder 1989). I set the predictor variable to the minimum number of time-steps required to produce a given cell size in the context of individual simulations[9], log transformed to ensure a balanced distribution of observations. The response variable, on the other hand, represents the maximum cell sizes evidenced at different points[10] along the simulations. Although leverage values indicated the presence of some influential

[9] For the purposes of the GLM simulation time-steps were counted from the first discard event onward; thus, the first discard event represents the first simulation time-step.
[10] Cell size was increased by one whenever a given time-step resulted in a higher maximum cell size than previously observed.

cases, removal of these did not affect the overall results (a difference of one percent or less in coefficient estimations, and no appreciable difference in *p* values); moreover, all other regression diagnostics were found to be within acceptable ranges, indicating that the model fits the data well[11].

The resulting regression formula indicates that maximum cell richness grows exponentially at a rate of 0.546 (SE = 0.0036, $p < 2*10^{-16}$) times the common logarithm of simulation length (intercept = 0.697 [SE = 0.0122, $p < 2*10^{-16}$]). This indicates, in turn, that based solely on the observed relationship between these variables simulations lasting approximately 14.5 million time-steps (i.e. $10^{7.16}$) or more would be required to generate cells (i.e. sites) which match or exceed the size of toolkits. More importantly, however, the formula indicates that approximately $10^{19.6}$, or ca. 50 quintillion (short-scale) time-steps would be required to generate cells comparable in size to sites such as Pech de l'Aze IV, where approximately 92000 lithic artifacts had been recovered by the end of the twentieth century (McPherron and Dibble 1999). Such simulation lengths are, unfortunately, virtually impossible to attain under the original definitions of the neutral model (the maximum length observed across all the 500 simulations was 50866 time-steps).

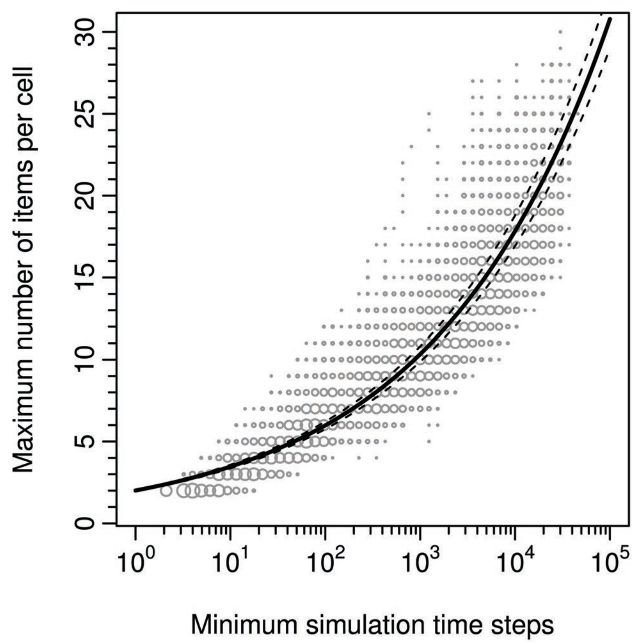

Fig. 4 Relationship between maximum cell sizes (i.e. number of items discarded at a single location) and the minimum number of simulation time-steps required to attain them in the context of individual simulations. A total of 7287 observations from 500 simulations are included. For display purposes observations are grouped into 50 bins along the *x* axis, and are represented by circles, whose areas indicate relative differences in the number of observations per bin at each *y* value. The regression line, defined by the equation $y = e^{0.697+0.546*log10(x)}$, is indicated in solid black, while the 95% confidence interval is identified by dashed lines. Note that the maximum value along the *y* axis exceeds the maximum recorded simulation length of 50866, so as to show the predicted minimum number of time-steps required to achieve the maximum observed cell size of 30

[11] The Python code for the generation of the raw data as well as the R code for all analyses are included in the Electronic Supplementary Materials (ESM2).

It could be argued that sampling toolkits for multiple items at specific spatial locations (i.e. grid cells) would yield larger sample sizes than those evidenced in the discard record. While this is true, such sample sizes would still fail to approach the size of many archaeological sites[12], and would in any case violate the definitions of the model (one and only one item may be removed from the toolkit at any one time-step). It could also be argued that simulating multiple foragers, either sequentially or in parallel, would result in the formation of much larger assemblages. This is also true. However, doing so would result in spatially biased outputs because the probabilities of termination vary across the simulated world: an agent cast near the edges of the world has a higher chance of being terminated quickly than one cast at the center of the grid, and consequently cells in the center would be visited more frequently than cells near the edges.

Given the preceding discussions it is clear that the original definitions of the neutral model render it ill-suited for its stated objective, namely the study of archaeologically visible patterns generated under the simplest procurement, transport, and discard behaviours. Nevertheless, all issues discussed above can ultimately be traced to a single design factor[13], namely the arbitrary conditions under which simulations terminate; consequently, removing these and forcing agents to remain within the confines of the simulated world would address all identified limitations. As shown, however, revising the original definitions is not enough – a change of focus from toolkit states to discard records is also necessary, because the patterns evidenced in the two data sets are not identical.

4.2. Discard records under a revised neutral model

I implemented the revisions suggested above and investigated the discard records produced under revised model definitions (see the Methods section) through three main simulations. Each of these simulations, henceforth referred to as A, B, and C, ran for a total of 250 million time-steps and allowed for an average of 1000 agent visits per cell. For simulation A Brantingham's default parameters were used (see Table S1 in ESM 1), while simulation B was run with a modified resource density of 0.002 (i.e. 500 sources). For simulation C I used the same resource density as in simulation B, but modified the carrying capacity of the toolkit to 200 units, therefore altering the toolkit size to discard rate (T/D) ratio; all other simulation parameters were kept constant across the three simulations.

[12] Multiplying the maximum cell site observed across all 500 simulations (30) by the maximum size of the toolkit (100) would yield but 3000 items.

[13] Two other aspects of the model may also prove problematic. First, random mobility cannot guarantee access to lithic sources (or indeed sites), and as argued by Oestmo et al. (2014) and also shown by my analyses (see ESM 1), this brings into question the survivability of foragers. However, the model makes no provisions for lithic recycling, which would allow foragers to recover previously discarded items, and it is in any case unclear whether access to lithic materials was as critical in the past as commonly assumed. While future revisions of the model could, and should, include provisions for non-random or semi-random mobility, whereby agents are allowed to gravitate around resources or sites, random mobility can nevertheless be accepted as a baseline. The second problematic aspect pertains to the number of modeled foragers: clearly, a single forager was not responsible for the formation of the archaeological record, and inter-agent communication likely played a major role. However, preliminary analyses revealed no differences between models run with multiple or single agents, and allowing for inter-agent communication would dramatically increase the complexity of the model. Therefore, as with random mobility, the patterns generated by a single agent provide an adequate baseline for interpreting the record and evaluating the effects of new variables that may be included in the model at a later stage.

My analyses focus on two different but complementary aspects of the discard records, namely raw material transfer and source representation patterns. I discuss these both at a macro level (i.e. the average patterns that would be observable in the aggregated data from multiple randomly selected sites) and at the level of individual cells (i.e. the patterns observable at specific locations). The patterns evidenced in the outputs of individual simulations are compared in order to determine the influence of the two non-constant model parameters (resource densities and toolkit sizes) at both levels of analysis. The results of this investigation are described in detail below.

4.2.1. General characteristics

The discard records generated by the three simulations (Figure 5a1,b1,c1) attained comparable maximum cell (i.e. site) sizes, exceeding the maximum observed in simulations run under original model definitions by a wide margin (918 to 1234 versus 30 items per cell). However, they varied greatly in terms of overall richness and in terms of the number of unique raw material types represented in individual cells (Table 1). The records share three general characteristics:

a. In all three discard records the quantity of items found in individual cells decreases rapidly with increasing distance from the nearest raw material source(s). This indicates that, regardless of what parameters (e.g. toolkit sizes, source densities) are used, the modeled behaviours are only capable of generating large "sites" at or very near to raw material sources. Importantly, this spatial pattern is not explicable in terms of biases in agent mobility or discard behaviours[14].

b. Some regions of the simulated world show a higher overall density of discarded items than others, notwithstanding any similarities in the distribution of sources. This occurs due to random variations in the number of agent visits per cell (see Figure 5a2,b2,c2), which in simulation A varied between 334 and 1378 (mean = 1000, SD = 95.6, matching theoretical expectations – i.e. the number of simulation time-steps divided by the number of grid cells, or the average predicted number of cell visits), and indicates that the effects of random walks must be carefully considered when investigating the compositional variability of individual cells.

c. Across all three simulations the contents of individual cells grew linearly with simulation length, but at a highly variable rate. In simulation A, for example, the contents of the largest cell grew at a rate of approximately one item every 200 thousand time-steps, while the contents of the smallest cell grew at the much slower pace of only one item per 7.2 million time-steps; in both cases the correlation between the variables was very strong ($r^2 = .9971$, $n = 1234$, $p < 2*10^{-16}$ and $r^2 = .925$, $n= 38$, $p < 2*10^{-16}$ respectively).

[14] The frequency of moves in each of the 9 possible directions was consistent with those expected under conditions of random draws from uniform distributions (Simulation A: χ^2=2.8047, df=8, p=0.946; Simulation B: χ^2=6.9466, df=8, p=0.542; Simulation C: χ^2=5.1084, df=8, p=0.746); the same was true with regards to the selection of items for discard: the distribution of *p* values for the observed versus expected frequencies of selected discard indices at different toolkit sizes was uniform across all three simulations, with Simulations A, B, and C yielding significant tests in 4.04, 5.05, and 3.02 percent of cases respectively at an alpha level of 0.05.

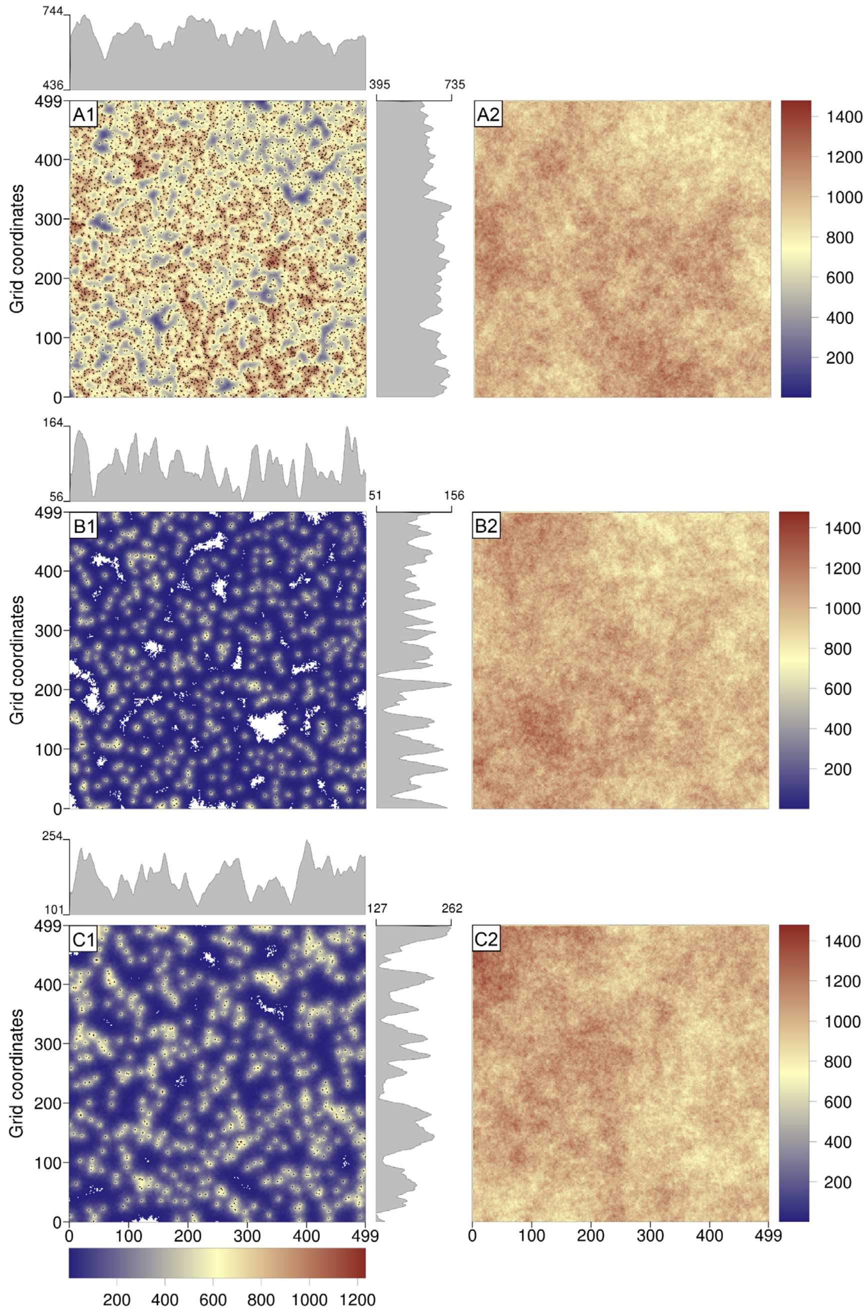

Fig. 5 Discard records (*a1, b1, c1*) generated by simulations A, B, and C, indicating the total number of items found at each grid location after 250 million time-steps. Raw material sources are indicated by black dots, while the gray margin plots show the mean number of discarded items per cell along the *x* and *y* coordinate axes. The colour scheme and legend for all discard record plots are identical. Total agent visits to individual grid cells are shown in subplots *a2*, *b2*, and *c2* for simulations A, B, and C respectively. The colour scheme and legends are identical across all three grid coverage plots

This is an important observation because the deterministic component underlying the observed relationship between cell sizes and simulation lengths reflects the spatial relationship between cells and sources in their neighbouring area, mediated by the transport capacity of the agent (see below). Thus, discarded materials can accumulate in cells (i.e. sites) at vastly different rates even if visited the same number of times by an agent(s) in the context of simulations run with identical population and behavioural settings (i.e. one agent, following constant behavioural rules). This strongly suggests that assemblage richness is, by itself, a very poor predictor of demographic parameters; consequently, unless the influence of the spatial distribution of sources is taken into account, very little (if anything) can be inferred in terms of differences in population history from differences in the size of assemblages or sites, even if it can safely be assumed that technologies, curation strategies, and sedimentation rates were constant.

Table 1 Summaries of simulation parameters and generated discard records. Model parameters not shown here are identical to the defaults used by Brantingham (2003) and specified in Table S1 of the Electronic Supplementary Materials (ESM 1)

Variable	**Simulation A**	**Simulation B**	**Simulation C**
Number of sources	5000	500	500
Toolkit size	100	100	200
Total number of discarded items	165,153,161	25,476,408	44,545,914
Discarded items relative to theoretical maximum (250 million)	66.06%	10.19%	17.82%
Cells with discarded items	100%	95.14%	99.52%
Minimum number of discarded items per cell	38	0	0
Maximum number of discarded items per cell	1234	918	1009
Modal frequency of unique raw material types per cell	34	3	5
Minimum unique raw material types per cell	5	0	0
Maximum unique raw material types per cell	64	11	18
Maximum attained raw material transfer distance (grid cells)	69	46	73
Modal transfer distance (grid cells)	3	3	5
Median transfer distance (grid cells)	6	6	8

4.2.2. Transfer distances

Raw material transport ultimately determines most aspects of the lithic discard record but, as noted by Brantingham (2006), archaeological sites only provide a direct record of transfer or displacement distances, on the basis of which transport patterns must be modeled. Such modeling is beyond the scope of this paper, however, and the following analyses focus exclusively on transfer distance patterns evidenced in the outputs of the three simulations. These transfer patterns can be approached from at least two different perspectives, namely: a) the spatial distribution of raw materials procured from a given source, and b) the contribution of different sources to individual assemblages (e.g. Luedtke 1992: 117; Féblot-Augustins 2009). Since each of these perspectives is expected to yield different insights, they are adopted here individually.

4.2.2.1 *The spatial distribution and overall abundance of individual raw material types*

The quantity of any given raw material type is, in all three discard records, highest at, or in cells adjacent to, its source, and rapidly decays with increasing distance from that source (Figure 6a; see also Figure 11 in Brantingham 2003). The actual number of items discarded at their source is highly variable, as is the total contribution of any one source to the overall record: in simulation A, for example, the total quantities of discarded raw materials procured from individual sources ranged between a minimum of 8058 and a maximum of 55997 items (median = 32970; IQR = 11268).

This variability is a consequence of two different factors, namely agent mobility (here a simple random walk) and the local density of sources. Both of these influence the degree to which individual sources are exploited through the same fundamental mechanism: they each partially determine the quantity of materials already present in the toolkits during source encounters, and consequently the amount of fresh materials that agents may collect (see Brantingham 2003). In essence, source densities determine the distances between sources, while agent mobility determines the speed (i.e. number of time-steps) at which those distances can be traversed. These two variables are expected to show opposing trends in terms of their influence on source exploitation since, all else being equal, speed is less important when distances are short.

Simulation data support this observation, as the local density of sources, considered here in terms of the mean distance between a source and its nearest four neighbours[15], was found to be positively correlated with the degree of source exploitation in all three discard records, albeit to different degrees. Not surprisingly, the strongest correlation was observed in simulation A ($R_s = .83$, n=5000, $p < 2*10^{-16}$; see Figure 6b), where the density of sources was highest, while the weakest correlation was observed in simulation B ($R_s = .356$, n=500, $p < 2*10^{-16}$), where the density of sources was lowest (for otherwise identical model parameters). The intermediate value of the correlation coefficient obtained for simulation C ($R_s = .487$, $p < 2*10^{-16}$) can be explained by the higher carrying capacity of the agents (200

[15] The choice of four nearest neighbours is arbitrary, and is used here only to illustrate certain patterns. The optimal number of nearest neighbours to use will depend on the relationship between the global density of sources, the size of the toolkit, and the specified discard rates. Mean distances are used because a fixed number of neighbours is considered, and considering median distances would result in outliers being essentially ignored which, in this particular context, is not desirable.

instead of 100 raw material units), which effectively decreased the distance between sources with respect to the relative depletion rates of toolkits.

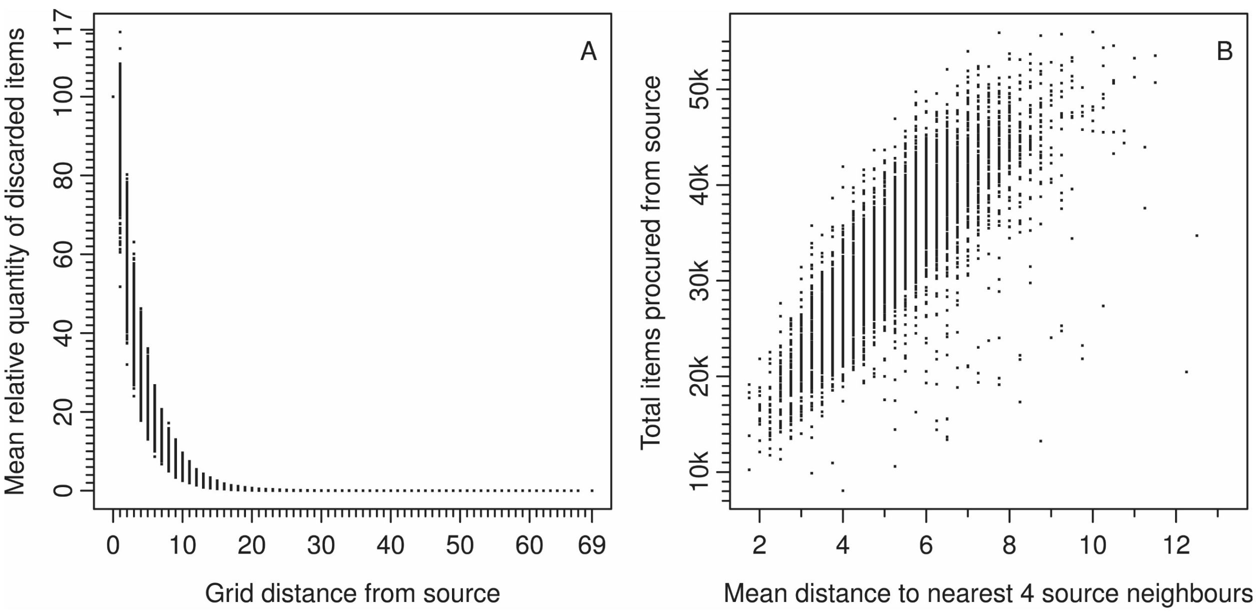

Fig. 6 The relative quantities of materials contributed by individual sources, expressed as a percentage of the number of items discarded at their source, decrease rapidly with increasing distances following a remarkably stable decay curve (*a*). These quantities are expressed as percentages because the absolute number of items contributed by individual sources is correlated with the distances between the sources and their nearest neighbours; subplot *b* illustrates this correlation using mean distances to the nearest four neighbours. All data are from simulation A

Figure 7 shows the distribution of two types of materials (a' and b') from simulation A in the areas surrounding their sources. These sources were selected based on their extreme values for mean distance to the nearest four neighbours, namely 13.25 and 1.75 grid cells respectively. As expected given the preceding discussion, the source of material a' contributed considerably more items to the discard record (54843 items in total, with a maximum of 518 per cell) than did the source of material b' (19150 items in total, with a maximum of 130 items per cell). Interestingly, however, the relative abundance of items at various distances from their sources seems unaffected by the distribution of other sources in the area, being more or less constant in all directions and quantitatively similar at both locations. In both cases, for example, the contour line representing a decay of 50 percent relative to the abundance of materials discarded at their source is more or less circular, and located at about 3 grid cells from the respective sources[16]. The overall effects of this decay pattern (see also Figure 6a) are visible in all three discard records (Figure 5a1, b1, c1), but are particularly evident in those of simulation B and C.

[16] The pattern is more irregular around source b' simply because of the lower sample sizes.

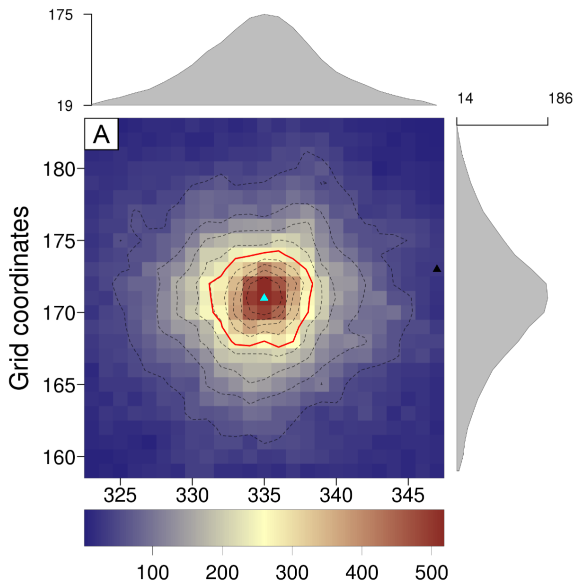

Fig. 7 Spatial distribution of two types of materials from simulation A in the vicinity of their sources (light-blue triangles), which were selected on the basis of their extreme mean nearest (4) neighbour distance values of 13.25 (a), and 1.75 (b) grid cells. Both materials are encountered most frequently at or near their sources, and their frequency decreases at more or less the same rate in all directions regardless of the presence of other sources in the area (black triangles). This is illustrated by the contour lines (dashed gray), which indicate decreases in the quantities of materials in increments of 10 percent relative to the amounts discarded at the sources; in both cases a decrease of 50 percent is observed at a distance of about grid cells (red contour lines). Note, however, that the actual amount of items contributed by the two sources varies dramatically

The relative stability of this decay curve suggests that, unlike the degree to which sources are exploited, the relationship between the relative abundance of a raw material type in a given cell and the distance to its source is virtually unaffected by global source densities or simulation lengths. To test this, the relative abundance of raw materials at a distance of exactly four grid cells from their source was plotted for all three simulations, as well as simulation A truncated to the first 100 million time-steps. The results, shown in Figure 8, confirm this hypothesis: the medians and interquartile ranges are virtually identical in simulation A and B despite the order of magnitude difference in source densities (0.02 versus 0.002) and the considerable (2.5x) difference in simulation lengths between the truncated and full simulation A data set. However, Figure 8 also shows that the parameters of raw material diffusion from sources are strongly affected by the toolkit/discard rate (T/D) ratios, as simulation C, with a T/D ratio of 200, showed a considerably higher median (though similar interquartile ranges) than the other two simulations.

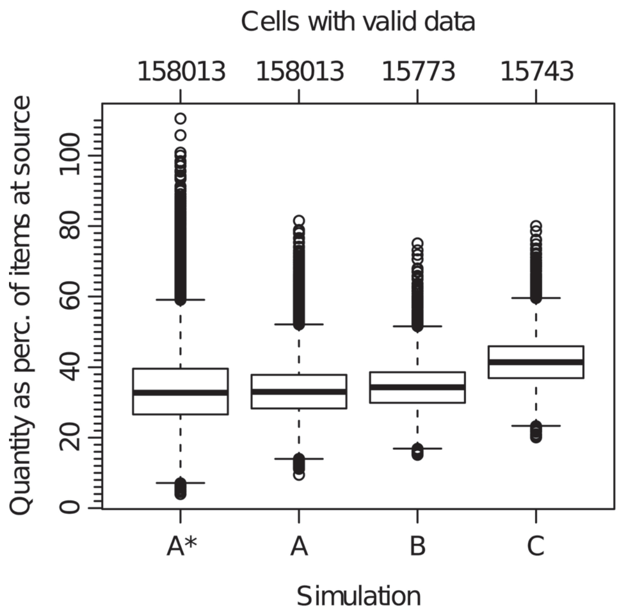

Fig. 8 Relative contribution of individual sources to the discard records at a distance of 4 grid cells. Data from all three simulations, as well as simulation A truncated to a length of 100 million time-steps (denoted here as simulation A*) is included. Note that quantities are expressed here as a percentage of the number of items discarded at their source

4.2.2.2 *Transfer distances recorded at individual sites (grid locations)*

The frequencies of transfer distances observed in the overall records of the three simulations (Figure 9) are qualitatively similar to those I observed in the toolkits states (Figure S8 in ESM1) and discard records (Figure 3) of the 500 simulations of the replicated model (cf. Figure 9 in Brantingham 2003). The modal and median transport distances evidenced in simulation A and B are identical at 3 and 6 grid cells respectively and, when sampled only at raw material sources, the records show main modes at zero and secondary modes that, with simulations A and B, are identical or nearly identical to the values obtained for all cells. While the T/D ratio does have an effect on the shape of the frequency distributions, the shape seems to be, as suggested by Brantingham (2003: 499) and my own analyses of toolkit patterns (ESM 1), only minimally affected by the environmental density of sources.

These are aggregated statistics, however, and there is reason to suspect that, due to the dependence of cell contents on the spatial configuration of sources in the area, they may not be representative of the patterns evidenced in individual cells. Indeed, if median, modal, and maximal transfer distance values recorded in individual cells are considered, an altogether different picture emerges (Figure 10). Cells from simulations B and C tend to show similar median and modal values, despite differences in T/D ratios, and in both cases these values are considerably higher than in simulation A, in which the density of sources was ten times greater.

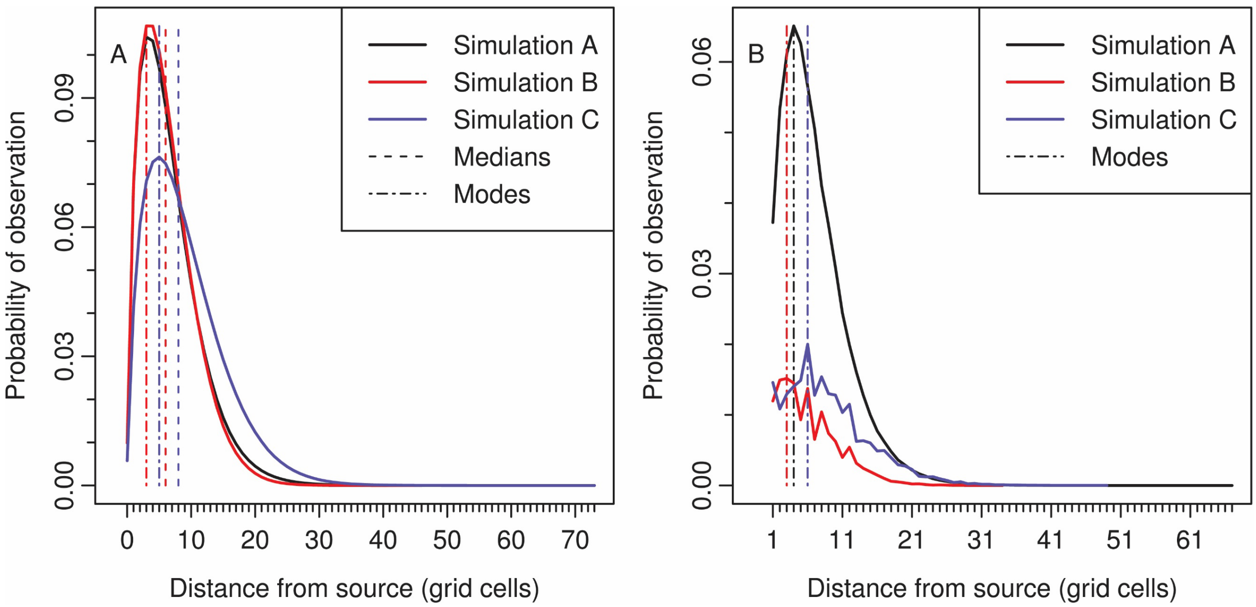

Fig. 9 Probabilities of observing specific transport distances in the aggregated data from all three simulations at: a) all grid locations, and b) at raw material sources

These patterns do not seem to be influenced by simulation length, as the values obtained for the full record of simulation A are virtually indistinguishable from those obtained for the same simulation truncated to a length of 100 million time-steps (Figure 10ab). Maximum transfer distances, on the other hand, do seem to be affected by source densities, T/D ratios, and to a lesser extent simulation lengths (Figure 10c), with a two-fold increase in T/D ratios (simulation C) having approximately the same effect as a ten-fold increase in source densities (simulation A).

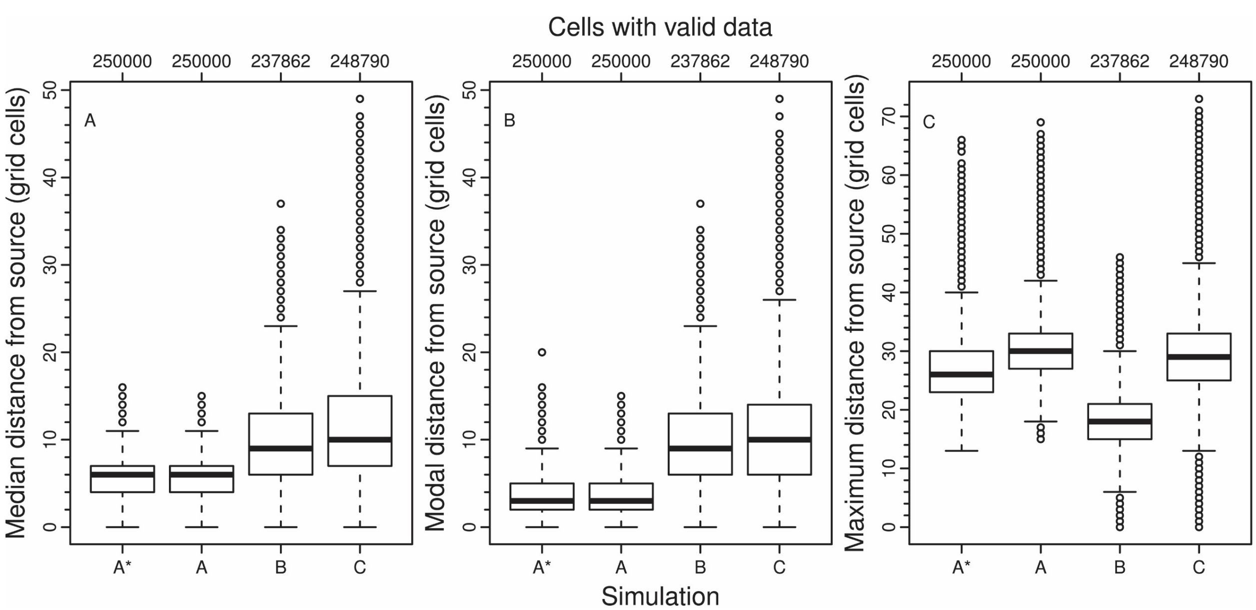

Fig. 10 Median (a), modal (b), and maximum (c) transfer distances observed in the three simulations, as well as simulation A truncated to a length of 100 million time-steps (denoted here as simulation A*)

In short, median and modal transfer distances recorded at individual discard locations do change with different environmental source densities (c.f. Brantingham 2003: 499) and, all else being equal, so do the maximum transfer distances. Consequently, the median ratio of maximal to modal transfer distances is highly variable across the simulations (medians of 9 [IQR=8.76], 1.9 [IQR=1.76], and 3 [IQR=2.75] for simulations A, B, and C respectively), rendering specific yet generally applicable predictions for one distribution parameter based on another virtually impossible to make (cf. Brantingham 2003: 501).

More importantly, perhaps, there is no evidence of a clear and consistent internal mode at individual raw material sources (cf. Brantingham 2003: 499). Indeed, at raw material sources, as well as at other grid locations, the frequency distribution of items procured from various distances is quite variable (Figure 11). This does not mean, however, that such variability is random; in the case of high source density environments at least, most of it is expected to be a function of the spatial configuration of sources in the area (Figure 6b).

To ascertain the degree to which this is so, the variability in transfer distance frequency distributions at one of the ten randomly selected cells shown in Figure 11 (all from simulation A, and all located on raw material sources) was investigated through the discard records produced by an additional nine full simulations (250 million time-steps each). The placement of sources in these simulations was identical to that of simulation A, as were all other general model parameters[17].

As shown in Figure 12, the frequency distribution of materials transferred across various distances at the investigated location is quite stable across multiple simulations, indicating that, as expected, random factors (i.e. the number of times specific paths are traversed) play only a minor role in determining compositional variability, at least with larger assemblages. The relatively low degree of variability observed in the results of the full-length simulations also suggests that it is possible to model the composition of actual archaeological assemblages, and therefore quantify departures from neutral expectations, with a fair degree of precision and known error ranges.

[17] The initial placement of the agent, as well as its mobility and discard behaviours, were fully and independently random in each simulation, as per the model's specifications.

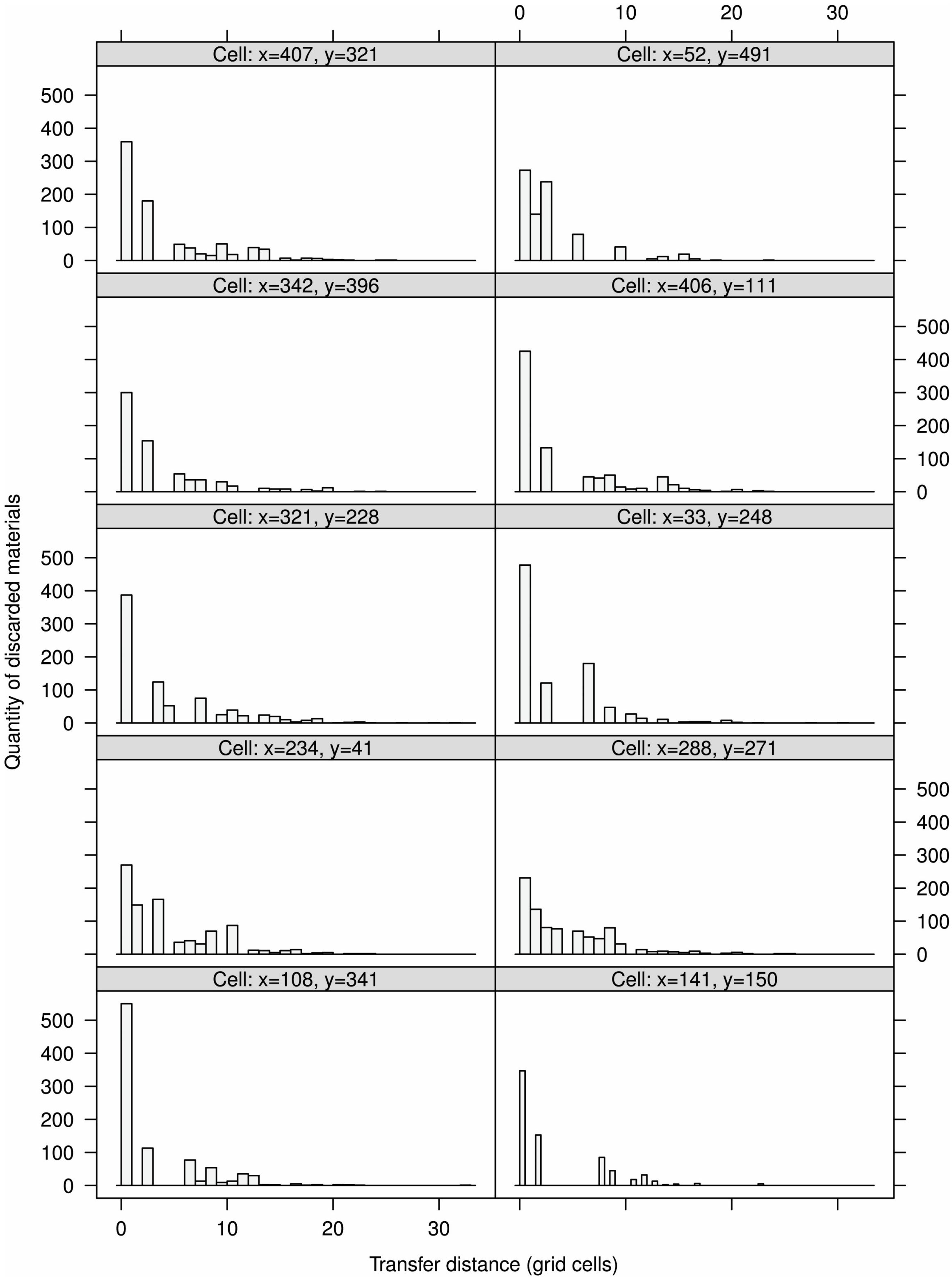

Fig. 11 Frequencies of raw material transfer distances recorded in a random sample of 10 cells containing raw material sources

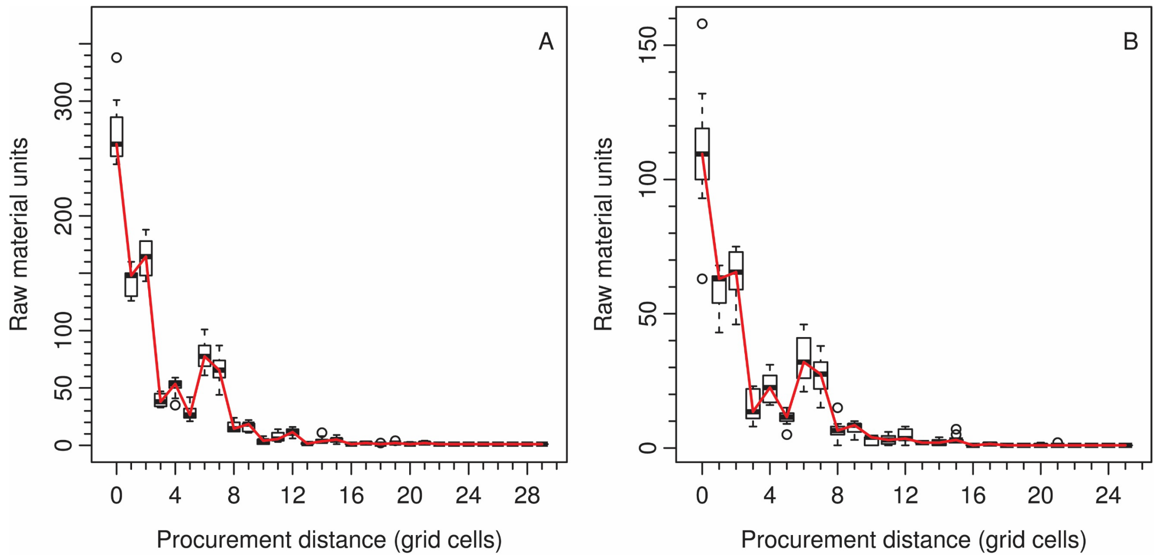

Fig. 12 Variability in the quantity of items procured from various distances at a single grid location, as evidenced in the outputs of 10 simulations run with identical parameters. The location was sampled after 250 million time-steps (a), as well as after only 100 million time-steps (b). Overall trends are illustrated by the line connecting the boxplot medians

4.2.3. Raw material richness

As shown in Figure S6a (ESM 1), the frequency distribution of *toolkit* richness states follows a smooth decline curve from a modal value of zero unique raw material types up to a maximum that depends, partially at least, on the density of sources as well as the toolkit size/discard rate ratios (see also Brantingham 2003: 494). The discard records investigated here demonstrate that all simulation parameters, including simulation lengths, affect not only the maxima and minima of that distribution, but also its overall shape (cf. Brantingham 2003: 494) which, when not truncated by factors such as very low source densities (relative to toolkit size/discard rate ratios) or short simulation lengths, tends to approach normality (Figure 13). They also show, in any case, that the distribution parameters, including minima and maxima, are quite different from those observed in the toolkits (cf. Figure S6 in ESM1).

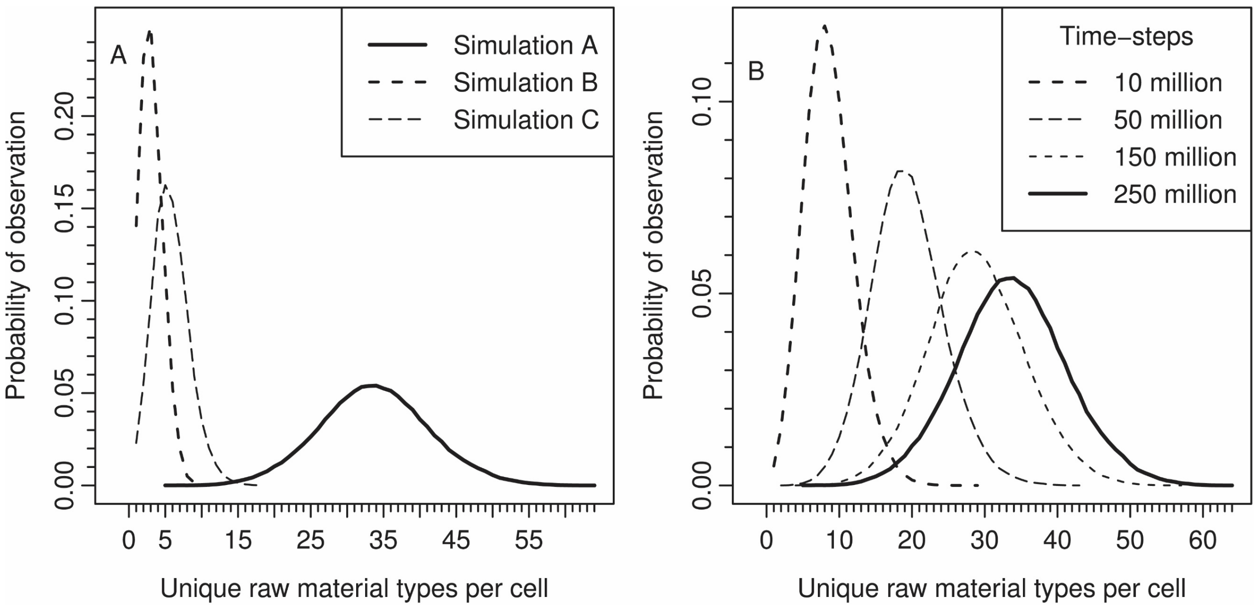

Fig. 13 Probabilities of observing different richness states (i.e. number of unique raw material types) at individual locations across the three simulations (a), as well as simulation A truncated to different lengths (b)

The maximum richness states were observed in simulation A, where the maximum number of unique raw material types represented in a single cell was 64, and the modal value was 34 (see Table 1). These values, which are much higher than those predicted by Brantingham for identical model parameters, do not represent absolute limits: all else being equal, longer simulations will tend to yield even higher median, modal and maximal values (see Figure 13b). Brantingham's observation regarding the maximum attainable toolkit richness states cannot, therefore, be extrapolated to the discard (i.e. archaeological) record. This is simply because, as discussed in section 4.1 above (see, in particular, Figure 2), the processes operating in that record differ from those governing the composition of toolkits.

On the basis of his analyses of toolkit states Brantingham (2003: 501) concluded that "[t]he fact that some raw materials present in the environment are never procured, others are only rarely procured, while a few are commonly procured need not imply raw material selectivity." The discard records analyzed here do not support this conclusion, insofar as "environment" is defined in a reasonable manner. On the contrary, these records show that *all* sources within a certain radius, the size of which depends on simulation length and the toolkit/discard rate (T/D) ratio, are represented at all landscape locations. In simulation A, for example, all sources within a linear radius of 10 grid cells are always represented after an average of 1000 visits per cell (Figure 14), matching, and in most cases exceeding, Brantingham's (2003: 495) predicted foraging radius of 10, itself an overestimation (see ESM1). In fact, only at a radial distance of 17 grid cells does the degree of source representation at any given location drop below an average of 99 percent[18]. It should be noted that with a lower average number of visits per cell (i.e. shorter simulations) this radius of full source representation is smaller, extending to only 8

[18] Consider that, in order to attain a modal representation of 34 unique raw material types per cell, as is the case in the discard record of simulation A, effective exploitation areas of roughly 1700 grid cells (i.e. a linear radius of approximately 23 grid cells) are required at the specified resource density of 0.02 (i.e. 5000 sources on a 500x500 grid).

and 2 grid cells with an average of 600 (150 million time-steps) and 200 (50 million time-steps) cell visits respectively. Still, even in simulations where the maximum attainable assemblage size is approximately 200 items (i.e. 50 million time-steps), over 99 percent of sources are represented, on average, within a linear radius of 9 grid cells.

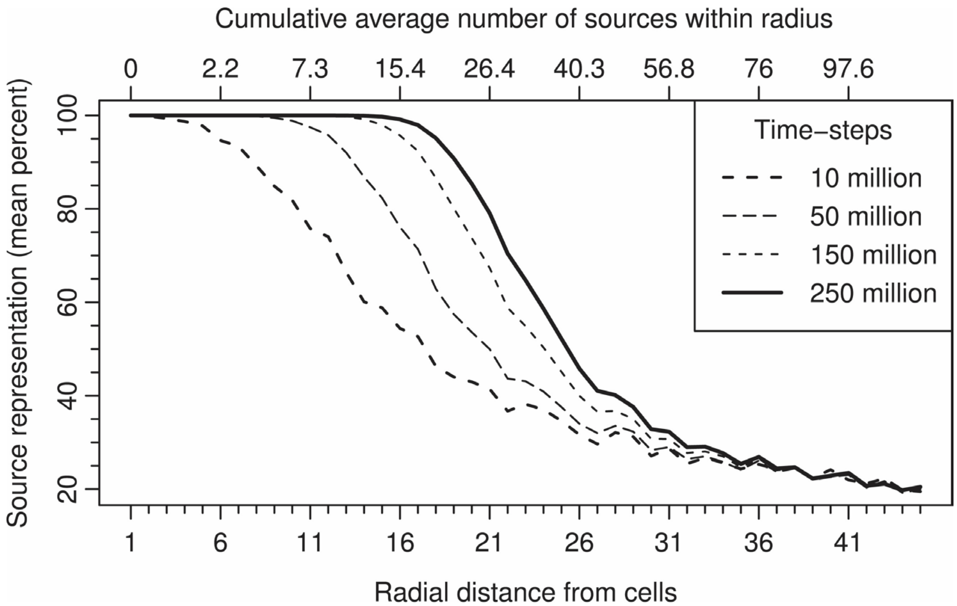

Fig. 14 Mean degree of representation of sources located at different linear distances from cells in simulation A. All 250,000 grid cells were sampled after 10, 50, 150, and 250 million simulation time-steps. Source representation was computed as the number of sources available within a radius of *i-1, i* (where *i* represents the indicated radial distance) of a given cell divided by the number of sources actually represented in that cell and multiplied by 100

Finally, Brantingham (2003: 502) noted that the neutral model predicts a dependence of richness states (i.e. number of unique raw material types represented in an assemblage) on assemblage size. The correlation between the number of unique raw material types and total cell contents is weak in the overall record produced by the simulations (R_s = 0.341, n= 250000, $p < 2*10^{-16}$ for simulation A), but subsamples of individual assemblages do show a moderate correlation between the variables. In the case of the largest cell (i.e. "site") generated in simulation A, for example, 30 sequential snapshots of approximately 8.3 million time-steps each evidence an apparently linear relationship between sample size and raw material richness (R_s = .67, $p < .001$), and it is likely that this relationship would be stronger still with larger sample sizes; more importantly, perhaps, it is very likely that with increasing sample sizes raw material richness would increase non-linearly, as suggested by the patterns evidenced in Figure 13b and Figure 14. However, any process that would impose fuzzy, steadily decreasing limits on raw material transfer would generate a similar relationship (i.e. dependence of raw material richness on the log of sample size).

5. Discussion

Brantingham (2003) focused on three aspects of raw material variability evidenced in archaeological contexts, namely: a) the number of different sources that are represented in a given assemblage relative to its size, b) the distances over which materials were transported, and c) the frequencies of different material types in relation to procurement distances. On the basis of his analyses he derived a series of predictions about what assemblage variability should look like under neutral behavioural assumptions, and argued, through two case studies, that these predictions seem to hold.

The analyses presented in this paper call into question some of Brantingham's original predictions. They also demonstrate that qualitative similarities in patterns generated by the model and those observed archaeologically cannot be used to prove, or disprove, the adaptive or functional significance of raw material variability, insofar as it can be accepted that both behaviourally neutral factors (e.g. the natural density of sources) *and* selection may have been at play.

The revised model presented here allows for new predictions to be made, based on the influence of relatively isolated variables (e.g. random mobility). Each of these predictions can be evaluated quantitatively, since it has been shown that the composition of individual assemblages can be modelled with a known degree of precision (Figure 12). Interestingly, the rejection of individual predictions may be traceable to behaviourally significant biases in particular domains. Thus, rejecting one prediction may indicate a preference for a specific material, while the rejection of another prediction may indicate biased mobility.

While predictions can be evaluated with a high degree of precision, and it is argued here that, except in extreme cases, such high precision is required in order to detect both the presence and absence of behaviourally meaningful deviations, the model is highly sensitive to any inaccuracies or omissions present in the source distribution and exploitation datasets. In other words, the model may only be useful in cases where highly reliable sourcing studies have been conducted.

Finally, the revised model also provides some insight on topics of wider archaeological relevance. Indeed, the model presented here is also, by necessity, a model for the formation of the archaeological record, although only from the perspective of the lithic components. Consequently, it enables an objective exploration of topics such as the relative importance of stone tools in past adaptations, and of the meaning of archaeological sites. While no conclusions can be reached on the basis of the model, it nevertheless allows for a value-free starting point for discussion of topics of fundamental importance for archaeological research. The foregoing issues are discussed in detail below.

5.1. Brantingham's original observations in the context of the revised model

5.1.1 <u>Assemblage raw material richness</u>

Brantingham (2003: 501) stated that under neutral assumptions raw material richness is always "constrained to be much less than the maximum richness theoretically attainable". If reasonable definitions of theoretical maximum are used[19] (e.g. the number of sources available within the foraging

[19] This theoretical maximum is ill-defined by Brantingham: it cannot be considered in terms of assemblage size, which Brantingham seems to imply, because the number of discarded items found in the assemblage may exceed the number of physically available sources, and it cannot be considered in terms of the number of physically available sources without limiting inquiry to a given area, and it is unclear how large that area should be.

radius), it can be shown that, on the contrary, the modeled behaviours would result in the full representation of *all* available sources in assemblages of sufficient size (Figure 14). Indeed, assemblages generated under the revised model are characterized by substantially higher raw material richness than that observed by Brantingham under identical model parameters (Figure 13). Thus, the analyses presented herein do not support the view that "[t]he neutral model anticipates the low observed richness relative to the environmental density of sources" (Brantingham 2003: 502) at Grotte Vaufrey.

My revised model does support Brantingham's observation that raw material richness co-varies with assemblage size, but does not support the view that biases in procurement probabilities arise from the path dependence of random walks. In fact, the effect of such path dependence can be shown to be minor because, over time, the influence of individual random paths averages out. Rather, procurement probabilities depend on the relationship between toolkit parameters and the specific spatial configuration of the sources in a given area (see Figure 6b).

5.1.2. Transfer distances

Under the original model the "frequency distribution of raw material transport distances [is expected to show] an internal mode" (Brantingham 2003: 501), which is virtually unaffected by the density of sources or toolkit parameters. Brantingham argued that the frequency distribution is also expected to show maximum values that are "three to four times the distance represented by the internal mode" (Brantingham 2003: 501). Analyses of individual assemblages generated by the revised model indicate that resource densities do affect the value of the internal mode (Figure 10), which is neither stable nor easily discernible in many cases (Figure 11). They also show that resource densities and toolkit parameters affect the ratio of modal to maximum transfer distance, which is in general higher than suggested by Brantingham (see Figure 10 and associated discussion). On the other hand the "long right skew" observed by Brantingham (2003: 498) for these distributions was also noted in the output of the revised model (Figure 9), and it is clear that he was right in stating that maximum transport distances do not relate to geographic ranges (Brantingham 2003: 501).

5.1.3. Distance decay patterns

Brantingham noted that the quantity of a given material will "generally [follow] an exponential decline with increasing distance from source" (Brantingham 2003: 501). He argued that materials from distant sources are expected to be found consistently in low quantities, while materials from nearby sources are expected be more common and show high variance. Analyses of the revised model largely support these predictions (Figure 6a).

5.1.4. Summary

The patterns evidenced in the discard records discussed in this paper are inconsistent with some of Brantingham's observations and predictions. Overall, the general similarities in the nature of the patterns generated by the neutral model and those observed in at least some archaeological cases do indicate that inferring specific behaviours on the basis of simple correlations or general shapes of frequency distributions may be unwarranted. However, it seems equally unwarranted to infer, on the same basis, that non-modelled behaviours (i.e. raw material selectivity) played no role in shaping raw material variability. Since we are not faced with an either/or scenario, it is theoretically possible, and even likely, that both modeled (e.g. the natural density of sources) *and* non-modeled (e.g. raw material selection) factors influenced assemblage composition.

As shown in the preceding sections, qualitative similarities in general trends of the kind discussed by Brantingham (2003) are not sufficient to either reject or accept the neutral model, except perhaps in extreme cases. For example, the discard records analyzed here show that patterns of individual cells do not necessarily conform well to aggregated patterns (Figures 9-10). Thus for individual sites (i.e. grid cells) where the predicted frequencies differ significantly from the general patterns discussed by Brantingham, a strong agreement with the latter would in fact indicate that non-modelled behaviours were at play.

Similarly, the general nature of the relationship between assemblage size and raw material richness cannot indicate, by itself, whether the neutral model is to be accepted or rejected - contrary to what is suggested by Brantingham (2003: 501), choice may be assumed to have played a role even if a single source predicted to have been exploited is found to have not been. In short, the neutral model can only be rejected or accepted on the basis of specific, quantitative predictions with known error ranges. Otherwise, the most parsimonious explanation for similarities with the model's output may simply be that the model is not sensitive enough to detect differences.

5.2. Predictions of the revised model

A series of predictions can be made on the basis of the revised model, and deviations from each of these may be traceable to biases in particular behavioural domains (e.g. mobility, raw material preferences, and carrying capacities or discard behaviours). These predictions are outlined below in a very general manner so as to convey the overall expectations. However, they can, and indeed *must* be, evaluated quantitatively through the variability evidenced in the output of multiple simulations, each run with an identical placement of sources and an identical set of toolkit/mobility parameters.

5.2.1. <u>Distribution of raw materials around a source</u>

Raw materials from any given source are expected to *always* be found in similar quantities at locations with similar access costs, regardless of access direction. For example, with the model parameters employed in simulation A, it would be expected that, if 100 units of raw material a' were discarded at their source, two assemblages located at 4 grid cells from that source would, in 50% of cases, contain between 28 and 38 units of this material (see Figure 8).

Under conditions of equal toolkit size/discard rate (T/D) ratios, major deviations from these expected abundances (i.e. an assemblage with 200 units of raw material a' at a distance of 4 grid cells from the source a') can only be explained by behaviours that affect mobility patterns. This is because the relative abundance of a certain material at a given distance from its source is minimally affected by simulation lengths and unaffected by source densities (Figures 7,8). Moreover, a preference or avoidance of the source would be manifested through its under- or over-exploitation.

5.2.2. Degree of source exploitation

Under the modeled behaviours it is expected that the most heavily utilized raw materials will be those from relatively isolated sources (Figures 6b, 7). In cases where the quantity of raw materials from this source follows a similar decline curve in all directions, which would be consistent with random mobility and similar accessibility from all sides, deviations from this expectation likely reflect factors that resulted in an avoidance of that source or raw material. Preferential exploitation of such a source would be expected to manifest in terms of a higher than predicted, but never lower, abundance of raw materials.

5.2.3. Assemblage size as a function of distance to nearby sources

Given the sharp decline in raw material abundances with increasing distance from their source (Figure 6a, Figure 7), it is expected that large sites will only form at or very near to raw material sources. The effects of this are most visible in the discard records of simulations B and C (Figure 5b1,c1). Deviations from this expectation can only be explained by behaviours that result in biased, non-random movement.

5.2.4. Raw material frequencies in an assemblage

All else being equal, the probability of observing a given number of raw material units of a specific type in an assemblage will depend not only on the distance between the assemblage and the raw material source, but also on the distance between the source and its neighbours (Figure 6b). Thus, the relative contributions of two sources located at an equal distance from a given assemblage are only expected to be equal if the distribution of sources in the landscape is perfectly uniform. In cases where the evidenced variability is consistent with random mobility, significant deviations from modelled frequencies are likely indicative of factors that resulted in preferential procurement or avoidance of particular raw materials.

5.2.5. Maximum transfer distances as a function of the density of sources

All else being equal, it is also expected that maximum transfer distances, as well as the ratio of maximum to median or modal transport distances observed in individual assemblages will be smaller under conditions of low source densities than under conditions of high source densities (Figures 9, 10). Deviations from these expectations may reflect biased mobility patterns, although they may also reflect other factors such as lithic recycling.

5.2.6. Raw material richness as a function of the density of sources

Finally, the number of unique raw material types represented in individual assemblages is expected to be low under conditions of low source densities (Figure 13). However, regardless of the local density of sources, all raw material sources are expected to be represented within a given radius, the size of which co-varies with assemblage size (Figure 14). Deviations from this expectation likely reflect a preference or avoidance of specific raw materials.

5.2.7 Summary

As shown in the preceding sections (see Figure 12 and associated discussion), assemblage composition can be modeled with a high and known degree of precision. The various expectations discussed above show that the revised model is, theoretically at least, capable of detecting the influence of both modeled and non-modeled behaviours quantitatively and within well-defined error ranges. The attainable precision does not guarantee accuracy, however, and overall the model is expected to be very sensitive to incorrect parameters. The availability of high-quality sourcing data is therefore essential for accurate interpretations of the model's output. Indeed, depending on its proximity to an assemblage, omitting a single raw material source may substantially alter the outcome of a simulation, and so would an incorrect assessment of the frequency with which individual sources are represented.

A further limitation of the model pertains to the fact that we have no direct way of estimating toolkit size/discard rate (T/D) ratios and these have a major impact on the model's output (Figures 5, 8, 10). While such estimation is beyond the immediate scope of this paper, at least two tentative solutions can be proposed: one approach would be to use maximum transport distances as proxies (Brantingham 2006), while another approach would be to estimate T/D ratios on the basis of the degree to which a subsample of assemblages (e.g. different levels at one site) fit the output of the model when different ratios are employed. Both of these approaches are problematic, and this subject will be treated in detail in a future paper. However, the advantage of the second approach is that, if different assemblages are found to be best explained by different T/D ratios, we can at least conclude that the assemblages evidence different behaviours (e.g. either a different capacity to carry stone or different rates of discard).

5.3. The wider implications of the revised neutral model for archaeological research

Regardless of whether practical or theoretical problems (e.g. estimation of T/D ratios) prevent the composition of individual archaeological assemblages from being accurately modeled, the revised model presented here provides some critical insights of wider relevance to the discipline. Amongst these, perhaps the most important is the fact that, as hinted by Brantingham (2003) and demonstrated here, the common practice of computing expected frequencies from distances to source is flawed, regardless of how such distances are measured (e.g. 'as the crow flies' or taking into account terrain difficulty). This is because the degree to which sources are exploited depends, to a rather large extent (a variation of over half an order of magnitude was observed in simulation A), on their proximity to other sources (Figure 6b). Interestingly, Browne and Wilson (2011) report a significant correlation between raw material utilization and inter-source distances at the Bau de l'Aubesier. The reported correlation was weak, and the authors eventually dropped inter-source distances from their model, but it is likely that a stronger correlation would have been observed if distances to multiple nearest neighbours had been used (see discussion associated with Figure 6b).

In any case, the analyses presented here also show that assemblages do not reflect, as it is all too often assumed (e.g. Brantingham 2003) the average composition of toolkits, even if all tools are assumed to have had equal use-lives. Moreover, they show that lithic densities, which in the context of the model are equivalent to "site" sizes (all grid cells are of the same dimension), are, by themselves, poor predictors of occupational histories. Indeed, even in cases where the influence of technologies, curation strategies, and sedimentation/erosion rates can be accounted for, major differences in assemblage growth rates can be observed (see section 4.2.1).

Ultimately, the model presented here is, as already pointed out, a model for the formation of the archaeological record; in this regard it is an imperfect model, of course, since only lithic components are considered, and a large number of relevant factors (e.g. topography) are not included. Nevertheless, it offers a glimpse of what an archaeological record *undisturbed* by factors such as erosion and differential sedimentation rates should look like under the simplest behavioural scenario. As such, it offers a value-free starting point for dialogue on the meaning of concepts such as "archaeological site" which are of fundamental importance to archaeological research. In the context of the model such sites are nothing more than random aggregates of items discarded over time by highly mobile agents which do not, in any meaningful sense of the word, dwell at any one location. While real sites may well represent episodes of continued habitation, the implications of the simple alternative suggested here are far too important to ignore, particularly in cases where the overall patterns generated by the model resemble archaeologically observed ones well.

As pointed out by Brantingham (2003: 503-504), it is essential to refine the model by including new variables and studying their effects on the overall patterns. Aside from Brantingham's (2003) own suggestions, it would be useful to study the effects of lithic recycling behaviours, since these may result in sites themselves being treated as raw material sources. It would also be useful to model semi-random mobility patterns, whereby agents gravitate around either raw material sources or sites, moving randomly until a certain condition is reached (e.g. toolkits become dangerously depleted, or too much simulation time has been spent away from a site), and then directly towards a target (i.e. site or source). Such mobility behaviours could be used to investigate whether archaeological variability reflects a need for constant access to lithic resources or landscape locations (i.e. sites), since preliminary analyses suggest that patterns generated under such conditions can be differentiated from those discussed in this paper with relative ease. What the foregoing analyses show, in any case, is that the model presented here can be a useful exploratory tool. As such, it allows not only for the objective assessment of the effects of different parameters and variables, but also for the detection of new variables that may be of interest (e.g. spatial distribution of sources at a local scale).

6. Conclusions

The analyses presented in this paper have shown that while Brantingham's (2003) neutral model correctly simulates raw material procurement and transport behaviours (i.e. the overall toolkit patterns were successfully replicated), it stops short of modeling how such behaviours translate into archaeologically visible patterns. Insofar as it can be accepted that discard records are a more direct proxy for the archaeological record than toolkits, my analyses failed to support some of Brantingham's original predictions. More importantly, however, I have shown that qualitative similarities between predicted and observed patterns are not sufficient to reject, or accept, the neutral model.

I introduced a revised model aimed at overcoming some of the original limitations. Detailed analyses of the discard records produced under this model have shown that, if parameters such as the toolkit size/discard rate ratio can be estimated, the raw material composition of archaeological assemblages can be predicted with a known and relatively high degree of precision. It is therefore possible, in principle at least, to detect deviations from model predictions even in those cases where factors such as the natural density of sources played a dominant role. More importantly, however, the ability to make quantitative predictions with known error ranges implies that the model can be rejected, or accepted, in a mathematically sound way.

I have argued that the attainable precision may be misleading if the underlying provenance dataset is inaccurate or incomplete. Indeed, the model is expected to be highly sensitive to: a) the omission of sources actually exploited in the past, and b) the erroneous identification of such sources in the record. In this regard the model may prove quite useful in determining the exact impact of such errors on the interpretation of raw material variability - to the best of my knowledge, the effects of different errors in sourcing datasets has yet to be evaluated quantitatively.

Overall, this paper has shown that models of the kind discussed here have much to contribute not only to raw material sourcing studies, but also to the wider discipline of archaeology, since they are, by definition, also models for the formation of the archaeological record. Indeed, they allow for value-free, objective discussions on topics of fundamental importance to archaeological research, including the meaning of archaeological sites, the nature of the archaeological record, and the relative importance of lithics in the past.

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Electronic Supplementary Material 1:

An independent replication of Brantingham's neutral model - summary of results

1. Simulation specifications:

Five hundred simulations of the replicated model were run with the baseline parameters specified by Brantingham (2003) and summarized in Table S1; all raw material source and initial agent locations were generated randomly for each of simulation. Unless otherwise noted, all results described below are based on data generated by these. These data consist of the following information, recorded at each time-step:

a. The position of the agent
b. The contents of its toolkit
c. The distance between the agent and the closest raw material source
d. The number of raw material units that were procured, if a source was encountered during the time-step.
e. Information on the type and toolkit position of the raw material item removed from the toolkit, if an item was discarded during the time-step.

Table S1 List of core model variables and baseline simulation settings.

Variable	Variable description	Units	Baseline setting
GridSize	Side length of the simulated square grid	Grid cells ($\mathbb{N}$)	500
ForagerLocation	Forager location as a grid coordinate	Coordinate 2-tuple ($\mathbb{N}_0$, $\mathbb{N}_0$)	Random = (0-499,0-499)
NrRawMatSources	Number of unique raw material sources	$\mathbb{N}$	5,000
RMSourceLocations	Location of raw material sources	Coordinate 2-tuple ($\mathbb{N}_0$, $\mathbb{N}_0$)	Random = [(0-499,0-499), 0-499,0-499), …]
ToolKitSize	Maximum <ToolKit> size	$\mathbb{N}$	100
ToolKitDepletionRate	Raw material consumption rate	$\mathbb{N}$	1
ToolKit	List of coordinate tuples for each raw material source in the toolkit	Coordinate 2-tuple ($\mathbb{N}_0$, $\mathbb{N}_0$)	Empty list
NrSteps	Simulation time step number (tick)	$\mathbb{N}_0$	0
MoveLength	Length of move	Grid cells ($\mathbb{N}$)	1
MoveProbability	Probability of moving to any of the cells in the Moore neighbourhood or staying in place	$\mathbb{R}$	1/9

All random variables drawn from uniform probability distributions

2. Data validation:

The output of all simulations was validated after these had finished running but prior to analysis, in order to ensure data integrity and full compliance with the definitions of Brantingham's (2003) neutral model. The validation tests (ca. 36 individual tests in total, depending on the characteristics of the output) are summarized in Table S2; all tests were passed by the simulations discussed here.

Table 2 Summary of validation tests conducted on simulation outputs.

Output component	Test description
Integrity of utilized raw material sources data	The source file utilized by the simulation contains the requested number of sources.
	All entries in the utilized source file are located within the bounds of the simulated environment, and are all unique.
Integrity of toolkit state data	The data file contains the correct number (and types) of variables. Time-step data are sequential (incremented by one).
Integrity of discard record data	The number of input events in the discard record matches the number of discard events recorded in the toolkit state data. The timing of the input events matches the timing of discard events in the toolkit states data, and the items entering the discard record are identical to those discarded from the toolkit
	The coordinates in the discard record data match the location of the agent as recorded in the toolkit state data for all discarded items.
Agent positions	Changes in the position of the agent along incremental time-steps are consistent with movements in Moore neighbourhoods (i.e. the agent only moves to adjacent cells).
	There is no significant difference between agent position changes and movement probabilities derived from a uniform random distribution with 9 possible outcomes (chi-square test). The uniformity of the distribution of p values across all simulations was checked.
Distances between the agent and the nearest sources	At least one source listed in the source output file is located at the recorded distance from the agent at each time-step, and no source is found in closer proximity to the agent.
Raw material procurement	Procurement events are recorded only at time-steps where the agent's position matches that of one of the raw material sources listed in the source output file.
	The number of procured raw material units (the toolkit size at the current time-step minus the toolkit size at the previous time-step) is equal to the specified maximum toolkit size minus the number of items currently in the toolkit
	The toolkit is always full at time-steps when the agent's position matches the location of a raw material source listed in the source output file.
	Only one source, which corresponds to the source indicated by the agent's current position, is represented in the procured materials.
Raw material discard	No discard event recorded in time-steps where toolkit is empty.
	Item(s) are always discarded at time-steps when the toolkit is not empty.
	The number of discarded items matches specified discard rates.
	The toolkit size recorded in the discard information variables matches the size of the toolkit in the previous time-step.
	The type of the discarded raw material unit matches the type of the unit at the index indicated by the discard information variables in the previous time-step.
	The number of units of the discarded type in the previous time-step is the same as the specified discard rate (one), accounting for source encounters.
Discard and Procurement	Sequential differences in toolkit sizes are explainable by procurement and discard behaviours.
Simulation end conditions	The last move attempt would have placed the agent beyond the boundaries of the simulated environment (edge encounter), or the agent moved to the location of an unvisited source after having visited 199 unique sources (source encounter).

Note that the randomness of resource placement, though not tested, conforms to theoretical expectations (Figure S2). All tests were conducted in R

3. **Preliminary observations**:

A number of problems were identified during the re-implementation of Brantingham's model. The first of these pertains to Brantingham's discussion of "foraging areas," which he defines as the "area[s] around a raw material source that can be effectively exploited with material from that source [and are] thus defined by radius *d*" (Brantingham 2003: 495; italics in original). This concept of foraging area is problematic in the context of a model which uses square tiling and allows for diagonal movements without penalty because the area defined by the radius is square, not circular (i.e. a forager can move diagonally over 10 grid cells in 10 time steps). Consequently, in the context of his model an area of radius *d*=10 (20x20 cells) will measure 400 grid cells and will contain an average of 8 raw material sources at a resource density of 0.02 sources per grid cell (i.e. 5000 sources on a 500x500 grid); conversely, if linear distances are considered, the area defined by that radius would be 314.16 grid cells, containing on average only 6.2 raw material sources. In short, using linear distances to derive foraging radii and average source densities (e.g. Brantingham 2003: 495-496) is not consistent with the definitions of the model.

To ascertain the actual mean of the distribution of agent displacement distances after 100 moves (i.e. the time it would take for a full toolkit to be cleared if no sources are encountered), which represents, according to Brantingham (2003: 495), the foraging radius *d*, a simple model was run a million times. In the simulations, which occurred on a 500x500 grid, the agent was placed at the center of the grid (x=250, y=250) and allowed to move randomly (1/9 probability of moving to a neighbouring cell or staying put) for 100 time steps. At the end of each simulation the minimum number of time-steps required to return to the point of origin was recorded. The resulting distribution (Figure S1) has a mode of 7, a median of 9, and a mean of 9.213, which is, as expected, somewhat lower than the number (10) used by Brantingham. More importantly, Figure S1 shows not only that the range of possible displacement values is high, but also that the distribution is skewed and, as indicated by the central tendency values listed above, most observations fall below the mean; thus, it could be argued that the modal or most frequently observed value of 7, rather than the mean, should be used as a proxy for the size of the foraging radii. In any case, it is clear that only probabilistic estimates of, rather than absolute values for, foraging radii can be given.

A second problem pertains to Brantingham's calculation of the maximum number of unique raw material types that can be expected in a toolkit. He suggests that this number "can be estimated empirically from the maximum number of unique sources that might be found within a foraging area of radius *d*" (2003: 495). On the one hand his calculations are incorrect because they are based on linear distances which, as discussed above, are not applicable in the context of his model; on the other hand, it must be noted that the maximum resource density in an area of a given size is not fixed - it will vary between simulated environments, and therefore it cannot be predicted in absolute terms *a priori*.

Indeed, there is a non-zero (albeit infinitesimally small) probability that an arbitrarily large area will be fully covered with sources provided that the number of sources is larger than the number of cells in that area, and that the distribution is indeed random (i.e. not uniform).

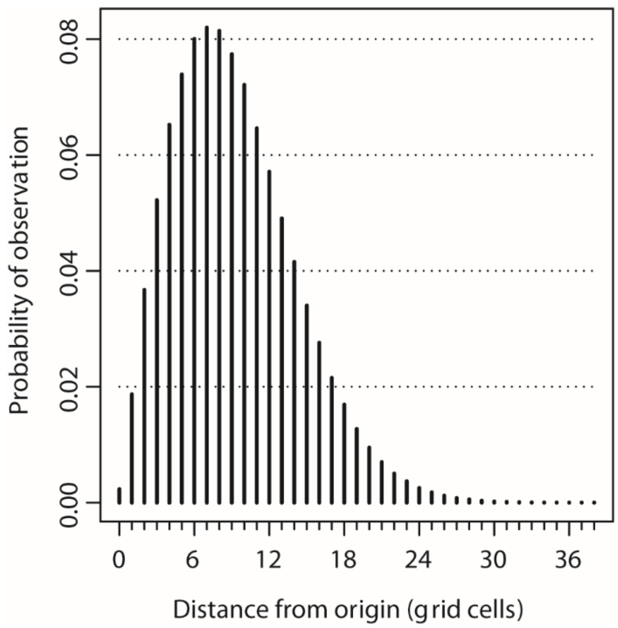

Fig. S1 Probability of traversing a given distance, where distance is defined as the minimum number of steps required to return to the starting location, using a random walk with 1/9 probabilities of moving to cells in the Moore neighborhood or staying in place. The figure summarizes 1 million runs (100 million time-steps)

For any given area the density of randomly distributed sources follows a Poisson distribution. Using Brantingham's displacement figure (*d*=10) and default resource density parameter (0.02 sources per cell), the foraging area in a square grid world would be 400 grid cells, and the λ parameter of the probability distribution would be 8. As shown in Figure S2, the probability of observing resource densities higher than the maximum suggested by Brantingham, namely 11, is relatively high; moreover, as also shown in the figure, the observed distribution of sources across the 500 main simulations run with the same density parameter closely matches this theoretical distribution. Since the density of local clusters cannot be predicted *a priori* except in probabilistic terms, the logic behind Brantingham's (2003: 496) calculations is difficult to follow, given that in the context of a single simulation the actual maximum density of sources does not have to be predicted – it can be computed with perfect accuracy.

A third problem arises from the fact that, if only probabilistic estimates of the foraging areas and maximum source densities can be given, it stands to reason that the maximum richness of toolkits will depend, to a certain degree at least, on the length of the simulations, as longer simulations have a higher chance of producing low likelihood events. As expected, data from the 500 main simulations show a strongly positive and highly significant correlation between these variables (Kendall's $\tau = 0.548$, $p < 2.2e^{-16}$), which suggests that arbitrarily ending the simulations upon encountering 200 unique sources, or upon encounters with the edges of the grid, may have biased Brantingham's analyses. In any case, as calculated by Brantingham, the maximum attainable toolkit richness state is a more or less arbitrary number from the upper tail of the probability distribution, one which represents neither the theoretical maximum nor the expected average maximum that would be observed over a large number of, or longer, simulations. The strong correspondence between the values observed and predicted by Brantingham is therefore due to chance (cf. Table 2 and related discussion in Brantingham 2003: 496).

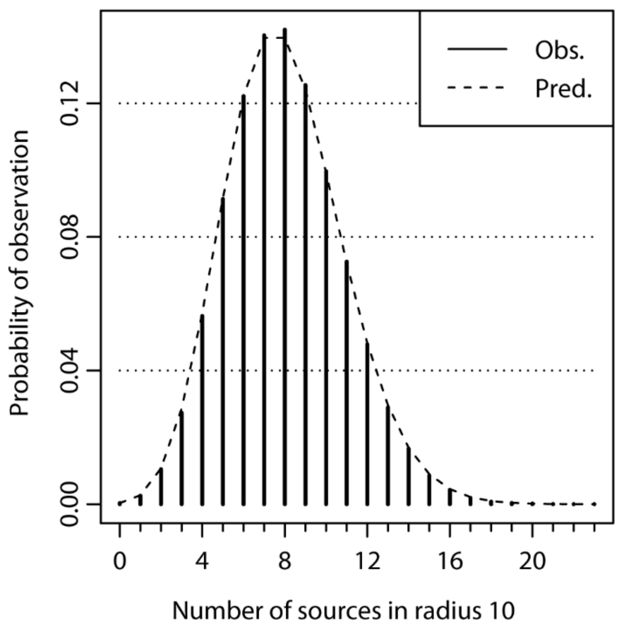

Fig. S2 Predicted and observed probability of a given number of raw material sources being allocated in an area of 400 grid cells, with source densities set to 0.02 (5000 sources randomly placed on a 500 × 500 grid). The observed probabilities were computed from 500 simulated environments, each split into 625 squares of 400 grid cells (*n* = 312,500). Note that the actual probability of observing the average value (8) is only about 14 %

4. Replication results:

4.1. General characteristics of the simulations:

The duration of individual simulations was highly variable, ranging from a minimum of one time-step to a maximum of 50866 (median = 13234, IQR = 27323), for a cumulative total of 8.11 million time-steps. The majority were terminated upon encounters with the edges of the simulated world (n=362, or 72.4%), although longer simulations were predictably terminated more frequently due to encounters with 200 unique raw material sources (Figure S3).

These relatively short simulations allowed the agents to cover only small areas of the grid, the maximum number of unique cells visited by an agent in a single simulation being only 12094 (median=4429.5, IQR=8387), or ca. 4.84% of the total space available to them. One consequence of such low coverage is that, in the context of a random (as opposed to uniform) distribution of resources, which guarantees variability in the clustering of sources at a local scale (Figure S2), conclusions drawn from but a handful of simulations may be unreliable.

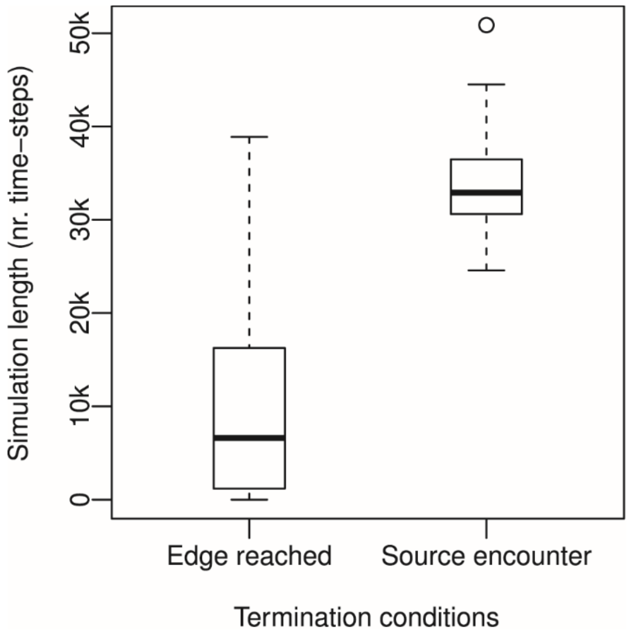

Fig. S3 Distributions of simulation lengths by termination conditions. Data from all 500 simulations is included

In terms of the number of sources visited by the simulated agents, the values varied between a minimum of 0 and a maximum of 969, with a median of 273.5 (IQR=550.25). This is consistent with the number of source encounters reported by Brantingham (2003: 499) for one simulation, namely 513. The agents seldom wandered far from raw material sources, being found most often at a distance of but two to three cells from the one nearest to them, and only very rarely at distances of 10 grid cells or more (Figure S4). While not surprising given the high density of sources - the linear average nearest neighbour distance between these was only 3.61 (SD=0.025)[1] – the ratio between the median number of simulation steps and the median number of visited sources is very high (ca. 48), indicating that source encounters are relatively rare.

[1] Note that this number is higher than would be expected from nearest neighbour analysis (Clark and Evans 1954, 1979), regardless of whether correction factors (e.g. Donnelly 1978) are used or not. This is because such analysis is based on linear distances between neighbours, and cannot be used in the context of Brantingham's model, as sources are allocated on discrete rather than continuous space. In such discrete space the minimum possible distance between two sources is not fixed (i.e. the distance to an adjacent source can be one if the source is at the left, for example, but it will be 1.41 if located at the top-left). Thus, the discrepancy between observed and expected nearest neighbour values is not indicative of a non-random distribution of sources (see Figure S2).

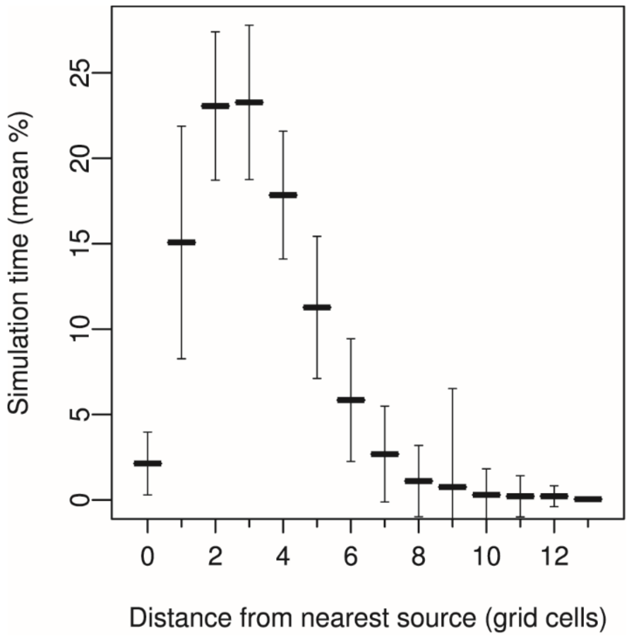

Fig. S4 Frequency of observed distances between the simulated agent and the nearest raw material sources, expressed as the average percentage (±1 SD) of simulation time over all 500 simulations

4.2. Mobile toolkit states:

With respect to the mobile toolkits, these were in an empty state between 0 and 100% of the simulation times, with a median of 35.13 (IQR=8.62) and a mean of 38.32 percent (SD=17.03); if only those simulations lasting 10000 time-steps or more (n=281) are considered, the percentage of simulation time spent in an empty toolkit state ranges from a minimum of 22.73 to a maximum of 44.67 percent, with a median of 34.58 (IQR=5.7) and a mean of 34.65 (SD=4.11) percent. Brantingham (2003: 494) reported that in a representative simulation the toolkit was empty approximately 25 percent of simulation time; while that value falls within the range of variability observed here, it is not representative of the overall results (Figure S5a).

The large number of time-steps spent without access to lithic raw materials could be problematic if one were to assume that such access was critical to forager survival. More important than empty toolkit occurrences, however, are the lengths of periods spent in such a state. The aggregated data from all 500 simulations (Figure S5b) indicates that the lengths of consecutive empty toolkit states were most frequently quite short (<20 time steps), but also that the probability of observing longer sequences is very high (81.2 percent for periods of 20 time-steps or longer, 15.6 percent for periods of 200 time-steps or more); indeed, the average length of empty toolkit periods was 108.75 (median=70), and the maximum recorded length was 1869. These numbers are surprisingly high given the density of sources (see above), and bring into question the survivability of foragers under Brantingham's neutral model[2].

[2] This was noted by Oestmo et al. (2014) also, but they investigated simulations run with non-random, clustered sources. In fact, as shown here, the presence of such clustered sources is not necessary to bring into question the survivability of Brantingham's foragers.

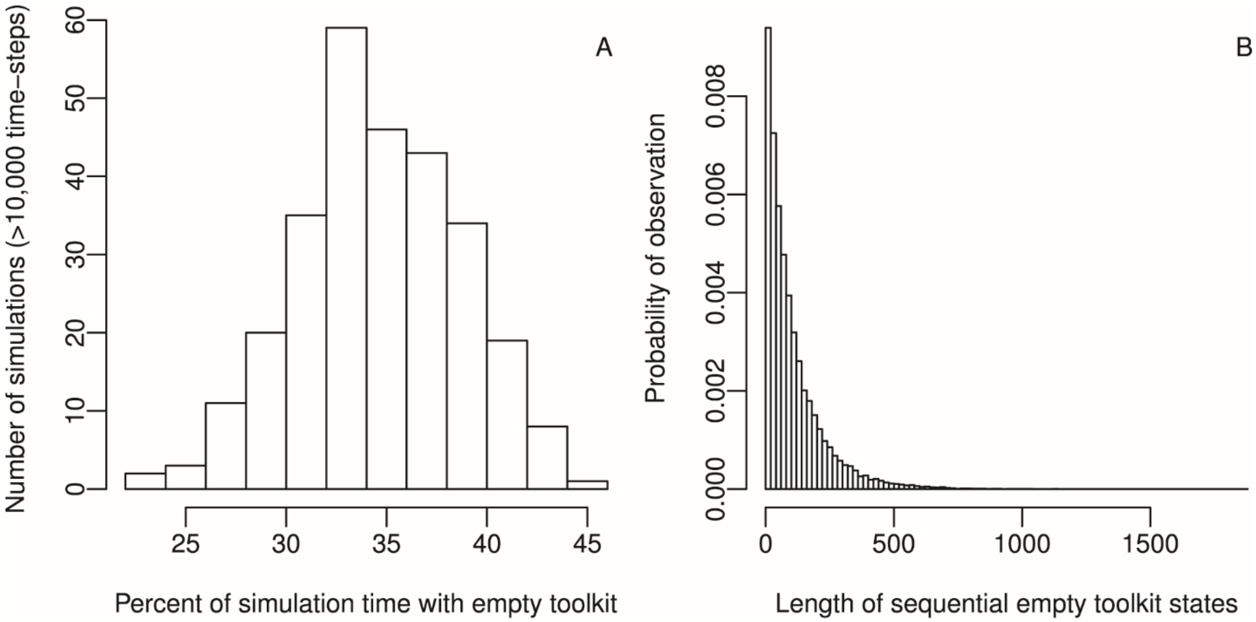

Fig. S5 **a** Frequency of empty toolkit occurrences across 281 simulations lasting 10,000 time-steps or more, expressed as a percentage of simulation time, and **b** the probability of observing sequential empty toolkit states of a given length. Subplot *b* includes all sequential empty toolkit state observations (n = 25,923) from all 500 simulations, binned in intervals of 20 time-steps

As expected given these observations, the modal average toolkit richness state observed across all simulations is zero (Figure S6a). From this modal value the distribution of mean richness state frequencies follows a smooth decline curve up to a maximum of 13 unique raw material types, and has a median value of 1 (IQR=2). This distribution is qualitatively similar to that reported by Brantingham for a single simulation (Figure 6 in Brantingham 2003: 494), although as expected given his flawed calculations of maximum attainable richness states (see section S1.3 above) and the uncommonly low frequencies of empty toolkit states reported for the simulations, there are slight differences in the median and maximum values. Overall, most simulations only attained a maximum richness state of 8 unique raw material types (Figure S6b), although the median maximum observed richness was somewhat lower at 7 (IQR = 3).

As noted by Brantingham (2003: 498), the maximum number of unique raw material types increases with the log of the amount of material in the toolkit. As shown in Figure S7, a virtually identical relationship can be observed in the output of the simulations discussed here (compare with Figure 8 in Brantingham 2003: 498); Figure S7 also shows, however, that all combinations of toolkit size and raw material richness can be observed, and that the overall relationship between the two variables is rather different.

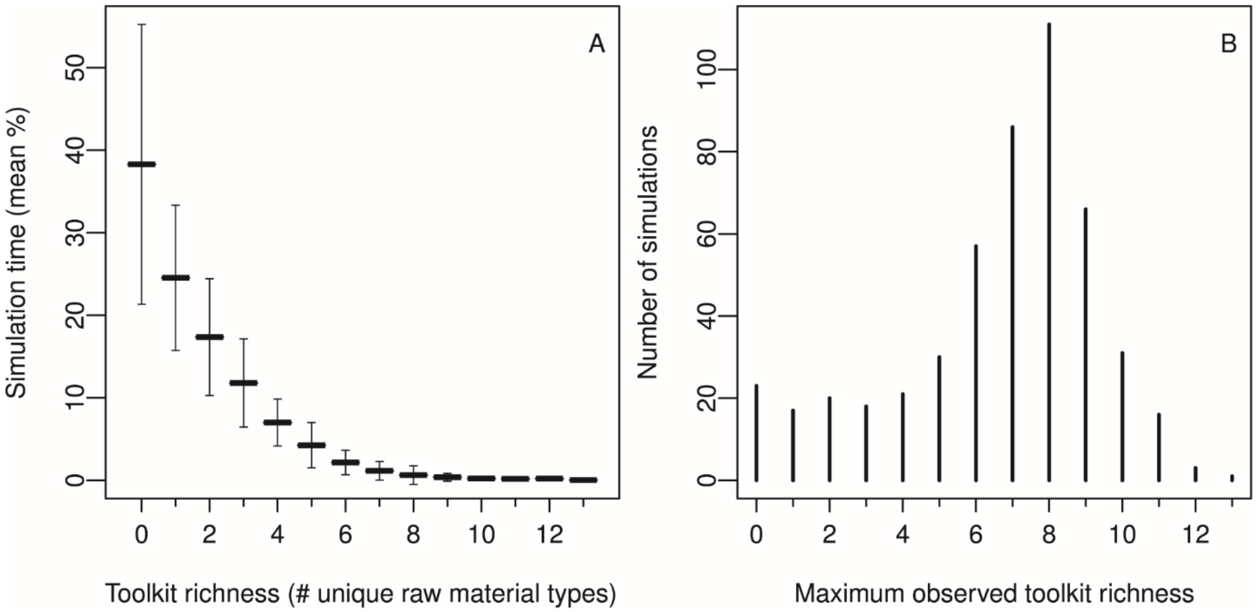

Fig. S6 **a** Average (±1 SD) simulation time spent in different toolkit richness states, and **b** the frequency of maximum attained toolkit richness states across all 500 simulations

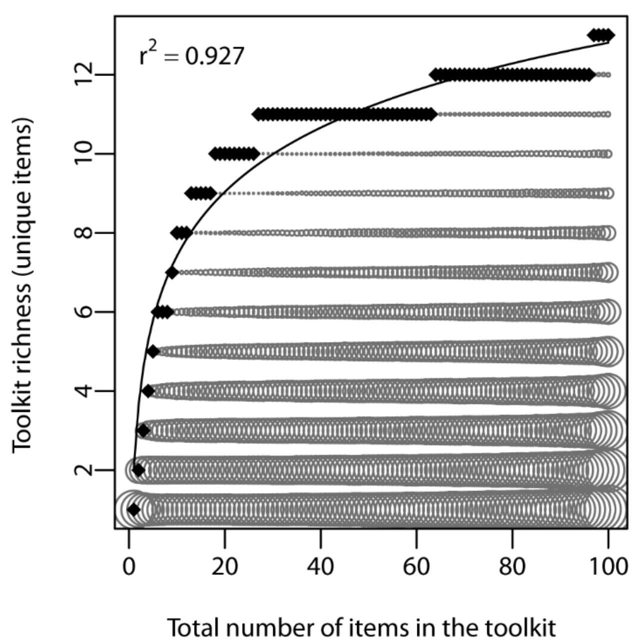

Fig. S7 Relationship between toolkit raw material richness and toolkit size in the aggregated data from all simulations. *Black diamonds* indicate maximum toolkit richness values attained at each toolkit size; as observed by Brantingham (2003: 498), a strong positive correlation ($r^2 = 0.927$, $p < 2.2e^{-16}$) between these maximum richness values and the log of the quantity of materials in the toolkits can be observed (*black regression line*). However, the overall relationship between the two variables is much less clear when all data points are considered ($n = 5.29$ million). These data points are represented here as *circles* whose size increases with the cube root of the number of observations for a given combination, so as to account for the extreme differences (the number of observations per combination ranges from 1 to 50719)

4.3 Transport distances:

The average transport distance patterns that result from combining the outputs of all 500 simulations (Figure S8) are qualitatively very similar to those observed by Brantingham (2003: 499); although the frequency of items found at their source is considerably higher when toolkits are sampled only at encounters with sources (Figure S8b), sample size effects and Brantingham's choice of histogram bin widths likely account for much of the difference. The maximum transport distance of 61 grid cells is also higher than observed by Brantingham (2003: 499), but this is expected given the probabilistic nature of the phenomena under consideration and the much larger number of observations (n=333.7 million versus less than 20000). Importantly, and as predicted by Brantingham (2003: 499), the modal transport distance across all observations (3 grid cells) is identical to the "internal mode" evidenced when only observations at raw material sources are considered.

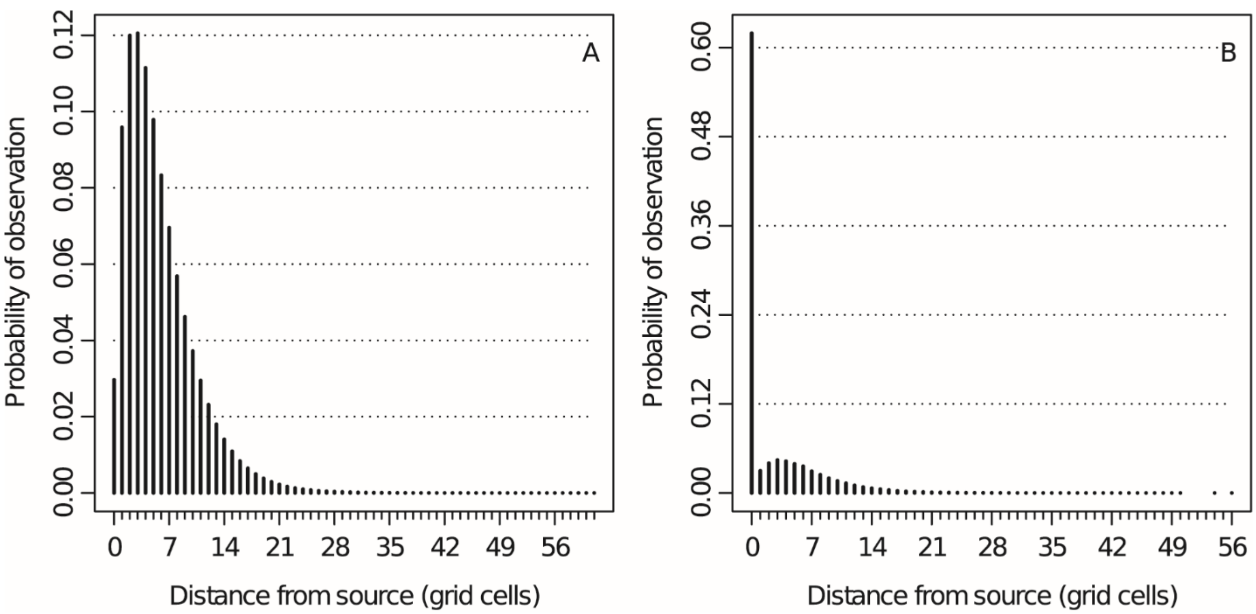

Fig. S8 Probability frequency distribution of raw material transport distances recorded in the mobile toolkits throughout the length of the 500 simulations, when **a** all data points are considered (n = 333.73 million) and **b** when toolkits are sampled at raw material sources (n = 159.83 million)

The pattern of decay in the quantity of a given raw material type with increasing distance from its source (Figure S9) is also qualitatively similar to that reported by Brantingham (cf. Figure 11 in Brantingham 2003); indeed, although the mean values vary somewhat from those reported by him, they fall well within one standard deviation from these.

Some differences were also noted, however, and these bring into question two fundamental relationships predicted by Brantingham. First, Brantingham (2003: 499) predicted that the modal/median transport distances will fall in the interval [d/2,d], where d is the foraging radius (10 for the default simulation parameters); the modal value obtained here falls outside of this range, while the

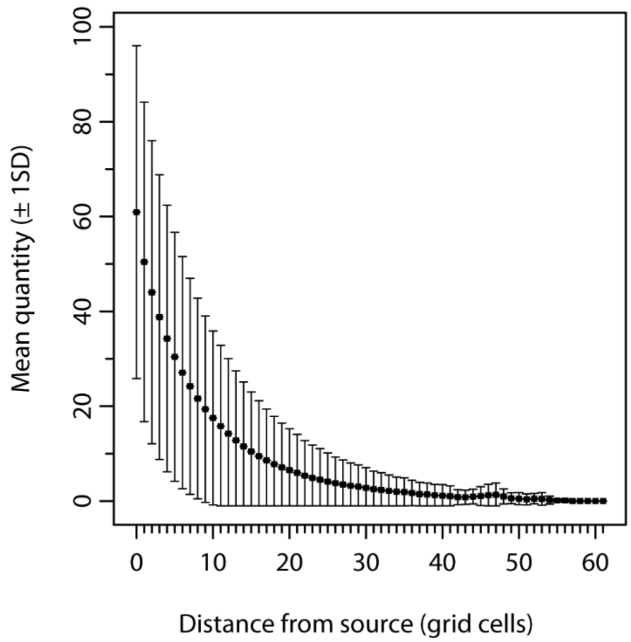

Fig. S9 Quantity of items in the mobile toolkit as a function of distances from their source. Data represent the averaged (±1 SD) frequencies recorded in the 500 simulations

median (5 grid cells) corresponds to its lower limit[3]. Secondly, Brantingham (2003: 500) predicted that the maximum transport distance should be approximately three to four times the radius *d,* although subsequently he states that the maximum distance is expected to be three to four times the mode (Brantingham 2003: 501-506). Notwithstanding this confusion, which has implications for Brantingham's (2003: 501-504) analyses of archaeological parallels[4], it can be noted that the maximum distance observed in the output of the 500 simulations discussed here is over 20 times larger than the mode[5],

[3] Note that the modal and median values reported by Brantingham do fall within the range of variability observed in the outputs of individual simulations; thus two simulations (0.4%) attained a median value of 9 (the maximum observed), and 22 simulations (4.4%) attained modal values equal to, or greater than, 5 (observed maximum = 11). Note also that the overall median value reported here was computed from a random sample (with replacement) of one million data points.

[4] Brantingham (2003: 498-499) reported a modal transport distance of 5 and a maximum of 43 grid cells; using these values, the maximum transport distance is 8.6 times larger than the mode, not 3-4 times as stated by the author. In the archaeological parallels discussed by Brantingham (Grotte Vaufrey and the Middle Palaeolithic record of Central Europe) the reported maximum transport distances are 2 and 4.6-6 times larger than the modes, falling well below the expected values. More importantly, Brantingham reported that the probability of observing a transport distance of 10 grid cells or more, which would be equivalent to twice the mode, is approximately 33 percent (see caption to Figure 10 in Brantingham 2003: 500). Thus, according to Brantingham's predictions, 33 percent of the artifacts recovered from Grotte Vaufrey would be expected to have been transported from a distance that is equivalent to, or greater than, the actual maximum observed. It is also telling, of course, that the maximum transport distances reported for the entire Middle Palaeolithic of Central Europe fall below the predictions of short (i.e. low sample size) simulations.

[5] Note that the probability of observing transport distances greater than 9 and 12 grid cells (i.e. three and four times the modal value observed in the aggregated data from the 500 simulations) are 16.9 and 7.9 percent respectively. In effect, this means that, using the figures obtained here, approximately 8 out of every 100 raw

and approximately 6 times higher than Brantingham's analytically derived foraging radius *d*. In fact, 126 simulations, or 25.2% of the total, yielded maximum transport distances greater than Brantingham's maximum predicted distance of 40 (four times radius *d*).

Be that as it may, Brantingham's observation that "median and modal transport distances do not change appreciably with different environmental raw material densities" (2003: 499) is accurate. An additional 200 simulations, run with source density parameters of 0.002 (500 sources) and 0.06 (15000 sources) respectively confirmed Brantingham's assertion that in cases of low raw material densities the "distribution loses its right skew and clusters more tightly around the [center]" (Brantingham 2003: 499). Across these simulations I observed a shift in modal and median values from 2 to 3, and 4 to 5 respectively, which for all practical purposes can be considered as minor. It should be noted, however, that the increased clustering around the modal and median values does imply that, under conditions of lower source densities, the probability of observing lower maximum transport distances is higher. In other words, the neutral model predicts that, all else being equal, maximum transport distances under conditions of lower raw material source densities should be lower than under conditions of higher source densities.

5. Summary of findings:

The patterns generated by the replicated model discussed here are qualitatively similar to those reported by Brantingham, and all values reported by that author fall within the range of variability evidenced in my simulations. However, his values are seldom representative (e.g. Brantingham's reported median transport distance is higher than the median observed in 99.6% of the 500 simulations), rendering several of Brantingham's conclusions problematic. In particular, I could not replicate the postulated relationship between modal and maximum transport distances, nor that between median/modal transport distances and the size of the foraging radius. The use of methods incompatible with the definitions of the model (e.g. those relying on linear distances) also renders some of Brantingham's analyses problematic; such is the case, for example, with his calculations of maximum toolkit richness states and of the size of foraging areas.

In general the simulation lengths and outputs were highly variable, and the probability of observing representative patterns across all investigated relationships in the context of a single or small number of simulations is low. This is mainly due to the arbitrary termination conditions stipulated by Brantingham, which result in a very low degree of coverage of the simulated environment and therefore in a high susceptibility to local differences in the placement of raw material sources. In this regard it should be pointed out that, although the average number of sources found in an area of radius 10 is 8, the actual probability of observing such an average value is only about 14% (see Figure S2).

The arbitrary end conditions also make it difficult to establish the actual parameters of the various distributions, because very short simulations, virtually always terminated by encounters with the edges of the simulated world (Figure S3), have undue weight. For example, the means and standard deviations

material units (e.g. artifacts) are expected to have been transported over a greater distance than the maximum predicted.

of the percentages of simulation time spent in an empty toolkit state change considerably depending on whether all simulations or only those lasting longer than 10000 time-steps are considered (see section 4.2 above). While it could be argued that only simulations above a certain length should be included in analyses, it is unclear what that threshold should be; at the very least simulations should be allowed to continue until the agent achieves complete or near complete coverage of the grid.

Aside from these issues, and as noted by Oestmo et al. (2014) also, the survivability of foragers under Brantingham's neutral model is questionable, since the simulated agents do not have any access to raw materials for relatively long periods. This is a natural outcome of employing random walk strategies, which cannot guarantee constant access to resources. Consequently, if it can be assumed that people required constant access to lithic raw material sources in the past, the mobility strategy employed by Brantingham's model cannot be used, and either a fully non-random or semi-random (i.e. random movement until certain condition is met) mobility strategy should be modeled instead.

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Chapter Four

A network model of local resource selection for evaluating landscape knowledge, navigation, and foraging extents at the Bau de l'Aubesier

Evaluating landscape knowledge and lithic resource selection at the French Middle Palaeolithic site of the Bau de l'Aubesier

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Evaluating landscape knowledge and lithic resource selection at the French Middle Paleolithic site of the Bau de l'Aubesier

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A B S T R A C T

We report on the application of a novel approach to exploring the degree of landscape knowledge, wayfinding abilities, and the nature of decision-making processes reflected in the utilization of stone resources in the French Middle Paleolithic. Specifically, we use data from the site of the Bau de l'Aubesier to explore the reasons why a majority of the 350 raw material sources cataloged in the surrounding region appear not to have been utilized, including several located near the site and yielding high-quality lithic materials. To this end, we focus on the spatial relationships between sources as an explanatory variable, operationalized in terms of minimum travel times. Using geographic information system software and a generalized linear model of resource selection derived from the Bau assemblages, we compute source utilization probabilities from the perspective of hominins located off-site. We do so under three optimization scenarios, factoring in the intrinsic characteristics (e.g., quality) and time required to reach each source on the way to the Bau. More generally, we find that in slightly more than 50% of cases, seemingly viable sources may have been ignored simply because the minimum cost path leading back to the Bau passes through or requires only minimal deviations to reach, higher quality options. More generally, we found that throughout the entire region, a cost/benefit analysis of competing sources favors those from source areas known to have been utilized. Virtually all the available information on lithic procurement at the Bau is consistent with a model of landscape utilization premised on detailed knowledge of a very large area, an ability to accurately estimate travel times between locations, and a pragmatic strategy of stone resource exploitation based on minimizing costs (travel and search times) and maximizing utility.

1. Introduction

Our understanding of the lifeways and evolutionary histories of our hominin relatives is premised to a very large extent on the degree to which their relationships with past environments can be elucidated. Indeed, knowledge of the affordances and constraints characteristic of specific landscapes provides essential context for evaluating both individual decisions and overall adaptive strategies. Such knowledge is difficult to acquire, however, as we face two major obstacles. The first involves reconstructing past conditions, such as the physical availability of resources and the presence of barriers and hazards, based on evidence that is fragmentary, biased by differential preservation, and generally available at coarse temporal and spatial resolutions. The second pertains to understanding what hominins could have done given these conditions, in other words, the nature of the physiological but also cognitive constraints—for example, limited spatial memory and information processing abilities—underpinning the relationships with their surroundings.

Among extant primate species, ours is unusual in terms of both our capacity to consciously modify the environment (Lewis and Maslin, 2015) and our abstract spatial reasoning skills. We can, for example, use flexible but cognitively demanding Euclidean mental maps to efficiently navigate to distant, out-of-sight resources (e.g., Dehaene et al., 2006; Trapanese et al., 2018), evidence for which remains elusive in other living species. Our spatial abilities appear to be tied to linguistic faculties and extended developmental trajectories (e.g., Spelke and Lee, 2012) specific to our

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genus (but see Normand and Boesch, 2009), and the question of when such abilities developed in our lineage is still a matter of some debate. Essentially modern spatial abilities appear to have already been present in *Homo erectus* prior to ca. 500,000 years ago (Wynn and Coolidge, 2016), but it has been suggested that novel spatial skills gave anatomically modern humans a unique advantage resulting in our worldwide dispersal (Burke, 2012). In brief, when considering hominin species other than our own, caution is warranted in assuming modern capacities to conceptualize and navigate space.

In this context, Neanderthals present an interesting challenge. Very closely related to us (e.g., Sánchez-Quinto and Lalueza-Fox, 2015; Roebroeks and Soressi, 2016), equipped with large brains and able to exploit the harsh mid-latitude Pleistocene environments of western Eurasia (e.g., Hublin and Roebroeks, 2009; Nielsen et al., 2017), these hominins left behind abundant material culture which sporadically comes tantalizingly close to suggesting fully modern human cognition (e.g., Zilhão, 2012; Radovčić et al., 2015; Jaubert et al., 2016; Hoffmann et al., 2018a, b). Yet, although the evidence clearly points to Neanderthals having been highly intelligent, it is far from clear whether they learned and processed information the same way we do. The relatively extensive evidence we have for their lifeways suggests that Neanderthals had a somewhat different relationship with their environment than our anatomically modern ancestors. They appear to have exploited a typically narrower resource base (e.g., Richards and Trinkaus, 2009; Stiner, 2013; Fiorenza et al., 2014; Power et al., 2018; but refer to the study by Henry et al., 2014) perhaps over a smaller territory (e.g., Verpoorte, 2006; Nava et al., 2020) and to have had higher energy requirements (e.g., Sorensen and Leonard, 2001; Macdonald et al., 2009; Sørensen, 2009; Hockett, 2012; Churchill, 2014; also refer to the study by Heyes and MacDonald, 2015), somewhat smaller group sizes and more spatially constrained social networks (e.g., Churchill, 2014; Pearce and Moutsiou, 2014; but refer to the study by Hayden, 2012) as well as a more limited ability to colonize new environments. It also appears that Neanderthals had somewhat different growth curves and that their brains developed along different, more archaic pathways than our own (Gunz et al., 2012; Hublin et al., 2015; Neubauer et al., 2018; but see Rosas et al., 2017). All of these differences have potential bearing on their spatial abilities, including memory and navigation.

Multiple lines of evidence can be used to investigate the spatial abilities of extinct hominins. These include diachronic changes in stone tool complexity, anatomical changes observable in the fossil record, the distribution of archaeological sites, and the patterns of faunal and lithic resource exploitation such sites document. Developments in lithic technology, for instance, provide clues about the evolution of abilities such as mental rotation and, more broadly, visuospatial integration, that is, the functional synthesis of visual and spatial perception (Overmann, 2015; Bruner et al., 2018). Moreover, stone tool complexity may also reflect degrees of landscape knowledge, with greater investment in tool manufacture, including raw material procurement, reflecting greater social knowledge of resource availability (Clark and Linares-Matás, 2020). The neurological and genetic underpinnings of spatial abilities and their ontogeny have been studied in extant humans as well as other primates, and the results can serve as a guide to interpret anatomical features of extinct hominins, including differences in gross neuroanatomy (e.g., Correira, 2013; Bruner and Lozano, 2014; Kuhn et al., 2016; Shakeshaft et al., 2016; Bruner et al., 2018; Hodgson, 2019). Finally, the distribution of sites and patterns of faunal and lithic resource exploitation supply critical information on spatial behaviors and cognition, including wayfinding and landscape learning (e.g., Raynal et al., 2013; Burke, 2015; Guiducci and Burke, 2016; Hussain and Floss, 2016; Kuhn et al., 2016).

In this study, we report on the application of a novel approach to exploring aspects of spatial cognition in Neanderthals using lithic data. Specifically, we investigate the degree of landscape knowledge, navigational abilities, and decision-making processes reflected in Neanderthals' use of regionally available stone resources at the French Middle Paleolithic site of the Bau de l'Aubesier (hereinafter 'the Bau'). We focus on stone because 1) archaeological preservation is not a major concern with this material, 2) it constitutes a predictable fixed resource, and 3) it is often possible to meaningfully narrow down locations from where rocks used to manufacture archaeological artifacts may have originally been collected. Indeed, it is generally acknowledged that evaluating the archaeological incidences of different raw materials in light of their environmental availability and distribution can provide crucial insights into past land use strategies at different scales (e.g., Féblot-Augustins, 2009; Frahm et al., 2016; Turq et al., 2017). At the Bau, this distribution, as well as the individual characteristics of the plentiful sources available within ca. 40 km of the site, are both well known and unlikely to have changed substantially since the initial occupation of the site (Browne and Wilson, 2011). In other words, using lithic provenance data from the Bau allows us to minimize the first of the challenges noted at the onset, that is, the need to reconstruct past conditions (cf. Dibble, 1991), and to focus instead on examining the constraints underlying resource use (also refer to the study by Wilson et al., 2018).

Our approach departs from most other lithic provenance studies in two important ways. First, we focus squarely on evaluating why a majority of the raw material sources available in the region surrounding the Bau were seemingly not used over a period of roughly 100,000 years. Typically, provenance studies concentrate on identifying the location of exploited raw material sources and on explaining their degree of utilization, paying less attention to why plausibly viable procurement options may have been ignored. This is understandable because many factors can explain a lack of use—for example, sources may simply not have been available—but it does mean that a potentially critical source of information on past behaviors may be underutilized. Second, we emphasize the spatial relationships between sources, operationalized here as minimum travel times, as an explanatory variable. It has long been recognized that a source is less likely to have been used if a better procurement alternative exists on the way to a site (e.g., Luedtke, 1976; see also Wilson, 2007a), but the effects of the spatial relationships between potentially usable sources are generally not quantified or modeled. And yet, as shown by Pop (2016), source utilization can be expected to be shaped by the presence or absence of other nearby sources even under entirely neutral mobility and resource exploitation conditions. Considering this, we make such spatial relationships central to our approach by conceptualizing each source as a node in a network of plausible procurement options and propose three possible nested explanations for the systematic, long-term avoidance of sources that may be witnessed at the Bau, differentiated by increasingly complex cognitive requirements.

Our hypotheses are formulated from the perspective of individuals engaged in some unknown off-site activity who are intent on procuring raw materials on their way to a camp and are all premised on Neanderthals having been rational agents who sought to optimize their foraging activity by transporting usable stone to a site from the best sources and along the most efficient routes. This is in line with the selectivity in lithic raw material procurement evidenced at the Bau (e.g., Browne and Wilson, 2011; Wilson and Browne, 2014). Of course, we do not know where Neanderthals made procurement decisions, but a source which is a suboptimal choice at its own location, because a better alternative exists en route to a destination site, cannot have been the best choice at any other location either. Moreover, it is possible to simulate procurement decisions everywhere individuals could have been located when they decided to collect rocks and to investigate where archaeological observations are compatible with the known distribution of used and unused resources under a given procurement scenario. Based on these insights, we use variations of an optimization algorithm, representing our proposed explanations and rooted in archaeologically evidenced selection criteria, to probabilistically classify all known sources in our study region as either exploitable or unexploited. We then evaluate the resulting modeled distributions against the archaeological representation of sources among the nearly 16,000 stone artifacts for which provenance is known. To the best of our knowledge, this constitutes a new approach to inferring wayfinding abilities from the representation of lithic raw materials at archaeological sites and adds to a growing number of novel quantitative studies (e.g., McPherron, 2018; Režek et al., 2018; Oestmo et al., 2020).

Our hypotheses are graphically represented in Figure 1 as simplified scenarios. They vary in terms of 1) the number of procurement options whose location (and characteristics) individuals would have had to accurately recall and 2) the number and complexity of the paths (i.e., straight to the destination, or including a detour to intercept other raw material sources) for which individuals would have needed to accurately estimate minimum travel times. Briefly, they are as follows:

Hypothesis 1. (H_1): Neanderthals optimized procurement at a localized scale, recalling and evaluating the potential of all lithic sources found directly along the least-cost paths to the site and collecting stone only from the best among these (Fig. 1A and B). Under this hypothesis, we classify as exploitable all sources for which no better alternatives exist en route to the Bau (e.g., source 2 in Fig. 1A and source 1 in Fig. 1B) and the remainder as unexploited.

Hypothesis 2. (H_2): Neanderthals optimized procurement at a regional scale by evaluating the potential of all sources in light of all other sources and only exploiting those that offered the best cost-benefit ratios (Fig. 1C). Under this hypothesis, we classify as exploitable sources for which no better procurement alternative is available anywhere in the region and the remainder as unexploited. In the sample scenario illustrated in Figure 1C, source 1 would therefore be classified as unused because a hominin would have found the extra effort required to reach another source (e.g., source 4) to be warranted owing to the greater quality or abundance of materials there; conversely, sources 4 and 5 would both be classified as exploitable (but note that only the evaluation of source 1 is shown in Fig. 1C).

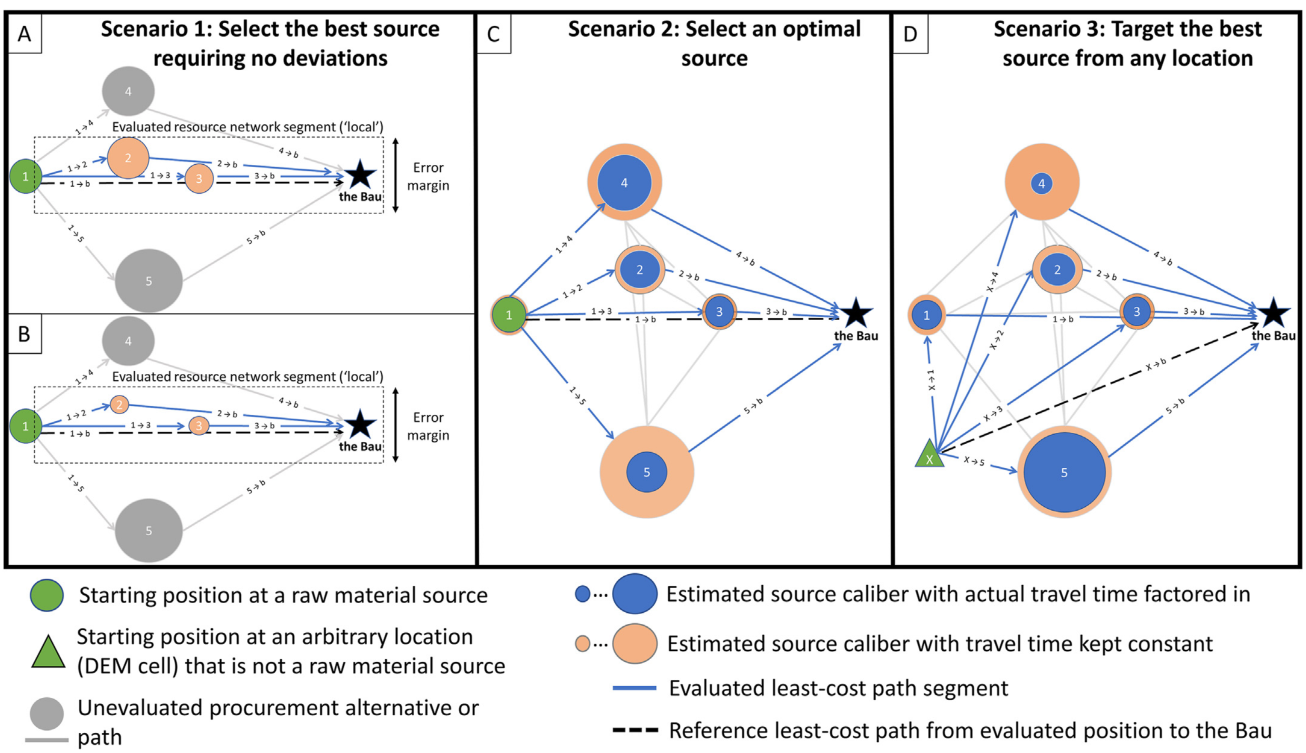

Figure 1. Schematic representation of three procurement optimization scenarios. Subplots A and B illustrate how a hypothetical source (1) would be evaluated under Hypothesis 1, that is, based on the presence or absence of better alternatives along the least-cost path to the destination, the Bau (arrow 1→b; note that we allow here for small uncertainties in travel time estimations). In these cases, sources are compared only in terms of the quality and abundance of their raw materials, represented by the size of the orange circles (larger is better). In the scenario shown in subplot A, source 1 would be classified as unexploited because source 2 is a better option, whereas in the scenario represented by subplot B, source 1 would be classified as exploitable. Note that sources 4 and 5 are not evaluated because they would not be encountered en route to the site. Subplot C illustrates how the same source (1) would be evaluated under Hypothesis 2. In this case, all known options are considered and, in addition to the quality and abundance of their raw materials, minimum required travel times are also taken into account to determine the relative benefits each offers (size of the blue circles; larger is better). Thus, the evaluated source (1) would be classified as unexploited because source 4 is a superior (and the best) procurement option and is expected to have been targeted instead. Note that source 5 has better and/or more abundant materials (compare the size of the orange circles), but the cost of reaching it on the way to the Bau (i.e., travel times along arrows 1→5 and 5→b) is too high to warrant the effort (hence the smaller blue circle). Subplot D illustrates how sources would be evaluated from an arbitrary landscape location (x), represented as a digital elevation model (DEM) cell, under Hypothesis 3. As shown in subplot C, the best procurement option (largest blue circle) when travel costs are factored in is presented by source 5, which is therefore predicted to have been targeted. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Hypothesis 3. (H_3): Neanderthals optimized lithic raw material procurement by optimally targeting the best sources (i.e., those identified as exploitable under H_2) from throughout the region (Fig. 1D). This hypothesis is a generalized version of the second one outlined earlier: for Hypothesis 3, the landscape and potential for exploiting sources are also judged from any other, nonsource points. Thus, for each landscape location (e.g., x in Fig. 1D), we classify a source as exploitable if it represents a good procurement alternative (e.g., source 5 in Fig. 1D) or unexploited if it does not. Under this hypothesis, we would expect the number of lithics procured from specific sources to covary with the number of procurement decisions taken at locations where they constitute the best alternatives.

The first hypothesis is thus a special case of the second, which in turn is a special case of the third. As already noted, the main difference lies in the number and complexity of paths (blue arrows in Fig. 1) and the range of alternatives that must be considered to determine whether a given source ought to be ignored or not. Collectively, these hypotheses enable us to ascertain, based on the degree to which each fits archaeological observations, whether Neanderthals were able to target a set of locally (H_1) or globally (H_2) optimal sources, and whether they could do the latter efficiently throughout the region (H_3). Alternatively, failure of our hypotheses to explain archaeological observations would signal that our fundamental assumptions regarding Neanderthal (optimizing) behavior are problematic or, possibly, that the lithic landscape that exists today is substantially different from what would have existed in the past. As discussed in the following part of the article, this does not appear to be the case at the Bau.

2. Materials and methods

2.1. Data

We rely on previously published data on lithic resource availability and use at the Bau de l'Aubesier (Wilson, 2007a, b, c; Browne and Wilson, 2011, 2013; Wilson and Browne, 2014). Compiled over the course of more than 25 years and including systematic characterizations of 350 raw material sources and nearly 41,000 archaeological pieces, they constitute one of the most comprehensive and consistent datasets available for a Middle Paleolithic site. These data, as well as the site and its regional context, are described in the following subsections.

The Middle Paleolithic site of the Bau de l'Aubesier The Bau de l'Aubesier is a large rock shelter located in the Vaucluse department of southeastern France. Known since the turn of the 20th century (Moulin, 1903), it has yielded a complex and rich archaeological sequence, approximately 13-m thick, which was deposited over the course of roughly 100,000 years or more ($\geq$200 kya to $\leq$100 kya; see Blackwell et al., 2000, 2001; Lebel et al., 2001; Wilson, 2021). The site is found at the intersection of multiple types of ungulate home ranges (Fernandez, 2001) in a region of variable topography and abundant sources of knappable materials (Fig. 2). The total number of lithics recovered from the partially excavated deposits, virtually all flint, amounts to at least 85,000; they are classified as Typical Mousterian of Levallois facies (de Lumley-Woodyear, 1969; Texier, 2004). Although early analyses (concerning only the upper deposits) had suggested substantial techno-typological homogeneity across the layers (e.g., Moulin, 1903; de Lumley-Woodyear, 1969), more recent work has highlighted diachronic changes that included important shifts in lithic raw material selection (Wilson and Browne, 2014; Wilson, 2021). Specifically, although the same major raw material types were exploited throughout, their proportions do vary by layer, and some layers show a greater diversity of types than others (see Supplementary Online Material [SOM] S1). In addition to lithics, the site has also yielded combustion features, more than 2700 identifiable ungulate remains resulting from anthropic accumulation and representing a minimum of 241 individuals (Fernandez, 2001, 2006) and isolated deciduous and permanent Neanderthal lineage teeth as well as a partial (pre-)Neanderthal mandible with substantial pathologies (e.g., Lebel et al., 2001; Wilson, 2021).

The study region The study region is defined here as a rectangular area of ca. 87 by 55 km that includes all raw material sources documented by Lucy Wilson near the Bau, regardless of whether or not they were utilized. Its limits are therefore arbitrary and not intended to represent home ranges or a discrete geographic entity with clear physical boundaries; indeed, the region is characterized by variable topography and resource availability. Importantly, however, and despite the presence of steep and inaccessible cliffs in certain areas, it is not partitioned by any major physical barriers that would have impeded human mobility. The region is home to several other important Middle Paleolithic sites, including the Baume des Peyrards, La Combette, and the rich stratified open-air site of Berigoule (see Texier, 2004) and was never glaciated. In fact, there is no evidence for major changes to the geomorphology of the landscape over the last 200,000 years. Thus, while it is probable that the characteristics of some raw material sources did change through time, it is reasonable to consider the overall lithic landscape that exists today as representative of that exploited by hominins during the deposition of the Middle Paleolithic levels at the Bau.

Regional raw material sources A total of 350 individual landscape locations with naturally occurring, potentially usable lithic raw materials have been cataloged to date, including both primary (outcrop) and secondary (alluvial or colluvial) localities. Throughout this article, we refer to such locations as sources. Some of these yielded abundant, high-quality rocks over a relatively large area, whereas others yielded only poor-quality stone in low quantities, in a variety of combinations of quality, extent, and abundances. These characteristics, as well as geographic coordinates, are among the variables that have been systematically collected and recorded for each source by Lucy Wilson since 1987.

Geological samples collected at these locations were characterized for the purposes of sourcing archaeological materials based primarily on their macroscopically visible features and petrographic thin sections. Analyses were supplemented by limited geochemical data and focused on properties that are useful in identifying materials by age and depositional environments (Wilson, 2007a; Browne and Wilson, 2011). Because the available information does not always allow for sources to be distinguished in terms of archaeologically visible properties, they have been classified into 122 groups, or 'source areas' (e.g., Browne and Wilson, 2013). Each such source area is characterized by a specific, archaeologically identifiable raw material type and may include one or more discrete sources (minimum = 1, median = 1, maximum = 15). The convex hulls that define these source areas vary in size and, as shown in Figure 2, at times overlap. With archaeologically represented raw material types that are procurable at multiple locations, it is impossible to say which location was in fact targeted, and to what extent.

Archaeological raw material variability A total of 15,674 of the 40,770 lithic artifacts examined to date for provenance purposes have been assigned to the source areas described earlier by Lucy Wilson using mainly visual and petrographic criteria (Browne and Wilson, 2011; Wilson and Browne, 2014). These artifacts include pieces of all types and sizes. The rest of the materials either were procured from sources that have not yet been identified ($n = 171$, or ca. 0.5%) or have been altered to such an extent by patination and burning as to prevent reliable classification (Browne and Wilson, 2011). The sourced lithics, which come primarily from 11 different archaeological layers that span the entire sequence (Wilson and Browne, 2014; see also SOM S1), are made from materials collected at a minimum of 17 and a maximum of 101 sources comprising 17 source areas; hereinafter, we refer to all sources assigned to these source areas as belonging to a set S_1. A large number of possible procurement locations ($n = 249$, from 105 source areas) therefore appear not to have been utilized at all, and hereinafter, we refer to these as belonging to a set S_0. Four of the seemingly nonutilized sources were situated on steep terrain (slope >60%) and were therefore not easily accessible, but many others are located in relatively close proximity to the site, on relatively gentle slopes (Fig. 2).

Overall, the archaeologically observed raw material variability and the distribution of possibly exploited sources suggest that the Bau was fairly centrally located within its raw material supply zone, with most artifacts being made from stone found within 13 km of the site. It must be noted, however, that archaeologically represented raw materials are rarely found in close proximity to the site—75% of their sources are found at 6.3 km or more from the Bau, and the average Euclidean distance is 10.9 km (minimum = 0.2, maximum = 47.3).

2.2. Analytical methods

Our approach to evaluating procurement alternatives can be conceptualized as involving a complete directed edge- and node-weighted network where accessible sources and the Bau constitute the nodes and least-cost paths constitute the edges (two for each pair of nodes). These edges have associated weights, which we define as the minimum walking times required to traverse them, while nodes have weights (see orange circles in Fig. 1, whose size remains constant across the different scenarios) that correspond to a combination of attributes (i.e., quality, extent, raw material abundance); hereinafter, we refer to the weight of the directed edge connecting a given node (or vertex) v to another node v' in the network of sources as $w_{v \to v'}$ and that of the edge connecting v' to v as $w_{v' \to v}$ (see blue arrows in Fig. 1 and Table 1 for a summary of all key variables and sets that are referenced in this study). As discussed in the rest of this section, we evaluate the relative merits of procuring materials from sources found along different network

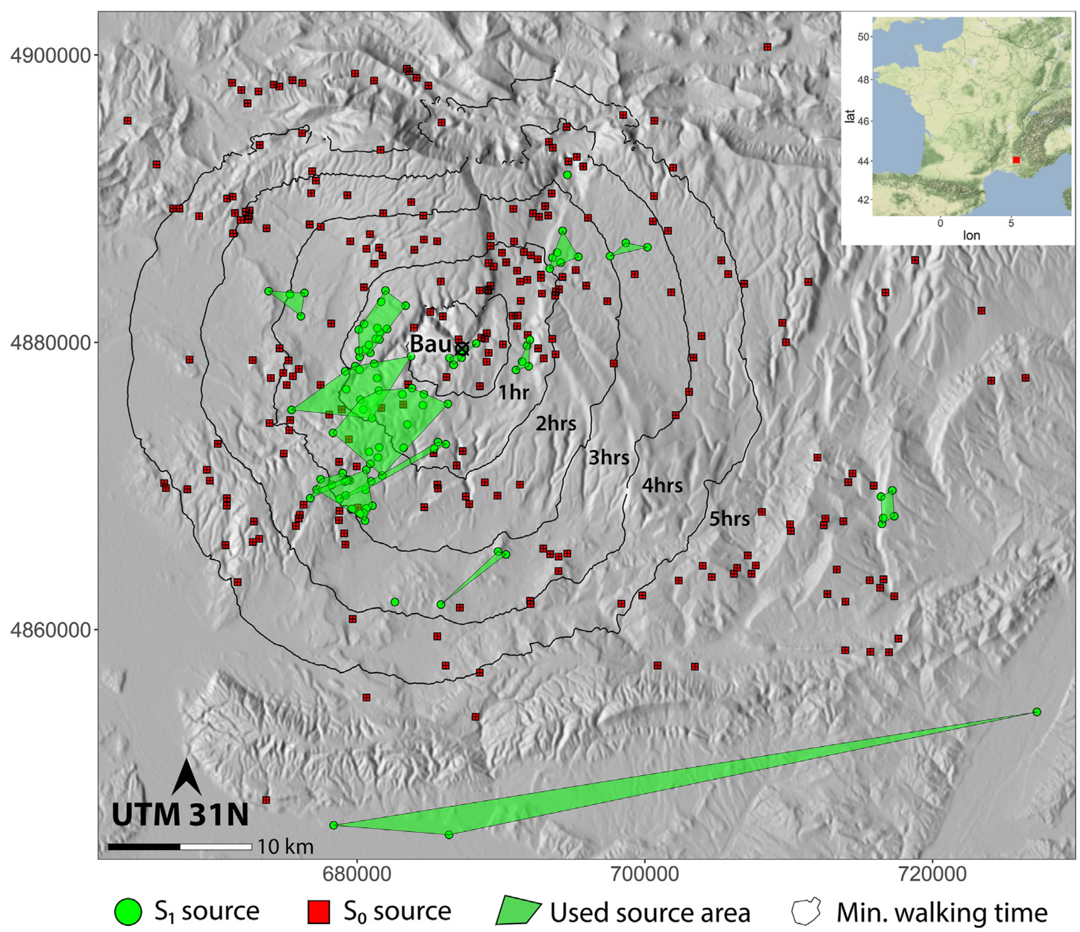

Figure 2. Study area and lithic resource distribution around the Bau de l'Aubesier. Sources of archaeologically represented raw materials (set S_1) are indicated by green circles, and sources of nonrepresented materials (set S_0), by red squares. Green polygons represent convex hulls encompassing sources from different archaeologically exploited source areas; note that these vary in size and at times overlap. Concentric rings show GIS-computed distances that can be covered while walking away from the site, in 1-h increments (minimum walking times). Note that several S_0 sources are located close to the site and that most S_1 sources are located at relatively substantial distances from the Bau. Two distant S_0 sources included in the dataset are not shown in this figure; one is located far to the west, and the other beyond the area's eastern limits. Coordinates are given in UTM zone 31N. Min. = minimum. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Definitions of key variables and sets discussed in the text.

Key	Definition
b	The Bau, considered as the end destination for a procurement trip.
E	The extent of a source, approximated to four values: 20 m^2, 706 m^2, 4416 m^2, and 17,663 m^2.
H_1	Hypothesis 1. Figure 1A and B illustrate how sources are evaluated under this hypothesis.
H_{2a}	Hypothesis 2. When sources with the highest $P_{S1\ (v')}$ values (i.e., 'optimal') at one or more nodes (i.e., sources) are predicted to be used (i.e., S_{1p}) and the rest are predicted to be unused (i.e., S_{0p}). Figure 1 C illustrates how sources are evaluated under this hypothesis.
H_{2b}	Hypothesis 2. When sources with $P_{S1\ (v')}$ values within the 95% confidence interval of the highest (i.e., 'good') at one or more nodes (i.e., sources) are predicted to be used (i.e., S_{1p}) and the rest are predicted to be unused (i.e., S_{0p}).
H_3	Hypothesis 3. Sources are evaluated as under H_2, but from all cells of the digital elevation model (DEM) which are reachable within 5 h of walking from the Bau. Figure 1D illustrates how sources are evaluated under this hypothesis.
L	The abundance of large rocks at a raw material source, expressed in terms of the approximate percentage of a source's surface area. Takes values of 0 (absent), 1 (<5%), 2 (5–24%), 3 (25–50%), and 4 (>50%).
P_{S1}	The probability that a source with a given combination of attributes and access costs belongs to the set of sources from utilized source areas (S_1), when access costs refer to minimum required travel times from the Bau. Can take values between 0 and 1.
$P_{S1\ (tc)}$	Same as P_{S1}, but with access costs kept at a constant value for all sources.
$P_{S1\ (v')}$	The probability that a source (v') belongs to the set of sources from utilized source areas (S_1) when the access costs factor in the minimum travel time from another source (v) to it and then to the Bau. Unlike P_{S1} and $P_{S1\ (tc)}$, this value will vary depending on which other source is considered. Under H_2, each source will have up to 346 $P_{S1\ (v')}$ associated values, corresponding to the number of accessible sources within the study area (see Fig. 1C, D for more details).
Q	The average quality or suitability for toolmaking of the raw materials found at a source. Recorded on a scale consisting of the following values: 0 (very poor), 1 (poor), 2 (fair), 4 (good), 8 (very good), and 16 (excellent).
S_0	The set of sources for which no evidence of exploitation is preserved at the site.
S_1	The set of sources from utilized source areas.
S_{0p}	The set of sources predicted to belong to the set S_0 under various scenarios.
S_{1p}	The set of sources predicted to belong to the set S_1 under various scenarios.
T	Access costs, defined as minimum walking times. In Eq. (1), T refers to the time required to reach a given source (v) from the Bau, and is equivalent to the weight ($w_{b\to v}$) of the path or network edge connecting the Bau to the node/source.
v	A raw material source, when considered as a node or vertex in the network of sources in the study area.
v'	A raw material source, when representing a potential procurement alternative being evaluated from another source (v), or from an arbitrary landscape location (x).
$w_{v\to v'\to b}$	Minimum travel time from source v to source v' and then to b (the Bau). Substitutes for variable T in Eq. (1).
$w_{v\to b}$	Minimum travel time from source v to b (the Bau). Substitutes for variable T in Eq. (1).
x	A digital elevation model cell reachable within 5 h from the Bau, and from where procurement alternatives (v') are evaluated under Hypothesis 3. Each x will have 346 associated $P_{S1\ (v')}$ values, one for each procurement option (v').

paths using a generalized linear model (GLM) that aims to reflect the relative importance given to these weights by the hominin inhabitants of the site.

Unless otherwise noted, all analyses described in this paper were conducted in Microsoft R Open, v. 4.0.2 (R Core Team, 2020) with the aid of a number of packages including 'car,' v. 3.0.8 (Fox and Weisberg, 2019), 'caret,' v. 6.0.86 (Kuhn, 2020), 'data.table,' v. 1.12.8 (Dowle and Srinivasan, 2019), 'ggplot2,' v. 3.3.2 (Wickham, 2016), 'raster,' v. 3.3.7 (Hijmans, 2020), and 'rgdal,' v. 1.5.12 (Bivand et al., 2020). Prior to performing these analyses, the random number generator was seeded with a predetermined value (corresponding author's birthday) to ensure the replicability of the results. Relationships between variables were evaluated using nonparametric Spearman's rank order correlation tests because they were not normally distributed, and significance throughout this study is given at an alpha level of 0.05. The R code is available on Zenodo (https://doi.org/10.5281/zenodo.5813254), whereas data on lithic resource use at the Bau are available from L. W. upon request.

Spatial data processing and edge weights All travel costs discussed in this study were computed based on digital elevation models (DEMs) using the processing tools provided by the GRASS, v. 7.4.0, open-source GIS package (GRASS Development Team, 2018). For reproducibility, we scripted all GIS operations with the GRASS Python library v. 2.7.5, and GNU bash, v. 4.2. We used 3 arc-seconds postprocessed Shuttle Radar Topography Mission (SRTM) DEMs, v. 4.1, provided by the International Center for Tropical Agriculture (Jarvis et al., 2008) as our data source because the resolution of SRTM DEMs has proven adequate for route calculations in this region (Browne and Wilson, 2013). Because the study area, defined here as 45°N, 43°N, 4°E, and 6°E (WGS84), spans two SRTM tiles, we merged these with the r.patch module. After importing previously published information on sources (WGS84; https://gisgeography.com/wgs84-world-geodetic-system/), we reprojected the spatial data to UTM zone 31N (EPSG 23031) with datum transformation 3 (France: 2-m horizontal accuracy). For this, we used the r.proj module, using bicubic interpolation (with fallback) for reprojection and for resampling of the DEM to a resolution of 80 m (from ca. 92.57 m by 71.15 m). We also filtered out areas with slopes greater than 60%, deemed inaccessible (Browne and Wilson, 2013), by first creating slope maps with the r.slope.aspect module (default precision parameter) and removing cells with values above the threshold using the r.mapcalc module.

From these data, we created anisotropic least-cost maps using the r.walk GRASS module and a maximum value of 20 hours. For this, we used the default cost and slope parameters, as proposed for modern hikers by Langmuir (1984) based on Naismith's rule, the 'knight's move' option for higher accuracy and constant friction values. While Henry et al. (2017) have published r.walk parameters specific to Neanderthals and anatomically modern humans, we considered empirically derived values as a more appropriate baseline. We generated such least-cost maps for all sources as well as for the site and queried these maps for travel times between locations. Thus, to determine minimum travel times from a source v to a source v', which would correspond to the weight $w_{v\to v'}$ of the network edge connecting v to v', we queried the value of the raster cell corresponding to the location of source v' on the map created for source v.

Resource selection model Previous research has successfully examined how source characteristics and access costs have shaped degrees of raw material exploitation at the Bau (Wilson, 2007b; Browne and Wilson, 2011; Wilson and Browne, 2014), demonstrating that it is possible to provide objective measures of what the Neanderthal inhabitants of the site considered important, and to what extent. Here we adopt a similar approach in that we use a GLM to quantify the benefits of targeting sources from the Bau based on the available archaeological information. However, instead of modeling the relationship between source attributes and artifact quantities, we use a simple logistic model with binomial error structure and logit link function (McCullagh and Nelder, 1989) to assess the probability P_{S1} that a source with a given combination of attributes and access costs belongs to the set S_1 of sources from utilized source areas (shown in green in Fig. 2) rather than to the set S_0 of sources for which no evidence of exploitation is preserved at the site (shown in red in Fig. 2); in other words, we model the relationship between the attributes of the known sources and the presence or absence at the Bau of the type of raw materials such sources yield. With each source, P_{S1} can therefore take a value between 0 and 1, with values closer to 1 ostensibly denoting more attractive targets from the perspective of a hominin located at the Bau.

Downscaling the data to a binary response may seem like an odd choice, but it has the distinct advantage of preserving information on source area membership, and therefore on degrees of archaeological utilization, as an external variable that should in no way shape the resulting probabilities. Indeed, as discussed in the next subsection, we use this variable to test whether our assumption regarding the meaning of P_{S1} values holds true. It should also be noted that our model is built on the combined archaeological information available for the entire sequence; that is, we do not distinguish between archaeological layers. Given our goals, using such aggregated data is advantageous because it increases confidence in the proposition that sources assigned to the set S_0 were intentionally ignored or avoided rather than simply unknown or unavailable to hominins inhabiting the site.

Because the available dataset includes multiple potential predictors, some of which are strongly correlated (Browne and Wilson, 2011), we performed an initial exploratory analysis of the data and formulated our model by selecting four predictors that showed the clearest separation between sets S_0 and S_1 (see SOM S2): 1) the quality of the raw materials (Q); 2) the approximate extent over which raw materials may be found at the sources (E); 3) the abundance of large rocks (L); and 4) access costs, defined as minimum walking times required to reach the sources from the Bau (T). Other available variables, such as the caloric expenditure required to reach the Bau from the various sources, the difficulty of the routes linking sources to the site, and the abundances of small, medium, and very large rocks were therefore excluded from consideration. Moreover, because our basic units of analysis are individual sources rather than source areas, we did not factor in source area characteristics (e.g., extents over which sources of a given raw material type can be found—'area of the source area' [AOSA] in the study by Browne and Wilson, 2011, 2013).

As detailed in previous publications (e.g., Browne and Wilson, 2011, 2013), quality, recorded on a scale from 0 to 16 (see Table 1), refers to a subjective measure of the suitability for toolmaking of the average rocks found at a given source; it was determined by Wilson (2007b, c) based on criteria such as the homogeneity, granulometry, and toughness of the materials, as well as the presence or absence of cracks, aspects which also impact functional performance (e.g., Pop, 2013). Extent, on the other hand, refers to the approximate size of a source, originally recorded on a scale from 1 (<10 m in diameter) to 4 (>100 m in diameter) and given here in square meters (see Table 1). The abundance of large rocks refers to the approximate percentage of a source covered by knappable rocks 16–35 cm in size and takes values from 0 (absent) to 4 (>50% of the area). Finally, the minimum walking times were computed based on SRTM DEMs as outlined earlier. We note that we used elevation data as the sole source for estimating movement costs owing to its availability and low expected variability over the time period considered here. We recognize that land cover affected minimum travel times, but presently neither the paleoenvironmental data available for the region nor the chronology of the site are sufficiently well understood to allow for the inclusion of this variable.

Prior to inclusion in the model, we applied a log transform to the quality variable (Q) and a square root transform to the extent and access cost variables (E and T) to minimize distribution skewness (and therefore the likelihood of influential cases). We also scaled (z-transformed) all covariates, so they comprise directly comparable units (see SOM S2 for descriptive statistics on individual variables). Our estimations of P_{S1} values for each of the 346 accessible sources (i.e., those not located on steep terrain) were therefore based on the following formula, where $_t$ denotes a transformed variable and β the coefficients estimated based on the observed archaeological presence or absence of the raw materials each such source yields. The probability that a source belongs to the set S_1 of sources from archaeologically represented source areas is thus given by

$$P_{S1} = \frac{\exp(\beta_0 + \beta_1 Q_t + \beta_2 E_t + \beta_3 L_t + \beta_4 T_t)}{1 + \exp(\beta_0 + \beta_1 Q_t + \beta_2 E_t + \beta_3 L_t + \beta_4 T_t)} \quad (1)$$

We assessed the model's validity and stability through various diagnostics and established that it met the relevant assumptions (see SOM S3). Finally, we established the significance of the full model by using a likelihood ratio test (Dobson, 2002) to compare its deviance with that of a null model containing only the intercept.

Cross-validation and performance To test the model's predictive ability, we used a repeated fivefold cross-validation procedure with stratification. This involved splitting the data into five groups (i.e., folds) of approximately equal size ($n \approx 69$ per group) and assigning an approximately equal number of randomly selected sources from S_1 and S_0 to each group so that they are representative of the overall population (i.e., a ratio of ~1:2.43 per group). P_{S1} values for sources within each fold were predicted using models trained on data from the other four folds. We repeated this cross-validation procedure 100 times to achieve more robust estimates for individual source probabilities and assigned to each source the average of the estimates. These average P_{S1} values were reclassified as '1' or '0' predicting membership in sets S_1 and S_0, respectively, with '1' being assigned to sources with values greater than 0.5 (50%). To avoid confusion, from this point forward, we refer to all predicted S_1 and S_0 sets as S_{1p} and S_{0p}, respectively.

The accuracy of the predictions was then assessed through a confusion matrix, a tool commonly used in the field of machine learning to evaluate the performance of classifiers. A confusion matrix has two dimensions—observed and predicted classes—and summarizes the degree to which these match. With binary classes (e.g., positive and negative, or classes that may be designated as such), the confusion matrix has four cells containing the number of true positives, false positives, true negatives, and false negatives. On the basis of these numbers, several performance measures can be derived, including accuracy, sensitivity, and specificity. Accuracy refers to the overall ability to classify cases correctly, whereas sensitivity and specificity refer to the ability to correctly classify true positives and true negatives, respectively (e.g., Kuhn, 2008; Kotu and Deshpande, 2014; Ting, 2017).

We further evaluated the predictions by means of Kvamme's gain statistic (Kvamme, 1988), often used to evaluate the performance of predictive models of site location. The statistic is calculated as $1-p_i/p_s$, where p_i is the proportion of the study area identified as a zone of interest and p_s is the proportion of sites within that zone of interest. Values can range from -1 to 1, with zero indicating performance at the level of chance and high values indicating good performance in the zone of interest. Because we consider sources rather than sites here, we define p_i as the proportion of the total sources that are predicted to have been used (i.e., having cross-validated P_{S1} values above the 0.5 threshold) and p_s as the proportion of sources from exploited source areas that are predicted to have been used.

Finally, we investigated whether the computed P_{S1} values are meaningful proxies for the degree to which specific sources were desirable exploitation targets. To this end, we tested for a significant correlation between P_{S1} values obtained for sources from exploited source areas and the number of archaeological artifacts derived from those source areas. Because information on source area membership did not factor into our model, the most parsimonious explanation for a significant positive correlation would be that P_{S1} values are indicative of source attractiveness, with the strength of the correlation providing an indication of the degree to which this is true.

Network navigation and the evaluation of procurement alternatives Preliminary results (presented in Section 3.2) indicated that the resource selection model described earlier enables us to quantify the caliber (P_{S1}) of a procurement alternative based on the attributes of a source and the cost of reaching it from the Bau. This alternative can be expressed in terms of a network node and path as $v_{b\rightarrow v}$, where v denotes the node (i.e., source) whose characteristics are considered (i.e., variables *Q, E,* and *L* in Eq. (1)), and $_{b\rightarrow v}$ denotes the network path (here, one edge) whose weight (i.e., $w_{b\rightarrow v}$) is factored in as variable *T* in Eq. (1). We suggest that this model can be used to evaluate procurement alternatives along other network paths as well, that is, using any edge weights that do not fall substantially (here, $\leq$5%) outside the range of values on which the model was formulated. We assume that 1) this can be done symmetrically, with either the start or the end of an evaluated path representing the Bau—in other words, that valid P_{S1} values can be calculated for $v_{b\rightarrow v}$ as well as for $v_{v\rightarrow b}$ using the same model (although the resulting values would, of course, be different). We also assume, out of necessity (see below), that 2) the costs of travel between nodes do not vary substantially depending on whether rocks are carried or not.

Because we defined a complete network, the node *b* representing the Bau is reachable from any other node either directly or passing through one or more additional nodes. Under the premise that raw materials would have been procured by an individual from only one source at a time, we restrict our evaluation of possible routes to the Bau to those involving at most two distinct network edges. If the two assumptions outlined earlier can be provisorily accepted, P_{S1} values for a given source accessed along different network paths can be computed by adding the weights (i.e., minimum travel times) of the network edges along those paths. Thus, the P_{S1} value of a procurement alternative that involves traveling from a node v to another node v^1, collecting materials at v^1, and then carrying those materials to the Bau, can be computed by replacing *T* in Eq. (1) with ($w_{v\rightarrow v1} + w_{v1\rightarrow b}$); hereafter, we refer to this alternative as $v'_{v\rightarrow v'\rightarrow b}$ and to the P_{S1} values computed for it as $P_{S1\ (v')}$, so as to avoid confusion; the sizes of the blue circles in Figure 1 represent these $P_{S1\ (v')}$ values. The same can be done to assess the alternative whereby materials are procured at v (i.e., where v and v' represent the same source) and are carried straight to the Bau (i.e., $v_{v\rightarrow b}$); in that case, *T* would be replaced by $w_{v\rightarrow b}$. The $P_{S1\ (v')}$ values obtained for these two alternatives can then be compared to assess which one ranks higher.

We acknowledge that the first assumption (disregarding direction of travel) may introduce some uncertainty, but our analyses focus on the relative ranks of the alternatives, not on absolute differences in computed P_{S1} values, and the resulting ranking should be relatively robust. If substantial errors are nevertheless introduced by this uncertainty, we would expect these to compromise our ability to explain the available data under our second and third hypotheses, not to improve it. The degree to which the second assumption (cost of load carried) holds is difficult to determine. There is clearly a cost associated with carrying additional weight, so this is not an irrelevant variable, but estimating that cost also requires making a series of assumptions. Put simply, we know of no reliable method for determining the cost difference between a path traversed empty-handed and one traversed carrying rocks, not least because we do not know how much lithic material Neanderthals may have been willing or able to carry at any given point. However, the consequences of any violations of our second assumption are predictable; they would introduce two types of bias, which should be considered when evaluating the results:

1) Bias 1—$P_{S1\ (v')}$ values calculated for $v_{v\rightarrow b}$ will be inflated relative to those calculated for $v'_{v\rightarrow v'\rightarrow b}$. This is because the assumed costs of traveling from node v to node v' and then to node b (the Bau) are higher than the real cost because materials would only have been carried part of the way ($v'\rightarrow b$).
2) Bias 2—If two sources v^1 and v^2 are evaluated as procurement alternatives for a source v, and v^1 is farther from the Bau than v^2, the $P_{S1\ (v')}$ value computed for $v^1{}_{v\rightarrow v1\rightarrow b}$ will be inflated relative to the value for $v^2{}_{v\rightarrow v2\rightarrow b}$.

Assessment of the proposed hypotheses To assess H_1, we evaluated each source (v) as follows. First, we isolated a local network segment by identifying a set of alternative sources requiring no or minimal deviations from the path to the Bau—that is, all v' where ($w_{v\rightarrow v'} + w_{v'\rightarrow b}$) is within 5% of $w_{v\rightarrow b}$. Next, we estimated, for each v and each v' in the local network segment, P_{S1} values using a non-scaled variant of our model, with *T* in Eq. (1) set to a constant equal to the minimum observed in the dataset. This enables us to compare the relative benefits afforded by the evaluated sources and their possible alternatives while controlling for access costs; to avoid confusion, from this point forward, we refer to P_{S1} values where access costs are controlled for as $P_{S1\ (tc)}$ (see also Table 1); these values are represented in Figure 1 by the size of the orange circles. For each source v, we then identified alternatives with greater relative benefits (i.e., greater $P_{S1\ (tc)}$ values), if any (see Fig. 1A and B).

We assessed H_2 by defining the relative benefits of each source and its alternatives as $P_{S1\ (v')}$ values that are computed for all valid procurement paths from each source to the Bau (i.e., $v_{v\rightarrow b}$, and $v'_{v\rightarrow v'\rightarrow b}$ for every alternative v'), using the procedure discussed in the previous section, concerning network navigation. For each source, we then identified the alternative with the highest $P_{S1\ (v')}$ value (i.e., optimal) as well as those ('good') alternatives whose $P_{S1\ (v')}$ values fall within the 95% confidence interval of the highest, to account for estimation uncertainties. We contend that although the sources we identify as optimal based on currently available data may not be identical to the set of true optimal sources (e.g., they might constitute a subset), the latter are likely to be included among the sources we identify as 'good.' This would be expected if source characteristics remained similar over time and our model performed well but not perfectly. We also performed the assessment on isolated subsets of the network that expand radially from the Bau to include nodes whose $w_{b\rightarrow v}$ edge weights (i.e., minimum walking times from the Bau) fell within cutoffs that increase in 10-minute increments. This allowed us to investigate the possibility that the evaluation of procurement alternatives may have been contingent on distance from the site and the area over which least-cost paths (i.e., network edges) must have been known. If this were the case, we would expect an increase in the ability to explain the data under H_2 up to a certain network size, followed by a steady decrease due to the addition of noise (i.e., nodes and paths that would have been too far to be considered in procurement decisions).

To assess H_3, we first identified all DEM cells reachable within 5 hours from the Bau, temporarily adding each as a node (hereinafter referred to as node *x*) to the network of sources. We chose a 5-hour cutoff somewhat arbitrarily, to keep computations manageable, but preliminary findings suggest that adding more distant locations would not have been informative (see Section 3.4). For each cell, we then evaluated all valid procurement paths to the Bau (i.e., $v'_{x\rightarrow v'\rightarrow b}$ for each cell *x*, and for each *v'* representing an accessible raw material source; see Fig. 1D), identifying optimal alternatives (i.e., highest $P_{S1\ (v')}$ value per cell) as well as 'good' alternatives whose $P_{S1\ (v')}$ values fell within the 95% confidence interval of the highest, to account for estimation uncertainties. We examined the proportions of S_0 sources among the 'good' alternatives at each DEM cell across the region, to determine the degree to which different landscape locations are compatible with H_3, and investigated any spatial patterning. Finally, for each raw material type, we also summed the number of DEM cells where their sources are identified as good or optimal procurement targets, that is, we calculated the areal extent over which a hominin could be expected to have targeted a given material and tested for a correlation with the frequency (i.e., number of lithics) with which the different raw materials are represented at the site.

3. Results

3.1. Resource selection model and P_{S1} estimation

A null model comparison indicates that the evaluated characteristics of the available sources have a highly significant combined influence on their probabilities (P_{S1}) of yielding raw material types that are also archaeologically represented at the Bau ($\chi^2 = 69.51$, df = 4, $p < 0.001$). As shown in Table 2 (see also SOM S4), the quality of the raw materials, the size of the area over which these are found, and the abundance of large nodules all had a positive effect. However, the strongest and most significant predictor is the minimum walking time required to reach the sources from the Bau, and its effect is negative; the higher the access costs of a source are, the less likely it is to provide raw material types represented at the site. These results are consistent with previous findings (e.g., Browne and Wilson, 2011) as well as theoretical expectations.

The estimated P_{S1} values for individual raw material sources are quite variable (minimum = 0.01, maximum = 0.89, mean = 0.29, SD = 0.2), and this is true even for sources assigned to the same source area. Estimated probabilities for the seven locations assigned to source area 55, for example, which yields the most common raw material type in the Bau assemblage (4981 artifacts), vary between a minimum of 0.27 and a maximum of 0.74, having a mean of 0.52. This variability is expected given the substantial differences in the characteristics of the sources (see SOM S2), including access costs (see Fig. 2) and the overall quality of the available nodules. It is nevertheless noteworthy because it strongly suggests that not all locations within a given source area represented at the Bau were exploited to the same extent and, indeed, some may not have been utilized at all. Also noteworthy, particularly given our present goals, is that several sources which are not represented at the Bau (n = 17, or 7%) were assigned high probabilities by our model ($P_{S1} > 0.5$, maximum = 0.87).

A confusion matrix analysis of cross-validated P_{S1} values indicates that our model can be used to classify sources as containing archaeologically represented raw material types with significantly more accuracy (76%, balanced = 65%, p = 0.018) than would be expected by chance alone based solely on the incidence of non-represented sources (245, or 70.8% of the 346 accessible sources) when using a threshold of 50% for the classification (that is, when sources with P_{S1} values greater than 0.5 are classified as used, and the rest unused). These results (Fig. 3) are driven mostly by the correct identification of sources with nonrepresented stone types (specificity = 0.91), as the sensitivity is low (0.39). In other words, the model performs well in assigning low probabilities to non-represented sources but also assigns low probabilities to many sources that provide stone types known to have been utilized at the Bau. This is not necessarily indicative of poor performance, however, because we do not know how many of these latter sources were in fact exploited by hominins inhabiting the site. It is quite likely that many were not, because a given raw material type could have come from a different source within its source area, so these results may well represent a worst-case scenario. Still, with eight of the 17 exploited source areas, all sources (22 in total) are assigned probabilities that fall below the threshold of 0.5, although their overall contribution to the Bau is only 104 lithics (0.7% of the provenanced pieces). Regardless, these results indicate that the model can be used to meaningfully predict likelihoods for new cases within the region, such as known sources being evaluated from different landscape locations and therefore having different access costs. For reference, the Kvamme gain (Kvamme, 1988) value here is 0.551.

3.2. P_{S1} as a proxy measure of relative benefit

P_{S1} values appear to be good proxy measures of the relative perceived benefits afforded by different procurement alternatives. A Spearman's rank correlation test revealed a strong and significant positive relationship between the number of stone artifacts produced from different raw material types and the maximum cross-validated average (across the 100 replications) P_{S1} values predicted for individual sources where such materials can be obtained (r_s

Table 2
Scaled logistic resource selection model coefficients with unscaled means and standard deviations.

Term (scaled)	Estimate	SE	Lower CL	Upper CL	Mean	SD	*p*-value
Intercept	− 1.122	0.144	− 1.414	− 0.849	N/A	N/A	<0.001
Q_t	0.449	0.134	0.190	0.718	0.785	0.486	<0.001
E_t	0.351	0.141	0.077	0.629	64.888	50.332	0.013
T_t [a]	− 0.889	0.158	− 1.212	− 0.592	107.837	33.387	<0.001
L_t	0.376	0.136	0.110	0.646	0.887	0.882	0.006

Abbreviations: Q_t = quality (log), E_t = extent (square root), T_t = time from Bau (square root), L_t = large rock abundances, SE = standard error of the estimate, CL = confidence limit, SD = standard deviation, N/A = not applicable.

[a] Corresponds to the minimum travel times required along least-cost routes from the Bau.

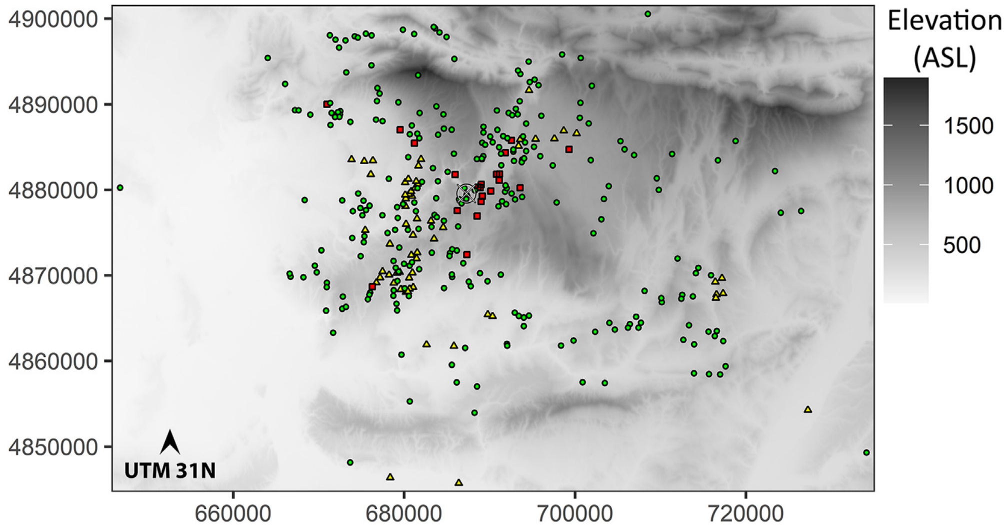

Figure 3. Compatibility of archaeological observations and source classification based on cross-validated P_{S1} values. Sources correctly classified as S_0 ($n = 224$) or S_1 ($n = 39$) when using a threshold of 0.5 are shown by green dots. Red squares identify unused (i.e., S_0) sources incorrectly classified as S_1 ($n = 21$). Yellow triangles identify S_1 sources (i.e., from exploited source areas) incorrectly classified as S_0 ($n = 62$). Note that most sources can be classified correctly based on their cross-validated P_{S1} values alone, but several misclassified unused sources with high values (i.e., unexplained) are located close to the site. In fact, most of the sources in the vicinity of the site (within ca. one hour of walking; see also Fig. 2) are incorrectly classified as yielding archaeologically represented materials. Coordinates are given in meters for UTM zone 31N, and elevation values are given in meters above sea level (ASL). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

[15] = 0.757; $p < 0.001$). This relationship remains significant if the mean (r_s [15] = 0.612, $p = 0.009$) or median (r_s [15] = 0.488, $p = 0.047$) estimates for source areas are used, but it is considerably weaker than observed with maxima, which to us suggests that exploitation was driven by the preferential use of the most desirable (i.e., highest P_{S1} value) sources; accounting for sources with relatively low P_{S1} values seems to add noise, likely because many such sources were not actually used. The strength of this relationship, which is visually represented in Figure 4, is consistent with a good overall performance of our model as well as with substantial uniformity in criteria shaping the management of lithic resources: factors that rendered specific sources of stone desirable from the perspective of the Neanderthal inhabitants of the Bau seem to have proportionally influenced the quantities of raw materials collected from these sources and/or the degree to which they were reduced before discard.

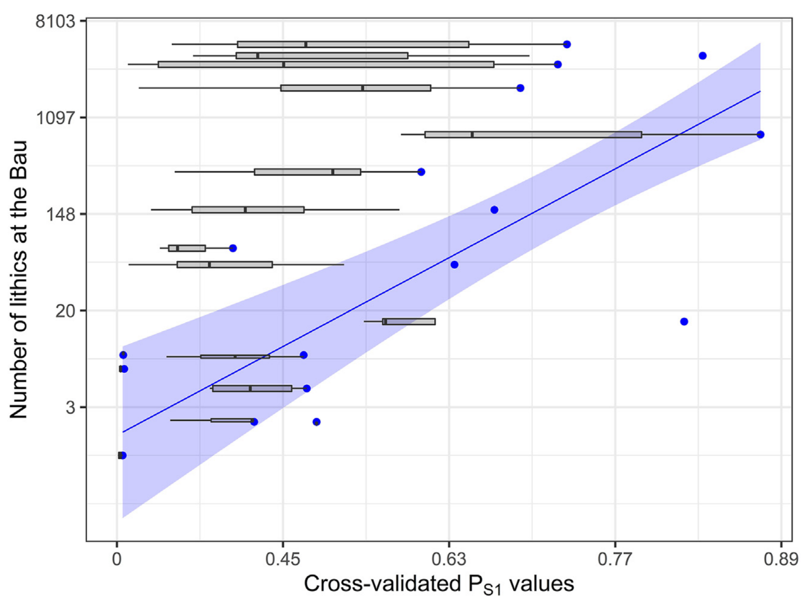

Figure 4. Cross-validated P_{S1} values as proxies for archaeological representation. The number of lithics at the Bau is significantly and positively correlated with P_{S1} values (maximum cross-validated averages; blue dots) estimated for source areas represented at the Bau. Blue line and shaded area show a fitted negative binomial model and its 95% confidence limits. Boxplots represent the range of variation in P_{S1} values per source area. Note that P_{S1} values are computed with access costs set to minimum walking times from the Bau. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.3. Evaluation of Hypothesis 1—Exploitation of the best sources available directly en route to the site

The data do not support our first hypothesis (H_1). Although this hypothesis can explain the lack of exploitation of a substantial proportion of the unused sources (at least 134, or 54.7%, and plausibly as many as 190, or 77.6%; see Table 3), a larger proportion (224, or 91.4%) can be accounted for simply by classifying all sources with a cross-validated P_{S1} value below 0.5 (i.e., 50%) as unused. Moreover, the sources which we cannot explain under this hypothesis (red squares in Fig. 5; see also Table 3) also cover a larger area than sources incorrectly classified based exclusively on their cross-validated P_{S1} values, and several are located close to the site (compare Figs. 3 and 5). Sources identified as exploitable under H_1—that is, those sources for which we found no better procurement alternatives on the way to the Bau—do explain a slightly larger fraction of the artifacts than sources with cross-validated P_{S1} values above 0.5, but the difference is negligible (15,574 lithics made from 10 of the 17 raw material types represented at the Bau, versus 15,570 made from nine such raw materials). In any case, the evaluation of this hypothesis does reveal an important fact: at most unused sources (54.7%), the best procurement option en route to the Bau would not have been the source itself, but rather a source from an exploited source area.

3.4. Evaluation of Hypothesis 2—Exploitation of the best sources available in the region

Full source network Overall, the available data provide support for our second hypothesis. Under this hypothesis, and if we consider only optimal procurement alternatives (hereinafter, H_{2a}), all but eight sources are predicted to have been ignored in favor of exploiting even better sources (see Fig. 1C for an explanation). Those eight optimal sources, for which we could identify no alternatives with higher $P_{S1\ (v')}$ values, include six S_1 sources (i.e., from exploited source areas) and two unused ones (i.e., S_0). The sources which cannot be explained under this hypothesis, namely the two optimal sources that should have been used but were not, and the 34 other sources where these constitute, according to our algorithm, the best procurement options (Table 4) are all located far from the site (Fig. 6). Conversely, all sources located within 17 km from the Bau can be explained: these are sources from where, according to our algorithm, the six optimal S_1 sources should have been targeted. The latter can account for five raw material types, or 12,986 (83%) of the lithics found at the site. It should be noted that reaching them from sources where they are identified as optimal procurement choices would have required substantial deviations from the direct, least-cost paths to the Bau (median = 9%, or 16 minutes; interquartile range

Table 3
Summary of the fit between observed and predicted source classification under Hypothesis 1.[a]

Actual set	Predicted S_0 (S_{0p})	Predicted S_1 (S_{1p})	S_{0p} with S_1/S_{1p} options	S_{0p} with S_1/S_{1p} best option	Misclassified as S_{1p}	S_{0p} and no S_1 options
S_0	217	28	190[b]	134	28	24
S_1	77	24	75	71	N/A	2

[a] Hypothesis 1 (H_1). S_0 = set of sources that are not represented at the Bau; S_1 = set of sources from archaeologically represented source areas; S_{0p} = set of sources predicted to be unused under H_1; S_{1p} = set of sources predicted to be used under H_1; N/A = not applicable. Options refer to better alternatives available enroute to the Bau. Columns 2 and 3 show the predicted versus observed source classification; columns 4 and 5 indicate unused or likely unused sources that are explainable under H_1; columns 6 and 7 indicate sources that cannot be explained under H_1.

[b] Excludes three cases where an S_1 option exists but is predicted to have been unused.

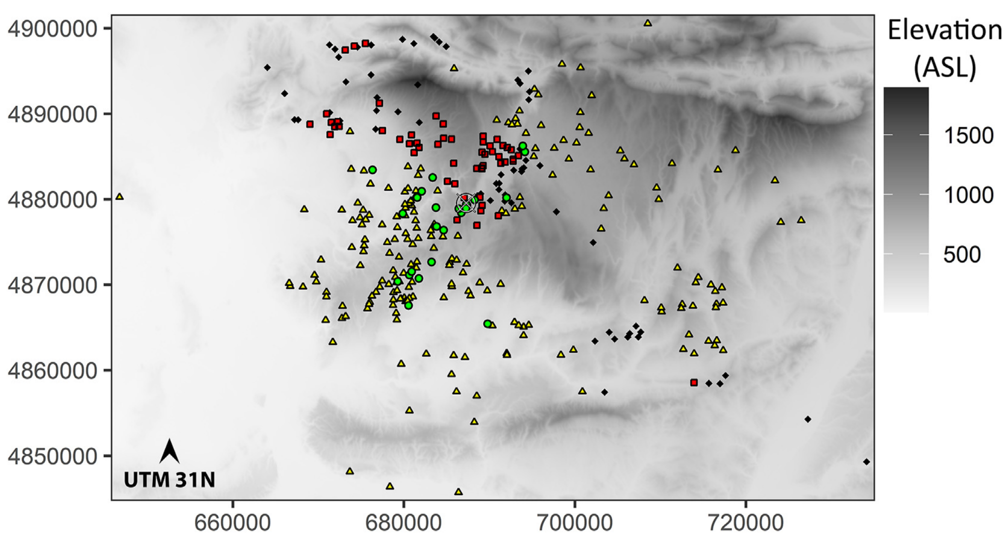

Figure 5. Compatibility of raw material sources with archaeological observations under Hypothesis 1 (H_1). Sources that cannot be explained under H_1 are identified by red squares (high confidence) if the only options from their locations are unused, S_0 sources, or black diamonds (lower confidence) if the best procurement option is an unused, S_0 source, but S_1 sources are identified among the possible alternatives. Sources that can be explained are identified by green dots or yellow triangles. The former denote sources predicted to have been exploited and which yield archaeologically represented materials; sources indicated by yellow triangles are predicted to have been bypassed in favor of sources identified by green dots. Note that fewer unused (S_0) sources can be explained under this hypothesis than if spatial relationships between sources are ignored and cross-validated P_{S1} values are used for classification (see Fig. 3). Note also that unexplained sources cover a large area around and to the northwest of the site. The location of the Bau is indicated by the circle with crosshairs. Coordinates are given in meters for UTM zone 31N, and elevation values are given in meters above sea level (ASL). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Summary of the fit between observed and predicted source classification under Hypothesis 2a.[a]

Actual set	Predicted S_0 (S_{0p})	Predicted S_1 (S_{1p})	S_{0p} with S_1/S_{1p} best option	Sources with misclassified S_{1p} best options[b]
S_0	243	2	210	35
S_1	95	6	94	1

[a] Hypothesis 2 (H_{2a}) with optimal alternatives. S_0 = set of sources that are not represented at the Bau; S_1 = set of sources from archaeologically represented source areas; S_{0p} = set of sources predicted to be unused under H_{2a}; S_{1p} = set of sources predicted to be used under H_{2a}. Options refer to better alternatives available on the way to the Bau. Columns 2 and 3 show the predicted versus observed source classification; column 4 indicates sources that are explainable under H_{2a}; column 5 indicates sources which are not.
[b] Sources where an unused source (S_0), wrongly predicted to have been used by our algorithm (column 3), was identified as the top procurement option.

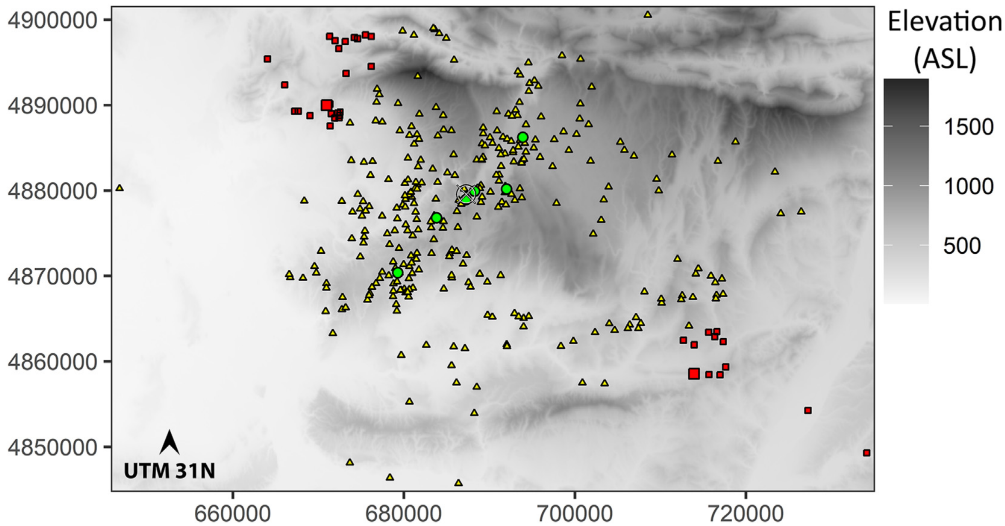

Figure 6. Compatibility of raw material sources with archaeological observations under Hypothesis 2, with optimal alternatives (H_{2a}). Sources that cannot be explained under H_{2a} are shown as red squares. Large squares denote optimal procurement choices that were not used; small squares denote sources where unused sources (large squares) are predicted to be top alternatives. Sources that can be explained are shown as green dots (sources predicted to have been used and which yield archaeologically represented materials) or yellow triangles (sources predicted to have been bypassed in favor of procuring materials from sources identified by green dots). The location of the Bau is indicated by the circle with crosshairs. Note that all unused sources found within 17 km of the site can be explained under this hypothesis, and the identified optimal exploitation targets (green dots) can account for 83% of the lithic materials found at the site. Coordinates are given in meters for UTM zone 31N, and elevation values are given in meters above sea level (ASL). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

[IQR] = 17.75%, or 32 minutes; with 25% of cases necessitating deviations of >20% or 38+ minutes).

If, to increase the likelihood of including all true optimal sources in the set of sources classified as S_{1p} (i.e., exploitable) under H_2, we also consider other ‘good’ options available at each evaluated location, the sources predicted to have been unused number 272. Of the sources thus classified as S_{0p} under this implementation of H_2 (hereinafter, H_{2b}; see Table 1), 70 are from exploited source areas (i.e., S_1) and 202 are unused (S_0) ones. Conversely, 31 of the 74 sources classified as S_{1p} are in fact S_1 and 43 are S_0. The latter are distributed throughout the region (pink squares in Fig. 7) and, although we cannot account for their lack of exploitation under H_{2b}, at no evaluated location do they constitute the only ‘good’ alternatives. Indeed, of the ‘good’ procurement options identified at each source (median = 8, IQR = 6, maximum = 33), one or more of the 31 S_1 sources typically constitute the majority (minimum = 17%; median = 63%; maximum = 100%). These S_1 ‘good’ alternatives belong to 14 of the 17 archaeologically represented source areas and can account for 15,659 (99.9%) of the lithic artifacts recovered at the site.

The three raw material types whose presence at the Bau cannot be explained under H_{2b} can only be found at substantial distances from the site (minimum = 3.9 hours). One is represented by a flake made of a volcanic rock collected along the Durance River, which could have reached the site by simple chance, as an unusual component of a mobile toolkit (see Brantingham, 2003; Pop, 2016). The other two consist of Oligocene flints collected in the eastern part of the study region from sources located at more than 5 hours from the Bau (Fig. 2) and silicified crust that formed on top of ochre deposits at Roussillon, closer to the site. While the presence of these materials is noteworthy, it is important to keep in mind that they contribute negligibly to the assemblage (15 artifacts, or ca. 0.1%). Overall, we find that when the entire network of sources is considered, H_2 fails to explain why up to 43 S_0 sources were never exploited, but also that it could explain them all, and that it may account for a larger proportion of archaeological artifacts and archaeologically represented raw material types than H_1.

Expanding source networks The ability to explain the available data under H_2 is likely contingent on the area covered by the evaluated resource network: the inclusion of very distant resources is likely to add noise, whereas the exclusion of all but the closest sources is likely to leave a large portion of the data unexplained. We therefore expected to see an increase in the ability to explain the data with a growing resource network, up to a point that reflects the size of the area over which procurement decisions were likely taken by hominins using the Bau, and then a gradual decline with the inclusion of sources located further away.

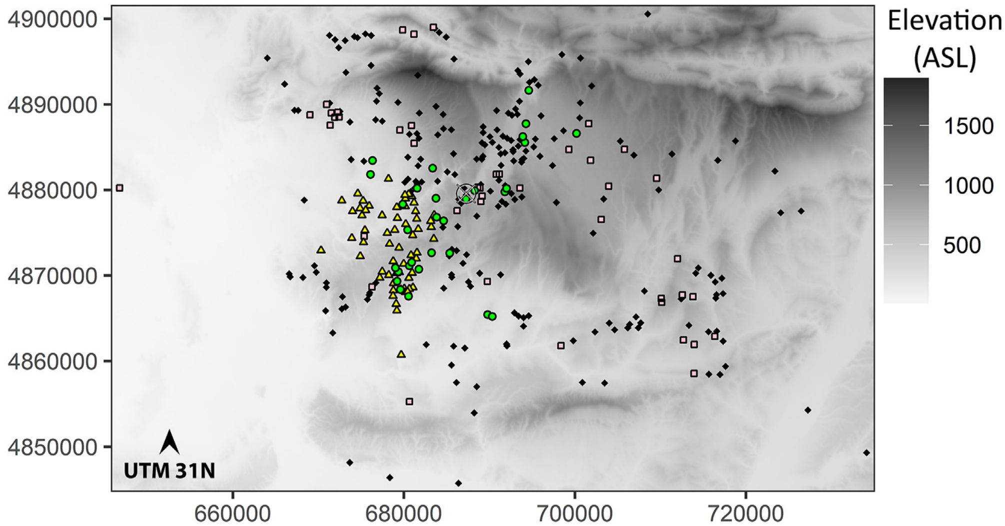

Figure 7. Compatibility of raw material sources with archaeological observations under Hypothesis 2, with 'good' alternatives (H_{2b}). Sources explainable under H_{2b} with high confidence are indicated by green dots (S_1 sources identified as 'good' alternatives) and yellow triangles (sources predicted to have been bypassed in favor of those 'good' alternatives; no 'good' S_0 alternatives identified). Sources explainable under H_{2b}, but with lower confidence, are indicated by pink squares (43 unused sources predicted to have been 'good' procurement options) and black diamonds (sources where 'good' alternatives could have included unused sources). Note that 'good' procurement alternatives from exploited source areas (green dots) exist for all sources in the region; in other words, the lack of archaeological representation of all unused sources may be explainable if we allow for some uncertainties in the identification of optimal procurement alternatives (cf. Fig. 6). The location of the Bau is indicated by the circle with crosshairs. Coordinates are given in meters for UTM zone 31N, and elevation values are given in meters above sea level (ASL). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Our results, summarized in Figure 8, indicate that this is indeed the case. The few sources found within 30 minutes of the site explain the data very poorly because 1) they can account for a maximum of 768 provenanced lithics (ca. 5%), 2) under H_{2b} we can only predict with relative confidence the lack of exploitation for ca. 33% of the S_0 sources available within this restricted resource network (black line 'A' in Fig. 8), and 3) only ca. 50% of the available 'good' targets identified under H_{2b} are S_1 sources (red dashed line 'B' in Fig. 8). From this minimum of explanatory power seen with sources found within 30 minutes of the Bau, the proportions of S_0 sources that can, with some confidence, be predicted to have been ignored under H_{2b} increases steadily as we increase the size of the evaluated network, and so does the proportion of 'good' procurement alternatives that are S_1 sources and, importantly, the number of explainable lithics (i.e., those that could have been procured from those S_1 sources).

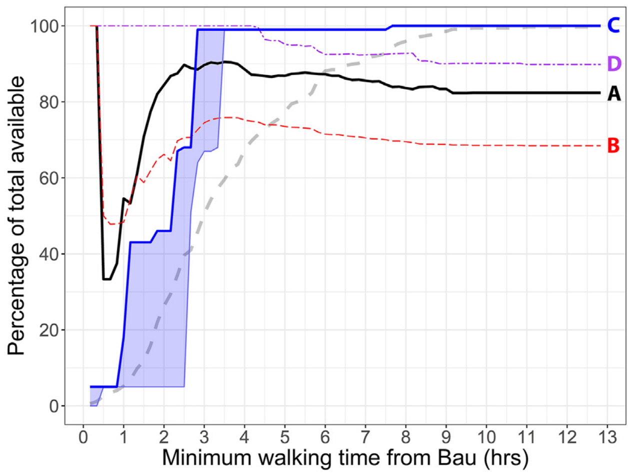

Figure 8. Hypothesis 2 with increasing resource network sizes. The ability to explain the data improves as more distant sources are added, up to the inclusion of sources requiring minimum walking times of ca. 3.5 h from the site, and then declines. The threshold (ca. 2.5–3.5 hours) likely represents the limits of the regular active resource exploitation area around the site. Note that the resource network is expanded radially from the Bau in 10-minute increments (minimum walking times) to include sources with increasingly greater access costs (proportion of the total [346] indicated by grey dotted line). Line A (black) represents the proportion of unused sources (S_0) predicted to have been ignored under H_{2b} at different network sizes. Also shown is the proportion of 'good' alternatives made up of S_1 sources (B, red dashed line), the minimum and maximum quantities of archaeological artifacts these good S_1 procurement alternatives can explain (C, blue line, with the range denoted by the shaded area), and the proportion of optimal procurement alternatives (H_{2a}) made up of S_1 sources (D, purple dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

This increase in the ability to explain the data can be observed until the weights of the network edges connecting the Bau to sources (i.e., minimum walking times) reach values of ca. 3.5 hours, at which point the resource network comprises 206 nodes/sources, or ca. 60% of the total. Within this network, optimal procurement targets identified under H_{2a} are S_1 sources in 100% of cases (purple line 'D' in Fig. 8) and can account for the utilization of 5 of the 17 exploited raw material types as well as 12,986 of the sourced lithics. Procurement alternatives identified as 'good' under H_{2b}, on the other hand, are mostly S_1 sources (76%; red dashed line 'B' in Fig. 8) and can account for 15,574 (ca. 99.4%) of the sourced artifacts and 11 of the 17 exploited source areas. Moreover, the proportion of available S_0 sources whose lack of utilization is confidently explainable under H_{2b} reaches 91%. The inclusion of sources located at more than 4 h from the site adds considerable noise, resulting in the identification of some unexploited (S_0) sources as optimal procurement targets (see purple line 'D' in Fig. 8) and a decrease in the proportion of 'good' candidates that are S_1 of sources (to ca. 68% if sources located at more than 10 hours from the Bau are considered), but it does not improve our ability to explain the archaeological data except very marginally (two additional raw material types, and 81 additional provenanced artifacts). In brief, under H_2, the available data are most consistent with an excellent knowledge of the best-available procurement options for locations reachable within 2.5–3.5 hours from the site; within this radius, H_2 can explain the lack of utilization of at least 91% of the available S_0 sources (possibly all), as well as the presence of most (99.4%) of the sourced lithics recovered at the site.

3.5. Evaluation of Hypothesis 3—Optimal exploitation of the best sources available in the region

The set of sources predicted to have been ignored or avoided under Hypothesis 3 (H_3), and consequently the set of sources deemed to have been exploitable, is identical to that predicted under H_2 for any given maximum cutoff value for travel times from the Bau (see Section 3.4). When this cutoff is set to 5 hours, six S_1 sources are identified as optimal alternatives over 96.2% of the area (ca. 1305 km^2 of 1356 km^2), and a lone S_0 source (ID 223) is identified as the optimal procurement choice over the remaining 3.8%—in other words, H_3, similar to H_2, can account for the lack of utilization of 99.4% of 175 unused (S_0) sources available within 5 hours of the site. The number of locations (i.e., DEM cells) where these S_1 and S_0 optimal alternatives are expected to have been targeted has a predictable but not statistically significant relationship with the number of lithics made from materials that can be procured at these, with one exception (Spearman's $r_s\ [3] = 0.9$, $p = 0.083$ with source ID 48 excluded; $r_s\ [4] = 0.37$, $p = 0.497$ with it included). This exception, which is identified as an optimal choice over ca. 31% of the area, only accounts for up to 16 of the provenanced lithics found at the site and may be explainable by a lack of utilization of certain areas or, possibly, by an incorrect (over-)estimation of its $P_{S1\ (v')}$ value. Be that as it may, optimal resource selection based on knowledge of the relative benefits afforded by the available sources (i.e., nodule sizes, quality of the materials, and extent over which they may be found) and the cost of accessing them, fit the data well, although not necessarily equally well, regardless of where a hominin might have been located when deciding where to procure raw materials on their way to the Bau.

The set of 'good' alternatives identified for locations (i.e., DEM cells) within 5 hours of the Bau includes 51 unique sources. Of these, 28 belong to the set S_1 that yields archaeologically exploited raw materials, representing 12 of the utilized source areas and accounting for up to 15,578 of the provenanced lithics (i.e., 99.4%) at the site. The other 23 are sources that are not represented at the

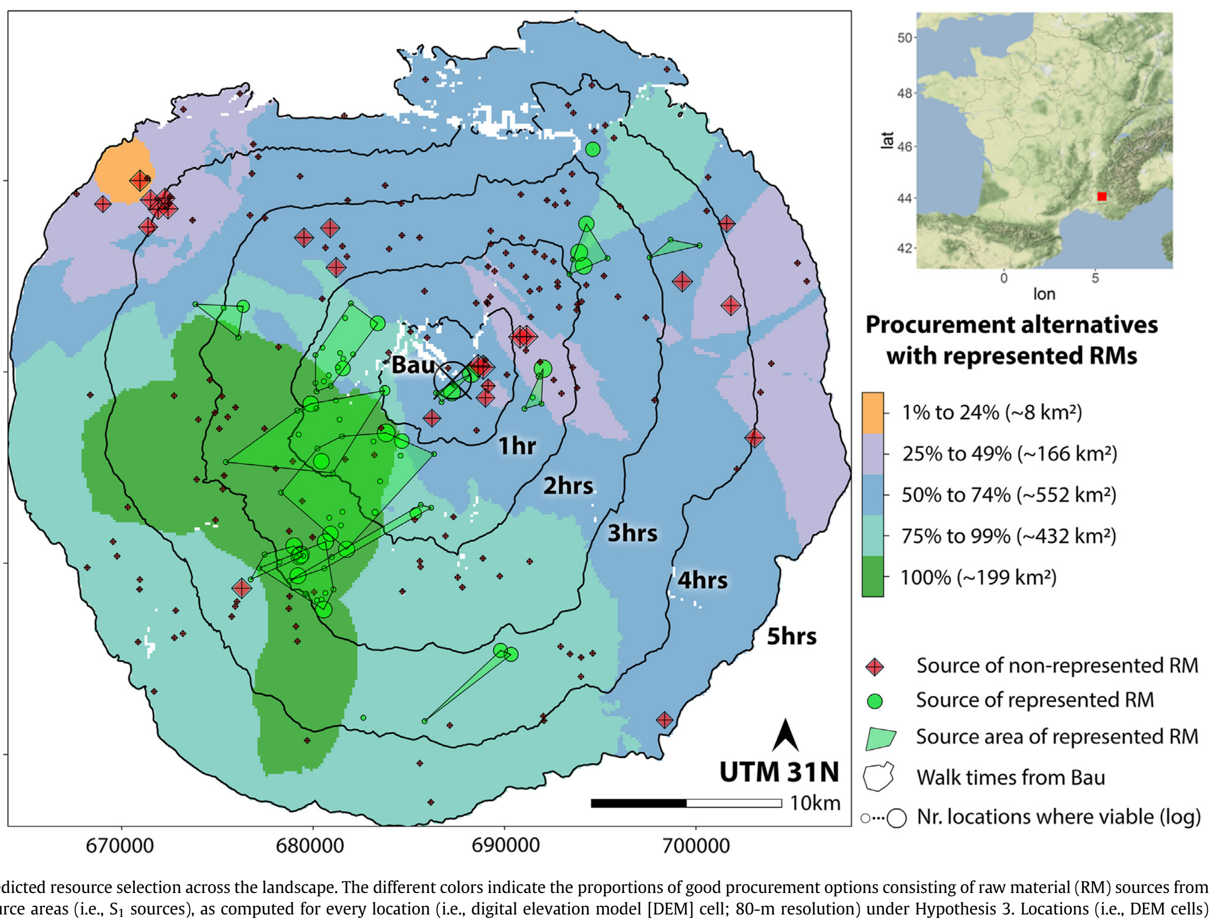

Figure 9. Predicted resource selection across the landscape. The different colors indicate the proportions of good procurement options consisting of raw material (RM) sources from exploited source areas (i.e., S_1 sources), as computed for every location (i.e., digital elevation model [DEM] cell; 80-m resolution) under Hypothesis 3. Locations (i.e., DEM cells) where these proportions reach minimal (1–24%) and maximal (100%) values are shown in orange and dark green, respectively, whereas cells with intermediary values are shown in purple, blue, and teal. Green circles represent S_1 sources available within 5 h of the site, whereas red diamonds represent S_0 (i.e., unused) sources; the size of the circles and diamonds indicates the size of the area (i.e., number of DEM cells) over which the respective sources are identified as good procurement alternatives, on a logarithmic scale. Green polygons represent convex hulls encompassing sources from individual exploited source areas, and concentric rings show GIS-computed distances that can be covered walking away from the site, in 1-hour increments (minimum walking times). Note that throughout the region the identified good procurement options are mostly sources from exploited source areas; some unused sources (red diamonds) located close to the site are identified as good procurement alternatives from a large number of locations, but from those same locations good alternatives also include S_1 sources, the latter accounting for a majority of options in most cases. Nr. = number. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Bau and set an upper limit to the number of seemingly unused sources (of the 175 available within 5 hours) that cannot be explained under H_3. The number of 'good' alternatives identified per DEM cell varies (mean = 9, SD = 3, maximum = 22), and as shown in Figure 9, they typically consist of S_1 sources (mean = 71.8%, minimum = 14%, maximum = 100%). At most locations (78.3%), these constitute half or more of the alternatives, and no 'good' S_0 options can be identified over an area of some 199 km^2 (14.7%).

Digital elevation model cells where specific sources are identified as 'good' options form areas of variable size (mean = 239.1 km^2, median = 90.3 km^2, maximum = 1310.3 km^2). A Spearman's rank correlation test indicates that when these areas are summed for each of the 23 raw material types represented by the 51 unique options, they are moderately and positively correlated with the number of sourced artifacts made from those materials (r_s [21] = 0.49, p = 0.017). If we assume the identification of nonutilized sources among the 'good' alternatives represents an error, and therefore only consider the areas serviced by alternatives from exploited source areas, the correlation becomes much stronger (r_s [10] = 0.76, p = 0.004). We interpret these correlations as indicating that 1) in the aggregate, and based solely on the lithic data, we cannot reject the possibility of a relatively uniform utilization of the region by the hominins responsible for the accumulation of the Bau assemblages and 2) that, regardless of where they might have been located, these hominins could identify and target sources that would have been optimal or close to optimal procurement choices.

4. Discussion

The idea that the probability of observing raw materials from a given source at an archaeological site depends not only on the characteristics and accessibility of the source itself but also on the presence of alternatives which may be intrinsically better, more accessible, or both, is certainly not new (e.g., Wilson, 2007b and references therein; Pop, 2016). Nevertheless, most lithic sourcing studies consider the impact of such alternatives only in terms of the position of different sources vis-à-vis a site, without considering spatial relationships between the sources themselves. Our results highlight the importance of such spatial relationships because several sources that may seem attractive when considered on an individual basis may turn out to be poor choices when considered in light of the alternatives. In this same vein, the results presented here highlight the interpretive potential of directly addressing another aspect that is seldom the explicit focus of sourcing studies, namely, why certain resources were not utilized at all.

At the French Middle Paleolithic site of the Bau de l'Aubesier, Neanderthals appear to have ignored many of the lithic resources available to them for some 100 millennia. In this study, we set out to evaluate three potential explanations for why this may have been the case, all premised on rational decision-making but requiring increasingly sophisticated spatial knowledge and navigational skills. To this end, we modeled the resource selection criteria evidenced in the archaeological assemblages and applied these to assess what procurement options would have been viable under the different scenarios if sources are considered as embedded in a network of potential alternatives. We found that most unused sources (55–77.5%) could be explainable by the simple fact that resources which would have been considered to be better, and which yield archaeologically represented raw material types, were available along the least-cost paths to the site (H_1).

We also found that a larger proportion of the unused sources (82–100%) may be explained if we allow for the possibility that hominins were able to identify and procure materials from globally (i.e., with all alternatives considered) optimal, or close to optimal, procurement targets (H_2). Indeed, if we further allow for the possibility that procurement was largely restricted to a 3.5-hour radius from the Bau, we can explain between 91% and 100% of the unused sources, while simultaneously accounting for 83–99.4% of the provenanced lithics recovered at the site. The identification of such globally optimal or close to optimal procurement targets would have required good knowledge of the available sources, including minimum travel times between each. However, the set of such targets is relatively small—a minimum of 14 optimal or close to optimal sources, or one per distinct raw material type, and a maximum of 31—and it is therefore possible that knowledge of their viability could have been transmitted socially, resulting in fixed reference points in foraging 'mental maps' (see Roebroeks et al., 2011). In fact, our second hypothesis is not informative with regards to how these optimal resources might have been targeted and exploited from the Bau.

We did, however, consider a scenario in which procurement decisions were taken, at least occasionally, while foraging for nonlithic resources within a 5-hour radius of the site (H_3), and we assessed whether the available archaeological data are consistent with an optimal targeting of lithic resources under such a scenario. If, in such an embedded procurement context (sensu Binford, 1979) trips to collect raw materials on the way to the Bau had an equal chance of being initiated anywhere in the region, reflecting a uniform utilization of the environment, raw material types identified as optimal alternatives over larger areas would be expected to be represented proportionally more frequently at the site. This is precisely what is observed at the Bau, where the correlation between these variables is in fact rather staggeringly strong, given the underlying assumptions. Such capacity to identify optimal procurement targets at arbitrary locations across large portions of the study region implies an ability to not only accurately recall the characteristics of nearby resources but also estimate access costs on demand, regardless of one's location; in other words, it implies more than simple knowledge of which resources are worth exploiting in the region, and which are not.

It should be noted that the degree to which H_2 and H_3 can account for archaeological observations at the Bau may be underestimated because violations of the assumptions that are built into our approach, and which are likely to some degree, should result in a lower-than-warranted fit. For instance, we would expect weak results if the resource selection model cannot be applied symmetrically, that is, regardless of which end of an evaluated procurement path represents the Bau. Similarly, violations of our null assumption regarding the effects of transporting rocks would reduce our chances of explaining nonutilized (S_0) sources under these hypotheses because $P_{S1(v')}$ values for evaluated sources, most of which belong to the set S_0, would be inflated relative to the $P_{S1(v')}$ values of the alternatives (see Bias 1 in Methods). The impact of a second potential bias (i.e., that sources located farther from the Bau may have inflated $P_{S1(v')}$ estimates compared to ones located closer by—see Methods) is more difficult to evaluate, but it is unlikely to result in more favorable findings, that is, in more S_0 sources being accounted for than warranted under H_2 and H_3.

Overall, we find that the lithic data from the Bau are most consistent with the direct (i.e., from the site) acquisition of raw materials over an active exploitation area of ca. 306–650 km^2 (a radius of 2.5–3.5 hours of walking). Only a few raw material types, accounting for a virtually negligible quantity of archaeological artifacts (n = 102), are better explained by indirect procurement through other sites. This is because we identified optimal candidates by computing access costs under the assumption that the Bau was the end destination of procurement journeys—from the perspective of other sites, the set of optimal candidates could indeed be very different. The results are therefore surprising because the distances involved extend beyond the daily foraging radius of five to perhaps 10 km normally seen with ethnographic hunter-gatherers (e.g., Kelly, 1995), and the exceptional circumstances under which larger distances are recorded for the latter (e.g., Bailey and Davidson, 1983) likely do not apply. Indeed, the active exploitation area at the Bau falls well within the range reported by Marlowe (2005) for minimum hunter-gatherer home ranges ethnographically documented across the world, which encompass all areas exploited by local groups and not just individual site exploitation territories sensu Bailey and Davidson (1983). It is possible, however, that allowing for inaccuracies in the detection of optimal candidates fits the data best because the former reflect the influence of procurement while at other camps. This is an alternative we are currently investigating through simulations of a minimally realistic, agent-based model of lithic raw material management for the region, which aims to evaluate the potential effects of residential mobility on raw material variability. Regardless, the lithic data from the Bau do not support the notion that Neanderthals exploited smaller territories than is typically seen with anatomically modern humans (cf. Verpoorte, 2006; Macdonald et al., 2009; Henry et al., 2017).

Our results indicate that Neanderthals were probably not at a disadvantage in terms of their spatial abilities, at least not in environments they were well acquainted with (cf. Burke, 2012; also refer to the studies by Raynal et al., 2013 and Wynn and Coolidge, 2016). As noted earlier, the avoidance of certain resources in the area surrounding the Bau is consistent with not only an excellent knowledge of the location, characteristics, and least-cost paths linking different resources to each other and to the site but also the ability to identify optimal or close to optimal procurement alternatives from arbitrary locations on the landscape. This would have presupposed accurate estimations of access costs, implying a location-specific awareness of directions and distances to different options that we contend is most easily explained in terms of Euclidean mental representations of space. Navigation using Euclidean mental maps is based not on salient landmarks and the reuse of paths but on comprehensive ‘birds-eye’ (Wynn and Coolidge, 2016) metric knowledge of the environment that allows access costs to be computed from any possible direction. Such navigational skills, proposed for chimpanzees (*Pan troglodytes verus*) by Normand and Boesch (2009) but generally considered to be absent today in species other than our own, represent the most efficient but also most cognitively demanding wayfinding mechanism (Normand and Boesch, 2009; Trapanese et al., 2018). Without the ability to use Euclidean mental maps, however, the surprising strength of the correlation reported in Section 3.5 is difficult to explain. The presence of such spatial abilities in Neanderthals, who began diverging from our lineage some 600–800 kyr ago or more (Prüfer et al., 2014; Gómez-Robles, 2019; Petr et al., 2020), would add support to the view that modern spatial cognition already existed by 500 kyr ago (Wynn and Coolidge, 2016, and references therein). However, although selectivity and optimization in raw material procurement are known from the Oldowan onward (e.g., Stout et al., 2005; Braun et al., 2009; Key et al., 2020), the kind and degree of optimization evidenced at the Bau remains, to our knowledge, undocumented in earlier contexts.

A conceivable alternative is that the topography of the landscape could have directed Neanderthals through source areas which are, as a result, more frequently represented at the site. While the mobility potential of the landscape likely did play a role, as highlighted in fact by the evaluation of our first hypothesis, we do not think it can explain the available data. In part, this is because under such a scenario, we would expect utilized source areas located closer to the site to be represented more frequently than sources further afield, yet this is clearly not what we see at the Bau. Nevertheless, examining the structuring effects of terrain on movement throughout the region is a research avenue well worth pursuing in the future, through the application of either White and Barber's (2012) ‘From Everywhere to Everywhere’ approach or Llobera et al.'s (2011) focal mobility networks. At the very least, it could lead to the incorporation of additional variables, such as source accessibility, resulting in a more refined model. A similarly promising avenue of research involves exploring the effects of carried load, and potentially the incorporation of this variable into a future iteration of the model presented here.

The use of stone resources at the Bau reflects overall pragmatic, rational, and informed choices aimed at optimizing returns. The strong correlation between P_{S1} values computed for the available sources and the number of artifacts made from materials that may be found at those sources further indicates remarkable consistency in raw material management strategies (from procurement to discard), in turn pointing to an essentially fully utilitarian use of stone. Indeed, the frequencies of lithic raw materials at the Bau appear to be largely explainable without consideration of how tools were used, curated, or reduced, without consideration of toolkit sizes or lengths of occupation, or other factors that may be expected to have played an important role in explaining specific instances of technological organization (e.g., Dibble, 1991; Kuhn, 1995; Andrefsky, 2008). We suggest that this is due, on the one hand, to the richness of raw material sources in the region, which placed no special constraints on the use of stone, and, on the other hand, to the fact that we considered the material consequences of human behaviors averaged over a time span of some 100,000 years. This meant that any workable explanation had to reflect fundamental and enduring principles rather than behaviors specific to individuals, groups, or time periods. In other words, we are not suggesting that individual Neanderthals or Neanderthal groups exploited the landscape uniformly, always striving to procure raw materials from optimal sources in accordance with some universal criteria, and producing implements from these in an identical manner. That was clearly not the case. When the archaeologically visible outcomes of all actions performed by every individual who spent some time at the Bau over a period of 100,000 years are considered together, however, such variability becomes little more than noise. This is a strength, rather than a weakness, of dealing with large-scale time-averaged palimpsests in human evolution because the physiological and cognitive affordances underlying such variability can become easier to distinguish. As it has long been recognized by proponents of time perspectivism, different processes and phenomena may become apparent depending on the chosen temporal scale and resolution, and, depending on the questions asked, coarser resolutions can be an advantage rather than a handicap (see Bailey, 2007; see also the study by Holdaway and Wandsnider, 2008).

It is important to note, however, that our results reflect solely the use of lithic materials at the site. They need not apply to the exploitation of other resources, which may well reflect different territorial extents, for instance (Cole, 2002). Regardless of the resource being examined, however, what our results do demonstrate is the importance of considering all alternatives available in an area, not just those for which we have clear evidence of utilization. They also warn against the hasty dismissal of nonutilized resources as simply unavailable in the past, or to their attribution to cultural factors (e.g., prohibitions against accessing certain areas). Finally, they underscore the fact that the purposeful selection of resources is compatible with embedded procurement, which need not presuppose chance encounters with raw material sources (also refer to the study by Elston, 2013).

5. Conclusions

Our analyses of the comprehensive stone resource utilization dataset available for the French Middle Paleolithic site of the Bau de l'Aubesier indicate that Neanderthals had excellent spatial knowledge and navigational abilities. These data suggest a detailed knowledge of a large area, an ability to accurately navigate the environment using Euclidean mental maps, and a pragmatic strategy of lithic exploitation based on minimizing costs (travel and search times) and maximizing utility. Virtually all the available information can be accounted for under this framework, including the exploitation of certain sources, the avoidance of others, and the degree of archaeological representation of different raw material types. While alternative explanations could undoubtedly be formulated, it is difficult to envision one of comparable simplicity and consistency with the entirety of the available resource procurement data.

Declaration of competing interest

The authors declare no known conflict of interest.

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Supplementary Online Material

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Supplementary Online Material (SOM):

Evaluating landscape knowledge and lithic resource selection at the French Middle Paleolithic site of the Bau de l'Aubesier

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SOM S1

Raw material distribution across the Bau sequence

The stratigraphy of the site is complex, and a large number of layers and sub-layers have been identified to date (Wilson, 2021). Some of the layers are substantially richer in archaeological materials than others, and this is reflected in the number of lithics with known provenance (SOM Table S1). As shown in SOM Table S2, the proportions and diversity of raw materials also vary (see also SOM Fig. S1).

SOM S2

Exploratory analyses

<u>Access costs</u> Previous work has suggested that site/source transfer costs measured along a straight-line route (allowing for deviations around inaccessible terrain, i.e., >60% slope) are better predictors of source utilization than those measured along least-cost routes (Browne and Wilson, 2013). However, here we target a different response (probabilities of belonging to the set S_1 of sources from archaeologically represented source areas) and calculate the cost of traversing least-cost paths in terms of minimum walking times rather than caloric expenditure (see also Browne and Wilson, 2011). Consequently, we re-examined the likely effects of easily computed access cost variables through simple descriptive statistics so as to identify the one resulting in the clearest separation of the data. Ease of computation was an important criterion because some of the analyses presented here involved a large number of evaluations (see section *3.5.* of the main text), and we envisioned our model being usable in agent-based simulations for future studies. Four highly and significantly correlated (r_{min} = 0.975, p_{min} < 0.001)

variables were investigated: 1) Euclidean distances, 2) surface distances on Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs), 3) minimum walking times from the Bau, and 4) minimum walking times to the Bau. The latter two are not identical because the cost of walking downhill is not the same as the cost of walking uphill (e.g., Langmuir, 1984).

The strongest differentiation between seemingly non-utilized (set S_0) and potentially used (set S_1) sources was observed with walking times along least-cost routes from the Bau to the sources, although distance measures appear to perform similarly well (SOM Fig. S2). This result was surprising, as we had expected, under the assumption that the cost of carrying rocks back to the site would have been a substantial concern, that walking times to the Bau would outperform walking times from the Bau. Overall, SOM Figure S2 suggests that the ability to reach specific areas within a reasonable time was a more important driver of selection than the cost of carrying materials back to the site and, indeed, that sources located at a walking distance of over four hours from the site were typically not exploited (see also SOM Table S3). There is indeed a clear gap in source utilization beyond a four-to-five hours of walking radius (or ca. 20 km) from the Bau, there being no sources classified as potentially utilized over a further two-to-three hours of walking. Exploited sources beyond this gap are represented by very few archaeological pieces (n = 7, or 0.04%), and it may be that the latter were procured indirectly, while residing at a different site.

<u>Source extents</u> As shown in SOM Table S4, there is no visible pattern in the non-utilized (S_0) sources in terms of their extent, although a likely trend can be observed with potentially utilized (S_1) sources. With S_1 sources, the data suggest a preference for larger sources or, conversely, an avoidance of smaller ones. Indeed, the largest differences are seen with the

smaller sources, which appear to have been seldom (if ever) exploited. More details on the distribution of source extents across exploited source areas are provided in SOM Table S3.

Rock size abundances In terms of the abundance of different rock sizes at the sources, no obvious trends that would allow for meaningful discrimination between potentially used (S_1) and non-utilized (S_0) sources are observable with small and very large rock size classes (SOM Table S5). The abundance of medium-sized rocks appears to be a more promising differentiator, but the distribution of frequencies across abundance classes is very imbalanced, with over 75% of the sources, regardless of their utilization category, falling under the ‘scarce’ classification. The most promising variable in this class, then, is the abundance of large rocks, which shows a more even spread of observations.

Raw material quality There are clear differences in the quality of raw materials found at seemingly non-utilized (S_0) and potentially utilized (S_1) sources (SOM Fig. S3). Non-utilized sources show a positively skewed distribution with most sources clustering at lower quality values, the median falling below the lower confidence interval of the median quality observed for potentially utilized sources. The distributions do show considerable overlap, however, and there are several high-quality sources which do not appear to have been utilized. Overall, raw material quality appears to be a good discriminator between the source utilization categories, but likely played a more modest role in determining the usability of a source than the access costs of the latter, since the median walking times from the Bau for potentially utilized sources fall outside the interquartile range for non-utilized ones (see SOM Fig. S2B).

SOM S3

Logistic model diagnostics

An examination of variance inflation factors (VIFs) revealed that collinearity was not an issue (maximum VIF = 1.12). Despite the imbalance in the frequency of the two response alternatives, the model also appears to be stable, as case-wise deletions do not substantially affect individual estimated coefficients (SOM Table S6; see also SOM Fig. S4 for standardized dfbeta values, which indicate the standardized difference between coefficient estimates with cases excluded one at a time).

We did identify 13 influential cases (SOM Table S7), defined here as having leverage values above a threshold of two times the number of predictors plus one divided by the number of cases (i.e., 2*6/346, or 0.035). However, removal of these influential cases does not have a major effect on the results: all coefficients remain within their standard error as observed in the full model with no cases removed, no coefficients change signs and no critical changes in the significance of individual predictors can be observed (see SOM Table S8). Most affected by the removal of influential cases is the estimate for the quality variable, which is not surprising given that the removed cases have some of the highest quality values in the dataset.

SOM S4

Logistic model results

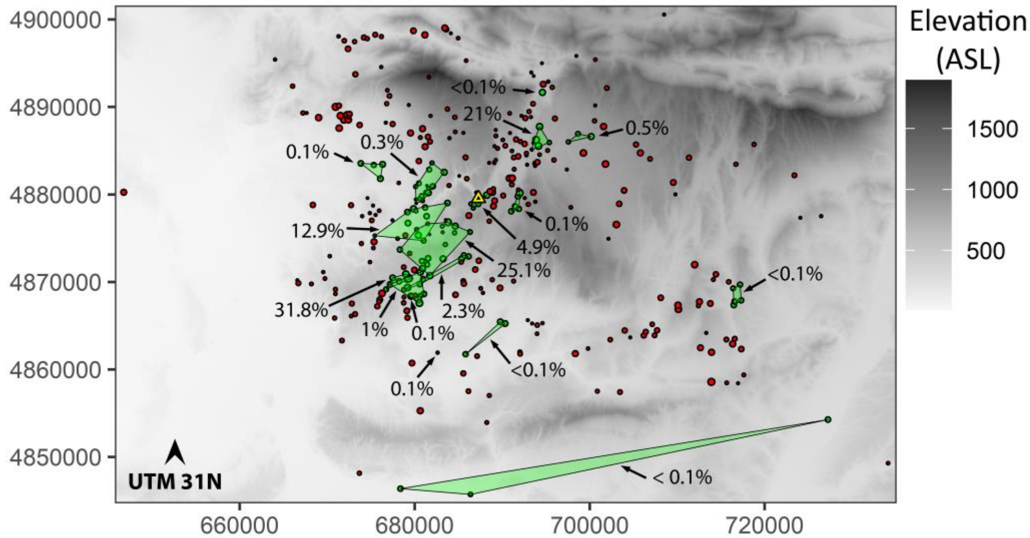
A null model comparison revealed that our logistic model of the influence of the four tested variables on the likelihood of sources being classified as potentially utilized or not is highly significant ($\chi^2 = 69.51$, df = 4, $p < 0.001$). As illustrated in SOM Table S8 and discussed below, the quality of the raw materials, the size of the area over which these are found and the degree to which they are present as large nodules (more flexible in their potential for reduction), all have a positive and significant impact on the likelihood of sources being classified as potentially utilized. However, the strongest and most significant influence is that of the time it takes to reach a source from the Bau, and its effect is negative—the higher the access costs of a source, the less likely it is to be classified as potentially exploited. These results are consistent with previous findings (Browne and Wilson, 2011) as well as theoretical expectations.

Minimum walking times from the Bau Supplementary Online Material Figure S5 shows the influence of the cost of reaching a source from the Bau on its likelihood of classification as potentially utilized, when controlling for the effects of the other variables considered. Sources of an average size (ca. 4210.47 m^2), yielding raw materials of average quality for the region (ca. 2.19), and characterized by an abundance of large rocks that is also typical for the study area (i.e., absent or scarce), have a probability of being classified as potentially utilized of about 78% (61–88 at 95% confidence level) if in the vicinity of the Bau (i.e., where the closest source classified as potentially utilized is located, or 6 minutes from the Bau). This probability falls below 50% if located at more than about 73 minutes from the site. Note that these probabilities do not account for the spatial relationship between sources.

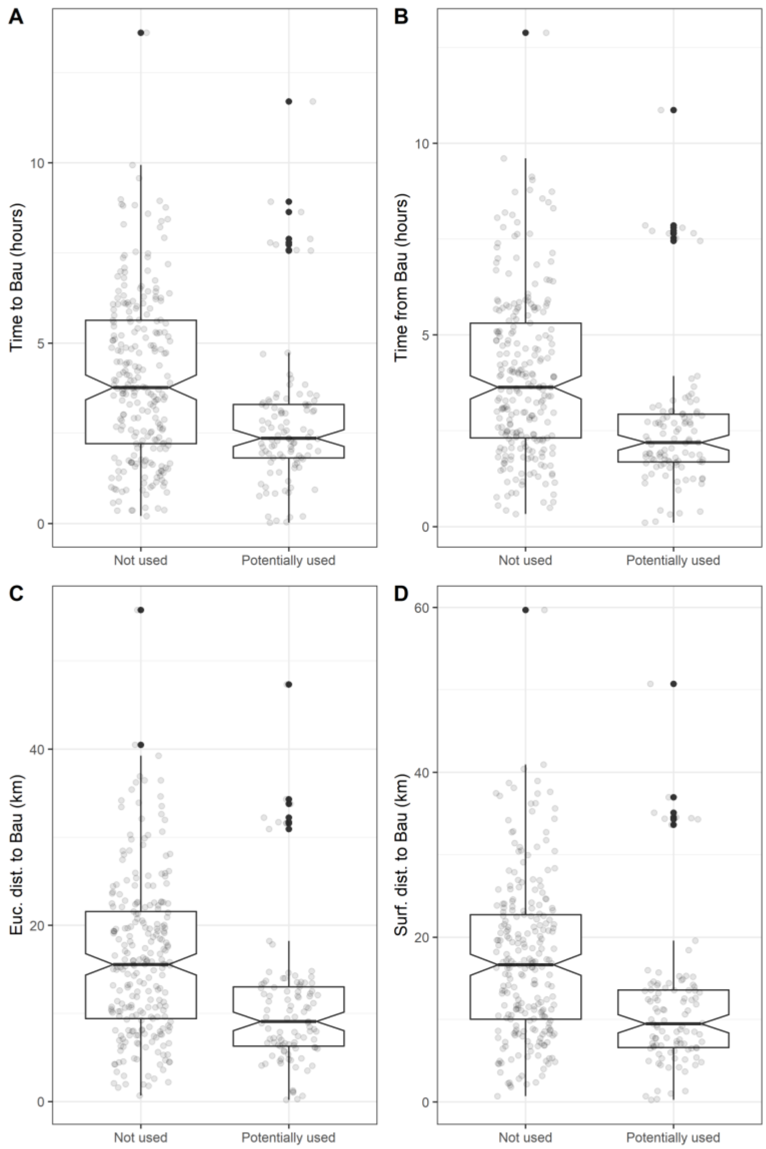
The influence of raw material quality The influence of raw material quality on the likelihood of sources being classified as potentially utilized when other variables are controlled for is shown in SOM Figure S6. As indicated in subplot A, these likelihoods are above 50% for sources with otherwise average characteristics for the region (i.e., scarce large nodules and a surface area of roughly 4210 m^2) and located in the vicinity of the Bau (i.e., ca. 6 minutes) in all but the lowest raw material quality cases. On the other hand, similar sources that are only reachable in ca. 3.2 hours or more from the Bau (the adjusted mean for the region) would have to yield materials of the highest quality (ca. 8) to have a greater than 50% probability of being classified as potentially utilized (subplot B).

The influence of source extent For otherwise average sources located in the vicinity of the Bau, the size of the area over which raw materials may be found somewhat shapes but certainly does not fundamentally determine their probabilities of classification as potentially utilized, which in all cases are above ca. 70% (SOM Fig. S7A). This variable has a somewhat clearer effect when access costs become a greater concern (SOM Fig. S7B), but in all cases the probability of classification as potentially utilized for otherwise average sources (scarce large rocks, relatively low-quality raw materials, ca. 3 hours away from the Bau) is well below 50%. Assuming classification probabilities are adequate proxies for selection probabilities, these data suggest that, when other criteria were met, larger sources were preferred, possibly because of a combination of factors such as being easier to find, easier to intercept on the way back to the site, and easier to casually procure materials from (having to work less to find suitable stone).

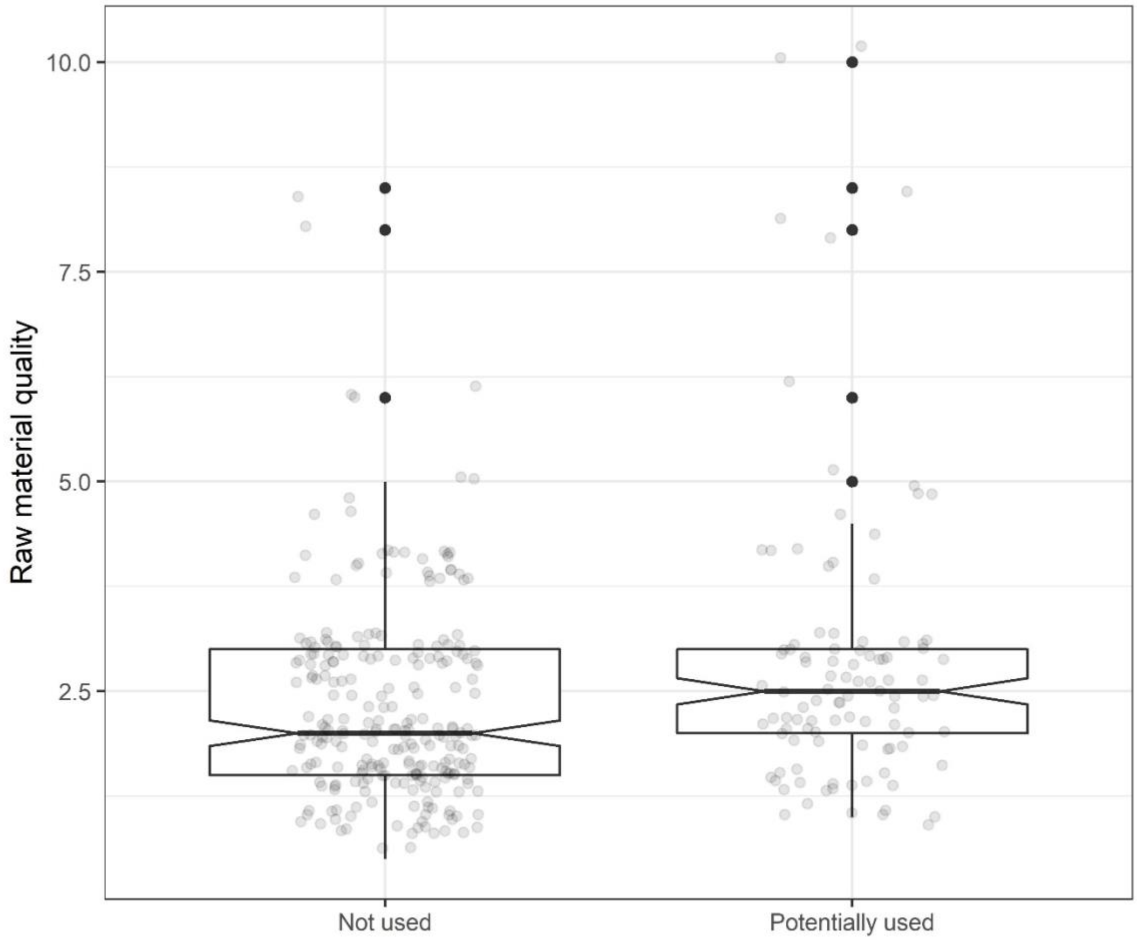
The influence of large rock abundances As shown in SOM Figure S8, and as with source extent, the overall effect of this variable with otherwise average sources located in the vicinity of the Bau is minor (above 50% in all cases, and there is overlap in the 95% confidence intervals of the maximum and minimum probabilities). For sources where access costs are greater the influence of this variable becomes more critical. All else being equal, a source which is average for the region in all respects (relatively low-quality materials found over a reasonably large area at ca. 3 hours from the Bau), has a very low probability of being classified as potentially utilized if it yields no or only few large rocks. However, for such a source the effect of having an abundance of large rocks is far more uncertain, as shown by 95% confidence intervals which, for the maximum predicted probability, span almost half of the possible range. If probabilities of classification can be taken as reliable proxies for source selection, these data suggest, overall, that when access costs were a concern sources with few large rocks were avoided, while for sources where the abundance of large rocks was not an issue, other variables played a more important role in determining their likelihood of selection.



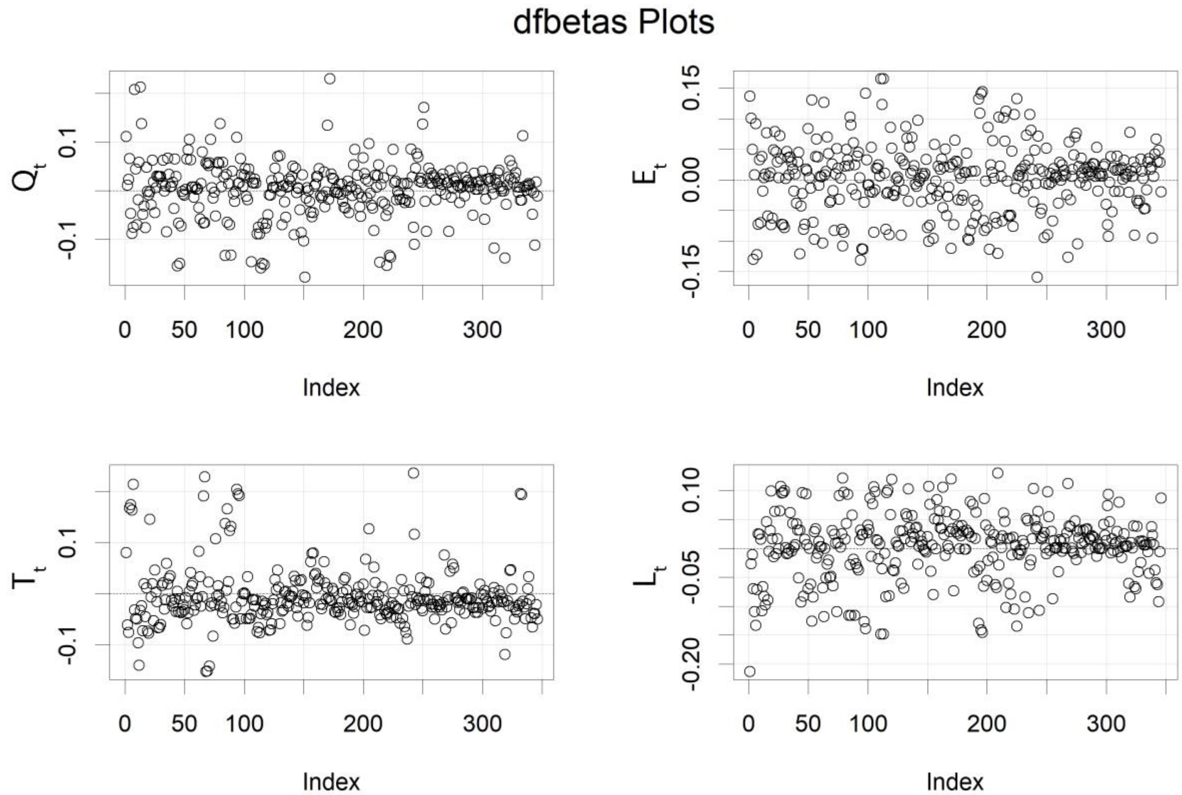
SOM Figure S1. Distribution of raw material sources near the Bau de l'Aubesier rock shelter. Unused sources (S_0) and sources that were potentially exploited from the Bau (S_1) are indicated by red and green dots respectively, while the location of the site is indicated by the yellow triangle. The size of the dots represents relative differences (cubed) in time controlled P_{S1} values ($P_{S1(tc)}$; see Table 1 in the main text), which are a proxy for overall source quality. Green polygons represent convex hulls encompassing sources from used source areas, and percentages represent the contributions of those source areas to the total number of lithics with established provenance recovered at the site. Note that most raw materials were procured from relatively distant sources and several good sources located close to the site (large red dots) were apparently not used. Coordinates are given in meters for UTM zone 31N, and elevation values are given in meters above sea level (ASL).



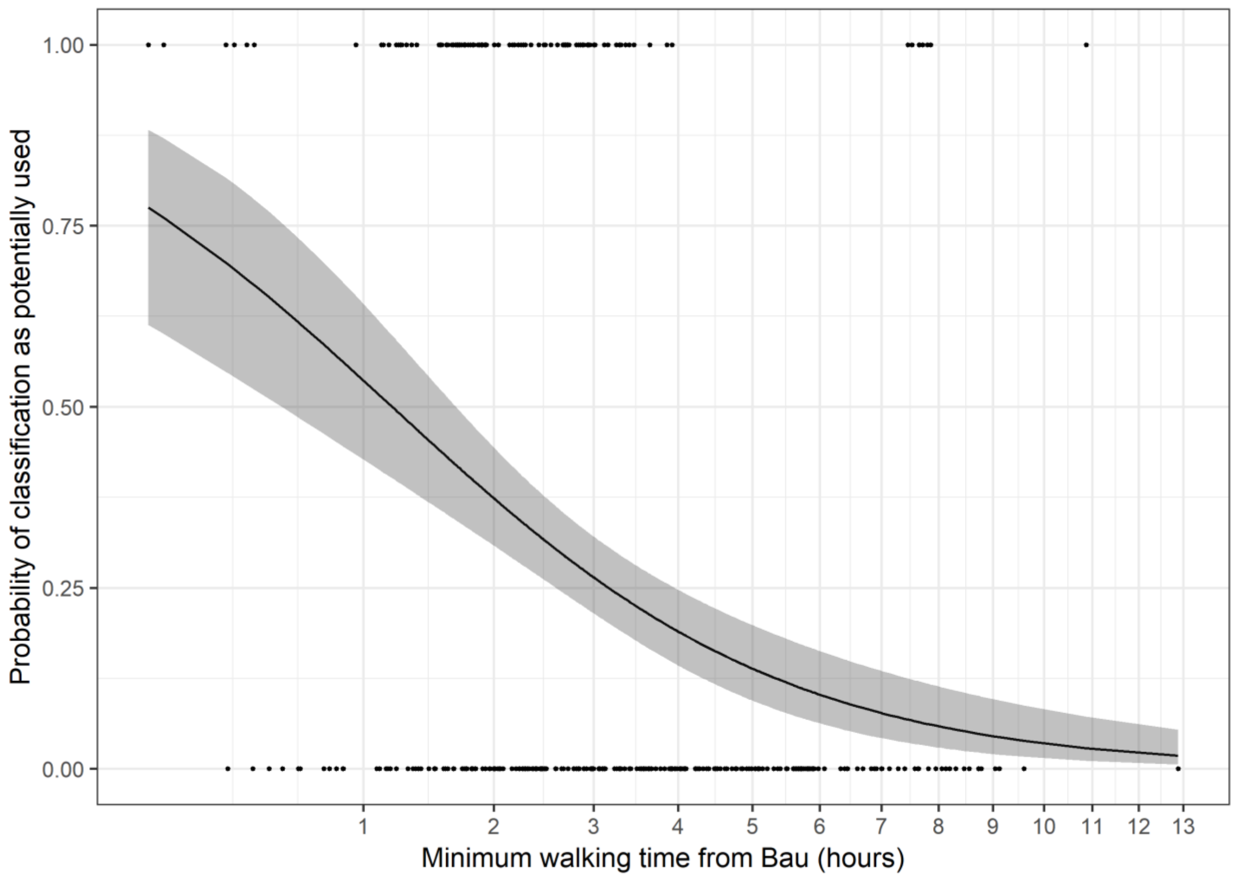
SOM Figure S2. Distribution of access costs across reachable (slope < 60%) potentially utilized (set S_1, *n* = 101) and non-utilized sources (set S_0, *n* = 245), defined as A) minimum walking times required to reach the Bau from the sources, B) minimum walking times required to reach the sources from the Bau, C) Euclidean distances (Euc. dist.) between the sources and the site, and D) minimum distances along the surface of the terrain (Surf. dist.). Black dots denote outliers (1.5 times the interquartile range) while grey dots indicate individual sources, with random horizontal jitter added to enhance visualization. Note that all four access cost variables discriminate well between unused (S_0) and potentially used (S_1) sources, but the best differentiation is seen with minimum walking times from the Bau (B).



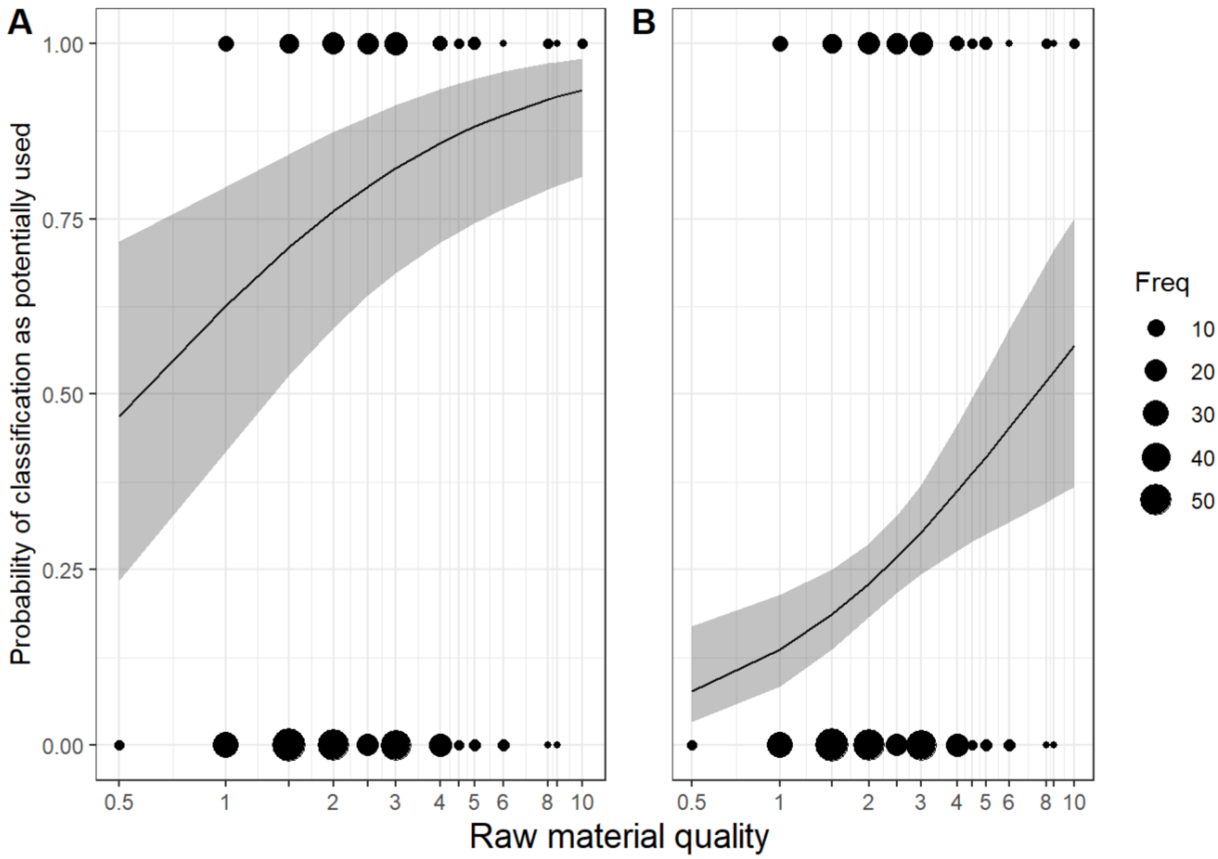
SOM Figure S3. Raw material quality at accessible (*n* = 346) non-utilized (S_0) and potentially utilized (S_1) sources. Black dots denote outliers (1.5 times the interquartile range) while grey dots indicate individual sources, with random horizontal jitter added to enhance visualization. Note that for both sets of sources the quality values span a similar range, but S_0 sources (Not used) are somewhat more variable, and both the median and maximum quality value for that set is lower than for S_1 sources (Potentially used). The lack of overlap in the notches (approximate confidence intervals for the medians) suggests raw material quality is a useful discriminator between the source utilization categories.



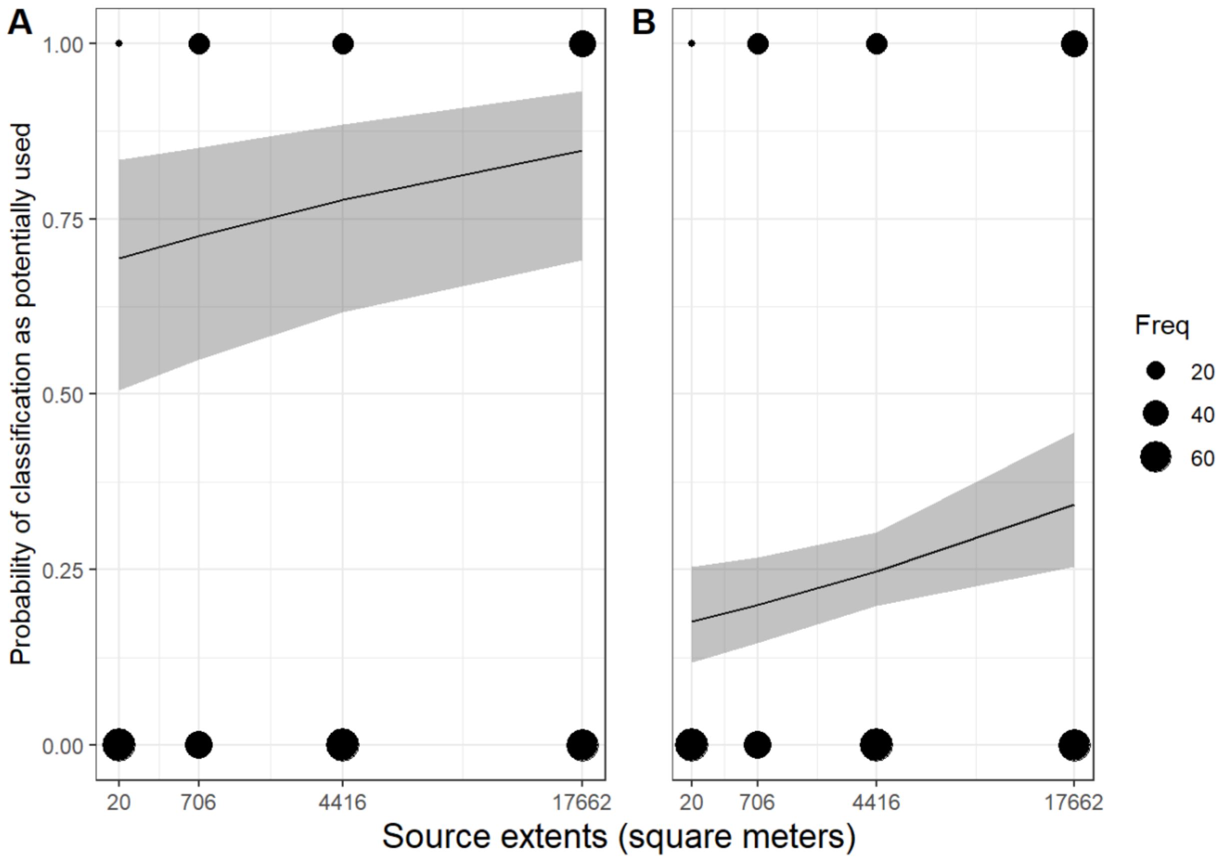
SOM Figure S4. Plot of standardized dfbeta values for individual scaled predictors. Q_t = quality (log), E_t = extent (square root), T_t = time from Bau (square root), L_t = large rock abundances. Low absolute values indicate that deletions of individual observations do not have a major effect on the estimated coefficients.



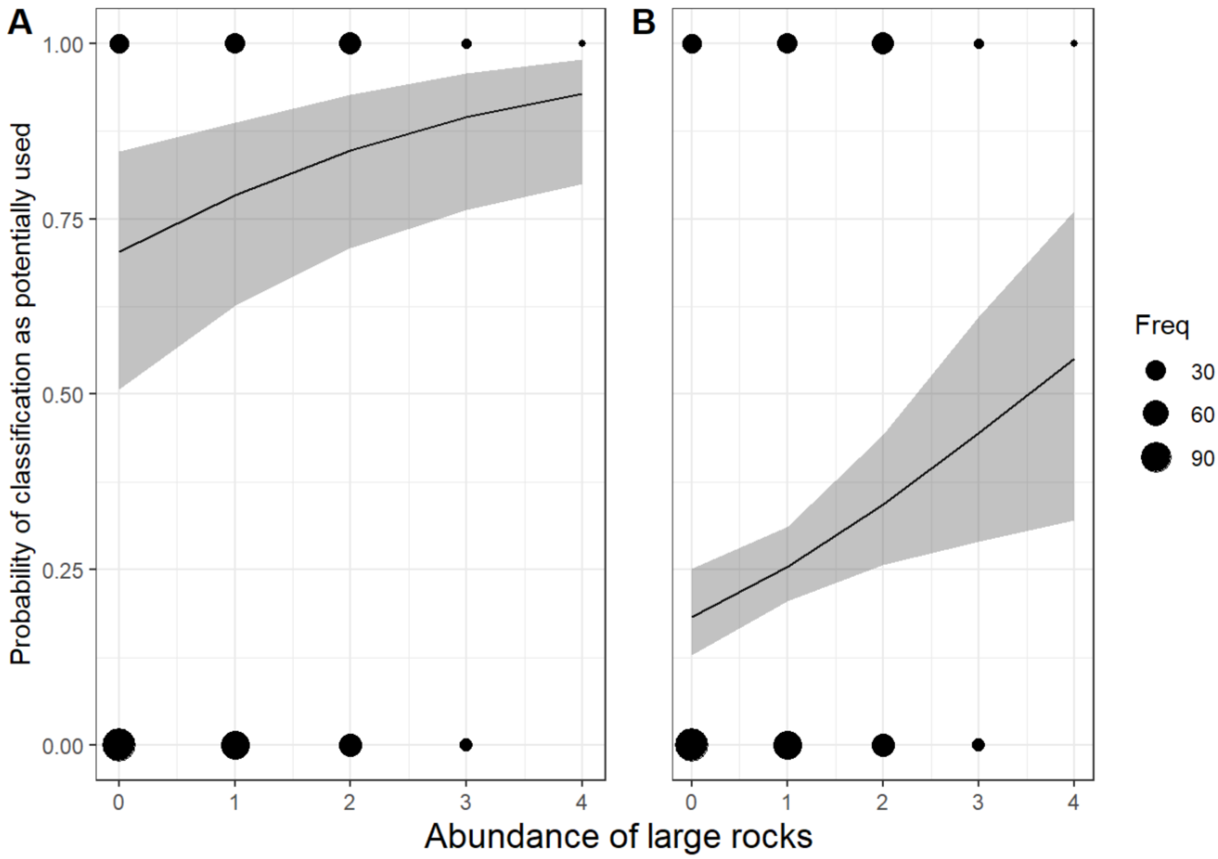
SOM Figure S5. Modeled probabilities of source classification (0 = unused; 1 = potentially utilized) based on the minimum walking times required to reach them from the from Bau, when all other source characteristics are kept at the mean values observed throughout the region. Black dots represent actual observations: sources from exploited source areas have values of 1.00, and unused sources values of 0.00. Note that this variable has a major effect on classification probabilities, with estimates ranging from more than 0.75 with average sources located close to the site to almost zero with average sources located at ca. 13 hours from the Bau.



SOM Figure S6. Modeled probabilities of source classification (0 = unused; 1 = potentially utilized) based on raw material quality, with minimum walking times (from the Bau) kept constant either at the observed minimum (A) or at the average for all sources in the region (B), and all other variables kept constant at their mean. Actual observations are represented by black dots whose size is proportional to the number of unused or potentially used sources with specific raw material quality values. Note that the presence of high quality raw materials plays an important role, but more so with sources that are not in the immediate vicinity of the site (B).



SOM Figure S7. Modeled probabilities of source classification (0 = unused; 1 = potentially utilized) based on source extents, with minimum walking times (from the Bau) kept constant either at the observed minimum (A) or at the average for all sources in the region (B), and all other variables kept constant at their mean. Actual observations are represented by black dots whose size is proportional to the number of unused or potentially used sources with specific extent values. Note that source extent plays a role, with larger sources being more likely to be classified as potentially utilized, but the influence of this variable is relatively minor.



SOM Figure S8. Modeled probabilities of source classification (0 = unused; 1 = potentially utilized) based on the abundance of large usable rocks, with minimum walking times (from the Bau) kept constant either at the observed minimum (A) or at the average for all sources in the region (B), and all other variables kept constant at their mean. Abundance values are given on a scale from 0 (absent) to 4 (very abundant; see also variable L in Table 1 of the main text). Actual observations are represented by black dots whose size is proportional to the number of unused or potentially used sources with specific abundance values. Note that the abundance of large rocks substantially and positively influences the likelihood estimates with sources that are not located in the immediate vicinity of the site (B).

SOM Table S1

Number of lithics assessed for provenance purposes, by layer (data from Wilson, 2021). Layers K2–C represent the stratigraphic sequence along the western wall of the rock shelter, with K2 being the oldest, while layers 5–2 correspond to the sequence observed towards the center of the rock shelter. The complete site assemblage used in the present paper also includes pieces from minor layers not shown here, and from test pits whose stratigraphic positions were not given layer attributions.

	K2	**J–K1**	**I**	**H**	**G**	**E**	**D**	**C**	**5**	**4**	**3**	**2**
Total	1290	2084	2077	7004	224	1998	147	860	546	19332	648	1962

SOM Table S2

Percentage of pieces by source area and layer (data from Wilson, 2021). Layers K2–C represent the stratigraphic sequence along the western wall of the rock shelter, with K2 being the oldest, while layers 5–2 correspond to the sequence observed towards the center of the rock shelter. The complete site assemblage used in the present paper also includes pieces from minor layers not shown here, and from test pits whose stratigraphic positions were not given layer attributions.

Source Area	K2	J–K1	I	H	G	E	D	C	5	4	3	2
Unidentifiable	53	41	58.4	58.2	14.4	90.1	92.5	75.8	61.5	63.1	66.7	47
Unknown	3.8	0.5	0.2	0.4	0.9	0.1	0	0.3	0	0.2	0.3	1.4
Faraud	9.9	8.8	12	14.4	8.1	3	2	7.3	4	9	7.3	10
Méthamis	5.3	3.8	9.1	7.7	0.5	1.3	0.7	2.7	8.8	4.6	1.4	1.6
Les Sautarels	0.3	0.2	0.1	0.2	0	0	0	0.3	0.4	0.5	0.8	0.5
Sault	8.1	10.9	4.6	6.4	35.1	3	4.8	9.4	2.2	8.3	11.9	14.1
Murs	17.7	27.9	13.1	11.1	39.2	2.1	0	3.3	22	11	8.2	15
Local	0.1	2	0.5	0.3	0	0	0	0.1	0.5	2.6	0	7.8
St. Jean de Sault	0	0.2	<0.1	0	0	0	0	0	0	<0.1	0	0.1
Roussillon	0	0	<0.1	0	0	0	0	0	0	<0.1	0	0.1
Murs-Bezaure	1.2	3.4	1.2	1.1	1.8	0.4	0	0.6	0.4	0.3	2	1.9
Ravin de la Treille	0.3	0	<0.1	0.1	0	0.1	0	0	0.2	0.1	0.2	0.3
St. Trinit	0.2	1	0.5	0.1	0	0.1	0	0	0	0.12	0.2	0.1
Durance	0	0	<0.1	0	0	0	0	0	0	0	0	0
Tertiary Calavon	0	0	0	0	0	0	0	0.1	0	<0.1	0	0
Tertiary Murs VdeV	0	0.1	<0.1	<0.1	0	0	0	0	0	<0.1	0.2	0
Mormoiron	0	0	0	0	0	0	0	0	0	<0.1	0	0.2
R de Guérin	0	0	0	<0.1	0	0	0	0	0	<0.1	0	0.1
N. Aurel	0	0	0	0	0	0	0	0	0	<0.1	0	0

SOM Table S3

Distribution of source extents across exploited source areas, as well as associated degrees of utilization (i.e., number of attributable archaeological lithics) and minimum/maximum access costs for sources of the latter, defined as minimum walking times (in hours) from the Bau.

Area	20 (m^2)	706 (m^2)	4416 (m^2)	17662 (m^2)	Lithics	Time (min)	Time (max)
55	0	1	2	4	4981	2.7	3.5
82	0	5	5	5	3935	1.1	2.8
45	1	1	1	3	3286	2.0	2.2
57	0	1	2	7	2015	1.0	3.6
53	2	2	0	2	768	0.1	0.2
36	0	2	4	1	355	1.6	3.4
61	0	4	0	4	162	2.4	3.6
47	0	1	1	1	73	3.0	3.1
59	4	1	5	5	52	1.5	2.5
58	0	3	0	2	16	1.2	1.0
37	0	2	0	0	8	3.0	3.3
76	1	0	0	0	8	3.9	4.7
75	0	3	2	0	6	7.5	7.9
35	0	0	1	3	4	2.7	4.1
64	0	0	0	1	2	3.2	3.1
67	0	0	2	1	2	3.3	4.7
13	0	0	0	3	1	7.5	11.7

Abbreviations: min = minimum, max = maximum.

SOM Table S4

Frequencies of source extents across reachable (n = 346) potentially used (set S_1) and non-utilized (set S_0) sources.

Factor	20 (m^2)	706 (m^2)	4416 (m^2)	17662 (m^2)
Potentially used	8	26	25	42
Not used	68	46	67	64

SOM Table S5

Frequencies of abundance values for different nodule sizes at the accessible sources (*n* = 346).

Type	Factor	None	Scarce	Relatively scarce	Abundant	Very abundant
Small rocks	Not used (S_0)	0	240	2	3	0
	Potentially used (S_1)	0	98	1	0	2
Medium rocks	Not used (S_0)	21	187	28	3	6
	Potentially used (S_1)	2	79	14	5	1
Large rocks	Not used (S_0)	115	80	43	7	0
	Potentially used (S_1)	28	31	38	3	1
Very large rocks	Not used (S_0)	209	25	11	0	0
	Potentially used (S_1)	86	13	0	1	1

SOM Table S6

Baseline scaled (z-transformed) logistic model coefficients with minimum and maximum ranges with case-wise deletions.

Coefficient	Slope estimate	Minimum	Maximum
Intercept	−1.1218	−1.1306	−1.1016
Q_t	0.4490	0.4249	0.4801
E_t	0.3506	0.3281	0.3741
T_t[a]	−0.8886	−0.9129	−0.8511
L_t	0.3760	0.3466	0.3939

Abbreviations: Q_t = quality (log), E_t = extent (square root), T_t = time from Bau (square root), L_t = large rock abundances

[a] Corresponds to the minimum travel times required along least-cost routes from the Bau.

SOM Table S7

Characteristics (unscaled) of influential cases with leverage values above selected threshold, ordered by their leverage values.

Source	Area	Classification	Minimum walking time from Bau (hr)	Quality	Extent (m^2)	Large rock abundances	Leverage
1	84	Not used	0.8	1.0	20	Abundant	0.0577
324	124	Not used	8.2	8.5	17662	Rel. scarce	0.0546
8	61	Potentially utilized	2.4	10.0	706	Scarce	0.0481
153	12	Not used	4.0	8.0	17662	None	0.0449
254	55	Potentially utilized	2.7	8.0	706	Rel. scarce	0.0447
325	73	Not used	7.6	4.0	20	Abundant	0.0437
69	53	Potentially utilized	0.1	3.0	20	None	0.0424
68	53	Potentially utilized	0.1	3.0	20	None	0.0413
13	55	Potentially utilized	2.7	8.5	4416	None	0.0407
174	61	Potentially utilized	2.9	8.0	706	None	0.0388
253	55	Potentially utilized	2.7	10.0	17662	Scarce	0.0383
207	41	Not used	0.3	1.0	20	Scarce	0.0375
226	12	Not used	4.0	6.0	706	Rel. scarce	0.0364

SOM Table S8

Baseline scaled (z-transformed) logistic model coefficients with and without influential cases removed.

Model	Coefficient	Estimate	SE	Z.value	*p*-value
	Intercept	−1.12	0.14	−7.80	<0.001
	Q_t	0.45	0.13	3.35	<0.001
All cases (*n* = 346)	E_t	0.35	0.14	2.49	0.013
	T_t[a]	−0.89	0.16	−5.63	<0.001
	L_t	0.38	0.14	2.76	0.006
	Intercept	−1.12	0.14	−7.74	<0.001
	Q_t	0.34	0.15	2.21	0.027
High leverage cases removed (*n* = 333)	E_t	0.35	0.15	2.41	0.016
	T_t[a]	−0.83	0.16	−5.07	<0.001
	L_t	0.44	0.14	3.07	0.002

Abbreviations: Q_t = quality (log), E_t = extent (square root), T_t = time from Bau (square root), L_t = large rock abundances, SE = standard error.

[a] Corresponds to the minimum travel times required along least-cost routes from the Bau.

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Chapter Five

Exploring home ranges and non-local procurement through a minimally realistic model of raw material management at the Bau de l'Aubesier

Lithic raw material resource management and group mobility at the French Middle Palaeolithic site of the Bau de l'Aubesier: Application of a minimally realistic agent-based model

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Lithic raw material resource management and group mobility at the French Middle Palaeolithic site of the Bau de l'Aubesier: Application of a minimally realistic agent-based model

Authors: Cornel M. Pop, Lucy Wilson, Constance L. Browne

Abstract:

In this paper we explore the impact of residential mobility on archaeological raw material variability at the French Middle Palaeolithic site of the Bau de l'Aubesier. We do so in view of better understanding lithic resource selection and regional land use strategies employed by the hominins who discarded or abandoned lithics at the site between roughly 200ka and 100ka BP. To this end we develop a novel, minimally realistic agent-based model of lithic resource management and apply it to simulate processes resulting in raw material transfers at a regional scale (here, an area of ca. 100 x 100 km). We demonstrate that, in southeastern France at least, Neanderthals selectively targeted lithic resources based on an intimate knowledge of their availability over a large area, and excellent navigational skills. Our results also indicate that Neanderthals regularly exploited lithic raw materials from residential camps over areas that were at least as large as those seen with ethnographically documented hunter-gatherer populations, and that the combined territories frequented by individuals who at some point also resided at the Bau over their lifetimes likely cover an area that, although large, nevertheless encompasses only a portion of the study region. Finally, we show that, except perhaps in highly unusual circumstances, and contrary to what is often assumed, raw material provenance data is unlikely to be informative with regards to the extents of the home ranges used by discrete Neanderthal groups, or of the settlement strategies such groups may have employed within those territories.

Keywords: Minimally realistic model; lithic raw materials; Middle Palaeolithic; simulations; agent-based modeling; provisioning strategies; hominin land use

1. Introduction:

Neanderthals are the most extensively researched extinct hominin species, yet many questions remain about their lifeways and their strategies of landscape utilization. One avenue of inquiry into the latter that has long been considered important is provided by lithic provenance studies. Since the geographic origin of archaeologically exploited stone can often be pinpointed with reasonable accuracy and precision, through such studies we can, at a minimum, determine the areas over which Neanderthals transported lithic materials. The picture that has traditionally emerged from this type of investigation is one of relatively restricted procurement zones around sites (e.g., Féblot-Augustins, 1993; 2009) and a general willingness to exploit easily accessible stone resources even if of questionable quality (e.g., Eixea, 2018; Sykes, 2017; Doronicheva et al., 2016; Pop, 2013). Procurement over distances exceeding expected home range limits is often documented (e.g., Doronicheva et al. 2016; Adler et al. 2014; Slimak and Giraud 2007), but such distantly procured materials typically amount to a small portion of the overall assemblages in which they are found (but see, e.g., Spinapolice 2012), and the pathways through which they were incorporated into the archaeological record are seldom clear (e.g., Turq et al. 2013). Beyond this general pattern, however, to which there are in any case a relatively large number of exceptions, our understanding of how stone procurement fit within wider Neanderthal adaptive strategies at a regional level is in many instances quite limited. Provenance studies may inform us of which geological sources were actively exploited at a given time, but the subsequent task of determining why and under what conditions, or the degree to which their exploitation reflects broader patterns of landscape use, remains a substantial challenge.

The Middle Palaeolithic site of the Bau de l'Aubesier (hereinafter "the Bau"), located in the department of Vaucluse in southeastern France, presents one case where the drivers of lithic resource selection and procurement are exceptionally well understood. Yet even in this case many unknowns remain regarding the pathways through which lithics were incorporated into the archaeological layers as well as the broader regional strategies of landscape use that they reflect. In this paper we seek to clarify some of these aspects by incorporating regional group mobility into existing explanatory frameworks. We do so with the goal of better understanding one of the remarkable characteristics of this site, namely that it does not conform to the general pattern noted above for the European Middle Palaeolithic, as most stone resources were procured at greater than expected distances (likely 8-13km) from the Bau despite the availability, today at least, of high-quality flint nearby.

It is of course possible that such nearby flints were unavailable to the Neanderthals who inhabited the site, but this *unavailability hypothesis* is difficult to defend given the time span represented by the archaeological layers (ca. 100,000 years) and the fact that there is little evidence to suggest dramatic changes to the lithic landscape since the initial occupation of the site some 200,000 years ago. Additionally, many (ca. 120) seemingly unexploited raw material sources are found within the minimum procurement area represented by raw materials utilized at the site (Figure 2) so it is very likely that hominins would have at least occasionally stumbled across these seemingly unexploited sources over the course of a hundred millennia. An alternative to the *unavailability hypothesis* is that sources were not exploited simply because, from the perspective of a Neanderthal inhabiting the Bau, it would have made no sense to do so.

We explored this possibility in Chapter 4, where we proposed an explanatory framework that considered sources not only in terms of their intrinsic characteristics, such as the quality of the available materials and the extent over which they are exposed, but also in light of their relative placement within the network of sources accessible from the site. With this conceptually simple framework we were able to identify sources that should have been used (optimal procurement candidates) as well as sources that should not have been exploited by the site's inhabitants even if seemingly appealing when considered on their own. With this framework we were also able to account for most of the archaeological observations. A pending question, however, is whether this *optimal-candidate hypothesis* can hold - that is, whether it can still explain the complete avoidance of sources over a 100,000-year period - if we factor in residential mobility and the concomitant input of raw materials procured at other sites.

To answer this question, it is necessary to consider which sources should have been targeted under the proposed *optimal-candidate hypothesis* at *other* sites frequented by the inhabitants of the Bau. It is also necessary to consider the likelihood that raw materials procured at such other sites would be transported to, and discarded at, the Bau. Finally, we need to consider how many such materials we may expect to find at the site, not least because it will affect their likelihood of identification among the rest of the archaeological materials. Unfortunately, we do not know how Neanderthal groups actually moved within the region, nor do we have compatible raw material data for contemporaneous sites in the area to serve as a guide. However, previous work (Chapter 4) has indicated that we cannot reject the possibility that landscape utilization was relatively uniform, at least when considering the aggregated data for the entire sequence at the Bau, so we do have a useful starting point. This, coupled with the quality of the lithic provenance dataset available for the site and the available resource selection models, makes it possible to address these issues through a simulation approach.

In this paper we therefore aim to introduce, test, and apply a minimally realistic, behaviourally and spatially explicit model of regional mobility and lithic management for the region surrounding the Bau so as to thoroughly assess the viability of the *optimal-candidate hypothesis*. The model we propose tracks raw materials throughout their entire use lives and allows us to make *quantitative* predictions with regards to raw material variability (see Pop 2016) at hypothetical sites throughout the region, using simple yet rigorously defined behaviours and a minimalist set of assumptions. These predictions are based on a combination of two methods, namely: a) estimating probabilities of source exploitation for each hypothetical site location on the basis of local conditions (i.e., spatial configuration of sources) and selection criteria evidenced at the Bau, and b) simulations of post-procurement management and transport implemented through an agent-based approach. Using this combination of methods, which gives us the ability to trace potential pathways followed by materials likely to have *actually* been exploited in the past, we address the following basic questions:

1. What proportions of lithics procured while at other sites (hereinafter, LPOS) should we expect to find at the Bau given a reasonable range of behavioural parameters?
2. What proportion of materials transported from other sites (i.e., LPOS) can we expect to originate from sources that were also exploited from the Bau (i.e., seemingly local)?
3. To what degree is the simulated variability among the LPOS compatible with archaeologically observed raw material variability at the Bau?
4. Can incorporating group mobility help us better understand land-use strategies in the region?

Taken together, answers to these questions have the potential to not only clarify raw material utilization at the Bau and the Vaucluse more broadly, but also to address the more essential question of the degree to which lithic raw materials can be informative with regards to the scale and nature of human mobility within a region. As noted at the onset, lithic sourcing studies have generally been assumed to have high potential in this regard, but few systematic evaluations of this potential have been conducted to date (e.g., Brantingham, 2003; Pop, 2016). Moreover, the minimally realistic model introduced here can also serve as the basis for more complex future simulations for the region, and may of course be applied to other context as well – indeed, it should be applicable in any Middle Palaeolithic context where the distribution of lithic resources is well-known.

2. Background: The Middle Palaeolithic site of the Bau de l'Aubesier

The Bau de l'Aubesier is a large rockshelter located at the western border of the sub-alpine chain in the department of Vaucluse, southeastern France. Found in rugged terrain halfway down the gorge of the Nesque river (Figure 1), the Bau is strategically placed at the intersection of multiple types of ungulate home ranges (Fernandez 2001) and provides easy access to water as well as high-quality flint in an area where the former can be scarce. The region is rich in Middle Palaeolithic sites and widespread surface artifact scatters suggest a relatively continuous utilization, and plausibly habitation, of the landscape. Lithic raw material sources are also abundant and well-known, with 350 outcrops and secondary deposits systematically investigated and catalogued by Lucy Wilson over more than two decades of extensive research (Figure 2). Since the raw materials found at these are sometimes very similar, the sources have been grouped into 122 source areas, each consisting of 1 to 15 discrete sources and yielding distinct, archaeologically identifiable stone types. These sources constitute a lithic landscape that, although not identical to what would have been available at specific points in the past, is nevertheless representative of that exploited by the region's Neanderthal inhabitants. This is because the area was never glaciated and has remained relatively unchanged since the initial occupation of the Bau (see, for example, Wilson and Browne, 2014).

The site contains thick deposits – ca. 13 m towards the back of the rockshelter – which extend over more than 250m^2 (e.g., Lebel et al., 2001) and are very rich in both faunal remains and lithic materials. Indeed, although the Bau has only been partially excavated, at least 85,000 lithics (Texier, 2004; de Lumley-Woodyear, 1969) and over 2,700 ungulate remains, representing a minimum of 241 individuals (Fernandez, 2001; 2006), have been recovered from Middle Palaeolithic layers since the initial investigations by Franki Moulin in 1901-1903 (see Moulin, 1903; 1904). Several isolated deciduous and permanent Neanderthal teeth, two of which are carious, as well as a partial mandible with substantial pathologies (e.g., Lebel et al., 2001), have also been found at the site. With the exception of the topmost two layers, where some undiagnostic late Palaeolithic and Neolithic artifacts have been identified (e.g., Blackwell et al., 2000), the remainder of the sequence yielded Middle Palaeolithic materials. Most of the Middle Palaeolithic layers, deposited over some 100,000 years across the Middle and Upper Pleistocene (roughly 200 kya to 100 kya - e.g., Wilson and Browne, 2014 and references therein), are thought to represent palimpsests of coherent occupations amounting to more than incidental short-term stays (e.g., Wilson and Browne 2014). The faunal remains are the product of anthropic accumulation, with only a few traces of carnivore presence being noted (see, for example, Fernandez, 2006; 2001), and they point to strategic hunting and systematic butchering of several taxa at different times of the year. Although multiple species were targeted, and generally hunted when most vulnerable and abundant, horse and aurochs appear to have been favoured throughout the sequence (Fernandez, 2001).

Figure 1: View of the Bau de l'Aubesier rockshelter. The site as seen from the opposite side of the Nesque river gorge.

The lithic artifacts from the Bau, virtually all flint, have been classified as Typical Mousterian of Levallois facies (e.g., de Lumley-Woodyear, 1969; Wilson and Browne, 2014). The assemblages contain a large number of cores and manufacturing by-products pointing to substantial on-site reduction (see Texier, 2004; Carmignani et al., 2017; cf. de Lumley-Woodyear, 1969) as initially suggested by Moulin (1903). Cortical debitage is rare, however, and this has been interpreted as indicating partial processing at procurement locations (Texier 2004). There is also evidence for off-site discard, as Carmignani et al. (2017) report that, at least for the lower levels, refits are rare. In these same layers the authors report that raw materials, although procured from relatively distant sources (i.e., 8-13 km), are represented through all stages of lithic reduction (Carmignani et al., 2017).

While early analyses suggested techno-typological homogeneity across the upper deposits (e.g., Moulin, 1903; de Lumley-Woodyear, 1969), by the early 2000s it was already apparent that differences existed between the levels of the sequence. These are evidenced in the lithic components (e.g., Fernandez, 2001; see also Carmignani et al., 2017), possibly in hunting strategies (e.g., Fernandez and Legendre, 2003), and in raw material resource selection (Wilson and Browne, 2014). Notwithstanding what appear to be diachronic trends, however, recent work has shown that to evaluate macro-trends (e.g., resource avoidance) considering whole-sequence composition is useful (Chapter 4; Wilson and Browne, 2014; see also sections 4.1 and 4.3 below).

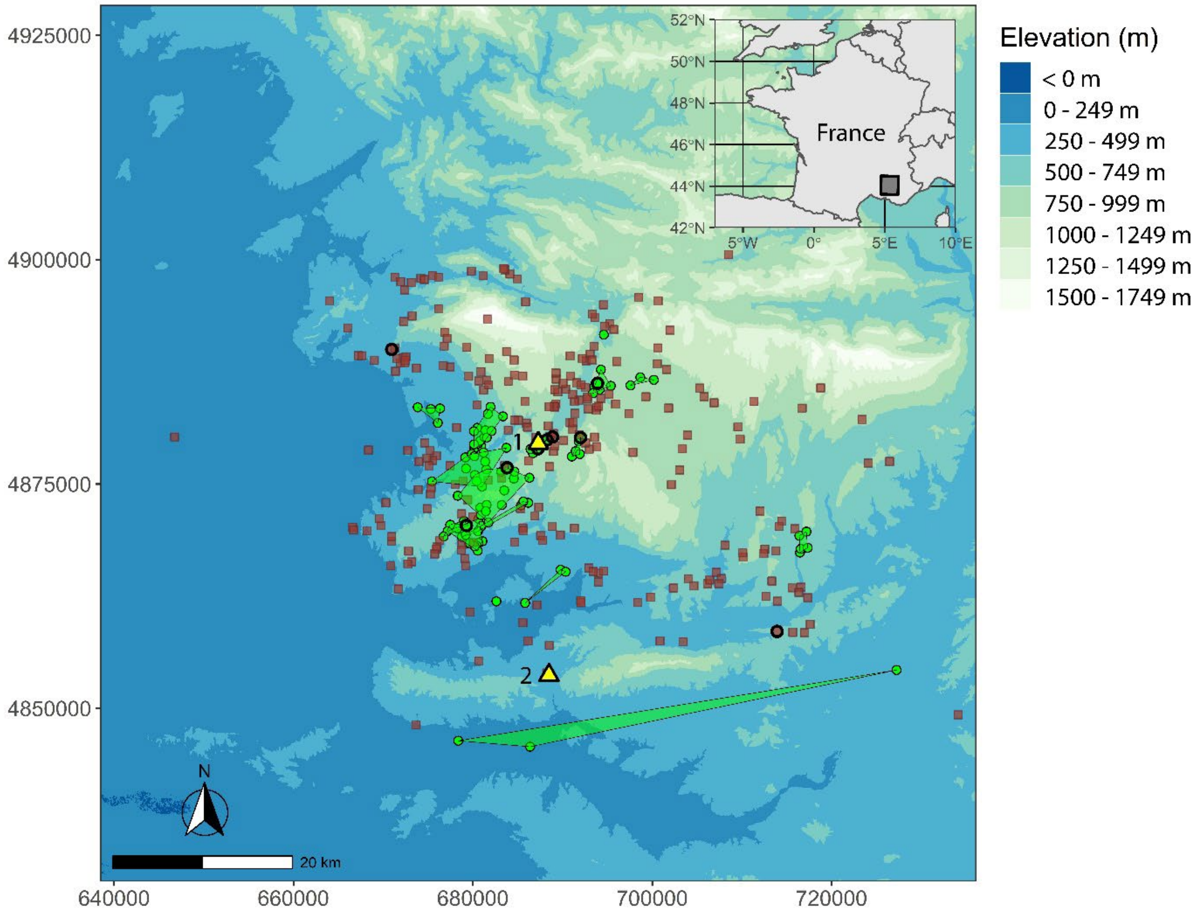

Figure 2: **The study region and the distribution of lithic resources.** The study region is defined on the basis of the 350 catalogued sources, shown here as green circles if they yield raw material types which are archaeologically represented at the Bau, and red squares if no evidence of archaeological exploitation is preserved at the site. Convex hulls enclosing sources belonging to specific, archaeologically represented source areas are shown as green polygons. The locations of the Bau (1) and of another Middle Palaeolithic site (2 – La Combette) for which relatively compatible raw material provenance data exist are indicated by yellow triangles. Hollow circles indicate sources considered optimal for exploitation from the perspective of hominins inhabiting the Bau, according to the method proposed in Chapter 4. Coordinates are given in UTM (zone 31N).

3. Towards a minimally realistic model (MRM) of Middle Palaeolithic lithic raw material management

3.1. *Why minimal realism?*

As the term is used here (c.f. Plagányi, 2007), a minimally realistic model (hereafter MRM) is one that seeks to bridge the gap between abstract neutral models (*sensu* Brantingham, 2003) and models which aim to emulate the past (*sensu* Premo, 2010). On the one hand, highly abstract models are not only difficult to interpret in terms of real-world relevance or applicability, even for the modeller (see Pop, 2016), but they also run the risk of unwittingly simulating impossible realities. On the other hand, attempts to re-create the past result in overly complex models that can be just as difficult to interpret, can lead to high scientific uncertainty (e.g., Wobst, 2010) and, as noted by Premo (2010), invariably have to contend with the problem of equifinality. To solve the problem of optimal complexity (see Lake, 2015 for a discussion), we follow Premo's (2010) general advice of including only the minimum required to address a given research question, with one simple but important caveat: we suggest that a minimally realistic model should *only* employ explicitly defined, real, and relevant units (e.g., grams of stone, actual coordinates or areas instead of abstract grid 'cells'). This additional rule, which helps ensure minimal consistency with reality, may require the inclusion of processes or parameters that, while not directly related to the research question (cf. Premo, 2010), are nevertheless necessary to develop a coherent model that accounts for the scale and nature of the chosen units.

In effect, then, an MRM seeks to be the simplest model (i.e., with the fewest variables or processes) that can generate patterns which are quantitatively comparable and compatible with archaeological observations (i.e., fit within basic observed constraints such as assemblage size) in the absence of a given mechanism (here selective land use and variable resource selection criteria), using real-world units (e.g., hours of travel), and postulating logically consistent behaviours and parameter settings that, based on our current state of knowledge, have a reasonable *a priori* probability of having been true in the target temporal and geographic context (cf. Brantingham, 2003; see Pop, 2016), and given the nature of the employed units as well as the chosen modelling scale. Therefore, as envisioned here, an MRM is necessarily both spatially and behaviourally explicit.

It should be stressed, however, that the goal of an MRM is *not* to replicate archaeological assemblages, but rather to produce output which is not fundamentally incompatible with archaeological observations (e.g., assemblages that are orders of magnitude smaller or bigger when using realistic parameters). In fact, we suggest an MRM should be employed to explore aspects of the record which are, today at least, unknowable (e.g., actual mobility at a regional scale), and advocate using more mainstream modeling approaches to understand aspects of the record which can, in fact, be known (e.g., variables influencing resource selection at a specific site – e.g., Browne and Wilson 2011; Wilson and Browne 2014; Wilson et al. 2018; see also Chapter 4).

3.2. *Model outline*

An outline of our model is shown in Figure 3, and a discussion of the chosen units, scales, and associated mechanics is presented in the next section. In essence, the model simulates a single autonomous agent, representing the residential group of an individual's descent line, which regularly moves camp within a region as resources are depleted. The agent's goal is to maintain a predictable raw material supply at camp and fully provisioned personal toolkits. The agent, aware at any time of its own position as well as the location and characteristics of nearby lithic resources, and able to efficiently navigate the landscape, achieves these goals by first identifying raw material sources that are optimal for exploitation (given their spatial configuration relative to the camp and the local topography) and then acquiring materials from one of these optimal sources at random according to empirically derived probabilities. Acquired materials are taken to camp and are used to replenish personal toolkits whenever needed, as materials are lost, discarded, or simply abandoned by agents in the course of daily activities both at camps and while engaged in off-site activities. For instance, some of the provisioned materials are abandoned during residential moves, which in effect results in the creation of small caches throughout the region that are likely to be available upon revisits.

The simulations start with the agent being placed at a random camp in the region, which is immediately provisioned with raw materials from a nearby source, and they end when the specified number of time steps is reached, since the model is discrete. The model does not specify foraging behaviours, nor the nature of processing activities performed at or while away from camp. It also assumes, as a baseline, both a uniform utilization of the landscape and resource selection criteria that remain constant at all locations. It further assumes that lithic sources, as well as the habitability of the given region, remained unchanged throughout the simulated period. Finally, the model does not specify any mechanism for learning – as a multi-generational group, the agent is assumed to have perfect (*collective*) knowledge of the topography and fixed resources in the region it inhabits, and to be capable of efficient allocentric navigation as indicated by previous work (Chapter 4; cf. Lake, 2015). It should be noted that, while the application presented here is context specific (i.e., it uses terrain, source, and assemblage data from a specific region), the model should be generally applicable to Middle Palaeolithic contexts.

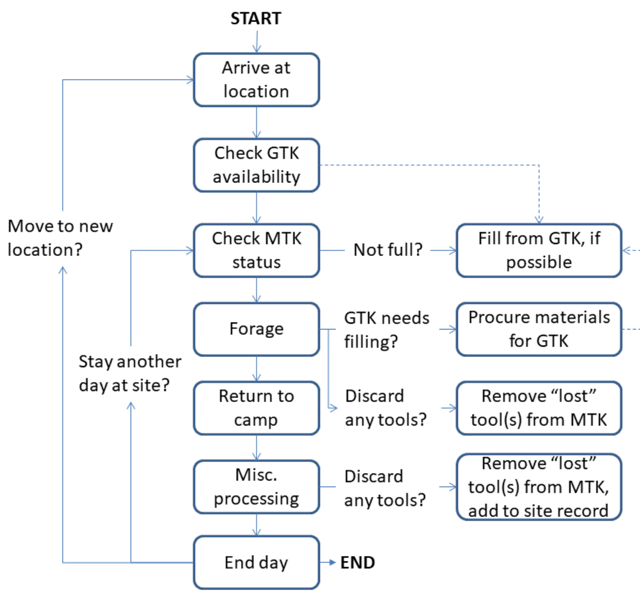

***Figure 3**: **Outline of the proposed minimally realistic model**. GTK refers to collective toolkits, that is materials available for group use at a given residential camp, while MTK refers to personal toolkits. In the context of the simulations discussed in this paper, only MTK items are carried between camps, and the number of days stayed at a camp is pre-determined upon arrival based on specified minima and maxima. Solid lines indicate steps taken by the agent, while dashed lines indicate steps that affect the refilling of personal toolkits from collective toolkits.*

3.3. *Elements of an MRM: Units and Scales*

3.3.1 Temporal scale

We propose simulating behaviours at a resolution or time-step equivalent to one day. Days, unlike other time units such as weeks or hours, represent full natural cycles at a scale at which human mobility, resource procurement, and lithic discard can be meaningfully studied from an individual or residential group perspective. Using larger cyclical periods (e.g., months, years), while useful for modelling larger scale phenomena (e.g., demographic changes), would result in what we would consider to be too much averaging of individual behaviours and would therefore be difficult to model in a behaviourally explicit way (i.e., how much is discarded, when, by whom, and procured where).

As with any scale of analysis, modelling daily behaviour under minimally realistic conditions does pose some challenges. Daylight, for example, varies throughout the year, placing constraints on foraging and travel, and so does the accessibility and distribution of resources. As Kelly (1995:

99) pointed out, “no environment is constant from season to season or from year to year”. On the other hand, daylight availability is unlikely to have been a problem throughout most of the Neanderthal range because the number of foraging hours, in recent hunter-gatherer populations at least (see Kelly, 1995), is limited and generally less than the minimum observable during the winter solstice (e.g., 8.9 hours observable today at the Bau – NRC Canada). With regards to seasonal or yearly changes in the availability of the only resource incorporated into our model, that is lithic raw materials, we suggest that making assumptions as to which resources would have been available, when, and in what quantities seems at least as problematic as assuming resources were generally accessible.

3.3.2 Agent

We envision a simple model which tracks the actions of a single agent which, conceptually, represents a small group of individuals. Modeling individuals is undesirable due to theoretical as well as practical considerations. First, humans as more or less fully individual agents, rather than relational entities which are part of kinship networks that strongly shape their decision-making processes, appears to be a recent construct (e.g., Henrich et al., 2010). Individuals are also unstable over time, in the sense that their mobility and the types of activity they engage in change throughout life. Furthermore, there are important differences between individuals (e.g., gender-specific activities) which may have an impact on factors such as mobility (e.g., Kelly, 1995), and modelling individuals would therefore require making a series of assumptions about the nature of such differences or, conversely, modeling the spatial behaviours of an ‘average’ individual who could never have existed. Second, the computational resources that would be required to model the effects of inter- and intra-individual variability (e.g., sex, age) over tens of thousands of years while simulating daily activities would be substantially higher.

On the other hand, we choose not to explicitly model “bands” (or other higher-level social units) because the concept is ill-defined in the first place (e.g., Binford, 2006; Kelly, 1995), and because “bands” are often fluid in group composition (e.g., Turnbull, 1987; Rai, 1982). Since resource utilization/processing generally occurs and is decided on at a family level (Kelly, 1995), and it is the spatial traces of these processes that we aim to simulate, we choose instead to define agents as simply groups serially linked through time by at least one common member. That is, we model the behaviours of the groups to which offspring of a common ancestor, along any branch of the descent line, belonged. We therefore make only minimal assumptions with regards to the nature of such groups (e.g., their range of sizes – see below), which may or may not correspond to bands, to individual families, or to other types of social units.

We argue that it is not unreasonable (i.e., it is minimally realistic) to model such groups over an extremely long timespan insofar it is acknowledged that their composition will vary and that they do not represent a coherent social unit across the entire modeled timeframe. Modeling such a “group” is justified because, unless the founding local population went extinct during the considered time frame, descent should always be traceable, in at least one case, through the entire period of interest. While our model assumes that the tracked lineage is always represented within a given study area, given the stochastic nature of the modeled processes (see below) exiting and then re-entering the area would only have a marginal effect, and this assumption should not, therefore, pose a problem. Moreover, whether multiple noninteractive or minimally interactive groups are considered or not, the resulting patterns are expected to be identical, so long as such groups are engaged in the same behaviours. Unless diachronic behavioural trends are sufficiently well understood for a target region so as to be reliably operationalized in the context of an MRM, we suggest assuming that baseline group behaviours were constant, and that agent choices can be adequately described as stochastic over the timescales involved.

3.3.3 Sites

We suggest defining agent mobility and procurement behaviours on the basis of randomly placed sites or camps, conceptualized as preferred (strictly in the sense of fulfilling basic needs) landscape locations used by the agents as places of residence for a variable number of days (see below). We acknowledge that camp locations were very likely strategically rather than randomly selected – this certainly appears to have been the case with the Bau (see Section 4) – but pending a better understanding of site chronology and placement in key regions we consider random distribution of suitable camping locations to be a useful starting point, so long as it is acknowledged as such. Placing sites randomly across the landscape in the context of each individual simulation has the advantage of accounting, at least partially, for the variability that may result from cyclical factors which are not explicitly considered in our model, such as seasonal fluctuations in resources or climatic variations over decades or millennia.

We make no formal distinction between functionally different site types, although various such types have been proposed to date for the Middle Palaeolithic (see, for example, Burke's, 2006 review; Daujeard et al., 2016). We do however account for a range of occupation types by allowing the agent (i.e., group) to select the length of habitation for every visit at every camp given simulation-specific minima and maxima. In reality, occupation length should reflect a complex mix of variables, such as availability of resources, return rates, and so on, but about these we make no assumptions, simply acknowledging that they will vary through time and from site to site. While the modeled behaviours remain the same regardless of the length of occupation, actions that would be expected to leave a clear "residential" signal, such as an abundance of locally procured materials and manufacturing waste, would occur much more rarely at sites inhabited by the agents for short periods than would be the case with long term occupations.

3.3.4 Mobility

Our model considers mobility at the group level in terms of "residential" moves between sites (see Turq et al., 2013), but we also factor in, albeit implicitly, the foraging activities of individual group members (see below – procurement). Since the frequency and length of residential moves may have depended on seasonal factors, we define the lengths of stay in terms of a range rather than a fixed value, as noted above. At the end of each stay at a site the agent (i.e., group) relocates to a new camp selected from the list of suitable locations available within a given simulation. This selection is limited to sites within a specified travel time interval from the agent's current position, and is random, with each site within the interval having an equal probability of being selected. The chosen time interval corresponds, minimally, to twice the maximum time individuals might have been willing to spend travelling, on a regular basis, to reach desirable resources from a given camp, a figure which, ethnographically at least, appears to be rather constant (Kelly, 1995). The logic is simple and is based on Kelly's (1995) central place foraging model: once it becomes undesirable to keep exploiting resources available within the given foraging radius, camps are relocated, generally to a place where there will be no overlap with the previous site's exploitation territory, and which is not unnecessarily far. The mobility condition defined here does allow agents to visit one location, and then immediately return to the previous camp, which is not something that would be expected if residential mobility is assumed to be primarily due to resource depletion. However, the probability of such occurrence is very low, given the relatively large number of viable candidates typically available with every relocation episode.

3.3.5 Toolkits

We define 'toolkits' at two levels: 1) a 'mobile toolkit' (hereinafter, MTK), which consists of personal gear (*sensu* Binford 1979), used both on and off-site, which is carried by tool users (a subset of the 'agent') whenever they are away from a camp (i.e., either during normal foraging activities, or during residential moves), and 2) a collective or group 'toolkit' (hereinafter, GTK), which consists of usable lithic materials available for the benefit of the group at residential sites. We make no assumptions about the technological or typological nature of the materials available in either the mobile or group toolkits, but we do assume that MTK elements represent coherent items (e.g., an actual flake rather than a group of unspecified artifacts), and that to a lesser extent the same is true of GTK items, which may be conceptualized as representing mainly individual cores or nodules.

3.3.6 Procurement

In the context of our model the tool users within the group are assumed to forage for unspecified resources around the sites, carrying with them raw material items of an unspecified techno-typological type that are occasionally discarded or lost while away from camp. Missing items are fully replaced on a daily basis with materials procured from the collective toolkit (GTK), individual MTK element sizes being determined prior to the transfer and drawn at random from an empirically derived distribution (see Methods), under the assumption that up to a specific percentage (see Discard/Waste below) of a GTK element may be collected as a single item (i.e., that the GTK element does not represent many small items). Each raw material type present in the GTK is given an equal chance of being selected provided that the needed quantities are present, under the assumption that any task-specific functional differences would be reflected in corresponding differences in the likelihood of the materials actually being collected and transported to the site. Moreover, in keeping with the goals of an MRM, we assume there were no biases in size selection by raw material type.

Agents also strive to maintain a predictable raw material supply at residential camps, collecting materials when needed (i.e., when the supply at camp is low). Unlike mobile toolkits, however, the collective toolkit is not always refilled, so as to reflect the substantial differences in required effort and to allow for the potential of alternative foraging priorities. When an adequate supply existed at a camp, for instance, time is likely to have been preferentially allocated to other tasks, while at times of very low GTK supply, procuring materials from sources in the area may well have been vital. Consequently, we set the likelihood of procurement within the course of any given day to be inversely proportional to the quantities available in the collective toolkit, whose maximum size is fixed in the context of individual simulations.

During procurement events materials required to fully replenish the collective toolkit, up to a set maximum (see section 4.3.1 below), are collected by an individual or foraging sub-group of the 'agent' from a single source. This source is selected from amongst those deemed viable for exploitation at a given camp according to the method proposed in Chapter 4. Our model does not define a hard distance or time-travel limit for lithic procurement around a camp, thus leaving open the possibility that some resources were procured through logistic trips *sensu* Binford (1979), during longer stays. However, given the abundance of lithic sources in the study area (see Figure 2), our baseline assumption is that, as has been suggested for similar contexts (e.g., Duke and Steele, 2010) such logistic trips would have been rare. We chose to model procurement from a single source at a time because such a strategy would have required only minimal coordination abilities (i.e., selecting an individual or sub-group responsible for procurement, when needed).

The overall provisioning strategy stipulated by our model is similar to Kuhn's (1995) and is based on similar assumptions (e.g., that most manufacturing and processing occurred at residential sites – see also Kelly 1995), but differs from the latter in some important aspects. First, we make no assumptions regarding the depth of planning reflected in provisioning of places versus provisioning of individuals. For example, our model does not assume that "[t]he strategy of provisioning of places […] requires some knowledge of both the timing and the probable location of future needs" (Kuhn, 1995: 23); rather, in our model the provisioning of residential camps (i.e., replenishment of the GTK) is simply a question of estimating how much material is more than enough. Second, our model makes no assumptions about the technological character of the transported materials. Finally, we do not assume that either the frequency of residential moves, or the duration of stays, is in any way strategically related to the provisioning of places or individuals (cf. Kuhn, 1995).

Our model of procurement does, however, make several important assumptions, including:

1) We assume replenishing toolkits in the course of daily foraging activities, upon chance encounters with good-enough sources for instance, would have been at best a minor component of the overall provisioning strategy. Violations of this assumption are incompatible with our identification of viable sources at the simulated camps.
2) We assume that the distribution of artifact sizes at a benchmark site, and consequently the distribution parameters employed here to estimate MTK element sizes (see Methods), is representative not only of the sizes of mobile toolkits carried by hominins while passing through said site, but also of their mobile toolkits at other sites. This assumption may be problematic (see Pop, 2016), but we suggest it still represents the best and most realistic way of estimating MTK element sizes given our current state of knowledge, and its reliability can in any case be assessed by examining discarded element counts.
3) We assume that the lithic resource selection criteria identified at the Bau are very similar to those at other camps. Differences would be expected to strongly affect the identification of viable sources across the landscape. We note that preliminary results of

a blind application of the resource selection model developed at the Bau to another site, La Combette, strongly suggest that this assumption is valid, since a moderate-to-strong and statistically significant correlation between predicted selection probabilities and observed raw material frequencies can be observed (see SOM 1).

4) An important assumption core to our identification of viable raw material sources at simulated camps (see Methods), which is nevertheless based on previous archaeological (Chapter 4) as well as ethnographic (e.g., Kelly, 1995) insight, is that of complete *group*-level knowledge of the lithic resources around camps.

3.3.7 Transport

Our model can accommodate two mechanisms for raw material transfers between camps, namely as regular elements of mobile toolkits (MTK) or as relocated collective toolkits (GTK) carried from one camp to the next. In the former case, from the perspective of raw material management, residential moves would be no different from other daily activities. On the other hand, collective toolkits may be expected to be at least partially transferred in the course of residential moves if the availability of materials at the target camp is unpredictable, and/or if the cost of resupplying said camp with suitable materials is expected to be high. In the context of an MRM, modelling relative risk (e.g., given position in the landscape), with concomitant assumptions regarding planning depth, seems undesirable, and we argue two simple scenarios should be favoured instead: agents should either transplant a fixed portion of the collective toolkits (<100% to provide a mechanism for the abandonment of non-exhausted items), assuming no information about the target camp, or carry nothing and make do with what is available in mobile toolkits. In this paper only this second mechanism is considered.

3.3.8 Discard

In our model there are multiple pathways for artifacts to enter the archaeological record. First, each element of the agent's personal gear (MTK) has an equal daily probability of being discarded and an associated likelihood of the discard event occurring either off-site (e.g., while foraging) or on-site. Personal gear elements discarded while at a camp, perhaps as part of regular maintenance tasks, enter the archaeological record directly, and are assumed to have never again been used as part of an MTK. This does not pre-empt the possibility that such discarded elements may have been recycled for on-site tasks, but we do assume no further reduction took place.

A second pathway consists of waste. Unspecified by-products of material transfer from collective to mobile toolkits (i.e., personal gear) thus enter the archaeological record directly during each MTK resupply event, amounting to a fixed percentage of the procured MTK element's mass. This is taken here to represent an average, and need not correspond to what is generated during a single event – in other words, this figure may include, conceptually, waste generated after a tool has been produced in the course of maintaining it while on-site. We make no further assumptions regarding this waste, and as such we make no attempt to specify the number of pieces it represents, or their characteristics.

A third and final pathway consists of sedimentation, which applies to the collective toolkits (GTK). We consider sedimentation in the context of an MRM because it is clear that in many contexts materials entered the archaeological record before being fully exhausted, and the size of many assemblages relative to the depositional time they represent suggests lengthy periods between revisits (see Methods below), enough for at least some 'abandoned' GTK items to have been covered by sediments. The inclusion of such a 'sedimentation' process is particularly relevant to instances where only mobile toolkit elements are transferred between camps (see above), since they provide a realistic (and here only) mechanism for the incorporation of non-exhausted elements into the archaeological record. In line with an MRM's goal of simplicity, each GTK item is considered to have had an equal daily chance of sedimentation through some process that would render parts of it, or all of it, invisible or inaccessible (e.g., a roof fall). To simplify the model, and since a GTK item may technically represent one or more rocks collected together (i.e., at a specific time) from a given source, the actual mass of the material that enters the simulated record is selected at random (uniform) from a GTK item's total mass. We acknowledge that this model of discard does not explicitly account for tools meant exclusively for on-site processing.

4. Methods and Data

We implemented our minimally realistic model using the Anaconda distribution of the Python language (v3.6.4) and ran a total of 320 simulations, or 10 per parameter combination (see Table 1), as detailed below. All GIS operations were scripted in Microsoft R Open (v3.5.1, R Core Team, 2018) and conducted in GRASS (v7.4.0, GRASS Development Team, 2018) using open-source R packages that included raster (Hijmans, 2017) and rgdal (Bivand et al., 2018). R was also used to process and analyze the simulation outputs. In order to ensure the reproducibility of our results, the random number generator was seeded with CMP's birthday or a variant thereof in all scripts that used it.

4.1. *GIS data and processing*

Our simulations used 3 arc-second (~90 m), void-filled SRTM (v4.1) digital elevation models (DEMs) provided by CIAT (Jarvis et al., 2008), which we processed and clipped to the region of interest (43^{o}N to 45^{o}N and 4^{o}E to 6^{o}E) as described elsewhere (Chapter 4). Over this area we placed 144,400 (380 x 380) uniformly distributed point features, ca. 257 m apart along a N/S or E/W axis and representing potential camping locations, and projected the known coordinates of two archaeological sites (the Bau and La Combette) as well as previously documented (e.g., Wilson and Browne, 2014) raw material sources. We did not consider any other landscape features (e.g., rivers, vegetation cover) except slope, as we filtered out inaccessible areas with slope values greater than 60% (see Chapter 4 for details).

We computed travel times (to and from) between all camps and raw material sources using DEM-derived anisotropic least-cost maps generated in GRASS with the r.walk module, employing a maximum cost value of six hours and default slope and cost parameters (see Chapter 4 for further details). We then filtered out potential camps located at more than three hours from the nearest raw material source, so as to simplify calculations, and computed travel times between each of the remaining 86,371 (i.e., $86{,}371^2$ minimum-cost paths) using the same method. This enabled us to filter out neighbours suitable for residential moves in the context of individual simulations (see below and section 3.3.4).

Source exploitation probabilities were pre-computed from the perspective of each potential camp location using a method first applied at the Bau in Chapter 4. In essence, the approach involves performing a cost-benefit analysis for each source in light of available alternatives and filtering out raw material sources that are identified as sub-optimal for exploitation. This requires evaluating the cost (here, time) of travelling between sources on the way to a given camp and considering this effort in light of the relative benefits (e.g., raw material quality) afforded by the alternative. With a small subset of optimal alternatives thus identified, we calculated their individual probabilities of exploitation by applying the logistic model derived from the Bau assemblage (see Chapter 4), under the assumption that resource selection remained stable across the region. With regards to this assumption it should be noted that the selection signal at the Bau represents the average observed over some 100,000 years, so it should capture fundamental aspects that may reasonably be expected to apply to other sites as well. As already noted above (section 3.3.6), we tested whether this is indeed the case by comparing source selection probabilities predicted for a different site, La Combette, against archaeological observations (see SOM 1).

To minimize model complexity and improve efficiency, we pre-selected a fixed number (see section 4.3.1) of potential camp locations for each simulation, drawing these at random (uniform) from the total of ca. 86,000 available overall, and always adding the target archaeological site – the Bau. For each we created a list of other included camps that were viable neighbours for the next residential move (see 4.3.1) and of exploitation probabilities for sources worth exploiting, and these data were pre-allocated for individual simulations.

4.2. *Archaeological data:*

We use previously published provenance data on 15,674 lithics from the Bau (e.g., Wilson and Browne, 2014), procured from a minimum of 17 and a probable maximum of 101 sources in the region (i.e., 17 source areas – see section 2). These lithics come from more than 11 layers at the site spanning approximately 100,000 years of deposition (see section 2) and represent all elements with an identifiable raw material type from a total of 40,770 examined pieces, the rest of which were too altered by patination or burning to allow for a reliable characterization. We also use currently unpublished data on the mass of 5,338 individually measured lithics from the Bau, amounting to ca. 86 kg, to empirically estimate the mass distribution of simulated mobile toolkit (MTK) elements. We achieve this by fitting a continuous Weibull distribution, shown to successfully model artifact size distributions of the kind considered here (see Lin et al. 2016 and references therein), and employing the resulting shape and scale parameters to draw MTK element sizes at random during procurement episodes.

4.3. *Operationalizing the MRM*

The MRM proposed above was implemented according to the flowchart described in section 3.2 and with the help of a custom simulation scheduler available at http://github.com/cornelmpop/sim_dispatcher. To capture the range of variability that may be expected given the random nature of the modelled processes and the uncertainties inherent in estimating past behaviours, we used extreme but realistic ranges instead of fixed values for many of our parameter settings, running 10 simulations of all possible minima/maxima combinations. As noted above, each simulation used a pre-allocated subset of the uniformly placed hypothetical camps, and each used a random seed based on CMP's birthday and the simulation's unique ID. Taken together, and given the stochastic nature of the modelled processes, the combined results of individual fixed-parameter simulations should also cover temporal fluctuations in said parameters (i.e., actual variations in group size through time), provided that these remained at all times within the defined ranges. This is true even if strong directional changes are archaeologically documented (see section 2), although of course in such cases the measure of centrality in the simulated distributions would be misleading. It must also be noted that the raw material provisioning strategy implemented and tested here is based on exclusively direct (i.e., from the camp) procurement of collective toolkit (GTK) elements (see 3.6).

As implemented here, the model individually tracks multiple sources of archaeological accumulation at specified camps (e.g., the Bau), namely: a) mobile elements discarded on site, b) waste associated with the transfer of material from the collective toolkit to mobile toolkits, and c) collective toolkit materials buried while the agent is away from a camp (see section 3.3). For each of these we record the geographic source of the raw materials, their original place and time of procurement, and their mass (in grams). Items discarded by the agent off-site are not tracked, and elements in the waste or sedimentation data represent events rather than individual pieces – in other words, only the association between mass and raw material type can be explored in these records.

4.3.1. Setting parameters

The model parameter ranges were set based on published literature and fine-tuned through a model calibration procedure described below. Within individual simulations these parameters are either set to a constant value (e.g., group sizes, or the probability of daily discard), or they are randomly selected when needed based on a set of circumstance-specific rules.

4.3.1.1. Baseline parameter ranges:

The length of the simulations was set to 100,000 years, so as to cover the depositional history of the Middle Palaeolithic layers at the Bau. Over this time span we modelled the daily behaviours of groups ranging in size from 5 to 28 individuals. The lower limit of this range corresponds to perhaps two adults and three children, assuming an interbirth interval of ca. 3 years as suggested by the evidence from El Sidrón (Lalueza-Fox et al. 2011; see also Nava et al. 2020). We consider this to be a highly extreme but nevertheless minimally realistic estimate for the size of the residential groups which a Neanderthal may have, at any one time, been a part of. The higher limit is also more extreme than commonly suggested (e.g. Lalueza-Fox et al., 2011; Vallverdu et al., 2010; Burke, 2006; Daujeard and Moncel, 2010; Churchill, 2014) and is based on Hayden's (2012) calculations. For the sake of reducing the number of simulations needed, we set the number of 'productive' individuals as a fixed percentage of these groups, namely 30%, rounding to the nearest integer value. The percentage was chosen to represent a situation with few adults and a large number of children, as suggested by the recent findings at Le Rozele (Duveau et al., 2019), and the resulting figure corresponds to the number of individuals envisioned to carry mobile toolkits.

The number of consecutive days the agent spends at a camp is, unlike other parameters, defined using ranges (see 2.2.3), set here to 1-6 and 15-90 days. On each relocation the agent selects the number of days to be spent at the new camp at random, with each value within the specified range having an equal probability of selection. The lower range reflects an extremely mobile groups, in line with Verpoorte's (2006) suggestion regarding the Neanderthal record, while the latter translates to an average of ca. 7 residential moves per year which falls more in line with ethnographically documented hunter-gatherer cases, for which Marlowe (2005) reports a median of 5. Both group sizes and residential moves are thus shifted with respect to modern hunter-gatherer populations, with the minima extending beyond their observed range and the maxima approaching the center of the documented distributions (see Marlowe, 2005).

We set the number of mobile toolkit elements carried by individuals to a minimum of 3 and a maximum of 9. Given a mean mass of 16 g (see section 4.2), and a turnover corresponding to an average of one item every 10 days, these figures would result in a consumption of ca. 111 to 333 tools per year, or a minimum of 1.8 to 5.3 kg per person. These are in line with, if not exactly equal to, estimates provided by Luedtke (1976) based on ethnographic cases, and the minimum would also cover the three different classes of personal gear elements documented by Binford (1979) with the Nunamiut. The maximum quantity of materials procured by foraging individuals or groups is set to between 5 and 15 kg per event, a range being used here mostly to estimate the impact of this variable on the overall output, while the actual amount procured is based on the availability of materials in the collective toolkit (see 2.2.5). These estimates are based loosely on: a) the assumption that special purpose procurement trips would probably have been rare (see 3.5), b) the observation that sources with large rocks (19-35 cm) were preferentially targeted at the Bau (e.g., Wilson and Browne, 2014) and that, at least in some cases, refits of nodules exceeding 9 kg are documented (e.g., at Maastrich-Belvedere, see Veerporte et al. 2016), and c) consideration of other parameters (e.g., raw material needed per individual) which would have made situations of inadequate supply requiring immediate procurement of larger packages unlikely.

Sedimentation rates were estimated from the characteristics of the Bau where, based on the available dates, approximately 6-7 m of sediments were deposited over the course of some 100 millennia, corresponding to an average rate of roughly one centimeter per 143–167 years. We acknowledge that this is a very rough estimate, and that sedimentation at other camps likely occurred at different rates, but currently we have no better basis for estimating sedimentation at random camp locations. At these rates we could reasonably expect that most if not all of a collective toolkit would be covered by sediment every 1500 years or so (i.e., 10 cm), but also that a substantial amount of the larger pieces (e.g., cores) would still be visible after ca. 800 years (i.e., ~5 cm of sediment). This suggests that, even envisioning extreme delays between site revisits, leaving collective toolkits behind during residential moves, as insurance or perhaps passive gear *sensu* Binford (1979), would have resulted in low-cost, predictable supplies throughout the region, with losses due to sedimentation being a minor concern. Under these conditions the size of the collective toolkit is not a major concern – after the initial cost of fully provisioning a camp, which in the context of 100,000 years of habitation is negligible, the cost of resupplying it based on need should remain constant. Consequently, we set the collective toolkit's size to an arbitrarily chosen value of 20 kg, and sedimentation probabilities to 1 per 1,000 years for every GTK item.

4.3.1.2. <u>Calibration of model parameters</u>*:*

As the model is defined here, the average quantity of personal gear produced and discarded at a site, which ultimately governs the overall size of the assemblage, can be estimated as the product of the length of habitation, in days (D), the number of productive group members (P) who carry mobile toolkits, the quantity of items carried by each of these (MU_p), and the probability each item of personal gear has of being discarded on a given day (M_d). Multiplying the resulting value by the probability of items being discarded on site (M_r) provides an estimate of the average number of mobile toolkit items to be found in a simulated assemblage (S_s). In short, the expected number of discarded personal gear items is given by the following formula:

$$S_s = D * P * MU_p * M_d * M_r$$

Thus, over a period of 400 years of habitation an average of 2 individuals carrying mobile toolkits consisting of 3 items each, would produce an assemblage of 29,000 items of personal gear (i.e., not including manufacturing waste) if each item had a probability of 1 in 10 of being discarded or lost on a given day, and a 1 in 3 probability of that discard occurring on site, with each tool user requiring approximately 2 kg of stone per year, not including waste and unused collective toolkit items. Even these very conservative parameter estimates thus result in simulated assemblages that, while realistic, are somewhat large given archaeological observations at the Bau, both in terms of mass and counts. Since it is very unlikely that there were fewer than two tool users per residential group, or that these carried less than three items of personal gear, either the total length of habitation is too high, or the probabilities of discard are too low, or both. In other words, assuming materials were not removed by post-depositional processes, the Bau was either inhabited for less than 0.5% of the depositional history thought to be represented by its Middle Palaeolithic layers, or its inhabitants discarded fewer items in total or more items off-site.

While no direct assessment of discard rate estimates is possible, we can probe habitation lengths further. Assuming a continuous habitation of the *region*, and the modelled approach to selecting the next residential site (see 3.3.4 above), the total number of days stayed (*D*) at a given location over the course of the simulated period is a straightforward function of the total number of camps considered per simulation (*N*). To derive a formula specific to our modeled conditions we ran a total of 4,000 simplified and shortened simulations (10,000 years each) where the agent took no actions while at a camp. These considered 10 different values for the number of sites (from 1,000 to 28,000 in 3,000 increments) and two different values for the lengths of stay and move radii respectively, with each configuration being replicated 100 times. The resulting formula is given below for the average cumulative total number of days stayed at any given camp over 10,000 years ($D_{10,000}$), but to obtain the number of revisits the result can simply be divided by the average lengths of stays:

$$D_{10,000} \approx 3.5 * \ e^{(13.84 - 0.9915 * \log N)}$$

Thus, we can expect that, on average, a single agent will spend a total of 963 days at each camp over the course of 10,000 years in a simulation where 4,000 viable camps are considered, and 1,913 days if 2,000 camps are considered. If the agent stayed at a camp for 1-6 days, the average number of revisits would be 275 and 547 respectively, while if the agent camped for 5-30 days the average number of revisits would be 55 and 109. With 4,000 and 2,000 camps, then, we would expect cumulative habitation of individual sites of ca. 26 and 52 years respectively over the course of the entire 100,000-year period considered here, with revisits occurring on average every 182 and 92 years. Given the sedimentation rates discussed above, it may well be that such discrete occupations, though separated by very long time spans, would be very difficult to distinguish archaeologically. Consequently, from a simulation perspective**,** it is impossible to reject the possibility that the Bau may, indeed, have been inhabited for a tiny fraction of the time represented by its Middle Palaeolithic layers.

Since the number of sites is expected to primarily affect assemblage size, we decided to set their number to 2,000 and to vary the probabilities of discard instead, since these are much more difficult to estimate. Moreover, to keep the number of simulations manageable we vary only the probabilities of the discard occurring on-site, from values of 0.2 (i.e., most personal gear will be discarded off-site) to a value of 0.8 (i.e., most personal gear will be discarded on-site, as suggested by Binford, 1979). These and other final parameters of the simulations are listed in Table 1 below, and the resulting simulated assemblages are expected to contain from a minimum of ca. 2,300 to a maximum of ca. 124,000 items of personal gear, which we deem to be sufficiently close to archaeological observations at the Bau to suggest the parameters used are minimally realistic.

Table 1: Simulation parameters. *10 simulations were carried out for each parameter combination. Using these parameters, the simulated assemblages are expected to contain a minimum of 2,300 and a maximum of 124,000 items of personal gear.*

Parameter	Setting 1 (min)	Setting 2 (max)
Simulation length	100,000 years	
Time resolution	1 day	
Group size (people)	5	28
Tool users	30%	
Days at camp	1-6	15-90
Items of personal gear per tool user	3	9
Personal gear item mass (g) – Weibull shape	1.177	
Personal gear item mass (g) – Weibull scale	53.06	
Probability of daily discard from personal gear	0.1	
Probability of on-site discard	0.2	0.8
Maximum procurement mass (kg)	5	15
Maximum collective toolkit size (kg)	20	
Yearly sedimentation probability	1/1000	
Number of viable camp locations	2000	
Travel time to locations considered for residential moves (hours)	4-5	

5. Results:

5.1. *General characteristics of the simulated Bau assemblages:*

The simulated Bau assemblages vary in size from 724 kg to 2,953 kg, with a mean mass of discarded or abandoned lithics of 1,377 kg (SD = 573 kg) and a median of 1,178 kg (IQR = 518 kg). However, these figures include outliers produced by one extreme parameter combination, namely group sizes of 28 individuals, personal toolkits consisting of 9 elements, and probabilities of on-site discard of 80%. With such outliers excluded, the total mass of the simulated assemblages attains a maximum of only 1,735 kg, with a mean and median of 1,181 kg (SD = 255 kg) and 1,097 kg (IQR = 436 kg) respectively.

Items discarded from personal gears (i.e., MTK) account for 3.3 to 60.2 percent of the simulated assemblages by mass, with a mean of 23.7% (SD = 16.6%) and a median of 19.9% (IQR = 22.1%), or up to 39.2% if the outliers noted above, and which only have a major effect on this component of the simulated record, are excluded. In that case the mean is 18.8% (SD = 11.1%) and the median 13.6% (IQR = 19.6%). Waste materials resulting from the creation of mobile toolkit elements from locally procured collective toolkits (i.e., GTK) account for 4% to 27.1% of the simulated assemblage mass, with or without outliers, having a mean of 11% (SD = 6%) and a median of 10% (IQR = 6%). Sedimented materials, on the other hand, account for 24.6% to 91.6% of the mass, with a mean of 64.9% (SD = 19.36%) and a median of 68.4.6% (IQR = 27.9%). The large proportion of sedimented materials *suggest* that either the sedimentation probabilities were set too high (likely, given that the estimated sedimentation rate at the

Bau is positively skewed due to episodes of roof fall which would have added a lot of material very quickly), that the maximum size of the collective toolkit is larger than would have been reasonable given the probability of site revisits, or a combination thereof. Regardless, the result is a likely inflated signal for locally procured materials. The overall raw material composition of the simulated assemblages is shown in Figure 4, aggregated by source area.

Only 91 of the known 122 source areas contributed materials to the virtual Bau assemblage across the entire set of 320 simulations. These included 16 of the 17 (missing ID = 76) with evidence of archaeological exploitation at the actual site, which account for 99.95% of the archaeological materials with known provenance. With 11 of these 16 source areas the range of the mass abandoned at the virtual Bau by the agent encompasses the mass of the actual archaeological materials, estimated on the basis of the number of pieces and the available weight distribution data; an additional source area (ID 13) falls outside the range only by a small margin (it contributed 1 archaeological piece to the Bau assemblage, and a few pieces - minimum of 55 grams - to the virtual Bau). 75 source areas are represented at the virtual Bau, but not at the actual site, so technically archaeological observations fall outside the simulated range. However, these source areas typically contribute very small amounts of material within the simulations (75% of these contribute as little as 7 grams or less), so this should not be interpreted as a poor fit; indeed, it is conceivable that some of these source areas are represented by the occasional small flake at the site, which may be among the many patinated or burned lithics whose provenance could not be established (see section 4.2).

Nevertheless, as evidenced in Figure 4, there are five cases where archaeological estimates fall well outside the range observed in the simulations. Of these, two consist of source areas (ID 36 and ID 57) that were exploited by the inhabitants of the site to a larger extent than expected under modelled conditions; their apparent overexploitation *may* indicate preferential habitation of areas where sources belonging to these appear as optimal procurement candidates, since neither the quality of the materials (maximum of 3 on a scale that reaches 10), nor their location relative to the Bau (1-2 hours) can explain their degree of archaeological representation. Of the three source areas that, under modelled conditions, should have been exploited to a substantially larger degree than is archaeologically observed, one (ID = 52) is represented by a low-quality source (ID 7) that was likely misidentified as an optimal local procurement candidate. If materials collected by the agent from that source while residing at the Bau are ignored, the simulated raw material frequencies fall in line with archaeological observations. The lower-than-expected exploitation of the remaining two source areas (53 and 58) remains currently unexplained and warrants further investigation in the future. Aside from this, however, archaeological observations are overall consistent with the results of our simulations, suggesting that the optimal candidate hypothesis can hold when factoring in the effects of residential mobility and inter-site raw material transport.

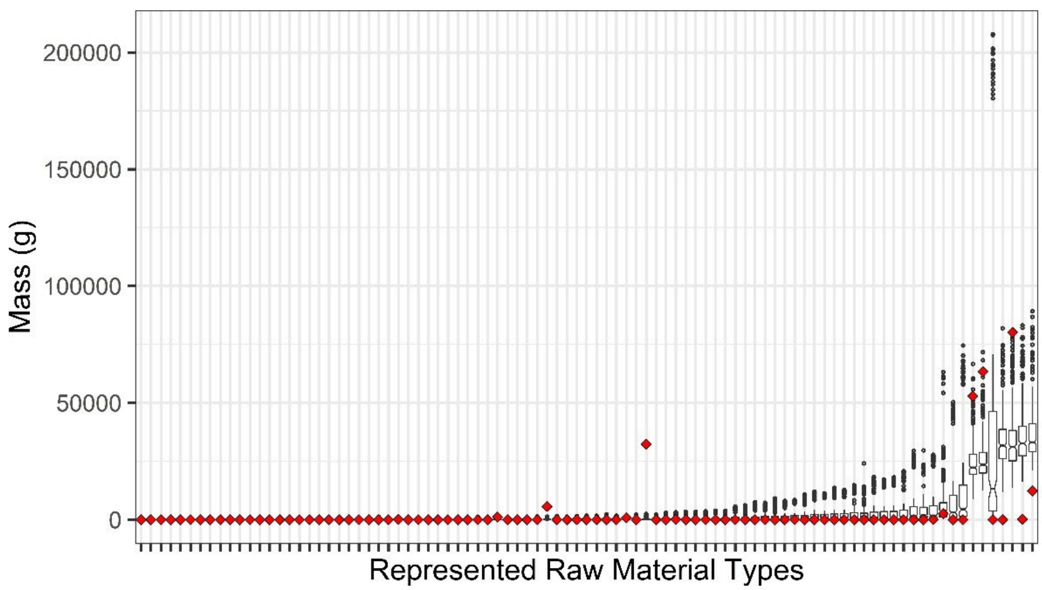

Figure 4: **Simulated raw material variability at the Bau de l'Aubesier.** Boxplots represent the range of variation in the mass of lithics made from raw material types found at source areas exploited by the agent (n = 90) and discarded or abandoned at the simulated Bau across the full set of simulations (n = 320), which covered all parameter combinations. Red diamonds indicate the estimated mass of actual archaeological materials recovered from the site, calculated by multiplying published counts by the median of the mass data to which the Weibull distribution was fitted (see section 4.4).

5.2. *Expected LPOS incidence:*

If lithics materials procured at other sites (i.e., LPOS), –which, as modelled here (see section 3.3.6) consist exclusively of personal gear items (i.e., MTK) - are considered in terms of their mass contribution to the overall simulated Bau assemblages, they account for a minimum of 0.6 and a maximum of 47.1 percent of the latter, with a mean of 11.6 (SD = 12) and a median of 7.1 (IQR = 10.7) percent. If sedimented materials are excluded, as they may be overestimated in our simulations (see above), the LPOS contribution varies between 6.8 and 64.4 percent, with a mean of 30.7 (SD = 21.3) and a median of 23.6 (IQR = 33.6) percent. With or without sedimentation, the variability is driven by the number of days stayed at camps, with shorter stays resulting in much higher representation of non-local materials (a mean of 50 [SD = 12.4] with stays of 1-6 days versus a mean of 11.5 [SD = 3.1] percent with stays of 15-90 days), and by the probabilities of on-site discard (on average 23.2 [SD = 14.9] percent of the mass if using probabilities of 20%, and 38.3 [SD = 23.9] percent if using probabilities of 80%). Other considered variables have no direct effect on these proportions, although they do influence the mass contribution of sedimented materials.

The proportion of LPOS among personal gear items (i.e., MTK) discarded at the virtual Bau was found to vary between a mean of 78.9 (SD = 0.5, n = 160) percent with short simulated occupations (1 to 6 days) and 18.7 (SD = 0.5, n = 160) percent if simulating longer stays (15 to 90 days). This suggests a straightforward relationship between the average length of stays and the average percentage of non-locally procured personal gear items discarded at a site. Comparisons in terms of mass revealed an almost identical picture, with virtually identical means but slightly larger standard deviations (0.64 and 0.68 percent with shorter and longer stays respectively). Other than the length of stay, no simulated variable played a noticeable role in the relative incidence of locally and non-locally procured personal gear items, not even the number of such items that are carried by the agent.

In short, these simulations reveal that, no matter how we look at an assemblage, we can generally expect a relatively substantial proportion of the discarded materials to have been procured while residing elsewhere, even if personal toolkits are considered as the only means of inter-camp transport (i.e., no trade, no general-purpose material transport between sites). They also reveal that, under modelled conditions and depending primarily on the lengths of residential stays, these non-local materials are brought in from a large number of camps, with individual ones seldom contributing more than a small number of artifacts (ca. 12 per camp per simulation, but the distribution is strongly and positively skewed, having a maximum observed value of 109 artifacts per camp across all 320 simulations).

5.3. *LPOS from sources also exploited at the Bau:*

Under modeled conditions, materials procured by the agent while residing at other camps from sources it also exploits when staying at the virtual Bau account for between 0.29 and 30.15 percent of the total mass of lithics discarded or abandoned at the simulated site (median = 3.5, mean = 6.4 percent), and for roughly half of the LPOS total. Indeed, as shown in Figure 5, there is a very strong correlation between the mass of such LPOS and those acquired from sources which are not exploited by the agent from the virtual Bau. The specific details of this correlation are not important, of course, since they are specific to the modelled conditions used here, which are only meant to be minimally realistic. The correlation does suggest, however, that the percentage of lithics which may appear to have been locally procured by hominins residing at the Bau, but which were in fact procured at other camps and transported to the site as elements of personal gear, could be estimated from the incidence of clearly non-local (i.e., unexploitable from the Bau) materials – as modelled here, at least, they occur in roughly equal amounts. These results also suggests that evidence for local lithic resource selection and management at sites where a large proportion of lithics are likely to have been imported from other camps should not be taken at face value.

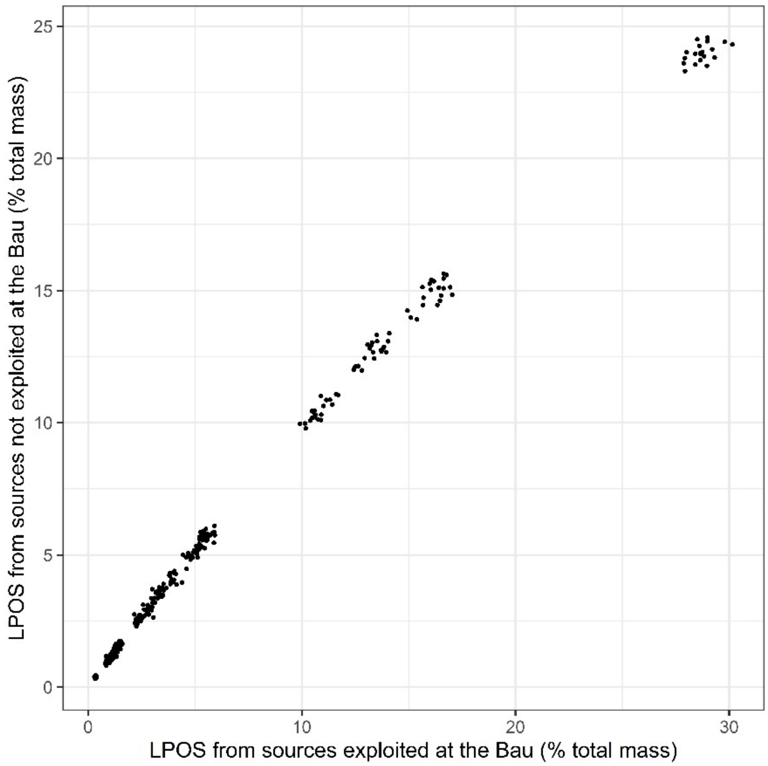

Figure 5: **Relationship between LPOS from sources exploited and unexploited at the Bau.** Lithics procured at other sites (LPOS) by the agent from sources that were also exploited from the virtual Bau account for a substantial proportion of the total simulated assemblage mass and show a very strong and predictable relationship with the incidence of LPOS procured by the agent from sources that are not exploitable from the site.

It is worth noting that our simulations indicate the likelihood of LPOS from locally exploited sources being discarded at a site may depend to some extent on the distance between the site and the material's source. With conditions specific to the study region, for instance, lithics procured by the agent from sources found within one hour of the Bau account for roughly one third of the total simulated Bau assemblage by mass (mean = 35.1, SD = 4.7 percent), and only a tiny fraction of these were indirectly procured by the agent while residing at other camps (min = 0, max = 1.26, mean = 0.18 percent). However, if sources found within 3.5 hours of the site are considered, and which contributed between 48.2 and 91.1 (mean = 77.6, SD = 9.7) percent of the total simulated assemblage mass, 0.2 to 24.1 percent of these (median = 2.67, mean = 4.95) were procured while at other camps.

5.4. *LPOS and observed raw material variability:*

As can be seen in Figure 6, the number of MTK (i.e., personal gear) elements made from specific raw material types and discarded by the agent into the simulated Bau assemblages exhibits a largely predictable relationship with the actual quantities of artifacts found at the site: materials which are archaeologically common are consistently well-represented in the simulated assemblages as well. Indeed, a Spearman's rank correlation test indicates a moderate and highly significant association between these variables ($r_s = 0.365$, $p < .001$), even if we exclude materials from sources that were, within our simulations, also exploited directly from the Bau ($r_s = .23$, $p = .01$). What is clear, however, is that several raw material types which are not archaeologically represented, or are very poorly represented, contributed rather substantially to the simulated assemblages (see also Figure 4). This could result from either a) an inability to accurately predict optimal sources at certain camps, perhaps due to the use of different resource selection criteria at these, or due to changes in the availability and/or characteristics of specific sources over time, or b) an underutilization of locations where non-represented raw material types should have been favoured.

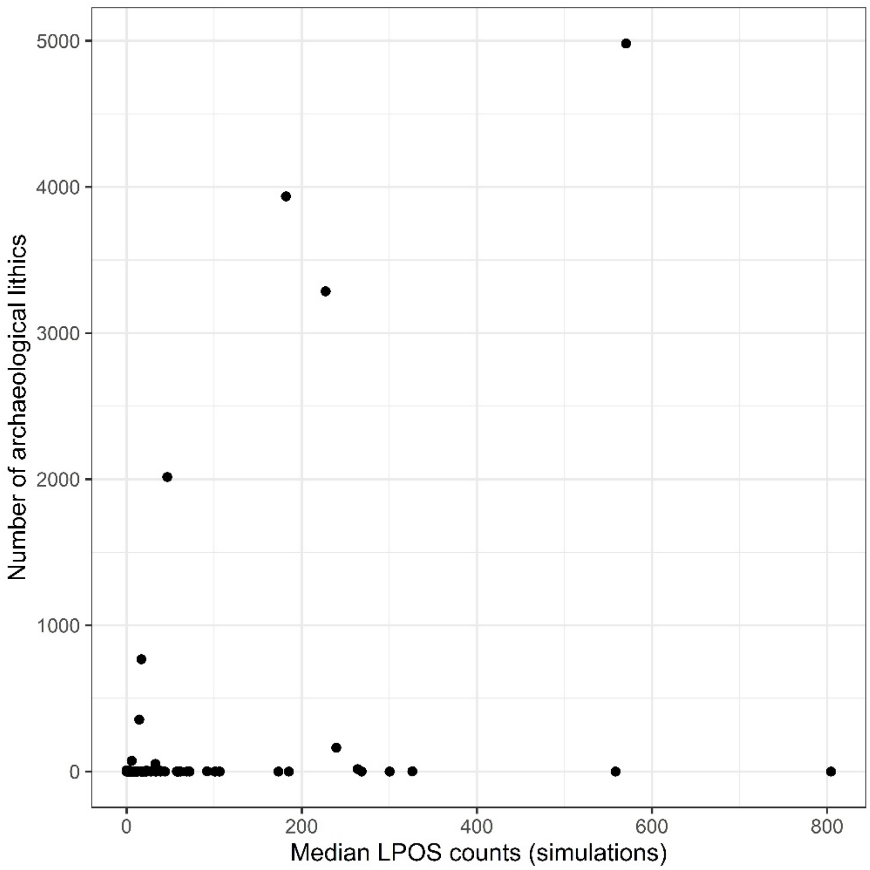

Figure 6: **Archaeologically observed raw material frequencies and simulated variability among LPOS.** The median incidence of 90 raw material types among the LPOS discarded at the simulated Bau over 320 simulations, plotted against their archaeologically observed frequencies. Under modelled conditions, LPOS (imported lithics) consist exclusively of personal gear items transported by the agent during residential moves.

5.5. *Regional patterns*

A map of hypothetical camp locations, color-coded by their broad compatibility with archaeological observations at the Bau (Figure 7), evidences substantial spatial patterning under modelled conditions. Red in the figure denotes camps which contributed exclusively archaeologically non-represented materials to the simulated Bau assemblages, while green identifies locations where all materials procured by the agent and eventually discarded at the simulated Bau are known to have actually been used by the inhabitants of the site. Camps with mixed contributions are shown along a palette diverging towards either extreme from a light blue center. Clear clustering with a typically gentle grading from zones of high compatibility to low compatibility ones can be observed.

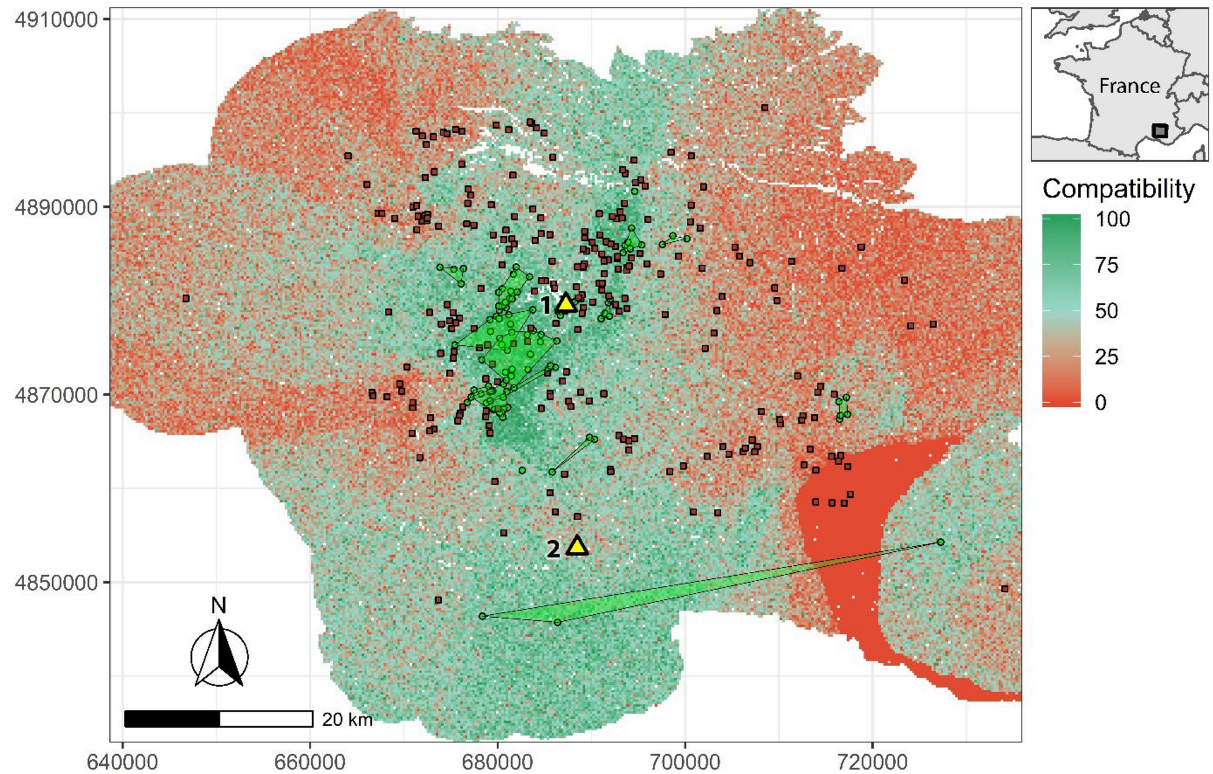

Figure 7: **Compatibility of possible camp locations with archaeological observations at the Bau.** Compatibility raster map created from the 85,808 virtual sites included in the 320 simulations. At each of these locations the agent procured raw materials from a small subset of sources that would have appeared to be locally optimal, and eventually transported and discarded some of these at the Bau. The colours indicate the mean proportion of such materials (number of items), aggregated across all simulations, that originate from source areas that are archaeologically represented at the Bau. If all lithics procured at and transported from a given location *x* to the Bau are fashioned from archaeologically represented raw materials, location *x* is considered to be 100% compatible with observations at the site and appears in green. Conversely, if all such lithics are made of materials which are not present in the Bau assemblages, the compatibility of location *x* is considered to be zero, and the location appears in red. Sources of archaeologically represented raw material types are indicated by green circles, while red squares denote sources lacking evidence of archaeological exploitation at the Bau. Green polygons represent convex hulls encompassing sources from archaeologically exploited source areas. Yellow triangles indicate the two Middle Palaeolithic sites discussed in the text, namely: 1) the Bau de l'Aubesier, and 2) La Combette. The raster resolution is 256 m. Coordinates are given in UTM (zone 31N).

This patterning is important because it shows that, although our minimally realistic model assumes a uniform utilization of the landscape as a starting point, simulations can be used to identify areas which are unlikely to have been inhabited by hominins who also resided at the Bau. This is because, if past behaviours are adequately captured by the extreme parameter ranges employed here (see Methods), and it can be assumed that drivers of lithic resource selection did not vary dramatically from site to site, materials from archaeologically non-represented sources should have made their way into the Bau if predominantly red areas were indeed regularly occupied. It is interesting to note in this context that the other site in the region for which relatively compatible raw material data is available, La Combette (2 in Figure 7), was not inhabited during the occupation of the Bau and is indeed located in a relatively low compatibility area – only 39% of the materials procured by agents occupying this location and contributed to the simulated Bau assemblages are of an archaeologically represented type.

The patterning further shows that simulations can be used to detect potential problems in the sourcing dataset. The sharply delimited, crescent-shaped zone of consistently incompatible locations at the south-east of the Bau is most likely an artifact resulting from such problems. Throughout this entire area a single source (ID = 324) was identified as worthy of exploitation, and it yields high-quality materials which are nevertheless not found at the Bau. It is unclear whether this artifact may be the result of changes in the characteristics of this source (e.g., degree of exposure) since the Bau was last inhabited, or of the presence of even more attractive sources in or near this area between ca. 100 ka and 200 ka, containing raw material types represented by the few unprovenanced lithics at the Bau.

Interpreting areas of high compatibility (i.e., green) is more difficult, since compatibility values provide no indication of whether and/or how often hominins may have actually occupied a specific area. However, if areas identified in Figure 7 as highly compatible were indeed preferentially inhabited, we would expect the quantities of artifacts procured by our simulated agent while residing there to be more strongly correlated with archaeologically observed frequencies than the baseline (see section 5.4 above). It should be emphasized here the *degree* to which specific archaeologically represented raw material types were exploited at a given location does not factor into how we defined compatibility above. If we consider the strength of such a correlation across locations above different threshold values, there is indeed evidence of a clear trend: eliminating locations with low compatibility values tends to result in stronger Spearman's rank correlation coefficients (Figure 8). This therefore hints at the possibility that the inhabitants of the Bau did favour areas shown in green in Figure 7, but validation using compatible raw material data from other, contemporaneous sites in the region is required to determine whether this was indeed the case.

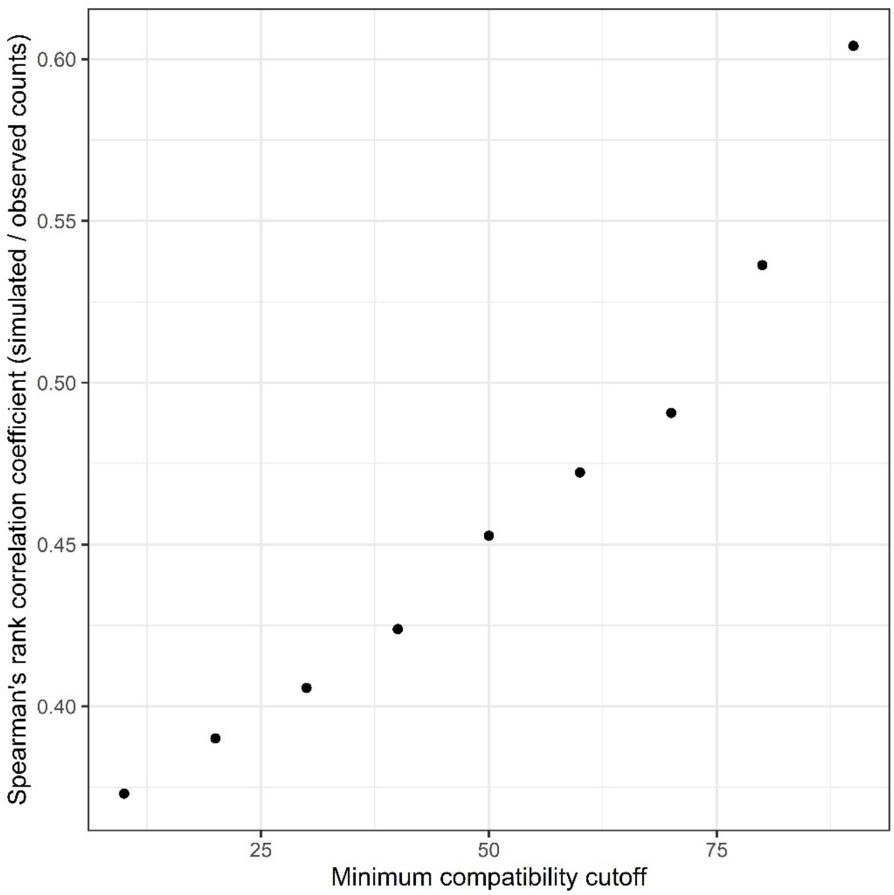

Figure 8: **Strength of association between raw material type frequencies in simulated LPOS and archaeological lithics at the Bau at different compatibility thresholds for contributing camps.** LPOS data consists of the aggregated raw material contributions to the virtual Bau (320 simulations) from all camps whose compatibility values are greater than the given threshold. These compatibility values refer to the mean percentage (number of items) of raw materials transported from said camps to the virtual Bau that originate from sources of raw material types that are evidenced at the site. See also Figure 7.

6. Discussion:

6.1. *The optimal candidate hypothesis still holds*

In this paper we introduced and applied a novel minimally realistic agent-based model to examine the potential pathways through which lithic raw materials may have been incorporated into the archaeological assemblages found at the French Middle Palaeolithic site of the Bau de l'Aubesier. We did this in view of ascertaining whether the hypothesis we recently put forward to explain the apparent avoidance of a very large number of sources in the region over a period of ca. 100,000 years, including some yielding high-quality materials and found in close proximity to the site, could hold if we factored in residential mobility and the concomitant import of materials from other sites. According to our hypothesis, sources were avoided because, from the perspective of a hominin intending to collect materials on her or his way to the Bau, better alternatives (i.e., higher quality and/or lower access costs) would have been available. But what of other camps such hominin stayed at? Would the raw materials that are represented at the Bau have been targeted at such camps also, or is it the case, perhaps, that materials procured as supplies for other sites would only have reached the Bau in negligible quantities?

Our simulations indicate that, under conditions of minimal realism (see section 3.1), we can expect ca. 0.6 to 47.1% of the total mass of lithics present at the Bau, perhaps slightly more (see 5.2), to have been imported from other sites. Our approach, which is not intended to emulate the past (see 3.1), does not allow us to further narrow down this range (see 4.5 for why measures of centrality should be treated with caution), but we can note that the relative amount of imported stone (i.e., lithics procured at other sites, or LPOS) will depend on the durations of continuous habitations of the Bau, as anticipated (see, e.g., Meignen et al. 2009), and to a lesser degree on the likelihood of implements having been discarded or lost outside the site (see 5.2). We know of no reliable way of improving our estimates for probabilities of off-site discard, which here refer exclusively to the abandonment of items during daily foraging activities, but the available lithic and faunal evidence is not suggestive of primarily ephemeral, very short-term stays (see section 2). In light of this, the lower end of this range is probably more representative of the amount of LPOS (i.e., imported materials) present at the Bau, particularly since our estimates for the degree of residential mobility are already positively shifted relative to ethnographic observations (see section 4.5.1s.1).

On the other hand, our results indicate that the importation of lithics as elements of personal gear could account for the presence of nearly all (16 of 17) raw material types found at the Bau without the need to invoke a misidentification of locally optimal sources as an explanation (cf. Chapter 4). Indeed, individual simulated Bau assemblages consistently yield most of the 17 archaeologically exploited raw material types (median = 15, with 13 present in 98% of the 320 simulations), and collectively almost all, despite only five having been exploited directly from the site by our agent. For this alternative explanation to hold, however, a minimum (see 5.3) of 17% of the analyzed artifacts recovered at the Bau - those made of materials from locally sub-optimal sources (see Chapter 4) – must have been imported to the site from other camps. This figure is well within the range observed in our simulations. In other words, although we cannot rule out the possibility that only a negligible quantity (i.e., 0.6% or so) of the lithic materials present at the Bau were imported from other sites, such a scenario may not be needed to explain the observed raw material variability.

There is, however, the matter of those lithic types which should be present at the Bau, but which nevertheless are not. In fact, the simulated assemblages are always more variable in raw material composition (36-79 unique types per simulation) than would be expected from archaeological observations (cf. Brantingham, 2003). More importantly, 13 seemingly unused types appear in 100% of our virtual assemblages, with a further 27 types appearing in 95% or more. Does this then mean we should rule out a scenario whereby the importation of stone from other sites explains important aspects of raw material variability at the Bau? We think not, for at least two reasons.

First, we know that our approach to identifying optimal candidates has important limitations, notably the fact that we evaluate all sources regardless of their distance to a site (see 3.3.6). While distance (or rather, effort) almost certainly did play a role, we had no reliable means of establishing a cut-off threshold that could be generalized to arbitrary camps. As a result, the misidentification of sources as optimal exploitation targets can be expected to be a common occurrence in our simulations – 25-33% observed at the Bau, after all (see section 5.1) – and may well be impossible to eliminate. The second factor to consider is how the landscape was actually utilized in the past. Our model assumes uniform habitability of the area and a random selection of camping locations, but this is just a baseline expectation (see 3.1). As shown in Figure 7, throughout substantial portions of the region, the extent of which is probably underestimated given our preceding observation, our agent exploited mostly or exclusively raw materials which are in fact represented at the Bau. If our agent preferentially resided in such areas, we would expect considerably fewer archaeologically invisible types at the virtual Bau.

Given the above, two scenarios are possible: first, it may indeed be that only negligible quantities of materials were imported to the Bau from other sites. In this case the presence of materials from locally sub-optimal sources could be due to an overly aggressive approach to filtering out viable procurement locations (see Chapter 4) resulting from, for example, an incomplete understanding of the drivers of raw material selection. Alternatively, our simulations are also consistent with a scenario in which materials were imported to the site by hominins who preferentially inhabited only certain areas of the region. Importantly, both scenarios are premised on hominins possessing excellent navigational abilities as well as detailed knowledge of the available lithic resources. Indeed, it is only by allowing for an outstanding ability to filter out sub-optimal exploitation targets in light of access costs to, and benefits afforded by, available alternatives, that we can explain raw material variability at the Bau under the second scenario. Thus, aside from indicating that our recently proposed optimal candidate hypothesis could explain the avoidance of at least two thirds of sources available in the region over some 100 millennia even if we assume that raw materials were regularly transported between camps, the results presented here also strengthen our previous conclusions regarding the spatial abilities of the Neanderthal occupants of the site.

6.2. *Neanderthal territories – what can raw materials tell us?*

The second scenario outlined above does raise the possibility that the areas of regular, direct resource exploitation around the Bau may have been somewhat smaller than previously suggested, more in line with ethnographic observations, but the overall conclusion that the Bau evidence is inconsistent with foraging radii smaller than typically seen with anatomically modern humans still stands (see Chapter 4). After all, a maximum of ca. 40% of the materials found at the site could have originated from sources found within a one-hour radius, and even simulations using the most extreme parameter combinations failed to produce assemblages where 60% of the materials were imported from other camps.

But what of the areas regularly used in the context of residential mobility by Neanderthal groups who inhabited the Bau (i.e., home ranges *sensu* Marlowe, 2005)? Unfortunately, our implementation of a minimally realistic model does not allow us to directly answer questions regarding the extent of such territories because we did not simulate discrete social units (see 3.3.2) nor the specific settlement strategies such units may have followed at a given time. Consequently, we are only able to provide insights into the possible extent of the combined territories frequented by individuals who at some point resided at the Bau, regardless of their social group affiliation. This is still informative with regard to the site's total sphere of socio-economic influence, however (i.e., site catchment – see Bailey and Davidson 1983 and Boyle 1998 for a review), and we contend here that this is the most reliable scale at which raw material data can be interpreted for most Middle Palaeolithic contexts. To assume provenance data can inform us of home ranges is to assume, amongst other things, that a) traces left by discrete Neanderthal groups can be archaeologically differentiated, and b) that such home ranges, and indeed groups, are stable over time. Both of these assumptions are problematic (e.g., Binford, 2006; Wobst, 1978). As noted above, if the lithic data from the Bau is informative with regard to landscape use beyond the site's direct exploitation territory, its sphere of socio-economic influence can be expected to have covered only part of the study region, although only maximal limits can be hinted at based on the available data (see 5.5).

6.3. *Further insights from the formulation and implementation of a minimally realistic model*

Aside from enabling a refined understanding of landscape use and resource selection at the Bau, our simulations allow us to make a series of observations of wider relevance. During our model calibration procedure, it became clear that a long total occupation of the site is difficult to reconcile with the available archaeological evidence (see section 4.5.1.1) notwithstanding the thick and rich sequence preserved at the site (see section 2). If the cumulative occupation of the Bau amounted to ca. 100 years or less, as would be the case with an average of ca. 8 cohabitating tool users (see 4.5.1.2), and if we can assume the *region* was inhabited throughout the entire 100 – 200 ka period, a large number of discrete locations must have been available and used for residential stays. Indeed, 1,000 sites would be needed to explain a 100-year cumulative habitation if the Bau was of a typical size for the region, and more if the Bau was among the richer, as it appears to have been the case. Using these figures, the Bau can be expected to have been revisited some 700 times assuming relatively long stays of ca. 50 days, or some 9,000 times if much shorter stays of ca. 4 days happened to be the norm. This, in turn, would imply an average time between revisits of ca. 143 and 11 years, respectively.

To what extent site revisits may have been clustered in time at the Bau is difficult to say given the available information on dates and sedimentation rates, but it is very likely that there were periods of frequent occupation followed by long gaps without human habitation. By itself, such clustering has no bearing on the preceding observations, although it would result in some differences in visible raw material selection signals if habitation clusters also coincided with differences in degrees of residential mobility. Indeed, since under the conditions modelled here increased residential mobility would increase the proportions of materials imported to the Bau from other sites, where access costs to sources would be different, we would expect proportionally more noise in variables quantifying procurement effort. The previously documented weaker influence of terrain variables in the upper layers at the Bau may therefore represent simple differences in the average lengths of individual occupation episodes without necessarily implying changes to raw material selection criteria or provisioning strategies (see Wilson and Browne, 2014).

Insight into the expected frequency and clustering of habitation episodes is also of consequence to understanding the possible role of lithic recycling as well as the theoretical potential of inter-site refitting studies. From the perspective of provenance studies, the impact of lithic reuse is important to consider because, amongst other things, it: a) influences the number of procurement episodes that may be expected to have taken place at a site and consequently the representativeness of the preserved resource selection signal; and b) may result in the displacement of lithic materials over distances exceeding the range of individual mobility, leading to an inflated estimate of a site's true sphere of socio-economic influence (cf., section 6.2 above). At large sites such as the Bau resource selection signals should be representative regardless of the degree of recycling, but the possible impact of lithic displacement via recycling deserves closer examination (see Turq et al., 2013).

Our results suggest that the opportunities for reusing previously abandoned materials, which in our model need *not* be waste (cf., Romagnoli, 2015), were likely plentiful. Indeed, even if habitation episodes were not clustered and revisits only occurred once every ten, or even every one hundred years or more, sedimentation was in most circumstances likely too slow to render such materials invisible (see section 5.1). This is consistent with the relatively common evidence of recycling of patinated lithics observed at many sites (e.g., Turq et al., 2013). If unused supplies were left behind, either cached in expectation future demand or simply to avoid carrying heavy rocks over substantial distances during residential moves (see 3.3.4) in an area where toolstone is easy to find, recycling may be expected to have played a role at the Bau notwithstanding the resource-rich environment in which the site is found (cf. Amick, 2014). From an archaeological perspective, the reuse of such partially worked materials, plausibly by completely unrelated groups, could well be impossible to detect, however, unless patination could be demonstrated to have occurred very quickly. Fortunately, while such recycling would affect our ability to reliably identify territories exploited by discrete hominin groups (see above), it has no bearing on interpreting raw material data in terms of a site's sphere of socio-economic influence. Indeed, only the recycling *and* subsequent off-site transport of previously imported materials (i.e., discarded personal gear items, as modelled here) would be of consequence (cf. Turq et al., 2013).

At the Bau such recycling is unlikely to have played a role, because raw material sources are abundant throughout the likely home ranges of hominins who inhabited the site (see Figure 7). In other contexts, however, where lithic resources are less readily available, such scavenging may have taken place on occasion and could explain the presence of *some* implements, and possibly curios, fashioned from unusually distant materials (cf. Duke and Steele, 2010). On the other hand, this type of recycling is unlikely to have played a very substantial role (Amick, 2014; see also Cuartero et al., 2015; Romagnoli, 2015) even under conditions of raw material scarcity, so it is doubtful that the re-incorporation of previously curated items (*sensu* Binford – see Shott, 1996) into personal toolkits could result in greatly distorted estimates of a site's catchment area in any context. Thus, unless substantial quantities of minimally worked materials were regularly transported between sites, the presence of more than a handful of lithics procured from very distant sources (e.g., 50+ km), as evidenced at several Middle Palaeolithic sites (e.g., Artenac, France - Meignen et al., 2009; Grotta del Cavallo, Italy – Romagnoli, 2015), is best explained by either unusual degrees of individual mobility or inter-group exchanges, depending on the distances involved (cf. Turq et al., 2013: 650).

In terms of lithic refitting, the possibility of reconstructing reduction sequences across sites is alluring. Indeed, since the recovery location of each refitted piece is known, it should be possible to trace the sequence of raw material movements across space, plausibly reflecting the mobility of a single individual or group. But is this a research avenue that is worth pursuing? Quite aside from the very substantial technical challenges refitting involves, and the added complexity *any* form of reworking (i.e., during recycling) implies, our results suggest that it is most likely not. Indeed, even using very conservative estimates for group sizes, on-site discard rates, and lengths of habitation, we would expect to see assemblages that are somewhat larger than archaeologically attested. If our lower estimate for on-site discard rates (one in five) is reasonable, a large majority of personal gear items must have been discarded in the course of daily activities away from residential sites (cf. Binford, 1979; see Luedtke, 1976). Thus, even if habitation episodes were clustered in time and consisted of revisits by a single group which made regular use of but a handful of known archaeological sites, the baseline expectation is that only a small portion of plausibly refitting pieces would have been transported between such sites. If habitation episodes were in fact not clustered, searching for refits across sites becomes largely a fool's errand. Under the conditions modelled here, the imported materials originated from virtually all camps included in the simulations, with each camp contributing only a very small number of items (12 on average, with a maximum of 109 observed across the 320 simulations). Considering that, as noted above, several hundred sites would be needed to explain a continuous habitation of the region *and* the presence of a site like the Bau, the probability of finding refits that are informative with regards to the movement of a discrete hominin group are very small indeed, even if refits could be evaluated for all archaeologically recovered pieces at little or no cost.

In short, based on our results, and in the absence of inter-group exchange, we can conclude that raw materials can be informative with regard to the maximal extent of a site's area of socio-economic influence, and of the minimal extents of areas directly exploited by its inhabitants for resources, if we are able to model resource selection in light of the network of available alternatives. Raw materials may also inform us of the areas most likely to have been frequented within the daily exploitation territories and beyond (see also e.g., Frahm, 2016; Ekshtain et al., 2014). What they likely cannot do, however, except perhaps in very unusual circumstances, is inform us of which areas were regularly exploited by specific hominin groups in the past, and how (e.g., circulating or radiating mobility strategies), particularly beyond a site's zone of regular, direct resource exploitation. Consequently, we should be very wary of interpreting archaeological raw material data in ethnographic terms.

These insights demonstrate that simulations of minimally realistic models (MRMs) of the kind proposed here are useful not only in testing specific hypotheses about the past (e.g., our optimal candidate hypothesis), but also in evaluating the potential of different avenues of research. Indeed, the advantages of MRMs are many: like null models, they can allow us to examine which variables influence outcomes the most, and to explore whether specific mechanisms (e.g., selective land use) played a role (see 3.1 and 5.5) but, unlike null models, they prevent us from inadvertently simulating impossible realities and present us with more easily interpretable outcomes, thereby lending greater validity to our conclusions. As shown in section 5.5, they can also allow us to identify aspects of our data that require closer examination, and ultimately they enable us to make specific quantitative predictions (e.g. resource use at arbitrary landscape locations) that may be easily rejected or supported by archaeological observations. On the other hand, developing an MRM is hard, not least because it requires a more careful consideration of parameters and assumptions than either neutral or realistic models. We consider this to be an advantage, however, as it forces us to grapple with issues that are ultimately profoundly relevant, such as the scales at which questions may be asked of the archaeological record.

7. Conclusion:

The design and implementation of a minimally realistic model of raw material management has allowed us to overcome an important limitation of a previously proposed explanation for the avoidance of lithic resources in the region surrounding the Middle Palaeolithic site of the Bau de l'Aubesier. Our findings indicate that, as long as we reject a uniform habitation of the region, the exclusive targeting of resources deemed optimal according to a cost/benefit analysis is consistent with the available data even if we allow for residential mobility and the concomitant import of non-negligible amounts of materials from other residential sites, where procurement costs would have been different. These findings lend further weight to our earlier suggestion that the level of spatial knowledge and navigational abilities of Neanderthals already matched our own. They also support the conclusion that these hominins regularly exploited territories comparable in size, though perhaps not exceeding (cf. Chapter 4), those exploited by ethnographic hunter-gatherer populations. Together with the plausibly substantial import of materials from other sites, which our simulations show can be expected with mobile populations, the results indicate that it is a mistake to view the presence of semi-local materials (e.g., procured from beyond the expected daily foraging radius) as indicating logistical mobility (cf. Romagnoli, 2015; Duke and Steele, 2010). Beyond this, our results highlight the usefulness of minimally realistic models, which extends beyond the simple evaluation of specific hypotheses about the past. As discussed above, MRMs can reveal alternative, simpler potential explanations for certain observations, such as the decreased importance of terrain variables in the upper levels at the Bau, as well as research avenues that are worth pursuing further.

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Supplementary Information

Lithic raw material resource management and group mobility at the French Middle Palaeolithic site of the Bau de l'Aubesier: Application of a minimally realistic agent-based model

A BLIND APPLICATION OF THE BAU-DERIVED RESOURCE SELECTION MODEL TO THE MIDDLE PALAEOLITHIC SITE OF LA COMBETTE

Some of the results presented in the main manuscript assume that the logistic model of resource selection we recently developed for the Bau (see Chapter 4) can be meaningfully applied to predict lithic resource utilization at arbitrary camp locations throughout the study region. Said model predicts the probability (hereinafter, P_{S1}) that a given source belongs to the set S_1 of sources known to have been exploited at the Bau on the basis of the costs of accessing such source from the site, quantified in terms of minimum travel times (see Methods in the main text for details of how these were computed), and the source's intrinsic characteristics (e.g., the quality of the raw materials and the extent over which they are found). Previous work (Chapter 4) demonstrated that, at least at the Bau, P_{S1} values are good proxies for degrees of source utilization. To test whether we can meaningfully predict and use P_{S1} values as proxies for resource utilization at other sites as well, using the model developed at the Bau, one of us (CMP) predicted P_{S1} values for 346 sources in the area, replacing access costs from the Bau with access costs from La Combette, a younger Middle Palaeolithic site located further south (see Figure 2 in the main text). CMP further applied three different options to filter out sources that are unlikely to have been utilized at the site regardless of their P_{S1} values, due to the presence of better alternatives on the way to La Combette (see *Hypothesis 2* in Chapter 4). Importantly, these predictions were done without knowledge of raw material variability at La Combette. Data on raw material frequencies, on the other hand, was compiled by LW and CB without prior knowledge of the model CMP used to predict P_{S1} values, or of the filtering method used to reduce the sample to sources viable for exploitation from the site. We then tested for a significant correlation between estimated archaeological raw material frequencies (see below) and predicted P_{S1} values using nonparametric Spearman's rank correlation tests. It should be noted that these two variables are fully independent (see Chapter 4 for details).

The provenance data available for La Combette is not entirely compatible with that available for the Bau, however. Although at both sites lithics are traced to so-called source areas, which may consist of one or more sources (i.e., locations where similar raw materials may be procured), such sources in the La Combette dataset can belong to multiple source areas. Consequently, matching up source areas, and therefore raw material frequencies for the two sites was not a simple process. As an admittedly imperfect solution, we calculated the maximum possible number of pieces (hereinafter, MPP) from La Combette that could have originated from a specific source – this ensured that no sources were underrepresented, but it also meant that many were likely overrepresented. To illustrate, if source area *X* in the La Combette dataset consists of three sources, such that *X* = {1, 2, 3}, and accounts for 10 archaeological pieces, and source area *Y* also consists of three sources, such that *Y* = {1, 2, 4} (note overlap with *X*), and accounting for 20 archaeological pieces, source 1 was assigned a value of 30, source 2 a value of 30 as well, source 3 a value of 10, and source 4 a value of 20. While these values therefore do not represent real lithic counts, it is assumed here that they constitute a sufficiently robust proxy for the latter to allow for meaningful detection of significant associations with predicted resource selection probabilities.

The results are as follows:

> **Filtering option 1:** P_{S1} values and MPPs were considered for all sources reachable within three hours from La Combette along least-cost paths, and which are deemed as plausibly exploitable (i.e., with P_{S1} values within the 95% confidence interval of the alternative with the highest P_{S1} value on the way to La Combette - see Chapter 4 for more details). With this sample the variables show a strong, positive, and statistically significant correlation (r_s = 0.659, n = 13, p = 0.014).
>
> **Filtering option 2**: P_{S1} values and MPPs were considered for all sources which are deemed as plausibly exploitable (see above), regardless of their distance from La Combette. With this sample, the variables show a moderate, positive, and statistically significant correlation at alpha level 0.05 (r_s = 0.483, n = 112, p < 0.001).
>
> **Filtering option 3**: P_{S1} values and MPPs were considered for sources deemed optimal for exploitation (i.e., with no better alternatives available on the way to La Combette). With this sample, the correlation between the variables is not statistically significant at an alpha level of 0.05 (r_s = 0.332, n = 14, p = 0.247).

We interpret these results as indicating that P_{S1} values are adequate proxies for the utilization of resources not only at the Bau, but also at other locations throughout the region. Allowing for some uncertainties in P_{S1} value estimation (i.e., considering all plausibly exploitable sources rather than only those deemed optimal) produces results that are clearly superior but, as at the Bau, it is unclear whether this is because such uncertainties mask the influx of material brought in from other sites, where procurement costs would have been different, and/or to the fact that no distance filter was applied under filtering option 3. Indeed, a source may appear as optimal, in the sense of there being no better exploitation alternatives on the way to La Combette, but such source may have nevertheless been located too far from the site to have been targeted by hominins residing there. Since our goal in this manuscript was to evaluate the possible effects of raw material input from other sites, in the context of residential mobility, we used filtering option 3 to predict raw material use throughout the region.

Chapter Six
Conclusions

1 Overview

Mobility is a critical variable underpinning hominin adaptation (e.g., Kuhn, 2020, and references therein). Despite the increasing availability of novel approaches to inferring aspects of human mobility in the Middle Palaeolithic, including stable isotope analyses (e.g., Richards et al., 2008; Moncel et al., 2019; Nava et al., 2020) and insights from energetics and biomechanics (e.g., Verpoorte, 2006; Henry et al., 2017), lithic raw materials are likely to continue supplying the bulk of essential information for the foreseeable future. In this regard, evidence of toolstone transfer across the landscape is widely thought to be informative with respect to the sizes of the territories regularly exploited by human groups at different scales (e.g., daily foraging areas, areas habitually used in the context of residential mobility, Gamble's [1999] 'landscapes of habit'), and of the land-use strategies such groups employed within those territories (e.g., Frahm et al., 2016; Turq et al., 2017; Kuhn, 2020). Beyond this, provenance data is needed in order to evaluate lithic raw material exploitation in light of its environmental availability and accessibility. This, in turn, provides critical information on how stone, the only resource exploited throughout the entire history of our genus for which evidence of use survives in a relatively unaltered state at the vast majority of prehistoric sites, was conceptualized, selected, and managed in the past.

While lithic provenance data is thus essential for understanding important aspects of our evolutionary history, interpreting them in terms of past behaviours is a difficult task. Unfortunately, the attention devoted to this task has not been commensurate with its significance, and we continue to be constrained by interpretive frameworks developed decades ago, at the dawn of provenance studies (see Chapter 1). Partly as a consequence of this, the present consensus view of Middle Palaeolithic raw material exploitation is rather monotonous and not dramatically changed since the 1980s, with a localized exploitation of lithic resources and a general lack of evidence for inter-group exchange being its main features across much of the Neanderthal range. To be sure, our understanding is now more nuanced (see, for example, Feblot-Augustins, 2009; Meignen, 2009) but, tellingly, few formal approaches have been proposed to investigate the intricacies of local source selection – the most salient aspect of Middle Palaeolithic toolstone procurement - in detail (e.g., Browne and Wilson, 2011; Frahm et al., 2016; Wilson et al., 2018). Rather than refining long-established frameworks through, for instance, more realistic methods of quantifying key variables (e.g., considering terrain when computing access costs), what may be needed instead is a rethinking of the questions we ask of the data, and of the methods we use to look for the answers.

As argued in Chapter 1, part of the reason why it has been difficult to move beyond the earliest interpretive frameworks is the under-reporting of basic provenance data and the often-uncritical use of key terminology. Progress has also been hampered by the subservient role provenance studies typically have within research agendas whose primary focus is on explaining lithic techno-typological variability – indeed, some have argued that sourcing can *only* be "relevant when integrated with a technological study" (Tomasso and Porraz, 2016). I do not dispute the importance of integrating provenance data with other lines of evidence in order to provide a fuller, more realistic picture of the past, but I argue that such integration should occur after toolstone procurement has been understood in its own terms. Consequently, this thesis has been an attempt to enable provenance data to provide, insofar as possible, their own, independent account of the past. My goal here has been to lay the foundation for an alternative approach to interpreting such data that can allow us to fully explore its intrinsic potential.

To this end, I began this project by undertaking the first systematic re-evaluation of a neutral, agent-based model of raw material procurement originally proposed by Jeffrey Brantingham in 2003. The model offered a point of departure that stood in stark contrast to traditional approaches, since it aimed to explore what raw material variability should look like under conditions of no optimization in toolstone procurement and on the basis of a minimalist set of assumptions. Computer simulations of the kind proposed by Brantingham (2003) seemed particularly promising because they are not inherently limited by the quality of archaeological provenance datasets, because they require explicit and formal definitions for all modelled behaviours and parameters, and because they are theoretically capable of generating hypotheses which can be unambiguously rejected on the basis of empirical observations. On the other hand, Brantingham's interpretation of qualitative similarities between model-generated and archaeologically observed patterns seemed unconvincing. As detailed in Chapter 3, my reassessment of the model revealed that its original implementation was indeed flawed, and so were some of Brantingham's interpretations. In Chapter 3 I therefore introduced a revised model and laid out a new set of expectations for lithic discard records generated under neutral behavioural conditions. Importantly, my reassessment also revealed a danger inherent in building neutral models of complex phenomena, namely the very concrete risk of unwittingly simulating impossible realities due to excessive abstraction, and the difficulties of evaluating whether this may have been the case.

Based on these insights, I sought to develop a minimally realistic simulation approach using real archaeological data from the Bau de l'Aubesier (hereinafter, "the Bau" - see Chapter 2), a French Middle Palaeolithic site chosen due to the availability of an excellent and well-published provenance dataset, and evidence of raw material exploitation that clearly deviates from revised neutral expectations. My goal was, after all, to develop an approach that could reveal meaningful aspects of past land and resource use beyond a simple confirmation (or rejection) of a null model (cf. Oestmo et al., 2020). As a critical step towards this goal, Chapter 4 introduced a new approach to generating and testing hypotheses of landscape knowledge, navigational abilities, and local resource selection criteria reflected in provenance data, one which, importantly, did not rely on other lines of evidence (e.g., ethnographic analogy). Beyond offering a simple and elegant explanation for the entirety of the Bau data, including the avoidance of a majority of sources available in the region over a period of roughly 100,000 years, my results provided essential information for developing a sound and well-calibrated minimally realistic agent-based model that is spatially and temporally explicit. In doing so it also addressed, albeit from a different perspective, important issues raised in Chapter 3 regarding a) the importance and conceptualizations of lithic resources in the past, b) the need to incorporate the spatial configuration of sources in our explanatory frameworks, and c) the need to consider unused resources as well, since, contrary to Brantingham's (2003) assertion, *all* resources within a given radius of a site should be used under neutral assumptions.

I proposed, implemented, and applied one such model in Chapter 5. This model addressed the challenge pointed out in Chapter 3 regarding parameter calibration and delivered on the promise of enabling precise quantitative predictions of archaeologically observable variability. My model's primary aim was to explore the effects of regional-scale mobility on observed raw material variability in view of further testing insights from Chapters 3 and 4. The model simulated and tracked the utilization of lithic raw materials throughout their use lives employing real units (i.e., grams of stone), thus allowing for a careful consideration of different pathways through which lithics may be incorporated into discard records. My analyses indicated that data available from the Bau are incompatible with the settlement of relatively large areas of the study region by hominins who a) also resided at the Bau and b) selected lithic resources according to broadly similar criteria to those evidenced at the site. Settlement of other, similarly large areas, however, are compatible with archaeological observations at the study site. Importantly, predictive maps generated on this basis, such as the one presented in Chapter 5, can be validated with empirical observations in a straightforward manner: a contemporaneous site located in an area of low compatibility should evidence different resource selection criteria than those seen at the Bau, while contemporaneous sites showing similar selection criteria should be located in high compatibility zones.

Aside from this insight into regional land use and a confirmation of the overall conclusions presented in Chapter 4, my analyses of the minimally realistic model also revealed that at many sites we may expect to find a non-negligible influx of materials collected while residing elsewhere and transported within mobile toolkits. Importantly, a substantial proportion of such materials (under modelled conditions, ca. 50%) may originate from sources that are also locally exploited. This has two major implications: on the one hand it suggests we may be underestimating the contribution of imported materials at many sites (e.g., if 15% of materials appear to be 'non-local', imported materials may account for 30% of an assemblage), and consequently the degree of mobility such assemblages may represent, and on the other it complicates the interpretation of raw material types that are represented at all stages of lithic reduction as locally procured (see also Turq et al., 2013).

2 Addressed research questions

Overall, the framework developed in Chapters 3-5 and briefly summarized above enabled me to answer the research questions presented in Chapter 1, as outlined below.

2.1 Neutral models as alternative, value-free starting points

Neutral agent-based models are useful points of departure for developing interpretive frameworks that minimize assumptions and maximize interpretive potential. Indeed, my re-evaluation of Brantingham's (2003) model led to critical insights that enabled me to develop the resource selection model presented in Chapter 4 and the minimally realistic model implemented in Chapter 5. These insights include the need to: a) consider all sources of usable materials available in an area, not just exploited ones; b) consider the spatial configuration of all sources in evaluating likelihoods of exploitation for any given one; c) explicitly focus on discard records instead of toolkits and, more generally, to d) avoid excessive abstraction and pursue instead a minimal degree of realism; e) to evaluate the degree to which lithic resources may have been essential to survival; and f) make quantitative predictions regarding archaeological raw material variability.

2.2 Areal extent of local resource exploitation in the Middle Palaeolithic

Provenance data available from the Bau de l'Aubesier suggest Middle Palaeolithic hominins regularly exploited resources reachable within 2.5 to 3.5 hours from home bases (Chapter 4), scheduling lithic procurement within other primary activities. It is possible that this 'foraging radius' may have been somewhat smaller (Chapter 5), but the available evidence provides no support for the view that Neanderthals regularly exploited lithic resources over a smaller extent than typically documented with ethnographic hunter-gatherer populations (Chapter 5). These results challenge aspects of the prevailing view on Middle Palaeolithic procurement, and suggest the latter may be in part a consequence of compiling and analyzing provenance data within interpretive frameworks that are poorly suited to the purpose.

2.3 Neanderthal home ranges

Raw material provenance data is likely uninformative with respect to the home ranges of Neanderthal groups, maximum transfer distances most likely reflecting instead the extent of combined territories utilized by individuals who at some point also resided at a site. Raw material frequencies therefore do seem to reflect the scale of adaptation (e.g., Binford, 1979), but not in a straightforward manner. Based on the results of Chapter 5 and insights derived from Chapter 3 and 4, I suggest that, to understand land use on the basis of archaeological raw material variability, we should model zones of compatibility with empirical observations using computer simulations rather than considering raw material transfer distances and directions. In the area surrounding the Bau de l'Aubesier, such zone of compatibility extends over only parts of the study region (ca. 1708 km^2 have estimated compatibility values greater than 50%).

2.4 Neanderthal conceptualizations of space and lithic resources

The evidence available from the Bau de l'Aubesier is most consistent with a strictly utilitarian and pragmatic use of lithic resources (Chapter 4). None of the analyses conducted in Chapters 4 and 5, however, lends support to one of the implicit assumptions of the neutral model re-evaluated in Chapter 3, namely that lithics may not have been essential for the survival of the site's residents. Consequently, and as underscored by the results presented in Chapter 5, concluding that lithic assemblage richness is, by itself, a very poor predictor of occupational histories (Chapter 3) is likely overly pessimistic.

Notwithstanding the strictly utilitarian use of stone, provenance data available from the Bau de l'Aubesier also indicate a high degree of selectivity, manifested in the consistent targeting of optimal or quasi-optimal procurement alternatives. As noted in Chapter 1, stone is a predictable resource, and as a consequence optimal sources can become known over time, eventually entering collective memory (see, e.g., Raynal et al., 2012). As shown in Chapter 4, however, the spatial knowledge of Neanderthals at the Bau amounted to more than simple awareness of the location of such optimal sources, as they appear to have been able to accurately calculate access costs to these from arbitrary locations on the landscape, which in turn suggests an ability to use Euclidean mental representations of space.

3 Other contributions of this work

The process of developing and implementing my proposed framework also enabled a series of insights of wider theoretical and practical relevance. These are summarized below.

3.1 Theoretical contributions

As noted in Chapter 3, agent-based models of the kind developed in this thesis are also, by necessity, models for the formation of the archaeological record. As such, they can enable important theoretical insights that extend beyond toolstone procurement proper. Thus, in Chapter 3 I demonstrated that archaeological assemblages *cannot* reflect the average composition of discrete mobile toolkits (cf., e.g., Brantingham, 2003), even if such toolkits consisted entirely of implements with identical use-lives and discard probabilities. Similarly, in Chapter 5 I demonstrated that lithic refitting across sites is, despite its hypothetical potential to inform us of the sequence of individual or group movements across a region, likely not an avenue that is worth pursuing, even if the costs of evaluating refits for all archaeologically known pieces was zero. Furthermore, the analyses presented in Chapter 5 also indicate that some types of lithic recycling may have been a common but possibly undetectable occurrence even in very resource-rich environments (cf., Amick, 2014). Overall, these results underscore the utility of agent-based models in evaluating the potential of different research avenues and the implications of the palimpsest nature of the archaeological record.

In this thesis I have argued that such models should strive to be minimally realistic. Developing minimally realistic models is not easy, as doing so presupposes exploring a range of assumptions and mechanisms that abstract models need not explicitly contend with; it also requires finding a more delicate balance between simplicity and realism. However, as demonstrated in this work, the 'details' that are glossed over in models such as Brantingham's are not always inconsequential, and the onus for demonstrating that they are must fall on the modeller, not on her or his audience. Because of this, I suggest here that abstract models which are not *easily* adjustable to employ real units (e.g., grams of stone, hours of work, *et cetera*) should be treated with a great deal of caution, as they are likely severely underspecified.

With regards to lithic raw material sourcing, my work underscores the need to pay close attention to all aspects of past resource selection, including source avoidance, in order to maximize the inferential potential of this important source of information on past lifeways. Indeed, the results of Chapter 4 show that we should not be too hasty in dismissing unutilized sources as unavailable in the past or, more generally, in *assuming* that the present-day environmental distribution of lithic resources is of questionable relevance (cf., Dibble, 1991). They also show that there is much to be learned from detailed examinations of 'local' resource use, which is often glossed over as uninteresting or easily explained (e.g., Mellars, 1996). As shown in Chapter 4, it is useful to conceptualize sources as nodes in a network of alternatives, since as demonstrated in Chapter 3, the utilization of any given source will be influenced by its placement relative to said alternatives.

Finally, the work presented in this thesis raises questions regarding the conceptualization and interpretation of key binary concepts such as embedded versus direct procurement (e.g., Binford, 1979; Gould and Saggers, 1985) and provisioning of places versus provisioning of individuals (Kuhn, 1995), which have been widely used to draw inferences from provenance data. With regards to the latter, Chapter 5 shows that neither the frequency of residential moves, nor the duration of residential stays, need to be strategically related to the provisioning of places versus the provisioning of individuals (cf., Kuhn, 1995). With regards to the former, it is typically assumed that a given raw material type was *either* collected from the inhabitants of a specific site casually while performing other activities at likely a negligible cost (i.e., embedded *sensu* Binford, 1979 – see, e.g., Tomasso and Porraz, 2016; Oestmo et al., 2020) *or* that it was collected during special purpose trips (direct procurement *sensu* Binford, 1979). This reasoning, as pointed out by others also (see, e.g., Surovell, 2009) is flawed. In Chapter 1, I argued that while lithic materials were probably not the main drivers of scheduling activities due to their predictability, their critical role in subsistence suggests they are unlikely to have been the least important ones either. Consequently, the targeting of lithic resources in the context of embedded procurement likely represented a compromise, with an implied cost of lost opportunities.

Beyond this, and as demonstrated in Chapter 3, constant access to lithic resources cannot be guaranteed by chance encounters with raw material sources, even in resource-rich environments; consequently (see above), most procurement episodes must have entailed *some* purposeful deviations from the least-cost paths linking a site to exploited non-lithic resources (see also Surovell, 2009), once again implying an added cost. Indeed, in Chapter 4 I demonstrated that data from the Bau are consistent with a scenario of fully embedded procurement in which sources are nevertheless purposefully and carefully targeted, sometimes with possibly substantial added effort (i.e., carrying rocks for some additional 40 minutes or more in 25% of evaluated cases), even if extraction costs are ignored (see also Elston, 2013; cf. Ekshtain et al., 2017). A careful reconsideration of the binary distinction between these two modes of procurement is therefore warranted, as it may be leading us astray. Indeed, a substantial presence of so-called 'semi-local' and/or 'exotic' materials within an assemblage, particularly if derived from a single or small number of sources, is often interpreted (e.g., Romagnoli, 2015) as indicating logistical as opposed to residential mobility - another problematic binary - but the results presented in Chapter 5 demonstrate that this may be unwarranted. Indeed, depending on the frequency of residential moves, more than half of an assemblage could realistically have been collected while residing elsewhere and transported in the course of regular camp moves. Depending on which areas of the landscape were settled, and the spatial configuration of sources, such imported materials could well have been collected from but a handful, or perhaps even a single, raw material source. It is only through simulations that such possibilities may be evaluated.

3.2 Practical contributions

An important contribution of this thesis is the release of the code used to implement the proposed approach under an open-source license. Indeed, only open-source software (e.g., R, Python, GRASS GIS) was used in this work, and only freely available geospatial data. The framework developed here should therefore be easy to adapt and apply in any other context where suitable provenance information is available, and where similar baseline behavioural assumptions can be made. Importantly, this framework has applications that extend beyond the research questions pursued here. The minimally realistic model proposed in Chapter 5, for instance, may prove useful in pinpointing areas of increased archaeological potential (i.e., those that are compatible with hypothetical site placement and known archaeological variability), since it is spatially explicit. Indeed, as discussed in Chapter 5, the implementation of a minimally realistic model can provide insight into the number of archaeological sites that we may expect to find in a given region, as well as the expected frequencies of habitation episodes for these. Moreover, because they enable the systemic effects of isolated variables and parameters to be studied in detail, minimally realistic agent-based simulations, and the resource selection model proposed in Chapter 4, should prove useful in determining the impact of unavoidable biases and errors in sourcing datasets, introduced by, for instance, recent anthropic modifications to the landscape. Along the same lines, simulations should prove useful in guiding the selection of optimal sourcing methodologies, so as to maximize inferential potential while minimizing the cost of sourcing lithics based on the specific geologic and geographic characteristics of a given region. Finally, as discussed in Chapter 5, simulations can give insight into the number of sites.

4 FUTURE DIRECTIONS

The envisioned practical applications discussed above highlight important future research directions facilitated by the present work. Particularly enticing, given the known changes to land cover, is the prospect of being able to quantify the likely impacts of the omission or incorrect characterization (e.g., of extents of exposure) of raw material sources, or other similar errors, on interpretation. While the analyses presented in Chapter 4 lend further weight to the suggestion that the lithic landscape in the area surrounding the Bau has not changed substantially since the initial occupation of the site (e.g., Browne and Wilson, 2011), I did identify a problematic source in Chapter 5, and it is clear that substantial changes did occur in many other regions. This novel avenue of research, first hinted at in Chapter 3, will therefore be pursued in future analyses of the Bau dataset, and subsequently of datasets from sites and regions.

In addition to pursuing such entirely new research directions, future work will also focus on refining the minimally realistic model. One aspect that requires greater attention is the distance parameter used for residential mobility, since at present the impact of using different settings is unknown. More importantly, a method is needed for reliably determining which “optimal” sources the simulated agent should target from a site, given the access costs. Currently no access cost cut-off is used, and as a result a substantial amount of noise is introduced to the simulation outputs. Finally, a more refined implementation of sedimentation processes is needed, so as to produce assemblages that are more realistic in terms of their size and composition.

Beyond this, future work should integrate faunal and techno-typological information available for the Bau, now that the intrinsic properties of the provenance data are well-understood. Given my observations in Chapter 5, it would be particularly useful to look at variability among tools versus waste materials, as this could clarify the degree to which sources exploited locally were also targeted at other sites from which materials were imported to the Bau. Information on the degrees and nature of lithic reduction will also be considered in future work, since the models presented in this thesis have considered how lithics may have been procured and discarded but have not focused on the intermediary stages of use. A more distant goal is to explore the feasibility of incorporating multiple agents, so as to investigate the possible effects of social contacts on lithic raw material variability, and determine the degree to which the latter may be informative with regards to the former.

Most importantly, however, the approach proposed here must be applied to other sites and regions, so as to better understand variability in land use across time throughout the Neanderthal range. As a first step in this direction, the model could be applied to La Combette, a younger Middle Palaeolithic site located near the Bau, for which a partly compatible provenance dataset exists (Wilson et al., 2018). Such application will lead not only to a better understanding of resource use in the region, but hopefully also to a more flexible model that could be applied with greater ease at sites where the available provenance information is less precise than at the Bau, as is in fact the case at La Combette. Applications to other sites in the region that are contemporaneous with the Bau are also needed, because they would enable ground-truthing some of the important insights discussed in Chapter 5 (e.g., regarding zones of compatibility of residential mobility with archaeological observations). Unfortunately, no such sites with compatible provenance data exist, so substantial prior work is needed. Beyond the studied region of southeastern France, viable, impactful applications to Middle Palaeolithic sites from the Iberian Peninsula and southwest Asia can be envisioned.

5 Concluding remarks

In this thesis I have shown that simulating lithic resource management and selection in order to make quantitative predictions with respect to archaeological raw material variability based on a well-defined behavioural framework, built on a minimalist and tested set of assumptions, is both feasible and necessary. Indeed, as shown in chapter 5, interpreting the record at ethnographic scales (e.g., Feblot-Augustins, 1993, 1999; Raynal et al., 2013) is problematic, and so is incorporating ethnographic insight naively into explanatory models of land use (e.g., *assuming* the size of daily exploitation territories based on ethnographic observations, e.g., Ekshtain et al., 2014). Such ethnographic insight is certainly useful (see Marlowe, 2005), but only insofar as its relevance can be independently demonstrated. These observations are not new, however (e.g., Wobst, 1978); the original contribution of this thesis consists instead of providing a concrete foundation for a viable alternative.

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Summary

Reliance on tools is a defining characteristic of our genus, and stone artifacts provide the oldest and most frequently encountered evidence for human tool manufacture. The rocks from which such artifacts were made, including but not limited to chert, quartzite, and obsidian, are typically found exposed over a limited extent and at discrete locations. These potential procurement locations often did not coincide with places where stone implements were needed, however, and consequently humans transported rocks over the landscape. Because they share at least part of their geological history with other rocks found today at their place of procurement, mineralogical and geochemical signatures preserved in stone implements recovered at archaeological sites can be used to identify their geographic origin. Such provenance data can thus provide critical clues regarding hominin mobility and environmental interactions over the last three-plus million years of our evolutionary history.

Human mobility was not restricted to trips between rock outcrops and archaeological sites where stone would be immediately discarded, however. Therefore, to be useful, the evidence of the directions and distances over which rocks were transferred, preserved in the static frequencies at which different rock types are represented at archaeological sites, must be interpreted in terms of dynamic human behaviours. Why are certain toolstone sources represented more than others, how were they exploited, and to what extent does their degree of utilization reflect broader patterns of landscape use? When considering artifacts made by individuals belonging to an extinct human species, answering such questions presents an immense challenge because we do not know to what degree our own behaviour, and the cognitive and physical abilities that underpin it, can serve as guide.

Of the known extinct human species, Neanderthals have been the most extensively studied, and are consequently the best understood. Despite being very closely related to us, the evidence we have of their lifeways suggests that these hominins, who are associated with Middle Palaeolithic industries, had a somewhat different relationship to the environment than our anatomically modern ancestors, and it remains unclear to what extent their cognitive processes resembled our own. In spite of this, current approaches to interpreting lithic provenance in Middle Palaeolithic contexts remain based to a large extent on models derived from ethnographic data. In view of better understanding how Neanderthals conceptualized and used their environments, this thesis lays the foundations for an alternative approach. The framework proposed here is based on computer simulations and is designed to maximize the inferential potential of toolstone provenance data while relying minimally on analogies to known present-day human behaviour. Instead of ethnographic data, this framework is developed based on insights gained from a re-evaluation of a neutral agent-based model of raw material procurement first proposed by Jeffrey Brantingham in 2003, as well as the analysis of actual archaeological data from the French Middle Palaeolithic site of the Bau de l'Aubesier.

The central findings reported in this thesis indicate that the hominins who resided at the Bau de l'Aubesier between ca. 200 ka and 100 ka BP had excellent spatial memory and were likely capable of navigating landscapes using cognitively demanding Euclidean mental maps. They appear to have regularly exploited resources reachable within 2.5 – 3.5 hours of walking from the site, scheduling lithic procurement within other primary activities. While provenance data appears to be uninformative with regards to territories exploited by discrete groups that resided at the site, they nevertheless point to the

use of large territories by Neanderthal individuals over their lifetime. They also point to a strictly utilitarian and pragmatic use of stone resources, which were nevertheless targeted with a high degree of selectivity. While these findings have to be confirmed for other contexts, they likely apply to Neanderthals living in other regions as well.

Samenvatting

Aanzienlijke afhankelijkheid van stenen werktuigen kenmerkt het genus *Homo*, getuige grote hoeveelheden teruggevonden werktuigen. De gesteentes waarvan deze zijn gemaakt, onder meer vuursteen, kwartsiet en obsidiaan, komen meestal zeer lokaal voor, op onderling wijdverspreide plaatsen. De voorkomens van geschikte steen waren over het algemeen niet de plaatsen waar de stenen werktuigen benodigd waren. Van de bron transporteerden vroege mensachtigen het lithisch materiaal naar de plekken waar ze werktuigen vervaardigden, gebruikten en achterlieten. De mineralogische en geochemische kenmerken van die werktuigen kunnen worden gekoppeld aan de plaats van herkomst van de grondstof. Dit levert een schat aan informatie op met betrekking tot mobiliteit en ecologie van vroege mensachtigen gedurende minstens drie miljoen jaar evolutie.

Die mobiliteit was echter geen rechttoe rechtaan heen-en-weer tussen voorkomens van materiaal en lokaties waar de werktuigen gebruikt en afgedankt werden. Statische gegevens zoals de frequentie van bepaalde materialen op een vindplaats en de afstanden waarover die materialen getransporteerd werden moeten worden geïnterpreteerd in termen van dynamisch menselijk gedrag. Waarom zijn sommige materiaalsoorten en herkomstgebieden beter vertegenwoordigd dan andere? Hoe werden die gesteentes geëxploiteerd? En welke bredere patronen van benutting van het landschap (*land use*) kunnen daaruit afgeleid worden?

Deze vragen staan centraal in dit proefschrift. De beantwoording ervan is vooral lastig omdat niet duidelijk is in welke mate gedrag, cognitie en cultuur van de recente soort waartoe we zelf behoren mag worden geëxtrapoleerd naar andere, eerdere soorten van het genus *Homo*. Dit voorbehoud geldt ook voor de best bestudeerde andere soort: de Neanderthalers. Hoewel nauw aan ons verwant laten hun midden-paleolithische technologieën een eigen omgang met het landschap zien. Ondanks dit gegeven leunt de analyse van ruimtelijke patronen in de omgang met lithisch materiaal door Neanderthalers sterk op etnografische gegevens van menselijke samenlevingen.

Om beter te begrijpen hoe Neanderthalers hun omgeving gezien en geëxploiteerd hebben presenteren we hier een alternatieve benadering, gebaseerd op computersimulaties. De inzet is optimale benutting van herkomstgegevens (met betrekking tot gebruikte gesteentes) onder minimale verwijzing naar recente etnografische gegevens.

Onze analyse bouwt kritisch voort op Jeffrey Brantingham's *neutral agent-based model of raw material procurement* van 2003 en richt zich op midden-paleolithische data met betrekking tot de Franse vindplaats Bau de l'Aubesier. De belangrijkste bevinding is dat de Neanderthalers die daar tussen ca. 200.000 en 100.000 jaar geleden actief waren een prima ruimtelijk geheugen hadden en zich waarschijnlijk in het landschap oriënteerden en verplaatsten met behulp van Euclidische mentale modellen.

De Neanderthalers van Bau de l'Aubesier hebben met grote regelmaat lithische grondstoffen gehaald op 2,5 tot 3,5 uur loopafstand, waarbij ze deze expedities efficiënt combineerden met andere cruciale taken. De herkomstgegevens van de gebruikte gesteentes laten geen precieze bepaling toe van de actieradius en het territorium van individuen, maar suggereren wel degelijk dat beide aanzienlijk waren. Tevens wijzen de herkomstgegevens erop dat men strikt utilitair en pragmatisch, maar ook erg selectief omging met lithisch materiaal.

Deze resultaten van ons onderzoek met betrekking tot Bau de l'Aubesier doen vermoeden dat hetzelfde gold voor Neanderthalers elders. Dit kan in toekomstig onderzoek getoetst kan worden.

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It has been an amazing journey.

Curriculum Vitae

Cornel Pop was born in Baia Mare, Romania, on the 7th of February 1981. He finished high school in 1999 at the Liceo Católico Atacama in Copiapó, Chile, and began his bachelor's degree at the University of British Columbia (UBC) in 2000. Between 2001 and 2010 Cornel also worked full time as a UNIX systems analyst at UBC, in what was then the Department of Earth and Ocean Sciences. His roles there included supervising a computing cluster and co-supervising the department's core servers, as well as developing or implementing an array of new technologies. After graduating from UBC with a BA in Anthropology in 2010, Cornel began a Master of Arts (MA) program, also at UBC, under the supervision of Prof. Michael Richards. His master's research focused on the Middle Palaeolithic period of present-day Romania, and he earned a Faculty of Arts Graduate Award and a SSHRC CGS Master's Scholarship grant. Cornel graduated from his MA program in 2013. In 2012 he started his doctoral research in the Department of Human Evolution at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, initially under the supervision of Prof. Michael Richards and then under the supervision of Dr. Shannon McPherron. Since 2016, Cornel has also been teaching anthropology at Columbia College in Vancouver, BC. After completing his doctoral research, partially published in international peer-reviewed journals and presented at international conferences, he submitted his dissertation to the University of Leiden in 2021.