Mobility of Paleolithic Populations: Biomechanical Considerations and Spatiotemporal Modelling

ERWAN VAISSIÉ*
Université de Bordeaux, UMR 5199 PACEA, Bâtiment B18, Allée Geoffroy St-Hilaire, CS 50023, 33 615 Pessac cedex, FRANCE; erwan.vaissie@u-bordeaux.fr

*corresponding author: Erwan Vaissié; erwan.vaissie@u-bordeaux.fr

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ABSTRACT

Questions relating to territories and mobility patterns during the Paleolithic are crucial to understanding the social geography of earlier populations. Despite significant progress in the analysis of mobility clues (faunal remains, raw material uses), there have been few advances in their representative models during the last 40 years. Use of GIS and cost distance modelling in this sense has proven to be of great value as they shed light on the impact of the environment on hunter-gatherer mobility patterns. The aim of this study is to present a protocol for cost distance modelling based on the data available from biomechanics on the metabolic cost of mobility and their applicability to the archaeological context. We apply this method to a Mousterian site in the French Massif Central to propose an alternative vision of the techno-economic zonation for lithic raw material acquisition and use. Our results show the impact of walking speed, body mass, terrain, topography, and load on human mobility and allow us to include 3D (highlighting potential paths) and even 4D (suggesting a travel time for covering these paths) models to socio-economic organization of space by human groups. We highlight a completely different perception of time / space relationships within a given territory compared to classical Euclidean representation and establish in a quantified manner the investment (in time and in energy) needed by the group to visit defined points of interest. We discuss the efficiency of GIS cost distance modelling to emphasize socio-economic patterns and choices for past human groups. The usefulness of models in highlighting potential factors behind behavioral variations in the management of space in prehistoric times is also addressed.

INTRODUCTION

By enabling us to address the spatial relationships that human groups maintain with their geographical space (Di Méo 2008, 2014), the notion of mobility structures our understanding of the social geography of earlier populations. This is even more true for prehistoric populations, who seem to have had a hunter-gatherer subsistence lifestyle, based on a succession of moves, following time patterns of varying lengths (daily, seasonal, annual, etc.). The movement of these individuals was organized within a territory according to the resources available to them and the environmental constraints (e.g., Binford 1978a, 1979, 1982, 2019; Birdsell 1953; Delpech et al. 1995; Hayden 1972; Keeley 1988; Mauss and Beuchat 1906). It should be noted that the notion of territory has given rise to a great deal of discussion (Fournier 2007) in that there is a lack of common understanding as to whether it refers to a social, administrative, political, or cultural sphere. This observation is all the more striking with reference to ancient times as it is not possible to determine the social construction of the space of associated human groups from material remains (Djindjian et al. 2009; Porraz 2005). Taking these issues into account, the term "territory" is associated here with the area covered and exploited viewed through the prism of archaeological documents (Jaubert and Delagnes 2007) and usually describes the structuring and spatial organization of a group. Recovering these mobility patterns is a very important aspect of prehistoric research and many land use models have been proposed. The aim of this article is to discuss mobility patterns using a new protocol for cost distance modelling based on the data available in biomechanics on the metabolic cost of mobility. This protocol is able to justify the choices made in the classes of slope and the associated raster cost values and to consider average daily walking times. Throughout the text, we will use the Mousterian site of Baume-Vallée (Hermens and Laborde 1965; Raynal and Decroix 1986; Vaissié et al. 2017), located in the French Massif Central (Haute-Loire), as a framework study to illustrate our point.

Questions relating to territories and mobility patterns during the Paleolithic have enlivened debates among the community of prehistorians for several decades, whatever the geographical and chronological context, especially since the beginning of the 1980s (Binford 1978a, 1982;

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Bressy et al. 2006; Conard and Delagnes 2004; Djindjian et al. 2009; Geneste 1985; Geneste et al. 1997; Jaubert and Barbaza 2005; Turq 1989; Vialou 2005). Depending on the degree of preservation, faunal data can be used to analyze mobility from information linked to seasonality, the biotopes frequented, and the relative remoteness of hunting areas (Binford 1978b; Churchill 1993; Daujeard et al. 2012; Delagnes and Rendu 2011; Discamps and Royer 2017; Kelly 1983; Kelly and Todd 1988; Laroulandie and Costamagno 2003; Niven et al. 2012; Rendu 2007; Stiner and Kuhn 2009; Yeshurun et al. 2007). However, when considering the question of mobility, the majority of studies are based above all on analysis of the origin of lithic raw materials (Ataman et al. 1992; Aubry and Walter 2003; Bettinger et al. 1994; Brantingham 2003; Demars 1998; Elston 1992; Féblot-Augustins 1997; Fernandes et al. 2008; Geneste 1985, 1992; Park 2007; Morala 1983; Kuhn 2004; Séronie-Vivien 2002; Surovell 2012; Turq 1989).

Following work on Site Catchment Analysis (Higgs and Vita-Finzi 1972), most authors have attempted to define an economic zoning of the supply territory by proposing a model of concentric circles centered on the site. This zoning usually includes three or four distinct zones—the local area, the intermediate area and the distant area (with sometimes a distinction between distant and very distant areas). In Western Europe, the model usually selected and still used today is that proposed by Geneste (1985) for the Mousterian in Perigord:

- local space within a radius of 5km around the site (distance grouping together points accessible within half a day's walk, there and back);
- intermediate space between 5km and 20km from the site; and,
- distant space further than 20km.

These zones give a first approach to economic behavior in the space surrounding the site. However, because they have been defined on the basis of archaeological assemblages, these zones also express the idea of a temporal segmentation of operational sequences determined by distance from raw material source. This theoretical model assumes that materials in the local area represent all phases of the *chaîne opératoire*, that those in the intermediate area represent diversified techno-economic behavior and hence certain phases of the operational sequence, and finally that those in the distant area represent only objects that have already been consumed and adapted, characteristic of the last phases of the operational sequence. Although this observation has been modified somewhat in the last decades (Lebègue and Wengler 2014; Porraz 2005; Slimak 2008), the consequence of this division of space is that the boundaries set for the local, intermediate, and distant areas can vary, sometimes significantly, depending on the techno-economic systems being studied. Thus, while there is a consensus for the model proposed by Geneste (1985) concerning the Middle Paleolithic, this is not the case for the Upper Paleolithic. If we take the example of the local area, it varies with different authors—between 7km and 20km for Djindjian et al. (2000), 10km for Larick (1986) and Delvigne (2016), 20km for Féblot Augustin (1999a) and Djindjian (2014), between 20km and 30km for Tarrino et al. (2015), and up to 40km for Gould and Saggers (1985). While these differences correspond to real differences in terms of the techno-economic processing of materials, such variations no longer follow the ethnographic guidelines proposed by Higgs and Vita-Finzi (1972) or Binford (1982)[1]. In addition, faced with such variability in definitions of the areas, how can we discuss the real value of changes in mobility between different physical environments and chronological periods?

In parallel with this work on the economic management of space, analysis of siliceous materials has made significant progress since the 1980s (Demars 1980, 1982; Masson 1979, 1981; Mauger 1985; Séronie-Vivien and Lenoir 1990; Séronie-Vivien et al. 1987; Torti 1980) and especially in France, thanks to a revival in methodology (Caux 2015; Caux and Bordes 2016; Delvigne 2016; Delvigne et al. 2017, 2019; Fernandes 2006, 2012; Fernandes and Raynal 2006; Fernandes et al. 2008; Tomasso 2014, 2018; Tomasso et al. 2019; Vaissié et al. 2017, 2021), which includes a renewal in the study of silicites. The notion of "evolutionary chain of sedimentary silicified rocks" (Fernandes and Raynal 2006) takes into account all silicification transformations from silicite's genesis until its discovery at the archaeological site. Using this approach provides information not only of stratigraphic origin (genetic type), but also on where it was collected in prehistory (primary or secondary outcrops). The resolution with which we are now able to determine the geographic origin of archaeological artifacts and understand the litho-space (Delvigne 2016) of populations in the past gives a better view of mobility patterns and the management of space by human groups (Caux and Bordes 2016; Delvigne et al. 2017, 2019; Fernandes et al. 2008, 2016; Langlais et al. 2018; Tomasso 2018; Tomasso and Porraz 2016; Vaissié et al. 2017, 2021).

Given the new developments in our knowledge of mineral resources, it is evident that the model for understanding space and mobility patterns as presented and developed since Geneste (1985) is now outdated. At the very least, it is limited, especially when it is skewed because its variability is too great (adapted to suit techno-economic systems) and because of the lack of any definition of the time required to travel the distances given for the economic zoning. In addition, with the 2D representation of the site-centered concentric circles, it is not possible, as the authors themselves pointed out (Geneste 1985; Turq 1989), to take into account physical parameters (topography, nature of the terrain, river network, etc.) or environmental parameters (snow cover, ice cover, etc.). These limiting factors therefore create a major discrepancy between the reliable techno-economic data collected from archaeological sites and the empirical discussions on the related mobility patterns. Such limits have been repeatedly highlighted in various studies dealing with the mobility of groups and their spatiotemporal relationships with their environment (e.g., Ekshtain 2014; Ekshtain et al. 2017; Hovers 1989; Wilson 2003, 2007) and, in particular, those relating to ethnographic observations that very early on presented graphic representations tak-

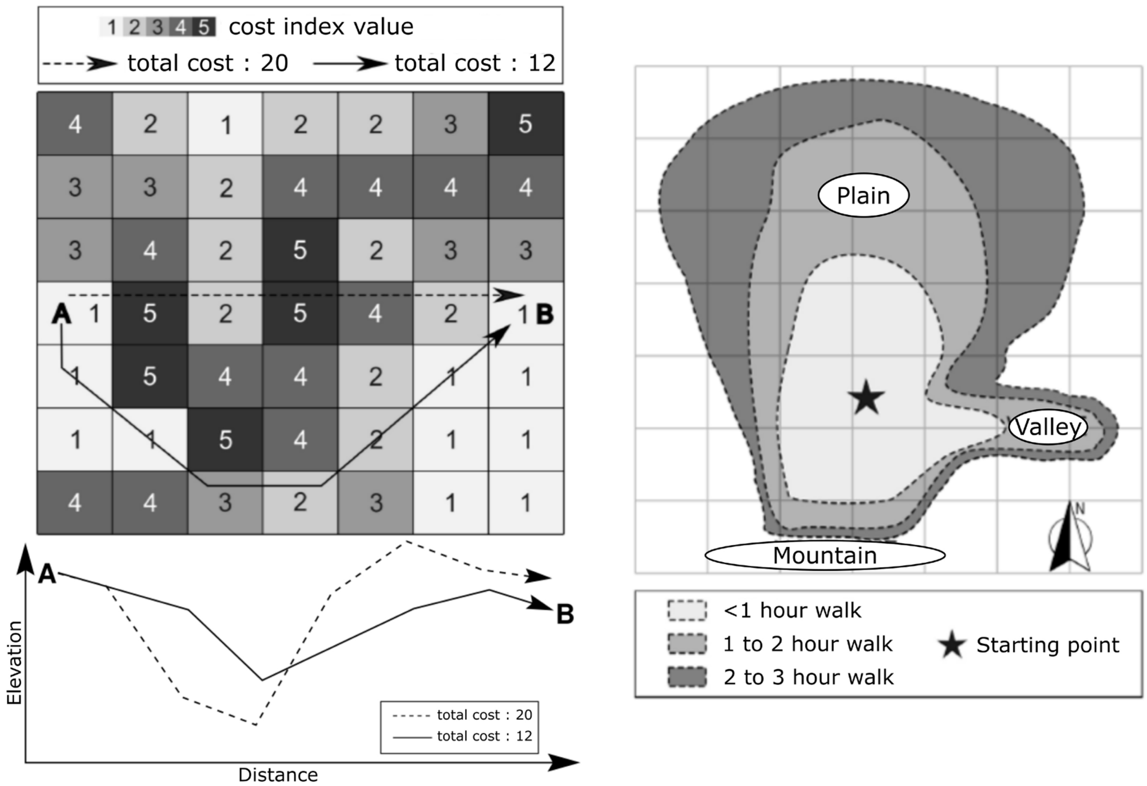

Figure 1. Left, theoretical representation of least-cost path model between two points. Right, theoretical example of isochronous curves around a site (after Sécher 2017: 53 – 54; modified).

ing into account the topography (e.g., Bailey and Davidson 1983; Binford 1982; Vita-Finzi and Higgs 1970).

USE OF GIS

For several decades, the increased use and widespread availability of computer technology has profoundly changed the way in which modern societies view their world. It has become an integral part of many disciplines, and is also behind a number of technological advances and changes in most areas of scientific research (Paoletti 1993). The field of archaeology is no exception (Djindjian 1986; Giligny 2011; Moscati 2014) and the use of computer tools is currently widespread in our discipline—tools for data entry and analysis (Djindjian 1986; Feugère 2015; Pagès 2004), inventories and prospecting (Déodat and Lecoq, 2009; Neubauer, 2004; Tuffery et al., 2017) and spatial analysis of remains and sites (Cahen et al. 1980; Farizy 1994; Lacrampe-Cuyaubere 1997; McCoy and Ladefoged 2009; Neruda 2017). The use of geomatics and GIS has also proved particularly interesting when considering land management, the movement of human groups, and the dynamics of settlement in ancient times (Balzarini 2013; Barge et al. 2004; Brunstein et al. 2018; Buchsenschutz et al. 2004; Cheylan et al. 1999; Votsing and Devaux 2005; Fusco 2016; L'Hostis 2003; Taliaferro et al. 2010). As well as providing a simple representation of information, GIS gives access to the spatial analysis tools used by geographers, which are able to cross-reference quantitative and qualitative data, producing applications specific to archaeology—provenance analysis of materials, predictive modelling, analyses of distances and contexts.

In prehistoric archaeology, studies exploring the modelling of potential routes between prehistoric sites and/or raw materials outcrops have emerged in recent years (Adriaensen et al. 2003; Barge and Chataigner 2004; Browne and Wilson 2013; Gustas and Supernant 2017; Hageman and Bennet 2000; Herzog 2014; Liu et al. 2019; Rogers et al. 2014; Sécher 2017; Taliaferro et al. 2010). They are the result of spatial analysis by least-cost path modelling or isochronous curve modelling and are based mainly on the impact of physical constraints (topography) on movement (Figure 1; Supplementary Information 1). By isochronous curves we mean the Euclidian travel distance one could reach in a certain amount of time taking into account the influence of different factors (topography, geographic obstacles…) on the speed of travel.

Regarding the choice of constraints, there are shortcomings when producing these models for periods in the past, such as the scarcity or absence of primary data on vegetation cover and its nature, or a lack of knowledge of paleo-hydrographic data (presence of natural bridges or fords, variation in river levels, etc.). Similarly, data on snow cover are rare or non-existent in models produced to date. However, there are many studies that have provided an understanding of spaces that were impacted by ice cover and permafrost during the Pleistocene (Andrieux et al. 2016; Bertran et al. 2008, 2014; Coutterand and Buoncristiani 2006; Etlicher and Hervé 1988; Guiot et al. 1993; Landais 2016; Valadas and Veyret 1981) although, given their imprecision at regional and local scales, these data should be used with caution. As a result of this chronic lack of data, the only limiting factor used in the mobility models applied to the archaeological guidelines is generally the topographic constraint, when it did not undergo any major changes during the Pleistocene (e.g., Besançon 1979; Defive et al. 2005; Larue 2003; Le Griel 1991). The choice made by the various authors to quantify the mobility penalties attributable to topographic variations is therefore based on creating a slope raster assigning a cost (value "C") to each pixel (value of slope "P") across the area being studied.

The selected slope classes are usually divided up arbitrarily into increments of 5% of slope (e.g., Sécher 2017) or defined according to geomorphological guidelines (Demek and Embleton 1978; Dramis et al. 2011). The associated raster cost values vary according to the different authors (Table 1): Sécher (2017) and Liu et al. (2019) define raster cost values arbitrarily. Barge and Chataigner (2004) obtained their values using the equation proposed by Eastman (1999: 61) which is expressed as follows:

$$C = 0.031\ p^2 - 0.025\ p + 1$$

where **C** is the raster cost value for a slope value **p** (expressed in degrees). This formula has been used in other studies (e.g., Alarashi and Chambrade 2010; Tomasso 2014) for similar applications.

The variations observed in the "C" values selected give rise to some considerable differences in models of distances and path costs (Figure 2)—to illustrate this situation, we produced cost distance models based on our framework study (the Mousterian site of Baume-Vallée), using the parameters and raster cost values selected by the above-mentioned authors (see Table 1) for an average travel speed of 5km/h^2 (as used in their respective studies). While the topography penalty for the journey can be seen in all three examples, with shorter maximum distances in the directions where the topographical variation is greatest, we can nevertheless see considerable variation in the length of the estimated journeys. Thus, the influence of topography is much greater in the model proposed by Liu et al. (2019) where journeys are much shorter than those proposed by the other models (between 40% and 70% shorter compared with Barge and Chataigner's (2004) model; 10% to 55% shorter than in Sécher's (2017) model). Modelling travel distances in association with one or another model, may therefore produce significant divergences and result in some widely varying interpretations.

In addition to the problem inherent in the use of different raster cost values, it is also necessary to underline the biases related to the arbitrary definition of these values (see Sécher 2017; Liu et al. 2019)—how do we justify selecting value **C** for slope **p** when we see the scale of the difference in results depending on the choice made (see Figure 2, b and c)? Questions are also raised when only the slope is considered as a variable influencing the travel constraint (see Barge and Chataigner 2004). While topography has an important role to play, other parameters have a major influence on the mobility of living beings (see below).

The aim of this article is to discuss the integration of variable parameters in cost distance modelling. Previous studies in this field have mainly considered the role of topography (i.e., slope) as the main variable influencing mobility. We want to express the importance of considering other parameters such as the weight of the individual, additional load, terrain factor (grassy, sandy, snowy ground…), and walking speed, and we based our protocol on the data available in biomechanics on the metabolic cost of mobility. First we discuss the available possibilities of mathematical equations for energy expenditure estimation, especially the energetic cost model developed by Pandolf et al. (1976, 1977; Epstein et al. 1987) and the applicability of its terms in archaeological context. Secondly, we propose a new formula to obtain, in a quantified way, the raster cost value **C** for cost path analysis using results provided by Pandolf's formula. And, finally, we provide and discuss a quantified method for calculating a theoretical "day's walk," based on the combination of Pandolf's formula with the energetic data provided by recent work on Neanderthals and anatomically modern humans (Aiello and Key 2002; Churchill 2006, 2009). Our definition for the theoretical "day's walk" will allow us to discuss daily variations in mobility in different environmental and human contexts. In our opinion, these data give a more precise understanding of the mobility patterns of past populations (mainly hunter-gatherers) and theoretical possibilities of travelling within defined spaces. In order to demonstrate this potential, we present an example of an application used in an archaeological context of the Middle Paleolithic. We chose the Mousterian site of Baume-Vallée (Haute-Loire), located in the Massif Central, as our framework study. Because of the great diversity of topography in the physical environment and the climatic constraints which were sometimes severe (significant snow cover, even glaciation), and because we have obtained some updated and unpublished data on mobility and ways of managing siliceous materials, this deposit seemed to be the ideal candidate to test the validity of the model presented in this article.

MATERIALS AND METHODS

For several decades, problems related to human motor performance and the associated energy balances have been the subject of numerous studies (Hatze and Buys 1977; Kleiber 1947; Mahadeva et al. 1953; Miller and Blyth 1955; Schmidt-Nielsen 1972; Strydom et al. 1966; Tucker 1970). As a result, estimates of energy expenditure in the action of walking or running have been modelled many times in the form of mathematical equations (for some examples, see Caron 2017: 54). Most of the different equations proposed express their results in units of VO_2 (volume of oxygen that can be taken up by the organism), and only Pandolf et al.'s (1977) and Brooks et al.'s (2005) equations express them as energy (Watts for Pandolf and Metabolic Equivalent of Task for Brooks). Because one of the essential prerequisites for the protocol described in this article is to estimate mobility in terms of energy expended by individuals, we chose to fo-

TABLE 1. EXAMPLE OF RELATIONSHIPS BETWEEN SLOPE VALUE AND RASTER COST VALUE USED BY DIFFERENT AUTHORS (Barge and Chataigner 2004; Liu et al. 2019; Sécher 2017).*

<table>
<tr><th rowspan="2">Slope value (en %)</th><th colspan="3">Cost value ("C")</th></tr>
<tr><th>Barge and Chataigner (2004)</th><th>Sécher (2017)</th><th>Liu et al. (2019)</th></tr>
<tr><td>0%</td><td>1.00</td><td>1</td><td rowspan="3">1</td></tr>
<tr><td>5%</td><td>1.18</td><td>2</td></tr>
<tr><td>10%</td><td>1.87</td><td>3</td></tr>
<tr><td>15%</td><td>3.04</td><td>4</td><td rowspan="4">5</td></tr>
<tr><td>20%</td><td>4.68</td><td>5</td></tr>
<tr><td>25%</td><td>6.76</td><td>6</td></tr>
<tr><td>30%</td><td>9.23</td><td>7</td></tr>
<tr><td>35%</td><td>12.05</td><td>8</td><td rowspan="8">10</td></tr>
<tr><td>40%</td><td>15.19</td><td>9</td></tr>
<tr><td>45%</td><td>18.59</td><td>10</td></tr>
<tr><td>50%</td><td>22.22</td><td>11</td></tr>
<tr><td>55%</td><td>26.01</td><td>12</td></tr>
<tr><td>60%</td><td>29.94</td><td>13</td></tr>
<tr><td>65%</td><td>33.97</td><td>14</td></tr>
<tr><td>70%</td><td>38.08</td><td>15</td></tr>
<tr><td>75%</td><td>42.22</td><td>16</td><td></td></tr>
<tr><td>80%</td><td>46.37</td><td>17</td><td></td></tr>
<tr><td>85%</td><td>50.49</td><td>18</td><td></td></tr>
<tr><td>90%</td><td>54.61</td><td>19</td><td></td></tr>
<tr><td>95%</td><td>58.65</td><td>20</td><td></td></tr>
<tr><td>100%</td><td>62.65</td><td></td><td></td></tr>
<tr><td>105%</td><td>66.58</td><td></td><td></td></tr>
<tr><td>110%</td><td>70.43</td><td></td><td></td></tr>
<tr><td>115%</td><td>74.18</td><td></td><td></td></tr>
<tr><td>120%</td><td>77.84</td><td></td><td></td></tr>
</table>

TABLE 1. EXAMPLE OF RELATIONSHIPS BETWEEN SLOPE VALUE AND RASTER COST VALUE USED BY DIFFERENT AUTHORS (Barge and Chataigner 2004; Liu et al. 2019; Sécher 2017) (continued).*

Slope value (en %)	Cost value ("C")		
	Barge and Chataigner (2004)	Sécher (2017)	Liu et al. (2019)
125%	81.43		
130%	84.91		
135%	88.29		
140%	91.58		
145%	94.79		
150%	97.89		
155%	100.89		
160%	103.80		
165%	106.64		
170%	109.37		
175%	112.06		
180%	114.64		
185%	117.13		
190%	119.53		
195%	121.88		
200%	124.14		

A slope of 100% represents a 45° slope; a 200% slope corresponds to a 63° slope.

cus on the equation proposed by Pandolf et al. (1976, 1977; Epstein et al. 1987), which is expressed as follows:

$$M_w = 1.5W + 2(W + L)\left(L/_{W}\right)^2 + \eta(\mathrm{W} + \mathrm{L})[1.5V^2 + 0.35GV]$$

where M_w is the energy ratio (in watts), W the weight of the body alone (in kg), L the weight transported (clothing and items carried; in kg), η the terrain factor, V the walking speed (in meters per second; $m.s^{-1}$) and G the slope (in %). The terrain factor η is derived from the work of Soule and Goldman (1972) and from additional experiments by Pandolf et al. in the 1970s–80s (1976, 1977). The values given in these articles have been recently reviewed and clarified (Richmond et al. 2015) and are summarized in Table 2.

Forecasts of the energy cost of this formula were able to be verified by several test phases on individuals from different classes of age and sex (Epstein et al. 1987; Pandolf et al. 1976, 1977) by varying the speed and the load carried. By its mathematical simplicity and its validity over a wide range of different individuals and constraints, this equation seems to be appropriate for the application to the archaeological context.

APPLICABILITY OF TERMS IN THE ARCHAEOLOGICAL CONTEXT

First, it is important to discuss the application of the proposed formula to the archaeological context. Calculations and confirmation experiments were carried out to forecast

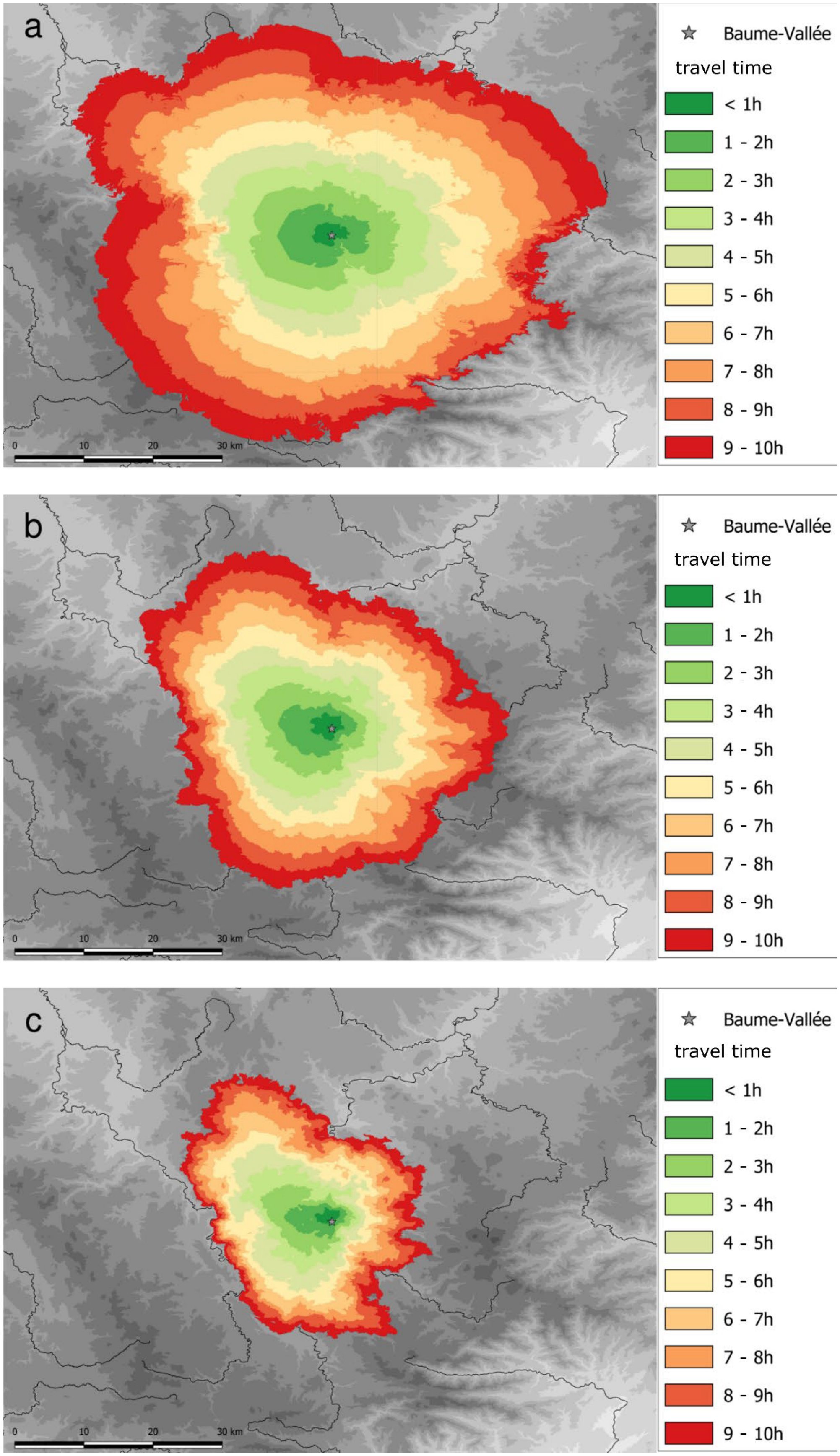

Figure 2. Modelling isochronous curves from the Mousterian deposit in Baume-Vallée using the raster cost values of (a) Barge and Chataigner (2004), (b) Sécher (2017) and (c) Liu et al. (2019) at an average travel speed of 5km/h.

TABLE 2. RECOMMENDED AVERAGE VALUES FOR η ACCORDING TO DIFFERENT TYPES OF TERRAIN WITH V IN $m.s^{-1}$ (after Pandolf et al. 1976; Richmond et al. 2015).*

Type of terrain	η	V=1.39m/s (5km/h)	V=1.94m/s (7km/h)
Slippery terrain	1.7	1.7	1.7
Vegetation	$\eta = 0.0718V^3+1.3V^2-5.3701V+6.0705$	1.31	1.07
Muddy terrain	3.5	3.5	3.5
Paved road	1.0	1.0	1.0
Path	1.2	1.2	1.2
Dirt track	1.2	1.2	1.2
Sand	$\eta=1.5+\frac{1.3}{V^2}$	2.17	1.84
Snow	1.18+0.089 d	1.18+0.089 d	1.18+0.089 d

*Factor d for snow represents the depth of footprint (in cm).

energy expenditure in a present-day Anatomically Modern Humans (AMHs). Different studies of animal and human locomotion (Alexander 1989, 2002, 2003; Bertram 2015; Halsey and White 2012; Tucker 1970) have highlighted the importance of gait as the main variable factor in energy expenditure in species and individuals of similar mass (Elftman 1966; Ivanenko et al. 2007; Selinger et al. 2015; Snaterse et al. 2011; Srinivasan and Ruina 2006). Morphological changes in living species tend to evolve towards a process of energy optimization and, in the case of locomotion, this involves adapting the gait so that it has the lowest energy cost. As variations in gait are dependent on the mode of locomotion and morphological characteristics (bipedal, partially bipedal, quadrupedal, etc.), many different species have gaits that are not significantly different (Alexander 2003) when their geometric proportions (ratio of mass to volume) are similar. AMHs in the Paleolithic had a similar gait to modern humans with only a very slight difference in terms of energy expenditure resulting from morphological variations[3] (Holliday 1997; Weaver and Steudel-Numbers 2005). This finding can be applied to other hominids, including Neanderthals. Several studies on the morphological features of their lower limbs have in fact shown some minor differences between Neanderthals and Paleolithic AMHs (Rak 1993; Tattersall and Schwartz 1998). As a result, Weaver and Steudel-Numbers (2005) estimate that there is a difference in daily energetic cost of foraging related to morphological variations in Neanderthals (shorter lower limbs than AHMs of the early Upper Paleolithic) of about +78 kCal per day, i.e., a little less than 7 kCal/km (based on a 12.2km/day average of round-trip foraging distances in ethnographic observations; Weaver and Steudel-Numbers 2005: 220). We are therefore able to weight the mobility costs obtained from Pandolf's equation using this estimate and thus take into account morphological characteristics specific to Neanderthals, then adapt our approach to this past humanity (i.e., our framework study) and to others according to the data available.

The variables proposed in the equation are directly applicable for periods of the Pleistocene (although we specify their limitations; Supplementary Information 2):

- walking speed **V** can easily be estimated from the many studies on locomotion (Alexander 1989, 2003; Bertram 2015; Halsey and White 2012; Tucker 1970) and the average speed most often used is that obtained from Tobler's hiking function (Tobler 1993):

$$W = 6e^{-3.5|S+0.05|}$$

where **W** is walking speed (in km/h) and **S** is slope (in degrees). This formula establishes the average walking speed on flat terrain at 5.037km/h. As the main value of **V** in Pandolf's formula, we chose to use this value (i.e., $1.39m.s^{-1}$) and a higher value of 7km/h (i.e., $1.94m.s^{-1}$). Many studies have demonstrated an increase in the average walking speed as a result of regular and/or intensive practice of this activity (Ades et al. 1996; Beaupied 2003; Billat 2001; Brose and Hanson 1967; Snook and Motl 2009). The nomadic or semi-nomadic lifestyle typical of the majority of populations in the Pleistocene (Barnard and Wendrich 2008; Beaudry and Parno 2013; Delagnes 2010; Delagnes and Rendu 2011; Féblot-Augustins 1999b; Jaubert and Barbaza 2005; Johnson 1969; Kelly 1983; Price and Brown 1985; Retaille 1998; Stépanoff et al. 2013) falls into this category, and we can therefore consider higher average travel speeds than for modern societies. Although it would be difficult to find a nomadism that is identical or similar to that of hunter-gatherers in the Pleistocene in the current ethnographic record, this lifestyle can be observed in current or

TABLE 3. AVERAGES OF WEIGHT, BASAL METABOLIC RATE (BMR), AND DAILY ENERGY EXPENDITURE (DEE) PRESENTED BY CHURCHILL (2009; modified) FOR NEANDERTHALS AND AMHS BY TYPE OF CLIMATE ENVIRONMENT.

Climate	Gender	Number of individuals	Body mass (kg)	BMR ($kcal.d^{-1}$)	DEE ($kcal.d^{-1}$)
Anatomically Modern Human					
Cold	F	10	60.3	1402	3084
	M	13	70.4	1766	4414
Temperate	F	4	55.7	1327	2256
	M	9	66.0	1639	3163
Tropical	F	1	62.3	1349	2294
	M	2	68.0	1622	3131
Neanderthal					
Cold	F	2	67.3	1448	3185
	M	7	80.2	1881	4701
Temperate	F	7	66.1	1417	2409
	M	9	75.8	1782	3439
Tropical	F	N/A			
	M	1	75.3	1730	3339

recent populations. We can take the example of peoples practicing nomadic pastoralism in Eurasia or Central Asia (Ferret 2014; Stépanoff et al. 2013 who sometimes demonstrate very great mobility (several thousand km travelled in a year). The speed of 7km/h is used here as a high value in order to test the influence of a higher speed on the cost and patterns of mobility;

- Slope **G** was obtained using Digital Elevation Models available on the CGIAR website[4] (resolution 90m). It was decided not to use a higher resolution of DEM (less than 90m) in order to limit as far as possible the influence of topographical changes associated with land use planning by humans during the Holocene. An initial slope raster was obtained using the spatial analysis tool in ArcGIS (*Slope*) and the slope values were classified in % in 5% increments from 0% to 200%. The topography of our study area has remained relatively unchanged since the end of the Upper Pleistocene (Defive et al. 2005; Le Griel 1991) and the topography today can therefore be used as the basis for modelling travel in Paleolithic times[5];
- Weight **W** represents the weight of the individual naked. There have been many paleoanthropological studies of human fossils from the Paleolithic (in contexts of cold, temperate, and tropical climate phases) from which it is possible to estimate body mass of more than sixty Neanderthal individuals and AMHs of both sexes (Beals et al. 1983; Churchill 2006, 2009; Feldesman et al. 1990; Grün et al. 2005; Henneberg et al. 1988; Kappelman 1996; Kennedy and Deraniyagala 1989; Mathers and Henneberg 1995; Oakley 1977; Oakley et al. 1971; Orschiedt 2002; Rosenberg 1988, 2002; Ruff et al. 1997; Shang et al. 2007; Trinkaus et al. 1998; Valladas et al. 2002; Vandermeersch 1981; Wild et al. 2005). The average weight used here are those given in Churchill (2009) and are summarized in Table 3.

TABLE 4. FORMULAS USED TO CALCULATE THE PENALTY *p* ASSOCIATED WITH SNOW OR ICE COVER OVER THE TERRAIN.*

	Vegetation	Tracks
Ice	$p = C_{ice} - C_{vegetation}$	$p = C_{ice} - C_{tracks}$
Snow	$p = C_{snow*} - C_{vegetation}$	$p = C_{snow*} - C_{tracks}$

*With constant values for *W*=*x*, *V*=*y* and *G*=*z*: C_{ice} estimated cost for terrain factor ice, C_{snow*} estimated cost for terrain factor snow (for a footprint depth *), $C_{vegetation}$ estimated cost for terrain factor vegetation and C_{tracks} estimated cost for terrain factor tracks. Values for cost *C* are calculated from the equation presented in Calculating Energy Cost and the Value of Cost C.

- Weight transported **L** represents the load carried by individuals as they travelled. We have no precise quantifiable data for the Paleolithic regarding the weight carried by groups as they travelled. While we are able to estimate the quantity and therefore the weight of lithic and/or animal resources present in the deposits, it is risky, however, to deduce the load carried directly by an individual from archaeological deposits. In order to test different models, we decided to select three different classes of weight transported: weight L=0 as the standard value for an individual with no weight constraint, weight L=5kg for an individual with a light load (clothing and minimal items) and weight L=20kg to illustrate the transporting of a large quantity of surplus weight (siliceous, meat and/or plant resources).
- We selected two main terrain factors (η; see Table 2 for recommended average values) in these models:
  - Walking in vegetation (see Table 2) where η=1.31 for V=5km/h and η=1.07 for V=7 km/h. This type of environment corresponds to the steppe and short-grass landscapes most frequently found in our study area. The difference in the value of n for the two speeds is explained by the lower grip of the grass—at lower speeds, the impact of the grip factor is greater. An example of this impact is given by some species of gecko that can run on water. If these same gecko walked, they would sink (e.g., Stark et al. 2015);
  - Walking on paths and dirt tracks where η=1.2.

Finally, we also created models incorporating an additional penalty ***p*** (and hence a change in the cost of mobility) for areas which, in a cold climate, have a covering of snow and/or ice considered as permanent. In addition to the costs calculated with the vegetation or track terrain factor, these penalties add the difference in energy expended using the terrain factors for ice (η=1.7) and snow for a footprint depression of 1cm (η=1.27), 5cm (η=1.625) and 10cm (η=2.07) deep. These penalties were applied by combining the different cost rasters using the *Merge* tool in ArcGIS and their values were calculated according to the formulas given in Table 4.

CALCULATING ENERGY COST AND THE VALUE OF COST C

Thus, the equation selected to test the energy expenditure in our mobility model is Pandolf's equation (see above), which we applied using the variables described above. We produced four examples of the model adapted to our area and our period of study—Neanderthal individuals, living in a temperate or cold climate. From the results obtained for energy expenditure, we developed a formula for the cost calculation, as follow:

$$C = \left[\frac{M_{w_G}}{M_{w_{G(t0)}}} + (M_{w_G} - M_{w_{G0}})\right] + \left[\frac{M_{W_L}}{M_{w_{L0}}} - 1\right]$$

- with constant values for *W*=*x* and η=*y*: *C*=cost;
- M_{w_G}=energy expenditure for a slope *G* (in $kCal.h^{-1}$);
- $M_{w_{G(t0)}}$=energy expenditure for zero slope (*G*=0%), zero terrain constraint (η=1; constraint value for treadmill) and weight *W*=*x*;
- M_{W_L}=energy expenditure for a given additional weight *L*; and,
- $M_{w_{L0}}$=energy expenditure for zero load (*L*=0) and value of *p* equal to that used for M_{w_p}.

The first term of the equation[6] expresses the effect on cost ***C*** of variations in slope ***G*** and in speed ***V*** compared to an ideal theoretical mobility model (walking on a treadmill with zero slope without additional weight; i.e., η=1, *G*=0 and *L*=*0*) for weight *W*=*x*. The second term[7] reflects the effect on cost ***C*** of increasing the weight carried.

Once the value of cost **C** is obtained, we are able to show the impact of topography on the distance travelled. Taking into account the speed variable as an indicator, we obtain a theoretical maximum cost distance, i.e., the maximum distance that can be reached without constraints due to the slope in a certain amount of time (e.g., one hour). It is this maximum distance that will decrease as a function of the topographical constraints (i.e., as a function of the value of the pixels in the cost raster). The various isochronous lines presented in the examples below are derived from this calculation. For example, for a speed of 5km/h, the maximum cost distance in 1 hour of walking is 5000 meters (7000 meters for a speed of 7km/h). Each isochronous line then represents the equivalent of 5000 meters (i.e., 1 hour's walking time), weighted by the cost value, and then indicates the distance covered in 1 hour taking into account the different variables (speed, slope, body mass...), affecting the time of travel.

RESULTS AND DISCUSSION

We give here as examples some cost distance models from the Baume-Vallée site varying the different parameters (Figure 3). The three models were all made for a female Neanderthal individual (W=67.3 kg) in a cold environment and on a grassy terrain (η=1.31), varying the speed (V) and additional load (L) parameters. The choice of a female individual here is arbitrary, as the difference is based solely on the lower mass, with little difference in gait efficiency between the sexes (e.g., Nigg et al. 1994). The first example (see Figure 3a) uses parameters V=5km/h and L=5 kg, the second example uses V=5km/h and L=20kg and the third uses V=7km/h and L=5kg. These examples clearly illustrate the importance of the different parameters in estimating achievable distances for a given time—journeys are limited in those places where topographical variations are greatest, and the heavier the weight carried, the shorter the distance achieved for the same energy expenditure. In the same way, a greater speed means that energy expenditure can be influenced more by the topography and weight parameters—on flat terrain and with a relatively small total weight (under 70 kilos), a speed of 7km/h means that greater distances can be achieved for the same energy expenditure as a speed of 5km/h. However, on rough terrain and/or carrying additional load, a speed of 5km/h proves to be more economical in terms of energy expenditure.

Many studies have demonstrated the automatic adaptation of locomotion effort to ensure the best return on action / cost of action in almost the entire animal kingdom (including our own species; Alexander 2003; Selinger et al. 2015; Srinivasan and Ruina 2006; Zarrugh et al. 1974). Based on these data, we selected the speed of 5km/h as the default speed and the most profitable in terms of distance travelled / energy expended.

DAILY TRAVEL TO TECHNO-ECONOMIC DOMAINS

For a better understanding of a group's mobility patterns within a territory, it seemed appropriate to define the notion of a "day's walk"[8]. A large majority of animal species travel (on a daily, weekly, or seasonal basis) in order to meet their daily needs (Alexander 1996, 2003; Tucker 1970), whether to reach new areas rich in resources (majority of herbivores) or to pursue prey (majority of carnivores). The amount of energy expended in the search for these resources is usually less than the contribution gained by consuming the resource (Alexander 1989; Emken et al. 2007) so that the daily energy ratio remains positive (if the daily energy ratio is negative too often, this leads irrevocably to physiological disorders that can result in the death of the organism). On the basis of this assumption, we established the basic unit for daily travel (the theoretical "day's walk") as the average distance that can be travelled in a day by an individual without the resulting caloric consumption exceeding the maximum value of the average estimated energy expenditure for daily activities. It should, however, be noted that the limit of the theoretical "day's walk" proposed here corresponds to a "maximum" limit considering that the totality of the daily activity is devoted to walking (to the detriment of all other activities, which seems unlikely, to say the least). The formula for this calculation is as follows:

$$t = \frac{(DEE - BMR)}{M_w}$$

where t is the estimated travel time (in hours/day), ***DEE***[9] is the average daily energy expenditure (in kCal/day), ***BMR***[10] is the average basal metabolic rate (in kCal/day) and M_w is the energy expenditure (in kCal / hour) calculated for one hour's travel (in accordance with parameters η, W, L, V and G selected and expressed previously). The subtraction of the BMR allows us to estimate the amount of energy allocated daily to activities.

Data about the DEE and the BMR are available for present-day humans, but also for the fossil register where the fairly large amount of data provides average indicative values for AMHs and Neanderthals in different climatic environments (Aiello and Key 2002; Churchill 2006, 2009; see Table 3). By using these data, we are able to propose an average number of hours that can be assigned to daily travel without incurring excessive energy expenditure, and this is done for different individuals determined as theoretically representative.

As an example, the daily travel time on flat grassy terrain (G=0% and η=1.31) at a constant speed (V) of 5km/h for a female Neanderthal (W=67.3kg) carrying an additional load (L) of 5kg in a cold climate is estimated at 5.37 hours per day; for a male Neanderthal (W=75.8 kg) in a temperate climate (for identical values of G, η, V and L), it is 4.58 hours per day.

By defining these theoretical "days' walks" for an archaeological site, it is then possible to propose a reasoned model of its techno-economic domains (local, regional, distant, etc. spaces) and to draw a schematic representation of potential time / space relationships for a given territory. This techno-economic zoning of territories (see above) based on prehistoric sites has been proposed on numerous occasions and for a variety of contexts (Binder 2016; Dubreuil 1995; Geneste 1985, 1992; Jaubert and Barbaza 2005; Tomasso 2018; Turq et al. 2017). It is usually presented in a simplified form (although the shortcomings of this representation are clearly indicated by the authors) with concentric circles (expressed in km) that are not able to take into account the influence of the topography and establish the time devoted to a day's walk in a fairly arbitrary fashion (duration of 7 to 8 hours of walking is typically used).

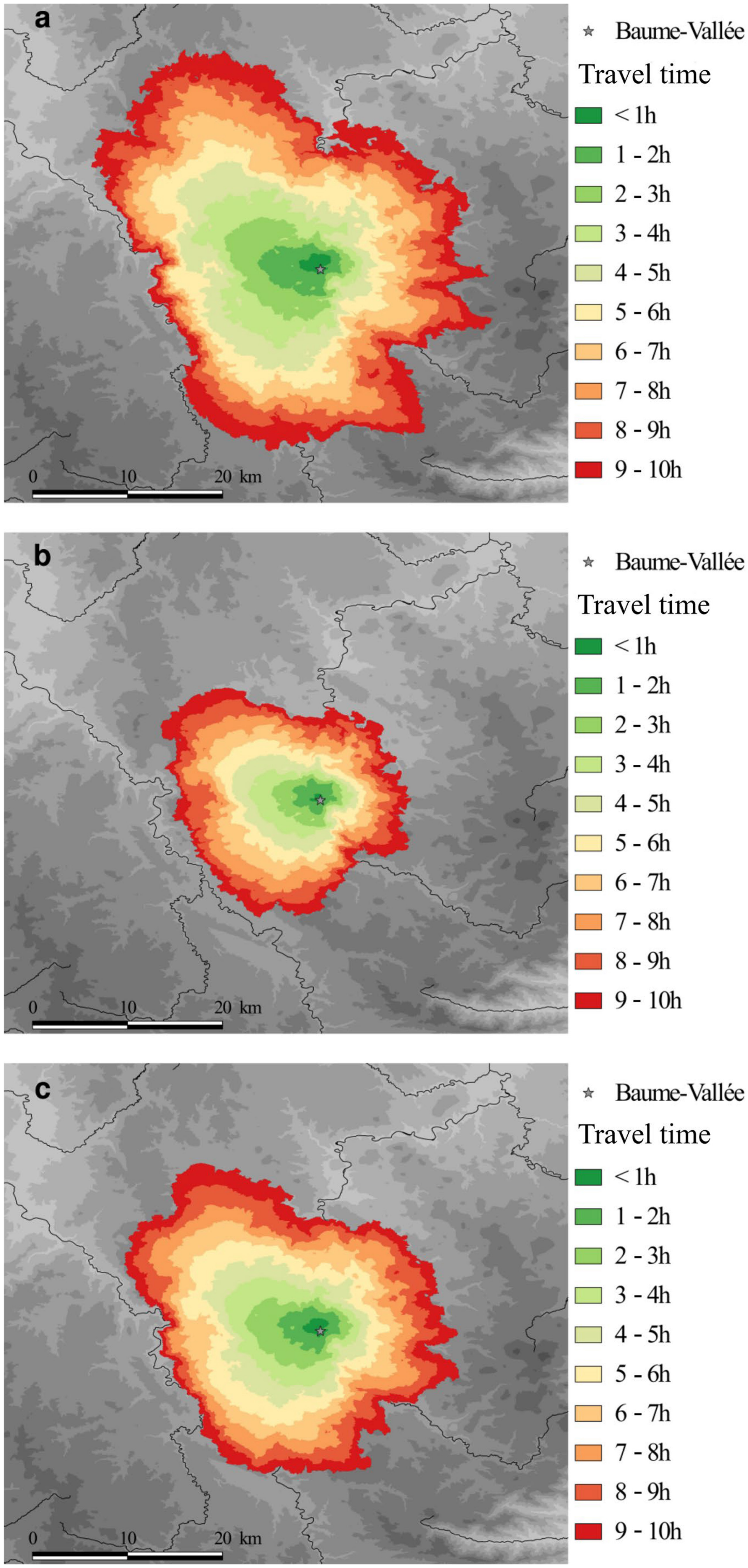

Figure 3. Examples of modelling isochronous curves applying the protocol presented in this article. Parameters used: (a) V=5km/h and L=5kg; (b) V=5km/h and L=20kg; (c) V=7km/h and L=5 kg.

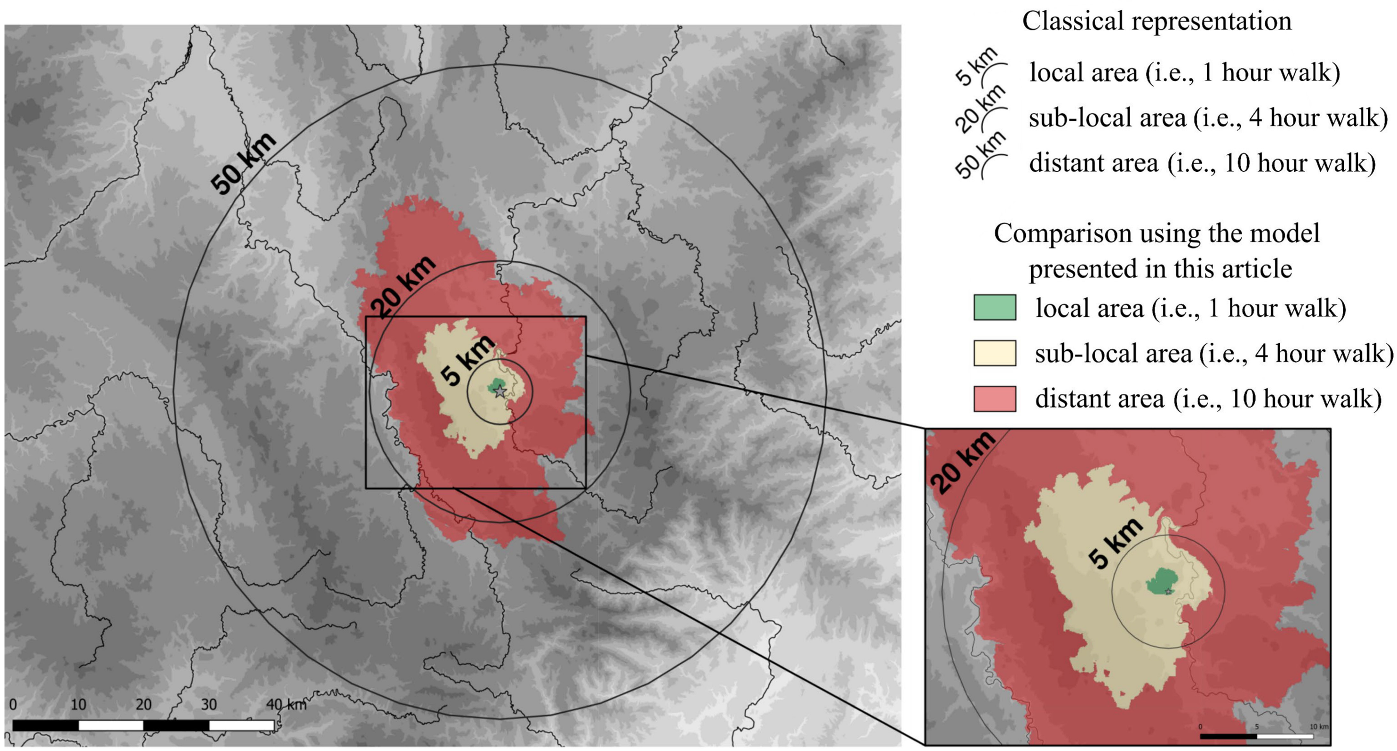

Figure 4. Comparison of representations of techno-economic spaces in the classic concentric circle model and the model proposed in this study.

ARCHAEOLOGICAL EXAMPLE: APPLICATION TO A MIDDLE PALEOLITHIC SITE

Using the notion of the "day's walk," as defined in this article with the formula mentioned above, results in a completely different perception of time / space relationships within a given territory. As an example (Figure 4), we applied this model to the Baume-Vallée site comparing it with representations of theoretical techno-economic domains proposed by Geneste (1985), which are broken down as follows:

- local space accessible in 1 hour's walking outward journey (or 5km as a Euclidean distance);
- semi-local space accessible in a half-day's walking outward journey (or 20km as a Euclidean distance);
- distant space accessible in one day's walking outward journey (or 50km as a Euclidean distance);
- very distant space beyond this limit.

We would like to point out that, whatever the selected parameters are (environment, gender, weight, additional load or not, speed, ground type…), the maximum daily walking time calculated is 7.73 hours' walking per day, rounded up to the next whole number (i.e., 8 hours' walking per day; Supplementary Information 3). Taking this into consideration, and whatever space is considered, there are considerable differences between the maximum Euclidean distances and those from our model protocol (see Figure 4)—for example, the majority of the space contained within the circle assumed to represent the semi-local space (20km radius as a Euclidean distance) is well beyond a half-day's walk outward journey, and even beyond that for a full day. Even considering an excessively high value for the daily walking time, this example points out how inaccurate the classical site-centered concentric circles representation is. These arbitrary circles (*sensu* Geneste) do not provide tools, in a sufficiently realistic way, which would allow us to discuss land use investment and correlated mobility reconstruction.

Concerning the lithic material of Baume-Vallée, we present here only the information concerning some raw materials from more proximal outcrops to the site in order to illustrate the potential implications in terms of interpretation (for more details see Vaissié et al. 2017; 2021). The outcrops discussed here are those that seem to have been regularly visited from the Baume-Vallée site, which functioned as a base camp in the exploitation of a vast regional space (Vaissié et al. 2017; 2021). By combining this map with techno-economic data from the lithic assemblages[11], we are able to identify distance / time relationships in the space around the deposits and thus reveal the implications of visits to deposits of raw materials. In the example shown in Figure 5 (and Table 5), we can clearly see that the techno-economic processing and the representation in the assemblage of a material cannot be directly dependent on a Euclidean distance. The materials located to the north-east (material B) and the south-west (material D) of the deposit, although they are at very different distances from the site (16km and 23km, respectively, on average), are located in approximately equivalent positions at the edges of the space and can be reached in 10 hours walking from the site. In the same way, materials located at the east of the deposit

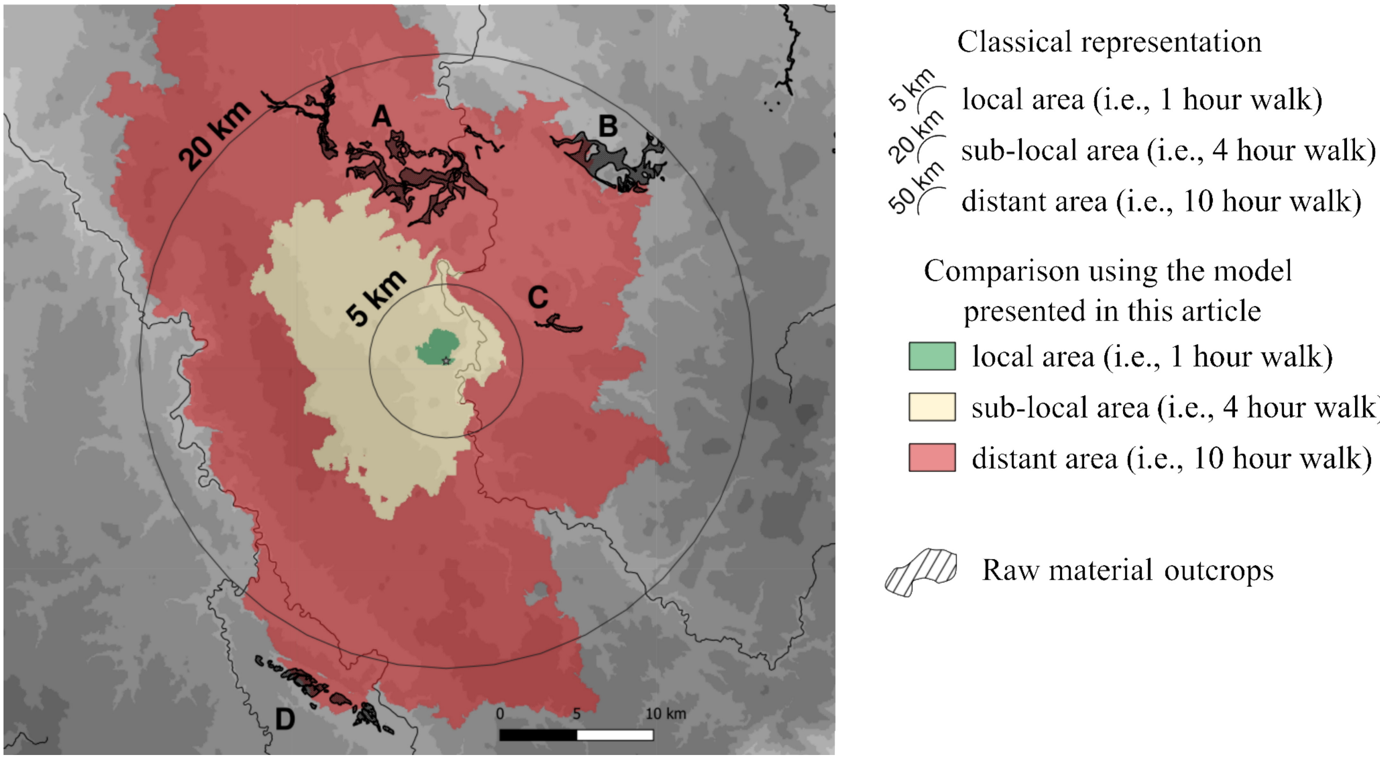

Figure 5. Representation of deposits of raw materials exploited at Baume-Vallée in a 30km radius around the site and incorporation into the different techno-economic spheres.

(material C) are fairly close to the site (about 7km) but have a fairly long access time (between 7 and 8 hours' walking), which is significantly different from the result when using Euclidean distances (semi-local domain in Euclidean distance, distant domain according to our model). Finally, the materials located to the north-west (material A), although about a dozen kilometers away from the site, on average, are the most easily reached from the site.

Given the classical idea that the representation of raw materials is inversely related to the distance of the outcrops (Brantingham 2003; Elston 1992; Surovell 2012), one could make two hypotheses—if we consider the classical site-

TABLE 5. TABLE OF DISTANCE/TIME RELATIONS AT THE SITE OF DIFFERENT RAW MATERIAL DEPOSITS AND ASSOCIATED TECHNO-ECONOMIC DOMAINS.

Raw material deposit	Average distance to site	Estimated walking time	Techno-economic area (Geneste)	Techno-economic area (Vaissié)	Average representation in archaeological levels	*Chaîne opératoire* representation in archaeological levels
A	12km	5 to 6 h	Semi-local	Semi-local to distant	40 to 50%	all the *chaîne operatoire* represented
B	16km	10 to 11 h	Semi-Local	Distant	5 to 10%	deficit for the initialization phases
C	7km	7 to 8 h	Local to semi-local	Distant	1%	isolated and / or retouched products
D	23km	9 to 10 h	Semi-local to distant	Distant	10 to 20%	deficit for the initialization phases

centered concentric circles representation, raw material C would be the most abundant in the lithic industry, then raw material A, then B, and lastly raw material D. If we consider our modelling, priority is given to raw material A, then C, and raw materials B and D are expected to be more or less equally represented. Looking at the raw material representation within the deposit, the mobility pattern that emerges seems to suggest that the space located to the north of the site (material A) was used most. This first observation agrees with our cost modelling and shows the importance of the energy cost compared to the Euclidean distance, regarding preferential use of a main raw material. But it could also be used to discuss space integration in mobility patterns. In this regard, without the use of the model presented here, one could underestimate the significance of the very strong representation of raw material A. If we refer to J.M. Geneste's classic breakdown, the visit to the outcrops and the return to the site can be done in one day. This assumption would greatly underestimate the topographical impact and therefore the logistical impact underlying the very high use of outcrop A. The application of our model supports the hypothesis of planned expeditions from the site to the area to the north for exploitation (whether solely for mineral resources or coupled with hunting activities). Despite its proximity to this apparently heavily visited area, material B is used relatively little, which seems to place it away from the main circulation routes. Material D, despite being a significant distance / time from the site, is nevertheless used regularly and fairly intensively, which testifies to the regular use of the spaces in the south-west of the site. Lastly, the low representation of material C could be explained in part by the small area covered by the deposits (which in addition has no other resources nearby) and in part by the fact that the time investment required to collect it would be too great in relation to the other points of interest available to prehistoric populations in this area. To support these interpretations, we should point out that the four materials mentioned above are all equally suitable for knapping ("quality" of the material) and comprise equivalent volumes of blocks. It would therefore seem that these factors cannot account for the preferential use of certain spaces.

The use of our model also allows us to discuss mobility strategies and potential transfer networks. If we consider, with our model, the four raw materials in this example, none could have been collected in a one-day round trip from the site. The one-day round-trip hypothesis could have been retained in the case of classical site-centered concentric circles, at least for raw materials A and C. This is a major improvement in our way of discussing mobility because, in the first case (our model), collecting those raw materials involves the implementation of logistic mobility with planned expeditions linked to the exploitation of high interest areas. Coupled with integrated data of petroarchaeology and techno-economy (Vaissié et al. 2021), our modelling seems to show differential use of spaces, perhaps related to movements between areas more or less strongly integrated into the subsistence territory. Testing our interpretations against quantified cost modelling, such as that developed in this paper, is key for highlighting human behavior and choices in terms of mobility patterns and land use.

While other parameters than those related to travel times can explain the representation and the processing of materials in the deposit (Browne and Wilson 2013), these models give a better understanding of the real investment in travel time required to visit different points within a given space. These data open up the possibility of identifying mobility patterns and human choices in relation to occupying the spaces surrounding the site. On a larger scale and for the most distant materials, this model can also provide a reasoned comparison of the time investment required to visit deposits of raw materials that, once again, will no longer be based on Euclidean distances as they represent an incorrect approach. It provides clues to discuss direct and indirect procurement, and can highlight probable social networks structured between territories (Vaissié et al. 2021).

CONCLUSION

Despite the inevitable biases to which models in these ancient contexts are subject, the model that we propose here enables us to optimize the techno-economic data available in archaeological assemblages. As can be seen in the context where the model was applied (the Middle Paleolithic site at Baume-Vallée), this approach led to a quantified redefinition and visualization (via a GIS model) of temporal zoning of routes in the space surrounding the site. This tool has proved to be flexible and applicable to different types of archaeological context. It is able to process in an equivalent and similar way different techno-economic systems, environments (controlling parameters such as the nature of the terrain, snow, or ice-covered areas) and even the composition of the human group (sex of individuals, body mass, with or without additional load). With these models it is therefore possible to incorporate and to take advantage of a wide range of archaeological data, according to its availability (paleoanthropological, geomorphological, paleo-environmental, archaeozoological, techno-economic, etc.). The tool that we propose is therefore no longer limited to a 2D model of litho-space but can create a 3D model (highlighting potential paths) and even 4D (suggesting a travel time for covering these paths). It is therefore able to define, for each archaeological context, economic zones based on the time required to obtain materials in the most suitable way for the assemblage studied. This approach allows for a more precise resolution of the socio-economic organization of human groups, and a more detailed vision of the everyday life of past populations by establishing in a quantified manner the investment (in time and in energy) needed by the group to visit defined points of interest. This allows us to study the implementation of logistic mobility with planned expeditions within regional space, as well as highlighting probable social networks structured between territories on a larger scale. By combining this approach with modelling eco-cultural niches, as proposed by W.

Banks (2017; Banks et al. 2006, 2011, 2013, 2014), we should be able to correlate changes in eco-cultural niches as new travel routes are abandoned or created—closure of valleys due to freezing, changes in vegetation, etc., all of which have repercussions for the time / energy investment of human groups. This would open up a broader discussion on the modalities of large-scale travel and the cultural variations observed during prehistoric times.

This approach also provides the opportunity to highlight the real techno-economic divergences between different human groups, cultures, chronologies, and environments. By establishing a quantified investment of space for each context, we will take a giant step forward in defining specific lithic technical systems for each cultural group, namely the relationship equilibrium that the group manages to find between needs / technical traditions and available resources, between culture and nature. Because, beyond the apparent homogeneity of the various cultural groups identified during the Paleolithic (Mousterians, Aurignacians, Magdalenians, etc.) and the general trends of change that result, this relationship equilibrium seems today to be a determining factor in understanding the cultural entities of the Paleolithic. This tool could enable us to identify regional variations in lithic technical systems and is a valuable asset in understanding the status of sites and places for past populations.

The protocol we propose here offers the possibility of creating reasoned and reproducible comparison models, as close as possible to the socio-economic reality of human groups, so as to compare them as objectively as possible in a wide range of chronological, physical, and anthropological contexts. It thus expresses a completely different reality which incorporates the geography objectively. Because it fills the gap between techno-economic data and interpretations of mobility, we believe that using this protocol will promote a better discussion of mobility patterns of human groups in the past and highlight the real factors of behavioral variations in the management of space in prehistoric times.

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ENDNOTES

1. The local area is assumed to correspond to the foraging radius, i.e., the area covered during the daily round-trip movement. While the distances suggested for this daily movement can vary according to context, it seems unlikely that points located more than 10km away could be visited with a return to camp within the day (Binford 1982).
2. The question of the value to assign to the average travel speed and its validity in an archaeological context will be discussed in a later section of this article.
3. Weaver and Steudel-Numbers (2005) calculate a difference in terms of energy expenditure based on morphological variations of less than 50 kCal per day between AMHs in the Mesolithic, early Upper Paleolithic, and recent Upper Paleolithic. These differences, estimated on the basis of a daily distance covered of 12.2km (Binford 2019), are very small compared with those resulting from variations in mass, which are included in Pandolf's formula, as used in this article, and can therefore be considered as negligible.
4. http://srtm.csi.cgiar.org/SELECTION/inputCorrd.asp
5. This observation is not valid everywhere and the knowledge of the geomorphological evolution of the study area is required.
6. $\left[\frac{M_{w_G}}{M_{w_{G(t0)}}} + (M_{w_G} - M_{w_{G0}})\right]$
7. $\left[\frac{M_{w_L}}{M_{w_{L0}}} - 1\right]$
8. A first attempt at a quantified definition of a "day's walk" was proposed by A. Tomasso (2014: 66–67), also based on using a GIS to adapt it to constraints associated with the terrain. It is expressed as follows:
   - $j_m = \frac{d_e}{35}$, where j_m is the number of days' walk needed to reach a point in space from the site;
   - d_e is the value of the cost-distance map at this point (in km); and,
   - 35 is the number of kilometers travelled in a theoretical day's walk (7 hours walking at 5km/h).

   Although this formula provides the time required to visit different points in space, it has limitations in the choice of the constraint calculation C (the same formula as Barge and Chataigner 2004; C=0.031 p^2 – 0.025 p + 1; see above) and in the typical day's walk (35km).
9. The DEE expresses the energy expended by the organism to ensure that its functions are maintained and that expended on average to carry out daily activities.
10. The BMR represents the minimum daily energy expenditure needed to maintain the organism's vital functions
11. The aim of this article is not to present the petro-techno-economic study of the lithic industry of Baume-Vallée. For details concerning the lithic industry, we refer the reader to the data already published which present the main petroarchaeological, techno-typological, and economic characteristics of the upper levels used in this example (Vaissié, in progress; Vaissié et al. 2017; 2021).

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SUPPLEMENTARY INFORMATION 1

Based on a given travel speed (the value most commonly used is 5km/h), the distances covered are weighted by penalizing factors defined by the user (the physical constraints mentioned above) in the form of a “cost raster”: each pixel in the raster is given a value *n* (see Figure 1) according to the pre-defined criteria so as to express the level of constraint that crossing this pixel causes during a theoretical journey. The resulting models usually produce isochronous curves showing the zones that are accessible in *X* walking time (method known as “cost distance” analysis; see Figure 1) and / or linear routes linking points according to the most economic route (method known as “least-cost path” analysis; see Figure 1).

SUPPLEMENTARY INFORMATION 2

Obviously, the protocol described here does not claim to accurately reconstruct the travel times within a space, but rather it offers a new angle from which to consider our perception of human mobility. Of course, the method and the calculations presented here suffer from inherent limitations of our knowledge of physical and human environments in the past and we therefore believe it is important to clearly express those limitations:

- Although subject to many experimental checks, Pandolf’s equation does not take into account energy variations resulting from the differences between uphill and downhill movement. Although it claims to be a verifiable and verified mean mathematical expression (Pandolf et al. 1976; 1977; Epstein et al. 1987), it only imperfectly expresses the response of individual physiological variability in the context of movement in changing topography;
- The weakness of the biomechanical repository for prehistoric populations is a shortcoming that has to be borne in mind—the abilities of individuals are necessarily different compared to our current repository. We decided to apply the paleontological principle of actualism that, despite the morphological and physiological proximity of Neanderthal populations and AMHs when compared with contemporary individuals, does not claim to establish an exact match with bio-mechanical realities in the past;
- The resolution scale selected for the Digital Elevation Models (90m) reduces local variations in the topography and as a result any micro-landforms that may affect journeys are ignored (narrow valleys, rocky outcrops, etc.);
- Our lack of knowledge of hydrographic paleo-networks, which may have changed regularly and often

in prehistoric times, meant that we were not able to include these parameters in the model—in the absence of exact data on possible crossing places and actual natural barriers, we decided not to take these into account. The assumption was that crossing points exist on a regular basis even over large waterways;

- The influence of additional weight carried (L) cannot be known with any accuracy and varies according to the individual and the route. We decided to select average values to illustrate its potential influence;
- The models show travel times for a theoretical individual and not for groups of individuals advancing at a variable pace. We decided to use the ethnographic assumption (Barnard and Wendrich 2008; Johnson 1969) according to which the travel speed of the group is adapted to the speed of its slowest member; and,
- In the same way, travel speeds and distances should be considered as maximum values rounded up—the journey is considered to consist of the shortest possible route, with no stops or detours associated with any activity along the way.

SUPPLEMENTARY INFORMATION 3

In order to get as close as possible to the theoretical breakdown proposed by Geneste, we would be constrained in our study framework, based on the factors used in our protocol, to select the following variables—a male Neanderthal in a cold climate (W=80.2kg) with no additional load (L=0 kg) on a grassy terrain (η=1.31) and at a speed of 5km/h. The daily walking time for these parameters is calculated as 7.73 hours walking per day, rounded up to the next whole number (i.e., 8 hours walking per day). The absence of additional load means a total absence of clothing or personal gear. This situation is unlikely to have occurred. And we choose a male Neanderthal in a cold climate because, based on the data provided by Churchill (2006, 2009), this case shows the biggest daily energy expenditure. This means that it is the case where the part of the daily energy expenditure allocated to the displacement can be the largest. The daily walking time calculated in these conditions is to be considered as a maximum and should not be taken with the examples proposed above which are intended to represent reality more faithfully.