Upper Palaeolithic Settlement and Mobility in the Armenian Highlands: Agent-Based Modeling, Obsidian Sourcing, and Lithic Analysis at Aghitu-3 Cave

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Abstract

Excavations at Aghitu-3 Cave in Armenia revealed stratified Upper Palaeolithic archaeological horizons (AHs), spanning from 39 to 36,000 cal BP (AH VII) to 29–24,000 cal BP (AH III) and from which we identified the sources of 1120 obsidian artifacts. Not only does AH III—deposited at the onset of the Last Glacial Maximum—have the most artifacts from non-regional sources but also the artifacts originate from the greatest variety of sources, including two ≥ 270 km on foot in different directions. The amount of retouch and density of lithics—as expressed by whole assemblage behavioral indicators (WABI)—suggest a trend from more expediency to more curation between the deposition of AHs VII and IV. This was followed by a substantial shift back to expediency during the deposition of AH III, corresponding to greater logistical mobility. Here, we use agent-based modeling (ABM) to interpret these data. Greater interactions between foraging groups are not an unavoidable outcome of a shift from residential to logistical mobility. Some variables (i.e., lithic stock, use intensity, provisioning strategy) can be ruled out, while other variables (i.e., decreased source abundance, a shift to direct procurement) appear inconsistent with the archaeological data. Territory spacing, in contrast, has a clear and predictable effect. A small decrease in territory spacing can yield notable increases in inter-group contact opportunities and can be explained by an increase in population densities as the climate cooled. Following this scenario, we assume that, as AH III accumulated, the cave's occupants not only moved farther distances but also more frequently encountered neighboring groups.

Keywords Computer simulation · NetLogo · Hunter-gatherers · Agent-based modeling (ABM) · Whole assemblage behavioral indicators (WABI)

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Introduction

"There are two general approaches to the study of social behavior: Collect observational, survey, or other forms of data and analyze them, possibly by estimating a model; or begin from a theoretical understanding of certain social behavior, build a model of it, and then simulate its dynamics to gain a better understanding of the complexity of a seemingly simple social system."
— T.F. Liao 2008

Archaeological deposits in Aghitu-3 Cave (A3C) reflect the behavior of the first Upper Palaeolithic (UP) inhabitants of the Armenian Highlands and preserve evidence of diachronic environmental changes during its occupation, as we have previously reported (Kandel et al. 2017). Calibrated radiocarbon dates and climatic proxies reveal the earliest occupations (i.e., archaeological horizon [AH] VII) occurred during a warm and moist phase circa 39,000 to 36,000 years ago (39–36 ka; all subsequent radiocarbon dates are calibrated as well). Mild climatic conditions continued into AH VI circa 36–32 ka. As the climate began to cool circa 32–29 ka, occupation intensity decreased markedly in AHs V and IV. Cooling intensified as the Last Glacial Maximum (LGM) approached, yet abundant lithics, faunal remains, and combustion features in AH III attest to intensive occupations circa 29–24 ka. Over these 15 millennia, lithic technology remained focused on a single pattern: unidirectional reduction of small cores geared to the manufacture of laterally retouched and backed bladelets. There were, though, diachronic shifts in toolstone transport. During the cooling associated with AH III, hunter-gatherers transported obsidian blanks from two sources more than 270 km away on foot in different directions. Concurrently, bone implements, including an eyed needle and a polished point, as well as pigmented and perforated mollusk shells appear within this layer. Such organic objects hint at complex clothing production and personal adornment. Therefore, the site's greatest behavioral changes—the emergence of bone implements and snail shell beads, more intensive (although still episodic) occupation, and far-traveled obsidians—coincide with cold and dry conditions leading into the LGM (26.5 to 20–19 ka; Clark et al. 2009). These phenomena, we previously speculated (Kandel et al. 2017), reflect different foraging groups coming into contact more often as they move over the landscape, but the mechanisms for such a diachronic change could not be explicated. This is not an uncommon issue. Wobst (1974) suggests that "Palaeolithic archaeologists often commit errors in scale" when endeavoring to extrapolate from a particular site to its broader context (147). To counter this, he advocates for the development and use of computational "models which have test implications for the archaeological record" (147). Here, we employ agent-based modeling (ABM) as a means to consider our archaeological observations at A3C, to identify and quantify those variables that best account for these observations, and to make predictions for which more fieldwork is required to test. That is, we consider the two general approaches in the opening quote as equal parts of an iterative process that involve cycles of taking observations and building models, with refinements in each cycle.

Archaeological uses of ABM have increased markedly in recent years (Wurzer et al. 2015). Some researchers seek to simulate complex societies using ABM (Axtell et al. 2002; Christiansen and Altaweel 2006; Griffan and Stanish 2007; Janssen 2009; Kowarik et al. 2015; Swedlund et al. 2015; Danielisová et al. 2015), while others focus on hunter-gatherers (Premo 2005; Brantingham 2006; Janssen et al. 2007; Powell et al. 2009; Barton et al. 2011, 2012; Barceló et al. 2014, 2015; Timm et al. 2016). It should be stressed that we are not attempting to produce a complete "artificial society" that exists as only ones and zeros (e.g., Epstein and Axtell 1996), nor are we endeavoring to recreate the Southern Caucasus in digital form. Instead, our model, as described by Gilbert and Troitzsch (2009:2), is "a simplification—smaller, less detailed, less complex, or all of these together—of some other structure or system." In other words, it is what Premo (2006, p. 91) calls a "digital caricature of past societies and paleoenvironments." We do not try to reproduce the "real" past but instead conduct controlled experiments—essentially a series of "what if?" scenarios—in which we can alter particular variables and monitor the outcomes.

ABM is attractive for interpreting our observations at A3C because such an approach "enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment" (Gilbert 2008, p. 2). In this case, that means modeling foraging groups as agents on a virtual landscape. Agents are social actors who follow rules that can create emergent behaviors, and the environment can contain different qualities or features, such as toolstone sources. The agents have the ability to perceive other agents or aspects of the environment (e.g., see toolstone sources), perform actions (e.g., carry toolstone), and have knowledge (e.g., know the size of their toolstone stock). Thus, in our simulations, we tested a series of behavioral and geographic variables to determine how—if at all—they influence opportunities for different foraging groups to encounter one another on the landscape, enabling transmission of materials (as well as, perhaps, innovations) between them. Our ABM is based on that of Barton and Riel-Salvatore (2013, 2014), which was originally designed to model the composition of lithic assemblages at hunter-gatherer sites scattered across the landscape. Our modifications to their ABM focus on modeling the frequency of contacts between two foraging groups.

For this study, the behavioral variables included agents' mobility, provisioning, and procurement strategies. As formulated by Binford (1980), mobility can be *residential*, in which an entire group moves from one camp to the next, or *logistical*, in which small parties set out from a central base camp on trips to obtain particular resources. Binford (1980, p. 355) recognized—as we do—that these mobility strategies exist along a continuum and "may be employed in varying mixes in different settings" by the very same foraging population. It has been hypothesized, for instance, that either a patchy or even spatiotemporal distribution of resources over a landscape—including the effect of seasonality—is likely to be a key factor (Fitzhugh 2002, p. 261). Given the energetic costs associated with transporting toolstone, mobility strategy is expected to shape lithic assemblages in various ways, as noted by Binford (1980, 1981), Kuhn (1991, 1994, 1995), and others. In this study, we use Barton and colleagues' (Barton 1998; Riel-Salvatore and Barton 2004; Miller and Barton 2008; Barton et al. 2011) approach of "whole assemblage behavioral indicators" (WABI) to identify the predominant mobility strategy in each

AH (while keeping in mind that each AH is a time-averaged palimpsest). Following Kuhn (1995), *individual provisioning*, which tends to occur when subsequent toolstone reprovisioning events are uncertain, involves carrying sufficient lithic resources with the group. *Place provisioning*, which is associated with predictable reprovisioning and low mobility, involves stockpiling toolstone at camp sites for later visits. Lastly, following Binford (1979), the procurement of toolstone can be *direct*, involving special-purpose trips to sources, or *embedded*, which occurs within the contexts of subsistence or other activities. This terminology differs from that of Close (2000), who uses "direct" to refer to procurement conducted by the same group of people who produce the tools (in contrast to "indirect" procurement, which, to her, denotes exchange).

The geographic variables for this particular study involve territory size, territory spacing, and the abundance of toolstone sources distributed over the landscape. Two of the principal abstractions in our model are circular territories (the size of which is defined by a user-specified radius) and a constant rate of movement between camps. Such abstractions are common when simulating the movements of hunter-gatherers (e.g., Brantingham 2003, 2006; Perreault and Brantingham 2011). The areas over which foraging groups move are, of course, never so simple. Indeed, this abstraction is evocative of an old joke among physicists of "spherical cows" (Harte 1988) or "spherical chickens" (Stellman 1973), acknowledging that models necessarily use simplifications of real-life phenomena that are considerably more complex. Territories within the current version of the model are flat and, other than toolstone sources, featureless. Future versions of the model might include geographic features, such as mountains or bodies of water, in irregular territories; however, such variability was not considered in the first phase of this research. The separation of the circular foraging territories, which can overlap, is also given by a particular value at the beginning of each simulation run. Additionally, the density of toolstone sources in the foraging areas is determined by a value at the start of each simulation. These sources are all equal in knapping quality, much like the excellent obsidian resources that occur throughout Armenia.

Finally, we considered two variables in lithic use and discard: (1) the maximum number of lithic artifacts that foraging groups can carry ("lithic stock") and (2) the maximum amount of utility that can be extracted from these artifacts via the tasks carried out at a camp ("use intensity"). Both of these variables have been proposed as important factors in the final composition of hunter-gatherers' lithic assemblages. For example, ABM simulations of Barton and Riel-Salvatore (2014) found that use intensity had a strong correlation to the abundance of retouched tools within a particular assemblage. Our modifications to this ABM allowed us to investigate if and how these variables propagate through and shape the frequency of encounters between two different foraging groups moving across the landscape.

Our simulations show that the relationships between mobility strategy and interactions are not linear and depend on variables such as territory spacing and procurement strategy. It is not as simple as logistical mobility yielding more or fewer opportunities for interaction between different foraging groups than residential mobility. Under many circumstances, a residential-to-logistical shift tends to have only a rather small effect. Additionally, territory size—that is, foraging distance—is not a simple, independent variable when it comes to opportunities

for inter-group contacts. Furthermore, certain variables (i.e., lithic stock size, use intensity, provisioning strategy) have no effect, and other variables (i.e., decreased source abundance on the landscape, a shift from embedded to direct procurement) appear inconsistent with the archaeological data. Territory spacing, in contrast, has a clear, predictable, and nonlinear effect—a small decrease in separation can yield large increases in contact opportunities, consistent with the findings of earlier simulation-based studies (Perreault and Brantingham 2011). Several researchers have previously hypothesized that the Southern Caucasus served as a refugium during glacial conditions (Bar-Yosef 1994; Dennell et al. 2011; Finlayson 2004). If foragers preferentially moved into more mild environments at this time, such a phenomenon could account for smaller territory separations during the deposition of AH III: increasing population densities would be anticipated in more stable environments as the global climate cooled. Therefore, these archaeological data and computer simulations point toward greater inter-group interactions during AH III as a probable outcome of closely spaced foraging groups.

Background: Aghitu-3 Cave

The sections that follow briefly summarize the site's stratigraphy, chronology, lithic technology, material culture, subsistence evidence, and environmental indicators, which are fully documented by Kandel et al. (2017) for readers seeking additional details regarding these topics.

Stratigraphy and Dating

Excavated by the Tübingen–Armenian Paleolithic Project (TAPP) from 2009 to 2016, this cave (39.5138° N, 46.0822° E, 1601 m asl) lies 115 m above the Vorotan River. It is the largest (11 m deep, 18 m wide, 6 m high) of several caves along the base of a basalt massif just south of Aghitu village (Fig. 1). Lithic artifacts > 20 mm were spatially recorded using a total station, whereas smaller artifacts were recovered from dry-screened sediments. By 2016, excavations had expanded to 40 m² inside the cave and reached a depth of 5.5 m, where archaeologically sterile sediments were encountered. A series of 33 ^{14}C dates (12 bones and 21 charcoal) constitute the cave's chronological framework. Seven stratified AHs are detailed by Kandel et al. (2017), so the descriptions here are abridged. The unconsolidated silt of AH I contains recent debris, Bronze Age to Medieval pottery, and rare UP artifacts, and AH II contains the same artifact types but with lower abundances. AH III (29–24,000 cal BP) has the first unambiguous evidence of UP occupation: copious lithics ($n = 4452$), fauna, and charcoal in addition to intact combustion features. AHs IV and V (32–29,000 cal BP) yielded few artifacts ($n = 5$ and 13 lithics, respectively), attesting to the existence, albeit sparse, of human occupation. AH VI (36–32,000 cal BP) contains concentrations of lithic artifacts ($n = 355$), fauna, and charcoal scattered around small hearth features, and AH VII (39–36,000 cal BP) yielded scattered finds (155 lithics) without intact hearths. Thus, the A3C preserves human behaviors dating back 39,000 years and lasting for the next 15,000 years into the LGM.

Fig. 1 A3C at the base of a basalt massif (photograph by A. Kandel)

Lithic Technology Overview

Attribute analysis of 4980 lithic artifacts (> 5 mm) establishes a focus on unidirectional reduction of small cores to produce backed and laterally retouched bladelets (defined as < 10 mm wide). Given that AH III represents 89% of the analyzed lithics, this stratum is numerically dominant in the brief overview here. Overall, both the number of cores (2%) and the amount of angular debris (3%) are small. The remaining pieces, in this classification system, are first considered to be "debitage" and then are classified into the categories of "flake" or "laminar." Laminar pieces are parallel-sided, at least twice as long as wide, and subdivided into blades (≥ 10 mm wide) and bladelets (< 10 mm wide). The debitage is then sub-classified either as a "tool" when it is retouched or as a "blank" when it lacks retouch. That is, an unretouched bladelet is considered a blank, whereas a retouched flake is considered a tool. Overall, the assemblage consists of 17% tools, but this proportion varies, for example, between 9% in AH VII and 21% in AV VI (Table 1). Laminar blanks compose half of the assemblage, about three-quarters of which are bladelets. These blanks were primarily selected for retouched tools, which are also primarily bladelets. Two types—laterally retouched bladelets and backed bladelets—compose 92% of the bladelet toolkit. It is possible that these bladelets reflect a continuum of retouch rather than two discrete types. Complete bladelets decreased in length over time: AH VII (33.1 ± 18.8 mm, $n = 31$), AH VI (29.6 ± 9.8 mm, $n = 83$), and AH III (25.7 ± 11.7 mm, $n = 700$). The decrease between AHs VII and VI is insignificant (Student's t test, $p = 0.1981$), but that between AHs VI and III is statistically significant ($p = 0.0036$). The bladelets slightly decreased in width between AH VII (7.8 ± 4.7 mm, $n = 31$) and AH VI (7.0 ± 2.9 mm, $n = 83$) before increasing in AH III (9.0 ± 4.4 mm, $n = 700$), yielding a net difference that is not significant ($p = 0.1389$). Other tools include burins, scrapers, and denticulated pieces

Table 1 Breakdown of recovered and sourced obsidian artifacts by lithic category

| | AH III | | | | AH IV | | | | AH V | | | | AH VI | | | | AH VII | | | |
| | Recovered | | Sourced | | Recovered | | Sourced | | Recovered | | Sourced | | Recovered | | Sourced | | Recovered | | Sourced | |
	n	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*
Blanks	3454	78%	666	79%	2	40%	2	40%	9	69%	9	90%	259	73%	150	90%	134	86%	96	97%
Tools	745	17%	158	19%	3	60%	3	60%	4	31%	1	10%	76	21%	11	7%	14	9%	3	3%
Cores	110	2%	13	2%									3	1%			4	3%		
Debris	143	3%	3	0.4%									17	5%	5	3%	3	2%		
Total	*4452*	*100%*	*840*	*100%*	*5*	*100%*	*5*	*100%*	*13*	*100%*	*10*	*100%*	*355*	*100%*	*166*	*100%*	*155*	*100%*	*99*	*100%*

The total numbers across lithic types are italicized

but in much lower frequencies. Technical pieces (e.g., crested blades and bladelets, core tablets) reveal that cores were shaped and rejuvenated during onsite manufacture of bladelets.

Lithic Raw Materials

The overall lithic assemblage is principally obsidian (84%, $n = 4211$) with lesser amounts of chert (15%, $n = 751$), dacite (0.4%, $n = 16$), and basalt (0.05%, $n = 2$). The proportions vary by stratum (Table 2), varying from 96% ($n = 149$) in AH VII to 69% ($n = 246$) in AH VI. The cherts include shades of brown, white, yellow, gray, red, and pink. Geological maps suggest that the nearest chert sources lie near the village of Brnakot (9 km west) and near the town of Goris (22 km east). Our field surveys found the Brnakot chert to be low quality and quite different than the A3C artifacts, and no chert nodules were identified in gravel deposits along the Vorotan. Surveys of the Syunik volcanic complexes, which include the closest obsidian sources, revealed large blocks of readily accessible obsidian at outcrops and on the slopes below them. In addition, large, water-worn obsidian cobbles (10–25 cm) are abundant along small tributaries surrounding these sources. Only occasional small obsidian cobbles (3–5 cm) were found within the Vorotan river valley near the cave, suggesting that acquisition of larger pieces, at least, occurred closer to the sources.

Bone Tools and Shell Beads

Three bone tools were recovered at A3C in AH III: a thin needle with a broken eye and a blunt tip, a sharp and polished point, and a polished awl with incomplete ends. We postulate that these tools are related to clothing production. Furthermore, eight small perforated shells (5–6 mm in diameter) were found in AH III. These shells belong to *Theodoxus pallasi*. Traces of ochre were noted on two shells, one of which exhibits striations indicative of being strung. We interpret these pigmented and strung shells as evidence of clothing adornments, necklaces, or the like during the deposition of AH III.

Subsistence Evidence

The Vorotan valley channels humans and their prey between the Zangezur and Syunik mountain ranges, creating a natural corridor. Therefore, A3C is well placed for seasonal hunting. Almost two-thirds of the large mammalian remains could be identified to at least the genus level. These remains primarily come from AH III (76%, NISP = 1749)

Table 2 Lithic raw materials present in each archeological horizon at A3C

Material	AH III		AH IV		AH V		AH VI		AH VII	
	n	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*
Obsidian	3799	85.3%	5	100%	12	92.3%	246	69.3%	149	96.1%
Chert	637	14.3%			1	7.7%	109	30.7%	4	2.6%
Other	16	0.4%							2	1.3%

and AH VI (17%, NISP = 398). Three taxa account for ∼90% of the fauna in these layers: sheep (*Ovis* sp.), goat (*Capra* sp.), and equids (*Equus* sp.). Sheep and goat drop from 83% (NISP = 195, MNI = 10) in AH VI to 54% (NISP = 628, MNI = 6) in AH III, whereas equids rise from 6% (NISP = 13, MNI = 1) to 37% (NISP = 427, MNI = 3). In contrast, hares are present at only 3% overall. Hence, mid-sized animals (size classes 2 and 3) were consistently important at A3C. Faunal preservation is best in AH III, allowing anthropogenic modifications (e.g., cuts, spiral breaks, burning) to be noted on 132 bones, outnumbering bones with carnivore damage (*n* = 24). Riverine brown trout (*Salmo* sp.) remains, primarily vertebrae, were found in AH III and suggest body sizes (up to 30–40 cm in length). These fish vertebrae appear indicative of a more diverse diet during this time, but the bones exhibit no clear traces of either cutting or burning.

Local Environmental Indicators

The A3C deposits contain environmental proxies that allow local conditions to be tied to global climatic changes. Warm, moist conditions prevailed during AHs VII and VI (39–32 ka), leading to a cooling trend through AH III (29–24 ka). Only AH VI yielded a sizable palynological sample, revealing deciduous forest, steppic, and herbaceous vegetation that is typical of a temperate and fairly humid biome. The qualitative palynological data from AHs V and IV support a cooling trend. In AHs VII and VI, the avian assemblages are indicative of a temperate, largely open environment with nearby river vegetation. Unfortunately, avian remains are rare in AH V to III, providing no clear ecological signals for those strata.

The microfaunal remains provide the most continuous environmental dataset available for A3C. The three most abundant taxa occur throughout the sequence: the field vole (*Microtus* spp.), Brandt's hamster (*Mesocricetus brandti*), and Afghan pika (*Ochotona rufescens*). Pikas are of interest given that they prefer cool, alpine habitats and that North American pika (*Ochotona princeps*) populations are in decline due to global warming (Galbreath et al. 2009). At A3C, the ratio of pikas to hamsters increases from AH VII to III, indicating a cooling trend. Pika is most abundant in AH III, when the micromammalian assemblage is consistent with a modern elevation > 2000 m, more than 400 m above the cave's location. In addition, the Transcaucasian mole vole (*Ellobius lutescens*) only occurs within AH VII, attesting to near-modern climatic conditions during that layer's deposition (circa 39–36,000 cal BP).

Global Climatic Proxies

Certain climatic changes are tied to atmospheric conditions (e.g., volcanic winters due to ash and other aerosols; warming due to greenhouse gases), but glacial and interglacial periods in the Pleistocene were orbital-forced climate shifts (Hays et al. 1976; Berger and Loutre 1991, 1999). Called Milankovitch cycles, the changes were due to Earth's orbital variations (i.e., precession, obliquity, eccentricity), which, in turn, altered the intensity of *in*coming *sol*ar radi*ation* (*insolation* for short). Figure 2 shows (a) July insolation values at 40° N (calculated from Berger and Loutre 1991, 1999) with (b) reconstructed changes in global average surface temperature (Snyder 2016) as well as (c) CO_2 and (d) δD data from Antarctic ice cores (Indermühle et al. 2000; EPICA 2004). The curves differ somewhat because
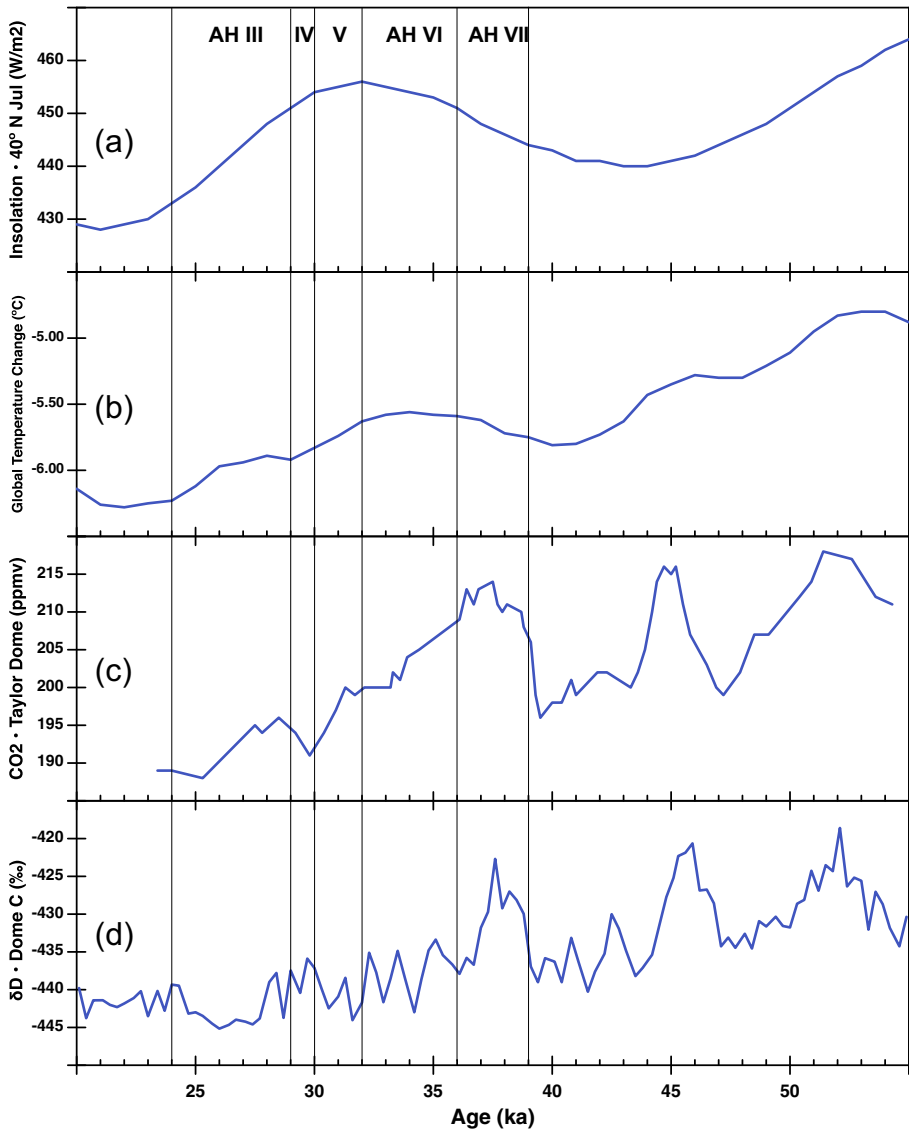
Fig. 2 Global climatic proxies circa 55–20 ka. **a** Insolation values (W/m²) for July at 40° N calculated from Berger and Loutre (1991, 1999). **b** Reconstructed change in global average surface temperature (GAST) in degrees Celsius, as calculated by Snyder (2016). **c** CO_2 concentrations (ppmv) from the Taylor Dome core, Antarctica, reported by Indermühle et al. (2000). **d** Deuterium–hydrogen ratios, δD (‰), in the Dome C ice core, Antarctica, reported by EPICA (2004). The approximate intervals of the A3C AHs III to VIII are labeled

insolation does not reflect the amount of glacial ice, as, for example, oxygen isotopes do. As illustrated in Fig. 2a, insolation remained fairly constant from the start of AH VI at 36 ka to the end of AH IV at 29 ka, but by the end of AH III at 24 ka, insolation had dropped 5%. Such orbital forcing is the principal mechanism

by which the region around A3C had nearly modern conditions during the deposition of AHs VII and VI and cooler conditions during the deposition of AH III, concurrent with the onset of the LGM.

Lithic Indicators of Mobility and Provisioning

We examined three indicators of mobility and provisioning in the A3C lithic assemblage: (1) the geographic origins of 1120 obsidian artifacts, as determined by chemical analysis; (2) the amount of cortex on the obsidian artifacts; and (3) the frequency of retouched tools relative to the artifact volumetric density. The third indicator recognizes that retouched tools are frequently components of a transported toolkit, so assemblages produced by highly mobile groups tend to have a higher proportion of retouched tools than those made by less mobile groups who remain longer at a given camp.

Indicator No. 1: Obsidian Sourcing

We used portable X-ray fluorescence (pXRF) to chemically identify the volcanic origins of almost a quarter of the obsidian artifacts ($n = 1120$). Our pXRF analyses followed procedures detailed in Frahm and Hauck (2017). Most of these analyses (93.2%, $n = 1044$) were conducted in Armenia in 2013 and 2015, and the attributions to particular volcanic sources rely on ratios among the so-called mid-Z elements (e.g., Nb, Rb, Sr, Zr), which are well measured using pXRF even for small or irregular artifacts (Frahm 2016). Figure 3 plots the data using discriminant functions in order to illustrate how multi-elemental measurements can be reduced to
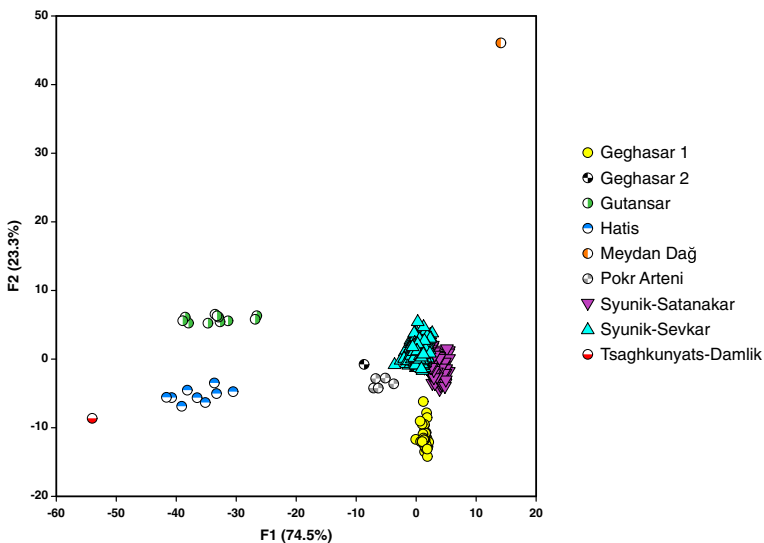

Fig. 3 Multivariate analysis of obsidian artifacts' trace-element concentrations reveals their different volcanic sources across Armenia and into eastern Turkey (i.e., Meydan Dağ)

two dimensions. We also conducted pilot sourcing analyses ($n = 76$) in 2012. For these data, we used different elements (i.e., Fe and Mn) for the source assignments because fingernail polish over the artifacts' labels contained enough Nb and Zr to interfere with their measurement. Just three artifacts from 2012 could not be matched to sources due to this interference. Relevant elemental data and their ratios for the artifacts and their sources are included in the supplementary materials.

Table 3 summarizes these results by horizon, and Fig. 4 shows the locations of the identified obsidian sources. Nearly all (99%) of the artifacts from AHs VII and VI originated from the two major Syunik obsidian sources: Sevkar and Satanakar (~30–40 km NW). In these two strata, just three artifacts were matched to sources located ~110–150 km NW: Geghasar, Gutansar, and Hatis. All artifacts in AHs V and IV originated from Sevkar, but lithic artifacts are sparse within these two layers. In AH III, the Syunik sources are still the most common at 92%; however, seven additional sources occur. Five of the sources are distant (110–180 km): Geghasar 1 and 2, Gutansar, Hatis, and Damlik in the Tsaghkunyats mountains. The remaining two are long-distance obsidian sources: Pokr Arteni (220 km linearly, ≥270 km on foot) and Meydan Dağ in eastern Turkey (250 km linearly, ≥270 km on foot). Even accounting for the sample sizes, far-traveled artifacts are rare in AHs VII and VI but occur more often in AH III. Compared to AHs VI and VII, there are statistically significantly more distant and long-distance obsidian artifacts within AH III (Z score = 3.1541 and 2.5294, respectively; $p = 0.00082$ and 0.0057, respectively). Hence, the rise in non-regional sources from 1% in AHs VII and VI to 8% in AH III is a noteworthy trend.

Table 1 shows a breakdown of recovered and sourced artifacts by lithic category (blanks, tools, cores, angular debris) and by horizon. This establishes that our sourced sample reflects the overall lithic assemblage well. In turn, we have confidence in our finding that there is no clear relationship between source and artifact type. For example, tools and cores comprise 18% and 3%, respectively, of distant (100–200 km) and long-distance (>200 km) artifacts, compared to 17% and 2% in the entire assemblage. Table 4 elucidates the types of distant and long-distance obsidian artifacts identified in AH III. Specifically, these far-traveled artifacts include laterally retouched and backed bladelets, two small bidirectional cores, one splintered piece, and a core tablet. Additionally, the size difference is marginal. The maximum dimension of these artifacts is, on average, 20.3 ± 8.9 mm for the regional sources ($n = 771$) and 17.5 ± 6.1 mm for the farther sources ($n = 67$). The size difference ($p = 0.012$) is not statistically different using a strict confidence level ($a = 0.01$), but it is significant using a lesser level ($a = 0.05$). In short, clear-cut relationships appear to be lacking between source-to-site distances and either artifact type, retouch, or size. We interpret these findings as evidence that the A3C occupants did not travel great distances (≥270 km on foot) for the reason of obtaining special obsidians favored for making certain tools. Nor did they traverse these distances so slowly that tools became increasingly retouched to the point that far-traveled ones became considerably smaller. We instead posit that as the A3C occupants acquired obsidian from long-distance sources, they used such far-traveled toolstone in the same ways they used regional obsidians. This leads us to conclude that the long-distance materials were likely obtained via interactions with neighboring groups.

Table 3 Summary of the obsidian sourcing results sorted by the sources' distance from A3C

Range	Volcanic source	Distance	AH III		AH IV		AH V		AH VI		AH VII	
		(km)	n	%	n	%	n	%	n	%	n	%
Regional (<50 km)	Syunik-Sevkar	40	579	69%	5	100%	10	100%	149	90%	74	75%
	Syunik-Satanakar	40	169	20%					10	6%	23	23%
	Syunik-undifferentiated	40	23	3%					4	2%	1	1%
	Total regional		*771*	*92%*	*5*	*100%*	*10*	*100%*	*163*	*98%*	*98*	*99%*
Distant (100–200 km)	Geghasar 1	110	39	4.6%					1	0.6%		
	Geghasar 2	110	1	0.1%								
	Gutansar	150	12	1.4%							1	1.0%
	Hatis	150	8	1.0%					1	0.6%		
	Tsaghkunyats-Damlik	180	1	0.1%								
	Total distance		*61*	*7.3%*					*2*	*1.2%*	*1*	*1.0%*
Long-distance (> 200 km)	Pokr Arteni	220	5	0.6%								
	Meydan Dağ	250	1	0.1%								
	Total long-distance		*6*	*0.7%*								
Unidentified			2	0.2%					1	0.6%		
Total			*840*	*75.0%*	*5*	*0.4%*	*10*	*0.9%*	*166*	*14.8%*	*99*	*8.8%*

The total numbers across sources are italicized
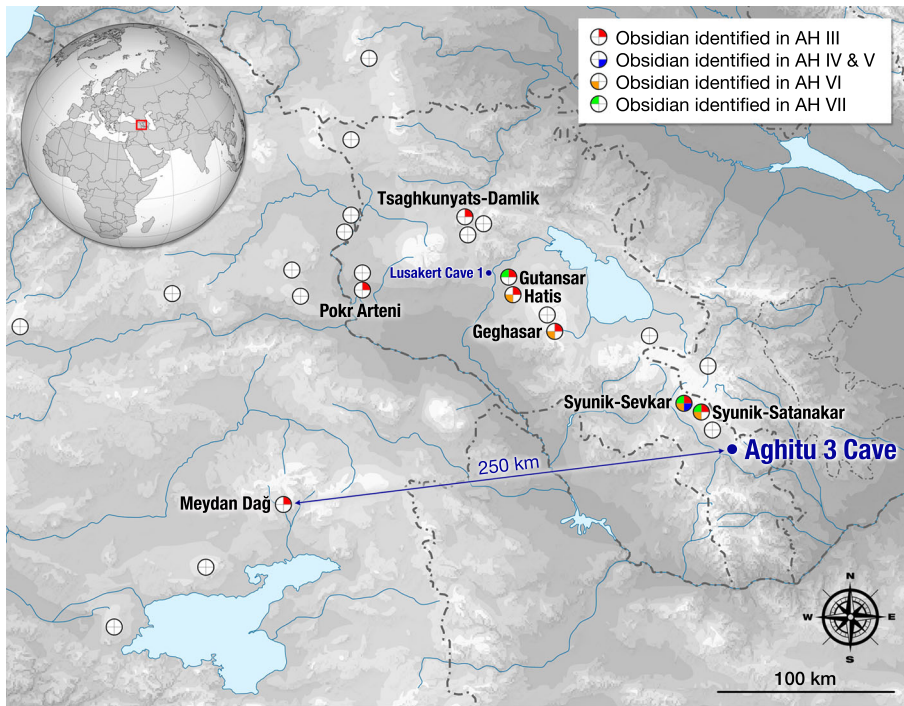
Fig. 4 Locations of obsidian sources relative to A3C (digital elevation data from SRTM3). The presence or absence of these obsidians at A3C is represented by each source's circular symbol. The empty circles correspond to obsidian sources that are not reflected in the A3C assemblage

Indicator No. 2: Cortex and Fracture Planes

The amount of remaining cortex in chert-based lithic assemblages has frequently been used as a proxy for the degree of its reduction (Andrefsky Jr. 1998); however, as pointed out by Dibble et al. (2005), the amount of cortex is also affected by the material itself. When an obsidian flow is exposed at the surface, it typically occurs as angular blocks, perhaps weathered but without chert-like cortex, due to fractures along natural

Table 4 Breakdown of distant and long-distance obsidian artifacts from AH III by lithic category

Lithic category	Distant obsidian sources								Long-distance sources			
	Geghasar		Gutansar		Hatis		Damlik		Meydan Dağ		Pokr Arteni	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Blanks (unretouched)	35	85%	8	67%	6	75%			1	100%	4	80%
Tools (retouched)	4	10%	4	33%	2	25%	1	100%			1	20%
Cores	2	5%										
Totals	41	100%	12	100%	8	100%	1	100%	1	100%	5	100%

cracks and weak layers (Fig. 5a). Secondary obsidian deposits along streams and rivers, though, can have rounded cobbles fully covered by cortex (Fig. 5b). As mentioned above, our surveys of the Syunik sources found large, cortex-free blocks at the outcrops, whereas cortex-covered cobbles within valleys decrease in size farther from primary outcrops. That is, conventional cortex occurs only on water-worn cobbles in secondary deposits. Consequently, while the abundance of cortex in chert-based assemblages is typically used as a metric for reduction, it can also reflect the frequency of procurement from secondary deposits versus primary outcrops, which can have implications for the transport distance as well.

While the cortex amount on the dorsal surface and the butt of blanks was originally recorded in increments of 10%, here we consolidate these data into classes of 20% (Table 5). We also recorded the natural fracture plane surfaces (Table 6) in the same way. Thus, we have two proxies that, together, can reflect collection from river gravels versus procurement from obsidian outcrops, respectively. Table 7 combines these data. Note that, when cortex and fracture planes are considered together, AHs III and VII exhibit similar values (e.g., 9.6% versus 9.5% with 1–20% coverage). The proportions of cortex and fracture planes, however, change. In AH III, the amount of cortex is high (14.3%), whereas fracture planes are less frequent (3.8%). The opposite pattern occurs in AH VII: fracture planes are more common (15.5%), while the amount of cortex is low (5.4%). Our data have two implications: (1) the degrees of lithic reduction in AHs III and VII are essentially the same when cortex and fracture planes are considered together, and (2) the AH III lithic assemblage reflects a greater degree of procurement from water-worn secondary deposits within gullies and valleys around the volcano,
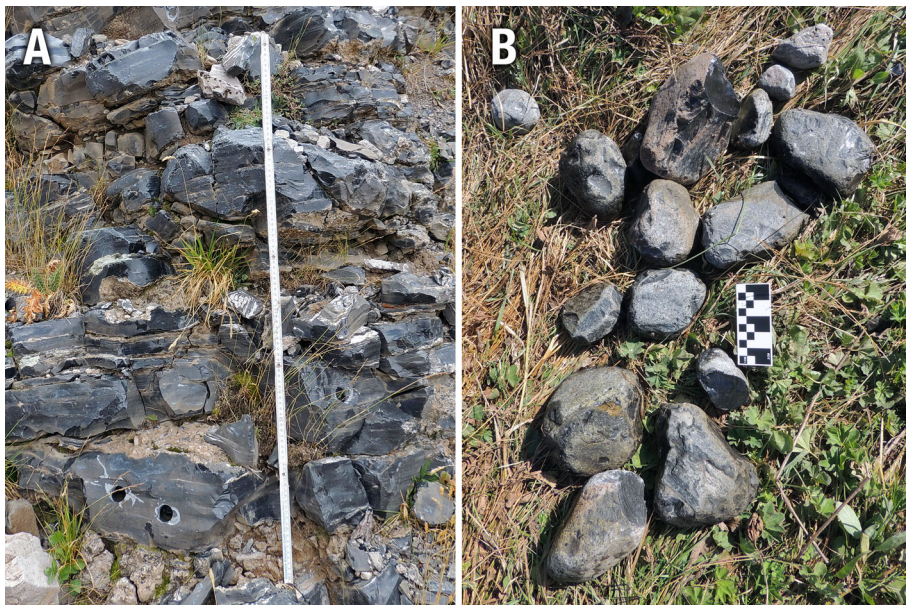

Fig. 5 **a** Example of angular fracture planes that are visible at a primary obsidian outcrop, in this case, the Baznek source within the Syunik region (photograph by A. Kandel). **b** Examples of rounded, cortex-covered river cobbles along a tributary of the Vorotan River near Sevkar and Satanakar (photograph by M.K. Parizi)

Table 5 Cortex on the dorsal surface and butt of blanks

%	AH III			AH IV			AH V			AH VI			AH VII			Total		
	n	*%*		*n*	*%*		*n*	*%*		*n*	*%*		*n*	*%*		*n*	*%*	
0	3598	85.7		4	80		13	100		328	97.9		140	94.6		4083	86.9	
1–20	322	7.7		1	20					6	1.8		2	1.4		331	7.0	
21–40	151	3.6								1	0.3		5	3.4		157	3.3	
41–60	69	1.6															69	1.5	
61–80	26	0.6												1	0.7		27	0.6	
81–100	33	0.8															33	0.7	
Totals	601			1			0			7			8			617		
	14.3%			20%			0%			2.1%			5.4%			13.1%		

Totals represent the numbers of artifacts with cortex and their percent frequency with respect to the layer

whereas the AH VII assemblage reflects a greater degree of procurement from the primary outcrops at the obsidian sources themselves.

Indicator No. 3: Whole Assemblage Behavioral Indicators

Social interactions during the UP were long viewed through a culture-historical lens, shaped by Bordes (1961), whereby the forms of retouched tools, after their discard, are viewed as intentional and culturally transmitted types. This approach was challenged by Dibble (1984), who showed that Middle Palaeolithic (MP) side-scrapers likely exist on a continuum of retouch and reshaping, rather than falling into discrete types. Therefore, instead of reflecting preconceived forms, tools record efforts to extend their use-lives through repeated edge modifications (Barton 1991; Dibble 1995). Equally important is the issue of how mobility can affect lithic technology (Binford 1980; Kelly 1992; Grove 2009).

Table 6 Fracture planes on the dorsal surface and butt of blanks

%	AH III			AH IV			AH V			AH VI			AH VII			Total		
	n	*%*		*n*	*%*		*n*	*%*		*n*	*%*		*n*	*%*		*n*	*%*	
0	4039	96.2		5	100		13	100		325	97.0		125	84.5		4507	95.9	
1–20	80	1.9								4	1.2		12	8.1		96	2.0	
21–40	37	0.9								5	1.5		8	5.4		50	1.1	
41–60	27	0.6								1	0.3		3	2.0		31	0.7	
61–80	7	0.2															7	0.1	
81–100	9	0.2															9	0.2	
Totals	160			0			0			10			23			193		
	3.8%			0%			0%			3.0%			15.5%			4.1%		

Totals represent the numbers of artifacts with fracture plane and their percent frequency with respect to the layer

Table 7 Cortex (Table 5) and fracture planes (Table 6) added together

%	AH III		AH IV		AH V		AH VI		AH VII		Total	
	n	%	n	%	n	%	n	%	n	%	n	%
0	3438	81.9	4	80	13	100	318	94.9	117	79.1	3890	82.8
1–20	402	9.6	1	20			10	3.0	14	9.5	427	9.1
21–40	188	4.5					6	1.8	13	8.8	207	4.4
41–60	96	2.3					1	0.3	3	2.0	100	2.1
61–80	33	0.8							1	0.7	34	0.7
81–100	42	1.0									42	0.9
Totals	761		1		0		17		31		810	
	18.1%		20%		0%		5.1%		20.9%		17.2%	

Totals represent the numbers of artifacts with either cortex or fracture plane and their percent frequency with respect to the layer

To consider these issues, Barton and colleagues (Barton 1998; Riel-Salvatore and Barton 2004; Miller and Barton 2008; Barton et al. 2011; Clark and Barton 2017) devised WABI to link mobility and lithic assemblages. Specifically, this approach uses the frequency of retouched tools in a lithic assemblage to explore how hunter-gatherers structured movements across landscapes to obtain resources. Applying the WABI approach to late MP and early UP sites has yielded compelling results (e.g., Villaverde et al. 1998; Riel-Salvatore and Barton 2007; Barton et al. 2013; Clark and Barton 2017). For example, in Italy, Riel-Salvatore and Barton (2004) identified similar land use patterns in MP Mousterian and UP Protoaurignacian assemblages, despite spanning the MP–UP transition and, in turn, the presumed replacement of Neanderthals by anatomically modern humans. Only the late UP Epigravettian assemblages exhibited a different pattern of land use—logistical, instead of residential, mobility—that Riel-Salvatore and Barton (2004) proposed as a behavioral adaptation to cope with the climatic conditions of the LGM. Similarly, in Spain, Clark and Barton (2017) used WABI to tie diachronic changes (circa 30–10 ka) in the La Riera lithic assemblage to global climatic conditions, testing whether behavioral adaptations were a response to increased cooling leading up to the LGM.

WABI is based on three pieces of information—(1) lithic artifact density and (2) the proportion of retouched artifacts divided by (3) the volume of excavated sediment—that have been demonstrated to correlate with mobility practices. This approach links lithic curation and expediency to mobility strategy, as outlined by Clark and Barton (2017). It should be stressed that there are debates not only whether the terms "curation" and "expediency" can be applied to assemblages as a whole or to particular artifacts or types in assemblages but also whether their associations with mobility strategies are better explained by site use. For our purposes here, these terms are used as postulated in WABI analysis. Consequently, the description of an assemblage as "curated" or "expedient" should be taken as shorthand for a collection of lithic artifacts that contains a higher or lower abundance, respectively, of retouched tools that could be considered curated. A key postulate of WABI states that retouch is intended to prolong

tools' use-lives via edge modification and resharpening (Dibble 1995; Shott 1996; Shott and Sillitoe 2005). The intense reworking of toolstone may, in turn, reflect relative scarcity on the landscape (Sackett 1991). WABI uses the frequency of retouched tools scaled to the abundance of lithic artifacts within an excavated volume of sediment as a proxy for how many—or few—tools in assemblages were curated.

In logistical mobility, base camps can be occupied for weeks to months, and their locations allow for radiating excursions, on the order of a few hours or days, to acquire resources and return with them. This stability lends itself to stockpiling toolstone at a base camp to accommodate demand in the future. Due to a reduced need to economize toolstone, it is expected that logistical base camps exhibit high lithic densities (due to intense occupation) but a low abundance of retouch. With fewer retouched tools than blanks, such lithic assemblages have been labeled as *expedient* (Nelson 1991), and such base camps tend to exhibit greater evidence for stays of longer duration, such as hearths. In contrast, a residentially mobile group, which tends to move between camps on the order of days to weeks, might be far from toolstone sources at many times, increasing the need for portable (i.e., lightweight) and flexible lithic toolkits. The anticipated outcomes, therefore, will be more *curated* artifacts, including a high proportion of retouched tools, and comparatively low lithic densities. Consequently, greater residential mobility is anticipated to (1) correlate with a greater abundance of retouched tools and (2) inversely correlate with lithic volumetric density (i.e., the number of lithic artifacts divided by excavated volume; Riel-Salvatore and Barton 2004). These variables can be plotted to separate degrees of expediency and curation exhibited by tools, which, in turn, can serve as proxies for logistical and residential mobility, respectively.

This basis of WABI has been tested both archaeologically and computationally. Archaeologically, based on New World data, Parry and Kelly (1987) demonstrated that statistically significant correlations occur between the degree of mobility and frequency of retouch, while others have shown a statistically significant inverse correlation between lithic volumetric density and frequency of retouch at Palaeolithic sites throughout Eurasia (Villaverde et al. 1998; Riel-Salvatore and Barton 2004, 2007; Sandgathe 2006; Clark 2008; Riel-Salvatore et al. 2008; Barton et al. 2013). Computationally, Barton and Riel-Salvatore (2013) used ABMs to establish that, despite variation in mobility and provisioning strategies, all of their simulated lithic assemblages exhibited the same inverse correlation between the volumetric density and retouch frequency. Thus, there is broad support—from both archaeological and computational evidence—for the relationships on which Barton and colleagues' WABI approach is predicated.

Such studies have, so far, been largely restricted to UP sites in Western Europe (e.g., Villaverde et al. 1998; Riel-Salvatore and Barton 2007; Barton et al. 2013; Clark and Barton 2017), especially the Italian and Iberian Peninsulas, where lithic assemblages are dominated by fine-grained toolstone such as chert, quartzite, or even limestone. Identifying the geological origins of such materials has been predicated on macroscopic, often subjective determinations (Mellars 1996 and references within). Armenia, though, is one of the world's most obsidian-rich landscapes, where lithic assemblages are predominantly obsidian and, thus, can be reliably matched to chemically distinct volcanic sources. Therefore, it is a rare landscape where we can couple (1) obsidian sourcing of UP assemblages to (2) WABI analysis as a means to better understand changes in mobility and land use.

Table 8 lists the values used in our WABI analysis for A3C, and Fig. 6 shows the pattern of the results. There is a gradual trend from greater expediency to greater curation over time from AHs VII to IV, followed by a strong shift back to expediency for AH III. By extension, AHs VII and III correspond to greater logistical mobility. AH IV would correspond to greater residential mobility; however, it is not clear if this result is meaningful or simply a spurious by-product of so few finds within that layer. AHs VI and V fall roughly halfway between and, in turn, exhibit less expediency than AHs VII and III.

These interpretations are consistent with other archaeological indicators at A3C, especially the occurrence of hearths. Combustion features were found only in AHs III and VI, including heat-reddened substrates overlain by ash and charcoal. AH VI had concentrations of lithics, fauna, and charcoal clustered about small, isolated fireplaces, whereas AH III contained abundant, more complex hearths (Fig. 7).

Summary of Lithic Indicators

The AH III lithic assemblage includes artifacts from long-distance sources—Pokr Arteni (≥ 270 km on foot to the northwest) and Meydan Dağ (≥ 270 km on foot to the west-southwest)—as well as artifacts from five distant sources. Taken together, non-regional artifacts comprise 8% of the AH III obsidian, compared to 1–1.2% in AHs VII and VI, differences that are statistically significant. Only one of the regional Syunik sources—Sevkar—accounts for all of the obsidian in AHs IV and V (although there are relatively few artifacts in these two layers). It is possible that the five distant obsidian sources—all 110–180 km from A3C and in approximately the same direction (i.e., to the northwest)—reflect greater distances traveled by the cave's occupants. Obsidian from Pokr Arteni and Meydan Dağ, however, was transported over distances more consistent with Gamble's (1996) social landscape rather than local movements. We interpret our results as evidence that, during the deposition of AH III, the A3C occupants not only more often traveled farther distances but also more frequently encountered neighboring groups.

WABI analysis indicates a trend from more expediency to more curation between the deposition of AHs VII and IV. AHs IV and V fit the expectations for very sporadic visits, including a very low density of lithics coupled with a very high frequency of retouch. This was followed by a substantial shift during the deposition of AH III. The WABI values of AH III arguably correspond to a shift back to greater expediency and logistical mobility. One, though, could also interpret this horizon as exhibiting a much greater lithic density than any

Table 8 Values used in our calculations for WABI analysis of the A3C lithics

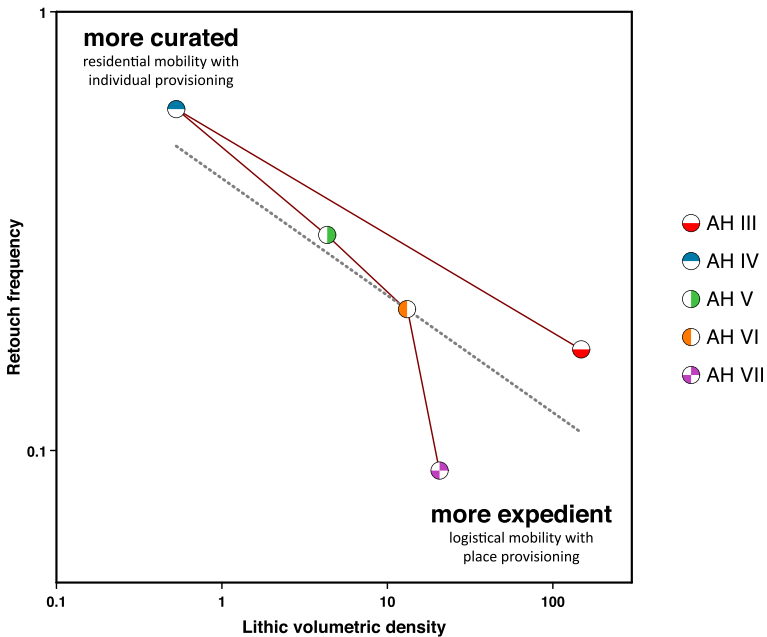|	AH III	AH IV	AH V	AH VI	AH VII
Mean thickness (m)	0.75	0.78	0.25	2.25	1.25
Excavated area (m²)	40	12	12	12	6
Excavated volume (m³)	30.0	9.4	3.0	27.0	7.5
Total lithics (n)	4452	5	13	355	155
Retouched lithics (tools)	745	3	4	76	14
Lithic volumetric density (n/m³)	148.4	0.5	4.3	13.1	20.7
Retouch frequency (tools/n)	0.17	0.60	0.31	0.21	0.09

Fig. 6 Following Clark and Barton (2017: Fig. 1 and Table 1), lithic volumetric density (logarithmic scale) versus frequency of retouched artifacts (on a logarithmic scale) for the A3C AHs. Curation (and, in turn, residential mobility with individual provisioning) falls in the upper left of the graph, while expediency (and, correspondingly, logistical mobility with place provisioning) falls in the lower right. The dashed line reflects the best fit for the dataset

earlier horizon (more than an order of magnitude) and a moderately low frequently of retouch (between those of AHs VII and VI). Consequently, the results of our WABI analysis may also point AH III exhibiting behavioral differences relative to the other four horizons.

In addition, while the degrees of lithic reduction in AHs III and VII are essentially the same, the AH III assemblage reflects greater procurement from secondary deposits, while the AH VII assemblage reflects greater procurement from primary outcrops at the obsidian sources themselves. AH VI begins a trend of fewer exterior cobble or block surfaces, consistent with an increased degree of reduction. It has been hypothesized that, within regions with cortex-bearing chert cobbles, direct procurement will increase the abundance of cortex (Hess 1997; Andrefsky Jr. 1998; Arakawa 2006). However, at Lusakert Cave 1 (Fig. 4), a MP site along the Hrazdan River in Armenia, embedded procurement took the form of collecting obsidian readily available in the river valley, rather than from primary outcrops higher up the slopes of Gutansar volcano (Frahm et al. 2016). Consequently, a greater amount of cortex on obsidian can instead reflect a higher degree of embedded procurement in a volcanic landscape such as this.

Expectations from Climatic Indicators

This increase in obsidian artifacts from distant sources in AH III is consistent with an increase in forager movement distances expected from the ethnographic findings of Kelly

Fig. 7 A photograph of complex combustion features observed in AH III. Multiple occupation horizons containing charcoal, ash, and rubified soil are interbedded between layers of compact yellow-brown silt. This particular section was collected as block sample no. 11-03 for micromorphological studies (photograph by A. Kandel)

(1983). In particular, he observed an inverse correlation between (1) the mean distance per move by hunter-gatherer groups and (2) the effective temperature (ET) in degrees Celsius, which is defined as:

$$ET = (18 \, MWM - 10 \, MCM)/(MWM - MCM + 8)$$

where MWM is the mean temperature of the warmest month and MCM is the mean temperature of the coldest month. That is, foragers in colder climates need to travel farther to sustain themselves. Only a few groups were exceptions to the trend, namely hunters who used horses and coastal forager-fishers under extreme territorial constraints. Kelly (1983) reported this inverse relationship to be linear, but a natural log curve yields a slightly better fit to the ethnographic data ($R^2 = 0.95$ instead of 0.92).

ET, of course, is easier to calculate for foraging populations today than for specific periods of the Late Pleistocene. It is simpler to adopt boundary conditions. We can consider somewhat high and low ET values with the understanding that the real ones likely fell somewhere between. In the warmest phases, the ET at A3C might have been similar to that of modern conditions. We calculate the recent ET for the nearby town of Sisian to be 12.3 °C. In the coldest times of the LGM, the ET would be unlikely to surpass historical arctic values of 8 °C. According to the correlation observed by Kelly (1983), such ETs correspond to distances of approximately 55 and 88 km, respectively—an increase of about 60%. These ET values are, however, extremes, while these distances are generalizations predicated on ethnographic data involving hunter-gatherers during recent times. Consequently, these distances should not be taken as actual values. Instead, the overall result—an increase in foraging movement distances resulting from lower food availability—is the "take away" message from this line of investigation.

Kelly ([1983](#)) also noted an exponential correlation ($R^2 = 0.93$) between (1) the number of annual *residential* moves by tropical foragers and (2) the available biomass on the landscape. That is, residential mobility decreased as the availability of food decreased. As shown in Fig. [2](#)a, insolation—and, in turn, the amount of solar radiation available for photosynthesis—increases from AH VII to VI, starts to decline in AH V, and continues to decrease from AH IV to III. Given that Kelly's relationship is nonlinear and derived from recent hunter-gatherers in tropical settings, the exact values are inconsequential. Instead, the relationship is most relevant to the issue at hand: residential mobility decreases with the available biomass. Therefore, consistent with the WABI lithic evidence for A3C, it is anticipated that the transition to the cooler and drier AH III phase was accompanied by greater logistical mobility.

Agent-Based Modeling of Hunter-Gatherers

The best known examples of ABM among archaeologists vary in both complexity and specificity from the Sugarscape model (Epstein and Axtell [1996](#)), in which bacteria-like agents move across an abstract grid in which the cells (or "patches") contain different quantities of sugar, to the Artificial Anasazi (Dean et al. [1999](#)), which simulated the population dynamics of Anasazi farming households in the Long House Valley of Arizona. Our use of ABM to better understand the A3C material culture in terms of UP mobility was principally inspired by the studies of Premo ([2012](#), [2015](#)), Tostevin and Premo ([2015](#)), and Barton and Riel-Salvatore ([2013](#), [2014](#)), whose ABM served as the basis for our model here.

Premo ([2012](#)) used ABM to test a claim from Barton et al. ([2011](#)) that a shift from residential to logistical mobility increases opportunities for interactions between different foraging groups. His model ultimately suggested that the "shift to a predominantly logistical mobility strategy can inhibit rather than enhance forager interaction" across the landscape (647). He notes that there are different ways in which to conceptualize "interaction" and explains that, in his model, it is defined as "any instance in which two residential camps are located within distance of one another at the same time" (648). In contrast, in our ABM simulations, we define the *opportunities* for interaction as occurring whenever the two groups are within a particular distance of one another, even if they are moving between camp sites at the time. It is also worth mentioning that Premo's ([2012](#)) ABM is more spatially abstract than ours. Specifically, Premo ([2012](#)) used a square lattice that is mapped onto a torus, so that an agent which leaves the right edge of the lattice re-emerges on the left edge. Two agents were randomly positioned on the lattice and allowed to freely place their base camp sites, from which they foraged for resources. Movements of these base camps, which occur only after resources in a given foraging radius were exhausted, take a single time step, making it essentially an instantaneous jump from one base site to another.

Subsequently, Premo ([2015](#)) extended this work to address the issue of cultural diversity within populations that are subdivided due to distance. Specifically, he employed ABM as a means to simulate diversity and differentiation in a selectively neutral cultural characteristic—in a computer simulation, this can simply be a numerical value or a trait such as color (e.g., blue or green). He concluded that, because a focus on logistical, rather than residential, mobility tends to decrease interactions

between groups and, thus, the potential for cultural differentiation. Tostevin and Premo (2015) bring the concept of taskscape visibility (Tostevin 2013) to transmission of these cultural characteristics between two foraging groups. When the characteristics have different locations from which they can be transmitted (i.e., a residential base camp), mobility strategy has an important effect. Their ABM showed that a trait transmitted only from residential bases exhibited higher diversity than one that can be transmitted from either residential bases or logistical camps. The transmission of cultural characteristics was not part of our current model, but it is a logical progression to incorporate such characteristics in future versions of our simulations as we continue to move forward with this line of investigation.

Barton and Riel-Salvatore (2014) used ABM with a different aim: investigating the processes that affect the composition of palimpsest lithic assemblages in the archaeological record. Their model placed a single agent, conceptualized as an individual foraging group, with a circular territory with a radius of 30 patches. A focus of their simulations was identifying key factors in the frequency of retouched artifacts. They found, for example, that greater access to toolstone decreases the frequency of retouched artifacts and that tasks involving greater lithic use intensities yield assemblages with more retouch. The choice of mobility strategy alone had little effect. In contrast, mobility coupled with provisioning—either logistical mobility with place provisioning or residential mobility with individual provisioning—had a considerable effect, consistent with empirical studies. Furthermore, their ABM simulations supported the underlying foundations of WABI analysis: the relationship between lithic retouch frequency and excavated artifact density can serve as a robust proxy for forager land use, as discussed above.

All of the above models—including ours—use the free, open-source NetLogo software package (Wilensky 1999). NetLogo is both a programming language, specifically a dialect of Logo, and a simulation environment (Wilensky 1999). It is commonly employed in the social and biological sciences as a means to investigate emergent phenomena produced by behaviors of individual agents. NetLogo was created by Uri Wilensky in 1999 at the Center for Connected Learning and Computer-Based Modeling (then at Tufts University and now at Northwestern University), and it has since been downloaded and used by thousands of students, scholars, and researchers.

Because we built our ABM on the code of Barton and Riel-Salvatore (2014), our model includes the same abstractions. For example, the cells that compose the agents' territories are simply "patches"—they do not represent a particular unit of measure, such as kilometers. Similarly, time passes as "ticks"—each computational cycle is not meant to reflect an hour, a day, or any other unit of time. Additionally, each agent represents a foraging group as a whole. Individuals within a particular foraging group are not modeled one by one. Consequently, while real hunter-gatherers are born, live, die, and so on, agents in our model do not, because they reflect the group as a whole. Readers interested in the reasoning behind these and other choices—as well as intricacies of the corresponding NetLogo code—are referred to Barton and Riel-Salvatore (2014, pp. 336−338), in particular their *Model Description* section.

Figure 8 is a screen capture of our ABM after running in NetLogo. There are differences from that of Barton and Riel-Salvatore (2013, 2014) worth noting. First, the landscape is no longer modeled onto a torus. Thus, an agent can no longer take a shortcut across its foraging territory by crossing over an edge and reappearing on the
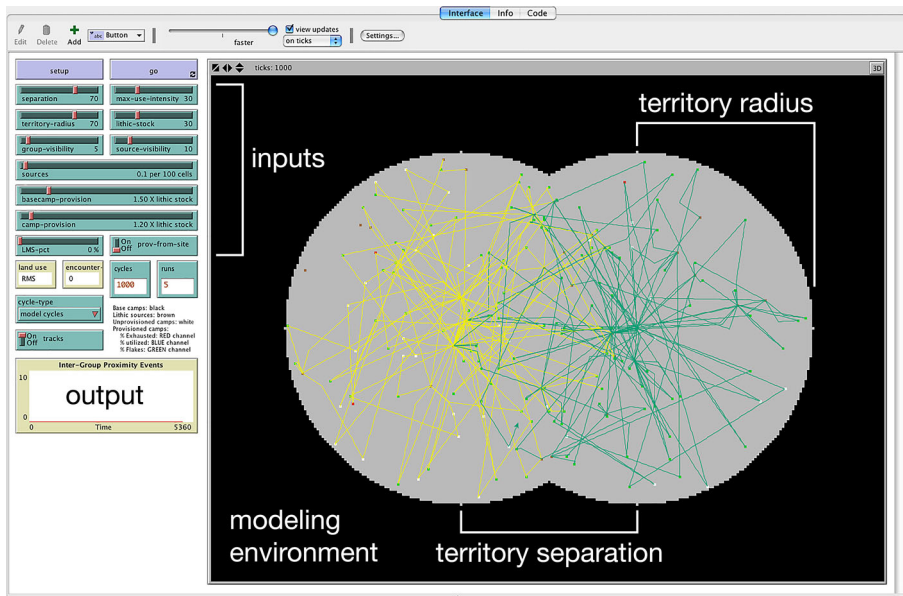
Fig. 8 Annotated screen capture of NetLogo (v. 5.3.1) running our agent-based model of two foraging groups moving through their circular territories to camps and toolstone sources

opposite side. Second, although Barton and Riel-Salvatore (2014) simulated one foraging agent, their model contained the code needed to distribute additional agents randomly across the landscape and ascribe each of them a circular territory for their camp sites. We modified the code to simulate two agents with territories separated by a user-set value, measured from center to center, that we varied from 30 to 90 patches. Additionally, while Barton and Riel-Salvatore (2014) simulated a single territory radius (30 patches), we varied the radii between 30 and 90 patches in increments of 10. Third, the output was counts of interaction opportunities during each simulation run. As mentioned above, an opportunity to interact was defined as the two agents within a user-set distance as they moved over the landscape. For our simulations here, the agents were only visible to one another within five patches, which is a shorter visibility distance than that for toolstone sources (10–50 patches). The behaviors of agents (e.g., how they practice logistical or residential mobility, how many stone tools they can carry with them) function precisely as documented by Barton and Riel-Salvatore (2014, pp. 336−338).

Hypotheses to Test via ABM

One key advantage of ABM is its potential to investigate the importance of individual variables on the opportunities for inter-group contacts. These models, which represent simplifications of the real world, allow us to test a range of behavioral (e.g., provisioning and mobility strategies) and spatial variables (e.g., territory radius and separation) and compare the magnitudes of their effects.

Hypothesis No. 1: Behavioral Differences Affect Contact Frequency

Differences in how foraging groups structured their movements across the landscape in order to obtain resources (i.e., residential versus logistical mobility, embedded versus direct procurement) and how they planned for shortfalls (i.e., place versus individual provisioning) are built into the ABM formulated by Barton and Riel-Salvatore (2014). Those portions of code are implemented as a means to investigate how these variables can increase or decrease opportunities for foraging agents' interactions.

Hypothesis No. 1a: Mobility Strategy (Residential vs. Logistical Mobility) Affects the Frequency of Inter-Group Contacts

WABI analysis implies that there were diachronic shifts in mobility strategy at A3C: AH IV exhibits features of residential mobility in Fig. 6, and AHs VII and III have the signatures of logistical mobility. Barton et al. (2011) argued that a shift to logistical mobility would increase interactions among hunter-gatherer groups, but Premo (2012) suggests that such a shift reduces opportunities for different foraging groups to encounter one another on the landscape. Barton and Riel-Salvatore's (2013, 2014) original ABM includes code to mimic these mobility strategies. For modeling residential mobility, an agent starts at a centrally placed patch and moves to a randomly placed camp in its territory, after which a new camp is randomly placed. For each new camp, there is a 20% chance that the central patch will be chosen again, replicating repeated visits to a particular location, such as a cave like A3C. For modeling logistical mobility, the central patch becomes a base camp, and short-term camp sites are randomly placed, one at a time, across a territory of specified radius. The agent repeatedly moves from the central base camp out to a camp site and back again, diverting only to collect toolstone. All other variables can be held constant while only the agents' "structural poses" (sensu Binford and Binford 1966) change.

Hypothesis No. 1b: Provisioning Strategy (Place vs. Individual Provisioning) Affects the Frequency of Inter-Group Contacts

Barton and Riel-Salvatore (2014) establish that provisioning either individuals or places has a marked effect on the formation of lithic assemblages, but it is unknown whether this effect propagates through to the frequency of inter-group contacts. Their ABM includes code that permits an agent to provision places by temporarily carrying more toolstone than its normal stock and leaving that material at the next camp. Because an agent is coded to leave a camp site with the least-used tools, this behavior can simulate place provisioning (sensu Kuhn 1992) by restocking from material left during past forays. When this behavior is turned off in the ABM, the agents follow individual provisioning, whereby they are limited to carrying a specific amount of material (the "lithic stock" variable).

Hypothesis No. 1c: Procurement Strategy (Embedded vs. Direct Procurement) Affects the Frequency of Inter-Group Contacts

The distance across which an agent can perceive a toolstone source is determined by a user-specified value, the magnitude of which can simulate embedded versus direct procurement (sensu Binford 1979). When this "visibility" radius has a low value, an agent will jump to a nearby source only when moving from camp to camp, simulating embedded procurement. When this radius is set to a high value, an agent can "see" sources at a distance and, in turn, can directly jump to them whenever new stone is needed, simulating direct procurement. Molyneaux

(2002) suggests that conspicuous landmarks exert a centripetal force on the movement of people due to their role in cognitive mapping. An obsidian source might exert a similar force, attracting individuals in need of stone to that location (Frahm 2012). It follows that such a toolstone source might be a place where different foraging groups are especially likely to encounter each other, thereby increasing opportunities for interactions.

Hypothesis No. 2: Spatial Variables Affect Contact Frequency

We modified Barton and Riel-Salvatore's (2014) ABM in order to simulate two foraging agents, which have circular territories, each with a user-specified radius, separated by a user-specified distance. As an agent moves from one camp to another, it may pass a toolstone outcrop (or more than one) along the way, and if the agent is in need of new toolstone, it will move to that source, perhaps encountering the other agent looking to restock at the same source at the same time. Otherwise, the two agents may encounter each other by happenstance as they are moving from one camp site to another.

Hypothesis No. 2a: the Territory Radius Affects the Frequency of Inter-Group Contacts Given Kelly's (1983) reported correlation between ET and foragers' traversed distances, we expect the A3C occupants covered greater distances during the climatic cooling leading into the LGM. Foraging agents move from camp to camp at a constant rate (i.e., one patch per tick), so larger territories mean, on average, more travel time between camps and, therefore, more opportunities to encounter different toolstone sources between camps. Using ABM simulations with systematically increasing territory radii, we can determine how such changes propagate and shape the frequency of foragers' interactions.

Hypothesis No. 2b: the Separation of Foraging Groups' Territories Affects the Frequency of Inter-Group Contacts It has been hypothesized that the Southern Caucasus functioned as a refugium during glacial conditions (Bar-Yosef 1994; Dennell et al. 2011; Finlayson 2004). If foragers tended to concentrate in mild and predictable environments, the global cooling leading into the LGM would be expected, accordingly, to correspond to increased population densities. The computational models of Perreault and Brantingham (2011) suggest a "mechanistic" link between the mean-squared spacing of hunter-gatherers and cultural transmission. In short, more closely spaced forager groups should lead to greater opportunities for them to interact, and this effect should be exponential rather than linear. ABM permits us to corroborate this phenomenon and, more importantly, to estimate its relative magnitude.

Hypothesis No. 2c: the Density of Toolstone Sources Affects the Frequency of Inter-Group Contacts In Armenia, obsidian sources are scattered across an expansive zone of Quaternary volcanism produced by the collision of the Arabian and Eurasian tectonic plates. In the ABM, however, the toolstone sources are randomly distributed following a density given by a user-specified value (i.e., sources per 100 patches). If indeed sources exert a centripetal force on foragers' movements, it is not obvious what effect

changes in source abundance would have on opportunities for inter-group interactions. It may be, for example, that more sources on the landscape will "dilute" such opportunities. Therefore, it is important to be able to computationally investigate this variable, which could reflect either changes in the amount of snow cover (e.g., outcrops at higher elevations becoming inaccessible in cold phases) or selectivity of which materials to use (e.g., selecting toolstone from a wider or narrower range of materials).

Hypothesis No. 3: Lithic Transport and Use Affect Contact Frequency

If, indeed, a toolstone source can exert a centripetal force on the movement of foraging groups, such a source might be a location where different groups are especially likely to encounter each other, increasing their opportunities to interact. It follows that behaviors which influence how often different groups visit a toolstone source (e.g., the size of their lithic stock, the intensity of lithic use) may potentially affect the frequency with which those groups encounter each other on the landscape.

Hypothesis No. 3a: Lithic Stock Affects the Frequency of Inter-Group Contacts The largest number of artifacts that agents within the model can transport from camp to camp is determined by a user-specified value. Given that agents will move to sources when fresh toolstone is required—that is, after their lithic stock has been exhausted—the stock size can influence how often agents visit sources.

Hypothesis No. 3b: Lithic Use Intensities Affect the Frequency of Inter-Group Contacts At a particular camp, agents use toolstone, transforming artifacts through four states within Barton and Riel-Salvatore's (2014) original ABM: unused (with a utility value of 3), used (2), retouched (1), and exhausted (0). The rate of this transformation from unused to exhausted is determined randomly, but the maximum possible amount of use at each site is determined by a user-specified value. The lithic use rate, consequently, has the potential to influence how frequently agents visit sources to procure new toolstone.

ABM Simulation Results

Each set of variables was modeled 200 times for 5000 time iterations ("ticks") using NetLogo v. 5.3.1, and the number of inter-group contacts resulting from each model run was output to a spreadsheet using the BehaviorSpace function. Figure 9, for example, reflects 39,200 model runs, corresponding to a total of 196 million computational iterations. For the four matrices in this figure, procurement strategy was constant (embedded) while mobility (residential or logistical), provisioning (place or individual), territory radius (30 to 90 patches), and territory separation (30 to 90 patches) were all varied in every combination of these four variables. Therefore, the hypothesis testing in the study reflects a total of 107,200 ABM model runs, corresponding to 536 million computational iterations. All of these models were run in Yale University's Digital Archaeology Laboratory on custom workstations built for demanding computational

Embedded Procurement
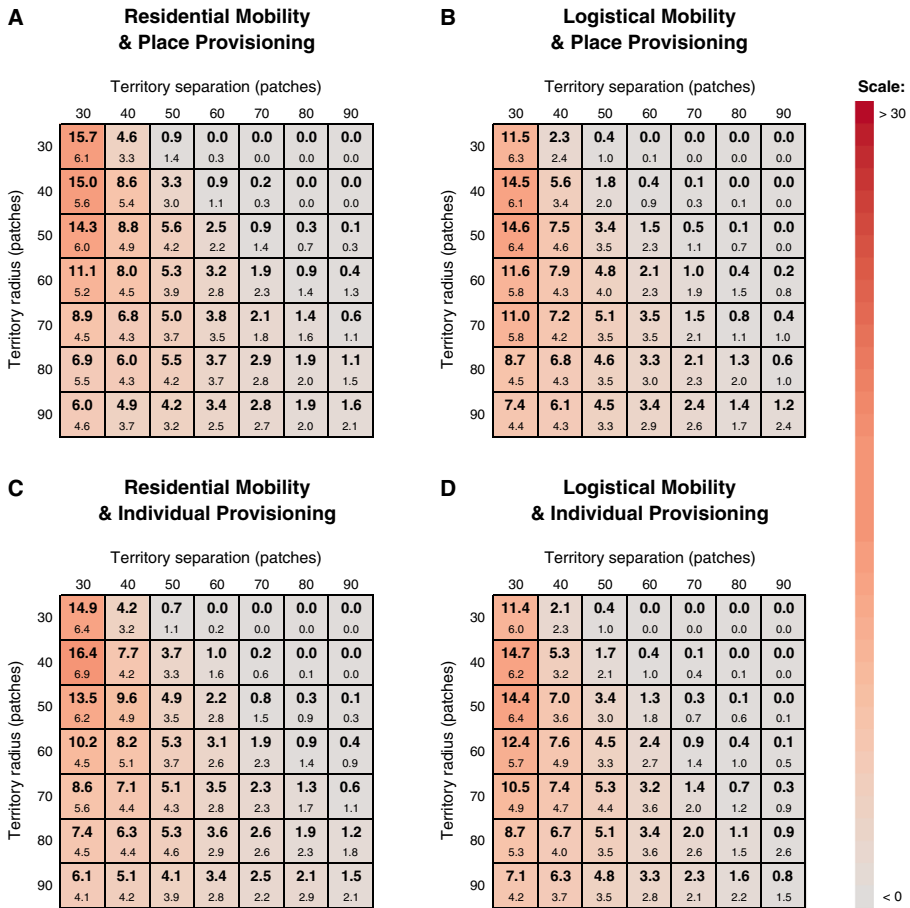
Fig. 9 The effects on inter-group contacts of changing territory separation and territory radius with embedded procurement and (**a**) residential mobility with place provisioning, (**b**) logistical mobility with place provisioning, (**c**) residential mobility with individual provisioning, and (**d**) logistical mobility with individual provisioning. The large, bold, top numbers are means, whereas the small, bottom numbers are standard deviations. Each cell is color-coded to highlight trends

applications (e.g., Intel i9-7940X 3.1 GHz 14-Core Processor, ASRock X299 Extreme4 motherboard). Using these high-end workstations, each model took about 20 s to run for 5000 ticks, so our data summarized here reflect approximately 600 h (25 days) of computing time.

Results Regarding Hypothesis No. 1

As shown in Figs. 9, 10, 11, 12, and 13, the conditions for Hypotheses No. 1a (residential versus logistical mobility), No. 1b (place versus individual provisioning), and No. 1c (embedded versus direct procurement) were applied to all of the variables tested in

Direct Procurement

A Residential Mobility & Place Provisioning

Territory separation (patches)

Territory radius (patches)	30	40	50	60	70	80	90
30	46.8 (13.5)	29.5 (9.7)	19.7 (8.1)	11.0 (5.8)	5.5 (4.0)	2.2 (2.3)	0.6 (1.2)
40	25.1 (8.5)	17.6 (7.6)	12.3 (6.2)	7.3 (4.6)	4.1 (3.2)	2.0 (2.0)	1.0 (1.3)
50	18.0 (6.9)	14.3 (6.3)	9.4 (5.3)	6.4 (4.4)	4.0 (3.6)	2.1 (2.0)	1.0 (1.2)
60	12.9 (6.2)	10.8 (6.4)	7.3 (4.8)	5.5 (4.3)	3.6 (3.3)	2.2 (1.8)	1.2 (1.7)
70	10.1 (5.4)	8.2 (5.1)	6.2 (3.9)	4.5 (3.4)	3.4 (3.0)	2.4 (2.8)	1.5 (1.9)
80	7.8 (5.3)	6.9 (5.2)	5.7 (4.2)	4.7 (4.0)	3.2 (2.5)	2.4 (2.9)	1.9 (3.4)
90	6.7 (6.0)	6.0 (4.8)	5.0 (4.0)	4.0 (3.8)	3.0 (3.2)	2.7 (2.7)	2.0 (2.4)

B Logistical Mobility & Place Provisioning

Territory separation (patches)

Territory radius (patches)	30	40	50	60	70	80	90
30	52.4 (17.1)	33.2 (14.5)	21.4 (11.0)	11.0 (7.3)	4.9 (4.3)	1.3 (1.6)	0.3 (0.7)
40	28.5 (9.4)	19.0 (7.2)	11.7 (6.3)	7.3 (5.0)	3.8 (3.1)	1.6 (1.5)	0.5 (0.8)
50	19.8 (8.6)	14.6 (5.6)	9.4 (5.6)	5.9 (2.6)	3.1 (1.9)	1.7 (2.0)	1.1 (2.0)
60	15.9 (6.8)	12.3 (7.1)	8.2 (5.5)	5.3 (4.0)	2.9 (2.8)	1.7 (1.6)	0.8 (1.0)
70	11.8 (5.9)	9.2 (4.8)	7.6 (4.7)	5.0 (3.9)	3.2 (2.8)	2.0 (2.2)	1.1 (1.3)
80	9.7 (5.4)	7.4 (4.0)	6.5 (5.0)	4.3 (3.6)	3.1 (2.5)	2.0 (2.0)	1.1 (1.6)
90	8.2 (4.7)	7.5 (5.3)	6.0 (4.8)	4.1 (3.5)	3.2 (3.3)	2.1 (2.3)	1.5 (2.1)

Scale: > 30

C Residential Mobility & Individual Provisioning

Territory separation (patches)

Territory radius (patches)	30	40	50	60	70	80	90
30	45.0 (13.6)	30.4 (10.5)	19.2 (8.5)	9.9 (5.5)	5.6 (4.4)	2.3 (2.2)	0.6 (1.0)
40	26.6 (10.4)	18.9 (7.8)	11.8 (5.9)	7.0 (4.5)	3.8 (3.1)	1.8 (1.6)	0.9 (1.1)
50	18.0 (7.4)	13.1 (6.4)	10.8 (6.2)	6.6 (5.1)	3.9 (3.0)	2.1 (2.0)	1.1 (1.5)
60	12.5 (5.6)	10.8 (6.6)	8.2 (4.9)	5.6 (4.0)	3.3 (2.3)	2.6 (2.9)	1.4 (1.8)
70	10.0 (5.5)	8.5 (5.2)	6.9 (5.1)	5.4 (4.6)	4.0 (3.7)	2.8 (3.1)	1.7 (2.1)
80	7.4 (4.3)	6.3 (4.5)	5.8 (3.9)	4.7 (3.8)	3.4 (4.5)	2.1 (2.0)	1.9 (2.7)
90	6.1 (4.1)	5.5 (4.5)	4.6 (3.6)	4.0 (3.8)	3.5 (3.1)	2.9 (3.1)	1.9 (2.9)

D Logistical Mobility & Individual Provisioning

Territory separation (patches)

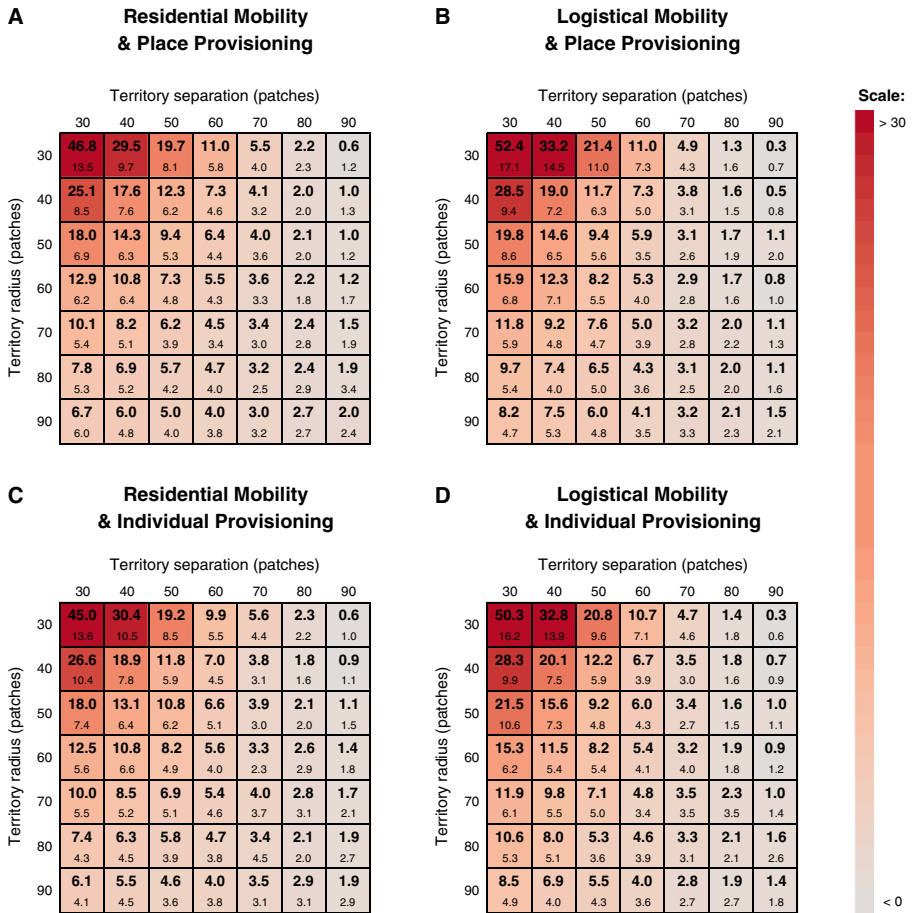| Territory radius (patches)	30	40	50	60	70	80	90
30	50.3 (16.2)	32.8 (13.9)	20.8 (9.6)	10.7 (7.1)	4.7 (4.6)	1.4 (1.8)	0.3 (0.6)
40	28.3 (9.9)	20.1 (7.5)	12.2 (5.9)	6.7 (3.9)	3.5 (3.0)	1.8 (1.6)	0.7 (0.9)
50	21.5 (10.6)	15.6 (7.3)	9.2 (4.8)	6.0 (4.3)	3.4 (2.7)	1.6 (1.5)	1.0 (1.1)
60	15.3 (6.2)	11.5 (5.4)	8.2 (5.4)	5.4 (4.1)	3.2 (4.0)	1.9 (1.8)	0.9 (1.2)
70	11.9 (6.1)	9.8 (5.5)	7.1 (5.0)	4.8 (3.4)	3.5 (3.5)	2.3 (3.5)	1.0 (1.4)
80	10.6 (5.3)	8.0 (5.1)	5.3 (3.6)	4.6 (3.9)	3.3 (3.1)	2.1 (2.1)	1.6 (2.6)
90	8.5 (4.9)	6.9 (4.0)	5.5 (4.3)	4.0 (3.6)	2.8 (2.7)	1.9 (2.7)	1.4 (1.8)

Scale: < 0

Fig. 10 The effects on inter-group contacts of changing territory separation and territory radius with direct procurement (sensu Binford 1979) and (**a**) residential mobility with place provisioning, (**b**) logistical mobility with place provisioning, (**c**) residential mobility with individual provisioning, and (**d**) logistical mobility with individual provisioning. The large, bold, top numbers are means, whereas the small, bottom numbers are standard deviations. Each cell is color-coded to highlight trends

Hypothesis No. 2 (territory radius, territory separation, and toolstone source abundance) and Hypothesis No. 3 (lithic stock size and use intensity). As we tested the effect of increasing territory size, for example, we also varied the mobility, provisioning, and procurement strategies. The figures illustrate how the opportunities for inter-group encounters change under a diversity of conditions.

Hypothesis No. 1a: Residential vs. Logistical Mobility Figures 9 and 10 illustrate how opportunities for inter-group encounters change between residential and logistical mobility under varying conditions. The four grids in Figs. 9 and 10 reflect the four possible combinations of residential or logistical mobility and place or individual provisioning. All
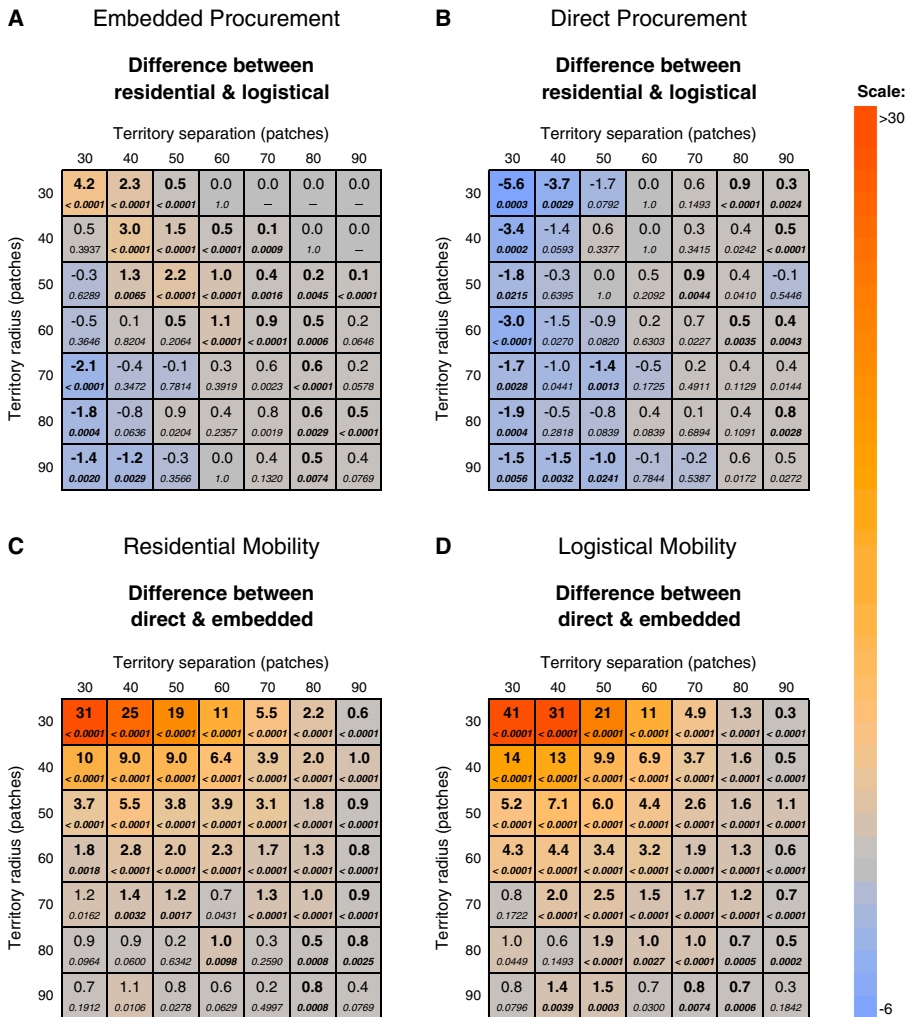
Fig. 11 Arithmetic differences between (a) residential and logistical mobility when there is embedded procurement, (b) residential and logistical mobility with direct procurement, (c) direct and embedded procurement with residential mobility, and (d) direct and embedded procurement with logistical mobility. All combinations involve place, not individual, provisioning. Each cell is color-coded to highlight trends. In this case, the large, top numbers are the difference, while the smaller, italicized, bottom numbers are p values calculated based on Student's t tests. Statistically significant differences ($a = 0.01$) are bold

of the combinations in Fig. 9 reflect embedded procurement, and all of those in Fig. 10 reflect direct procurement. The results establish that the effects of a mobility shift are consistent with both Barton et al. (2011) and Premo (2012). Under some conditions, Barton et al. (2011) were correct that a shift from residential to logistical mobility increased opportunities for inter-group interactions, whereas Premo's (2012) proposal that such a shift can reduce the opportunities for interaction is also accurate, albeit under a different set of circumstances.

A   Embedded & Residential

Difference between place & individual provisioning

Territory separation (patches)

Territory radius (patches)	30	40	50	60	70	80	90
30	0.8	0.4	0.2	0.0	0.0	0.0	0.0
	0.2014	*0.2192*	*0.1129*	*1.0000*	*1.0000*	*1.0000*	*1.0000*
40	-1.4	0.9	-0.4	-0.1	0.0	0.0	0.0
	0.0264	*0.0635*	*0.2054*	*0.4668*	*1.0000*	*1.0000*	*1.0000*
50	0.8	-0.8	0.7	0.3	0.1	0.0	0.0
	0.1905	*0.1033*	*0.0709*	*0.2342*	*0.4911*	*1.0000*	*1.0000*
60	0.9	-0.2	0.0	0.1	0.0	0.0	0.0
	0.0649	*0.6777*	*1.0000*	*0.7115*	*1.0000*	*1.0000*	*1.0000*
70	0.3	-0.3	-0.1	0.3	-0.2	0.1	0.0
	0.5551	*0.4908*	*0.8033*	*0.3444*	*0.3334*	*0.5450*	*1.0000*
80	-0.5	-0.3	0.2	0.1	0.3	0.0	-0.1
	0.3203	*0.4908*	*0.6500*	*0.7637*	*0.2675*	*1.0000*	*0.5465*
90	-0.1	-0.2	0.1	0.0	0.3	-0.2	0.1
	0.8186	*0.6136*	*0.7794*	*1.0000*	*0.2239*	*0.4225*	*0.6342*

B   Embedded & Logistical

Difference between place & individual provisioning

Territory separation (patches)

Territory radius (patches)	30	40	50	60	70	80	90
30	0.1	0.2	0.0	0.0	0.0	0.0	0.0
	0.8710	*0.3954*	*1.0000*	*1.0000*	*1.0000*	*1.0000*	*1.0000*
40	-0.2	0.3	0.1	0.0	0.0	0.0	0.0
	0.7452	*0.3641*	*0.6261*	*1.0000*	*1.0000*	*1.0000*	*1.0000*
50	0.2	0.5	0.0	0.2	0.2	0.0	0.0
	0.7548	*0.2268*	*1.0000*	*0.3334*	*0.0307*	*1.0000*	*1.0000*
60	-0.8	0.3	0.3	-0.3	0.1	0.0	0.1
	0.1649	*0.5156*	*0.4138*	*0.2323*	*0.5494*	*1.0000*	*0.1346*
70	0.5	-0.2	-0.2	0.3	0.1	0.1	0.1
	0.3523	*0.6539*	*0.6152*	*0.3986*	*0.6261*	*0.3855*	*0.2938*
80	0.0	0.1	-0.5	-0.1	0.1	0.2	-0.3
	1.0000	*0.8098*	*0.1539*	*0.7630*	*0.6839*	*0.2586*	*0.1285*
90	0.3	-0.2	-0.3	0.1	0.1	-0.2	0.4
	0.4859	*0.6183*	*0.3783*	*0.7259*	*0.6724*	*0.3096*	*0.0463*

C   Direct & Residential

Difference between place & individual provisioning

Territory separation (patches)

Territory radius (patches)	30	40	50	60	70	80	90
30	1.8	-0.9	0.5	1.1	-0.1	-0.1	0.0
	0.1848	*0.3738*	*0.5474*	*0.0523*	*0.8121*	*0.6570*	*1.0000*
40	-1.5	-1.3	0.5	0.3	0.3	0.2	0.1
	0.1151	*0.0922*	*0.4092*	*0.5101*	*0.3415*	*0.2701*	*0.4068*
50	0.0	1.2	-1.4	-0.2	0.1	0.0	-0.1
	1.0000	*0.0575*	*0.0157*	*0.6748*	*0.7630*	*1.0000*	*0.4620*
60	0.4	0.0	-0.9	-0.1	0.3	-0.4	-0.2
	0.4987	*1.0000*	*0.0643*	*0.8098*	*0.2922*	*0.0982*	*0.2540*
70	0.1	-0.3	-0.7	-0.9	-0.6	-0.4	-0.2
	0.8545	*0.5606*	*0.1239*	*0.0266*	*0.0756*	*0.1764*	*0.3185*
80	0.4	0.6	-0.1	0.0	-0.2	0.3	0.0
	0.4077	*0.2180*	*0.8052*	*1.0000*	*0.5830*	*0.2292*	*1.0000*
90	0.6	0.5	0.4	0.0	-0.5	-0.2	0.1
	0.2437	*0.2832*	*0.2938*	*1.0000*	*0.1133*	*0.4918*	*0.7073*

D   Direct & Logistical

Difference between place & individual provisioning

Territory separation (patches)

Territory radius (patches)	30	40	50	60	70	80	90
30	2.1	0.4	0.6	0.3	0.2	-0.1	0.0
	0.2081	*0.7784*	*0.5614*	*0.6772*	*0.6535*	*0.5574*	*1.0000*
40	0.2	-1.1	-0.5	0.6	0.3	-0.2	-0.2
	0.8360	*0.1354*	*0.4131*	*0.1816*	*0.3260*	*0.1979*	*0.0193*
50	-1.7	-1.0	0.2	-0.1	-0.3	0.1	0.1
	0.0790	*0.1487*	*0.7016*	*0.7988*	*0.2584*	*0.5594*	*0.5359*
60	0.6	0.8	0.0	-0.1	-0.3	-0.2	-0.1
	0.3570	*0.2054*	*1.0000*	*0.8051*	*0.3854*	*0.2409*	*0.3658*
70	-0.1	-0.6	0.5	0.2	-0.3	-0.3	0.1
	0.8677	*0.2458*	*0.3034*	*0.5849*	*0.3444*	*0.3054*	*0.4596*
80	-0.9	-0.6	**1.2**	-0.3	-0.2	-0.1	-0.5
	0.0933	*0.1912*	***0.0061***	*0.4246*	*0.4780*	*0.6261*	*0.0211*
90	-0.3	0.6	0.5	0.1	0.4	0.2	0.1
	0.5324	*0.2020*	*0.2732*	*0.7783*	*0.1854*	*0.4257*	*0.6094*

Fig. 12   **a–d** Differences and *p* values (Student's *t* test; *a* = 0.01) between place and individual provisioning for the combinations of mobility (i.e., residential or logistical) and procurement (i.e., embedded or direct) strategies. The one bold *p* value is, apparently by chance, statistically significant

Figure 11 reveals the differences in interaction opportunities between residential and logistical mobility with embedded (A) and direct (B) procurement and between direct and embedded procurement with residential (C) and logistical (D) mobility. That is, the top, larger values in Fig. 11a reflect the values from Fig. 9b subtracted from Fig. 9a, and the values in Fig. 11b reflect the values from Fig. 10b subtracted from Fig. 10a. The lower, italicized, smaller numbers are *p* values. Both values are
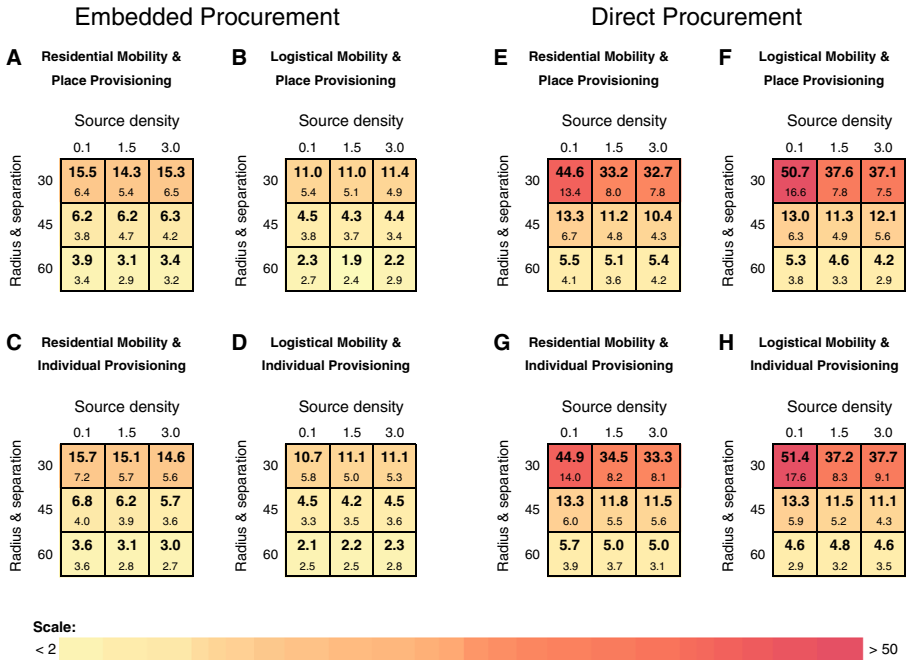
Fig. 13 **a**–**h** The effects on inter-group contacts of changing source density on the landscape (0.1, 1.5, or 3.0 sources per 100 patches). Each set of conditions was modeled for three territory radii and separations (30, 45, and 60 patches). The large, bold, top numbers are means, whereas the small, bottom numbers are standard deviations. Each cell is color-coded to highlight trends

bold if the difference is statistically significant (confidence: $a = 0.01$). A positive difference means that there are more chances, on average, for interaction under residential mobility than under logistical mobility, whereas a negative difference means that there are more opportunities under logistical mobility. Similarly, the values in Fig. 11c reflect the values from Fig. 9a subtracted from Fig. 10a, and the values in Fig. 11d reflect the values from Fig. 9b subtracted from Fig. 10b. Consequently, a positive value in Fig. 11c or d means that there are more opportunities for interaction to occur under direct procurement, while a negative value means that there are instead more interaction opportunities under embedded procurement.

Figure 11a,b establishes that, with greater territory separations (≥ 70 patches; right side of the grids), slightly more interactions occur under residential mobility compared to logistical mobility, as the differences are predominantly positive. However, when the territories are close (separation of ≤ 50 patches; left side of the grids) and large (radius of ≥ 70 patches; bottom part of the grids), there are slightly fewer interactions under residential mobility relative to logistical mobility, as shown by negative values. Another difference emerges between embedded (Fig. 11a) and direct procurement (Fig. 11b) when the territories are both close (≤ 50 patches; left side of the grids) and small (≤ 60 patches; top part of the grids). With embedded procurement (Fig. 11a), residential mobility yields more interactions than logistical, but with direct procurement (Fig. 11b), logistical mobility

yields more interactions than residential. Thus, our ABM simulations demonstrate that these are not entirely independent variables. It is also worth noting that, under a variety of conditions, the differences are not statistically significant.

Hypothesis No. 1b: Place vs. Individual Provisioning Across all of the tested conditions, the effect of provisioning strategy—place versus individual—is not significant. Note how similar Fig. 9a appears to Fig. 9c, Fig. 9b to d, Fig. 10a to c and Fig. 10b to d More quantitatively, Fig. 12 shows these similarities between place and individual provisioning, including p values from Student's t tests, for the combinations of mobility (i.e., residential or logistical) and procurement (i.e., embedded or direct) strategies. Out of the 196 cases, only once, apparently by chance, is the difference statistically significant between place and individual provisioning ($p = 0.0061$, $a = 0.01$). Therefore, we can reject this hypothesis.

Hypothesis No. 1c: Embedded vs. Direct Procurement Procurement strategy—embedded or direct—had a clear effect on inter-group contacts. As demonstrated by Fig. 11c, d, regardless of mobility strategy, direct procurement leads to greater interaction opportunities than embedded procurement, as attested by entirely positive values in these two grids. This outcome might be a product of Molyneaux's (2002) "centripetal" effect, whereby a toolstone source, under direct procurement, can exert a "force" on agents over the greatest distance and move them to that location. Indeed, based on our ABM simulations, an agent is much more likely to cross over into their neighbor's territory when a toolstone source is highly visible, thereby increasing the opportunities for interactions between the two groups.

Results Regarding Hypothesis No. 2

Figures 9, 10, and 11 also summarize our results for variable territory sizes to test Hypothesis No. 2a and variable territory separations to test Hypothesis No. 2b. Figure 12 shows our data for the effect of variable toolstone source abundance on the landscape (Hypothesis No. 2c). The territory radii and territory separations were tested at 30–90 patches in increments of ten (Figs. 9, 10, and 11), and source density on the landscape was tested at low (0.1 sources/100 patches), medium (1.5), and high (3.0) levels (Fig. 12).

Hypothesis No. 2a: Territory Sizes The relationships between territory radius and contact frequency are complex. As illustrated in all grids of Fig. 10, with direct procurement and with low to moderate territory separations (30–70 patches; left sides of the grids), inter-group contacts decrease as territory radius increases (lower rows of the grids). For example, in Fig. 10a, with a separation of 30 patches as well as residential mobility and place provisioning, contacts drop from a mean of 46.8 at a radius of 30 to a mean of 6.7 at a radius of 90, a decrease of 86% ($p < 0.0001$). With larger separations (80–90 patches; right sides of the grids), there are small overall increases in contacts as the radius increases. For example, in Fig. 10a, with a separation of 80 patches as well as residential mobility and place provisioning, contacts rise from a mean of 2.2 at a radius of 30 to a mean of 2.7 at a radius of 90, an increase of 23% that

is not statistically significant with a high confidence level ($p = 0.0469$, $a = 0.01$). For embedded procurement, as illustrated by the grids in Fig. 9, the pattern is equally complex. In Fig. 9a, with the smallest territory separation (30 patches), residential mobility, and place provisioning, contacts decrease from a mean of 15.7 at a radius of 30 to a mean of 6.0 at a radius of 90, a decrease of 62% ($p < 0.0001$). At the greatest separation (90), contacts increase from zero at a radius of 30–40 to a mean of 1.6 at a radius of 90 ($p < 0.0001$). With intermediate separations, however, the frequency of contacts initially increases and then decreases. For example, at a separation of 40 patches (with residential mobility and place provisioning), contacts first increase from a mean of 4.6 at a radius of 30 patches, reach at peak of 8.8 at 50 patches ($p < 0.0001$), and then decrease to a mean of 4.9 at 90 patches ($p < 0.0001$). Ultimately, the effects of territory radius on the frequency of inter-group contacts are nonlinear and depend on both separation distance and the toolstone procurement strategy (i.e., embedded vs. direct).

Hypothesis No. 2b: Territory Separation Figures 9 and 10 demonstrate that—regardless of mobility, procurement, or provisioning strategies—there is a relationship between territories' separation and the frequency of contacts: contacts are less common as separation increases. This relationship is nonlinear (i.e., a third-order polynomial is the best fit), but it exists under all circumstances. This is consistent with the findings from Perreault and Brantingham (2011), who simulated an exponential relationship between the spacing of hunter-gatherers and the chances for cultural transmission.

Hypothesis No. 2c: Toolstone Source Abundance Under many circumstances, there is no significant difference in frequency of contacts as the abundance of toolstone sources changes (Figs. 13 and 14). Only with direct procurement (Figs. 13e-h and 14e-h), small territories (≤ 45-patch radii), and small separations (30 and 45 patches) is there a statistically significant decrease in contacts as source density increases from 0.1 to 1.5 sources per 100 patches. It seems that this could be due to a "centripetal" force that occurs with direct procurement. The decrease in contacts, therefore, may reflect a "dilution" of the effect, whereby different groups are more likely to encounter one another at toolstone sources only if there are fewer sources from which they can choose to acquire fresh material. Although, as the radii and separation of the territories increase, decreases within the inter-group contacts are no longer statistically significant (Figs. 13e-h and 14e-h). Consequently, any effect from toolstone abundance requires all three conditions—(1) direct procurement, (2) small, and (3) close territories—to be satisfied.

Results Regarding Hypothesis No. 3

Varying lithic stock and maximum lithic use intensity were tested with a constant radius (60 patches) and separation (60 patches) of the agents' territories; however, the procurement, mobility, and provisioning strategies all varied. These values are the middle points for our tests in Figs. 9, 10, and 11. Figure 15 reveals that varying lithic stock size and maximum lithic use intensity had little influence on the

Embedded Procurement

A   Residential Mobility & Place Provisioning

	30 Patches			45 Patches			60 Patches		
	Source Abundance			Source Abundance			Source Abundance		
	0.1	1.5	3.0	0.1	1.5	3.0	0.1	1.5	3.0
0.1	—	0.043	0.757	—	1.000	0.803	—	0.012	0.131
1.5		—	0.095		—	0.823		—	0.327
3.0			—			—			—

B   Logistical Mobility & Place Provisioning

	30 Patches			45 Patches			60 Patches		
	Source Abundance			Source Abundance			Source Abundance		
	0.1	1.5	3.0	0.1	1.5	3.0	0.1	1.5	3.0
0.1	—	1.000	0.438	—	0.594	0.782	—	0.118	0.721
1.5		—	0.424		—	0.779		—	0.260
3.0			—			—			—

C   Residential Mobility & Individual Provisioning

	30 Patches			45 Patches			60 Patches		
	Source Abundance			Source Abundance			Source Abundance		
	0.1	1.5	3.0	0.1	1.5	3.0	0.1	1.5	3.0
0.1	—	0.356	0.089	—	0.130	**0.002**	—	0.122	0.060
1.5		—	0.377		—	0.184		—	0.716
3.0			—			—			—

D   Logistical Mobility & Individual Provisioning

	30 Patches			45 Patches			60 Patches		
	Source Abundance			Source Abundance			Source Abundance		
	0.1	1.5	3.0	0.1	1.5	3.0	0.1	1.5	3.0
0.1	—	0.461	0.472	—	0.378	1.000	—	0.689	0.452
1.5		—	1.000		—	0.399		—	0.707
3.0			—			—			—

Direct Procurement

E   Residential Mobility & Place Provisioning

	30 Patches			45 Patches			60 Patches		
	Source Abundance			Source Abundance			Source Abundance		
	0.1	1.5	3.0	0.1	1.5	3.0	0.1	1.5	3.0
0.1	—	**<0.001**	0.527	—	**0.001**	**<0.001**	—	0.301	0.810
1.5		—	**<0.001**		—	0.080		—	0.444
3.0			—			—			—

F   Logistical Mobility & Place Provisioning

	30 Patches			45 Patches			60 Patches		
	Source Abundance			Source Abundance			Source Abundance		
	0.1	1.5	3.0	0.1	1.5	3.0	0.1	1.5	3.0
0.1	—	**<0.001**	**<0.001**	—	**0.003**	0.132	—	0.050	**0.001**
1.5		—	0.514		—	0.129		—	0.199
3.0			—			—			—

G   Residential Mobility & Individual Provisioning

	30 Patches			45 Patches			60 Patches		
	Source Abundance			Source Abundance			Source Abundance		
	0.1	1.5	3.0	0.1	1.5	3.0	0.1	1.5	3.0
0.1	—	**<0.001**	**<0.001**	—	**0.010**	**0.002**	—	0.066	0.048
1.5		—	0.142		—	0.589		—	1.000
3.0			—			—			—

H   Logistical Mobility & Individual Provisioning

	30 Patches			45 Patches			60 Patches		
	Source Abundance			Source Abundance			Source Abundance		
	0.1	1.5	3.0	0.1	1.5	3.0	0.1	1.5	3.0
0.1	—	**<0.001**	**<0.001**	—	**0.001**	**<0.001**	—	0.513	1.000
1.5		—	0.566		—	0.402		—	0.551
3.0			—			—			—

Fig. 14 **a**–**h** Calculated p values (Student's t test; $a = 0.01$) for changing source density on the landscape (0.1, 1.5, or 3.0 sources per 100 patches). Each set of conditions was modeled for three territory radii and separations (30, 45, and 60 patches). The bold p values are statistically significant

frequency of inter-group contacts. That is, in each of these possible combinations of mobility, provisioning, and procurement strategies, varying lithic stock size and maximum lithic use intensity yielded similar results. Figures 16 and 17 show that—for every iteration of mobility, procurement, and provisioning strategies—the various combinations of lithic stock and maximum use intensity yielded, by chance, barely significant differences only twice (i.e., $p = 0.010$ and 0.009; $a = 0.01$). Every other combination in these grids yielded statistically insignificant changes. Thus, *Hypotheses No. 3a and No. 3b* are not supported. We can rule out both of these variables, which, while they reflect fundamental choices in the organization of lithic technology, do not appear to be important factors in shaping the opportunities for
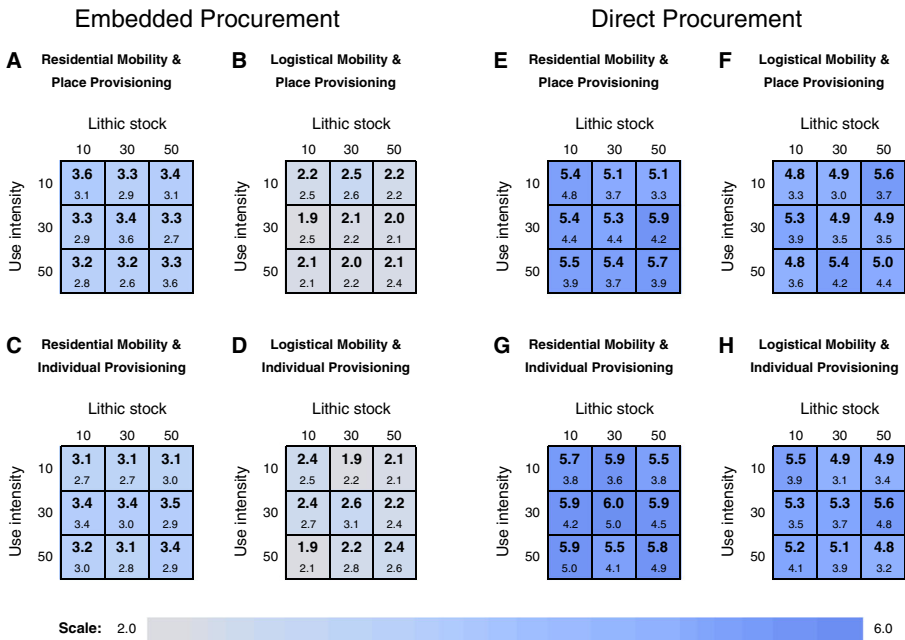
Fig. 15 a–h The effects on inter-group contacts of changing lithic stock and lithic use intensity. Each set of conditions was modeled for place and individual provisioning. The large, bold, top numbers are means, whereas the small, bottom numbers are standard deviations. Each cell is color-coded to highlight trends

different foraging groups to encounter one another as they move throughout the landscape.

Interpretation

WABI analysis (Fig. 6) suggests that the greater expediency in AHs VII and III reflects a greater reliance on a logistical mobility strategy, that AH IV reflects a greater reliance on residential mobility in comparison, and that AHs VI and V are intermediate. Our ABM simulations show that relationships between mobility strategy and inter-group interactions are nonlinear and depend, in large part, on the territory separation and embedded versus direct procurement. It is not as straightforward as logistical mobility leading to more or fewer opportunities for interaction than residential mobility. For example, when the foraging territories are small and close, embedded or direct procurement makes a difference between a drop or rise, respectively, in contacts during a change from residential to logistical mobility. This, then, explains the disparity noted by Barton et al. (2011) and Premo (2012). Consequently, it is an example of a complex system behavior that cannot be explained via simple cause-and-effect relationships.

Our sourcing data reveal more and farther obsidian sources in the A3C lithic assemblage as the indicators of logistical mobility increase (i.e., the most and farthest obsidian sources from the most varied directions occur in AH III). Given that we consider the variety, distances, and directions of obsidian sources represented in an AH
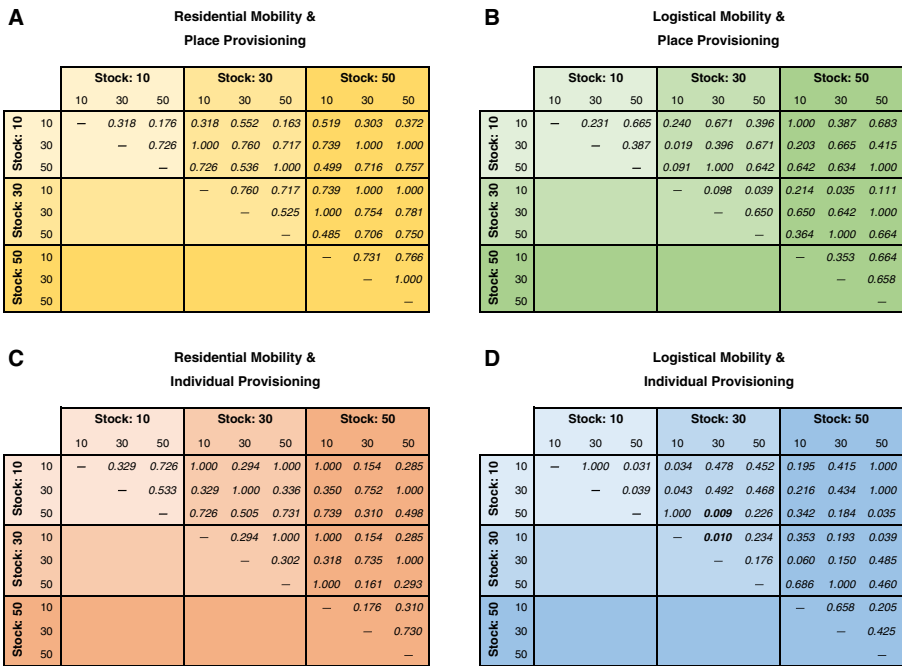
Embedded Procurement

A Residential Mobility & Place Provisioning

		Stock: 10			Stock: 30			Stock: 50		
		10	30	50	10	30	50	10	30	50
Stock: 10	10	—	0.318	0.176	0.318	0.552	0.163	0.519	0.303	0.372
	30		—	0.726	1.000	0.760	0.717	0.739	1.000	1.000
	50			—	0.726	0.536	1.000	0.499	0.716	0.757
Stock: 30	10				—	0.760	0.717	1.000	0.754	0.781
	30					—	0.525	1.000	0.754	0.781
	50						—	0.485	0.706	0.750
Stock: 50	10							—	0.731	0.766
	30								—	1.000
	50									—

B Logistical Mobility & Place Provisioning

		Stock: 10			Stock: 30			Stock: 50		
		10	30	50	10	30	50	10	30	50
Stock: 10	10	—	0.231	0.665	0.240	0.671	0.396	1.000	0.387	0.683
	30		—	0.387	0.019	0.396	0.671	0.203	0.665	0.415
	50			—	0.091	1.000	0.642	0.642	0.634	1.000
Stock: 30	10				—	0.098	0.039	0.214	0.035	0.111
	30					—	0.650	0.650	0.642	1.000
	50						—	0.364	1.000	0.664
Stock: 50	10							—	0.353	0.664
	30								—	0.658
	50									—

C Residential Mobility & Individual Provisioning

		Stock: 10			Stock: 30			Stock: 50		
		10	30	50	10	30	50	10	30	50
Stock: 10	10	—	0.329	0.726	1.000	0.294	1.000	1.000	0.154	0.285
	30		—	0.533	0.329	1.000	0.336	0.350	0.752	1.000
	50			—	0.726	0.505	0.731	0.739	0.310	0.498
Stock: 30	10				—	0.294	1.000	1.000	0.154	0.285
	30					—	0.302	0.318	0.735	1.000
	50						—	1.000	0.161	0.293
Stock: 50	10							—	0.176	0.310
	30								—	0.730
	50									—

D Logistical Mobility & Individual Provisioning

		Stock: 10			Stock: 30			Stock: 50		
		10	30	50	10	30	50	10	30	50
Stock: 10	10	—	1.000	0.031	0.034	0.478	0.452	0.195	0.415	1.000
	30		—	0.039	0.043	0.492	0.468	0.216	0.434	1.000
	50			—	1.000	**0.009**	0.226	0.342	0.184	0.035
Stock: 30	10				—	**0.010**	0.234	0.353	0.193	0.039
	30					—	0.176	0.060	0.150	0.485
	50						—	0.686	1.000	0.460
Stock: 50	10							—	0.658	0.205
	30								—	0.425
	50									—

Fig. 16 **a–d** Calculated p values (Student's t test; $a = 0.01$) for changes in lithic stock and maximum lithic use intensity for different combinations of mobility (residential versus logistical) and provisioning (individual versus place) strategies with embedded procurement. The two bold p values are barely statistically significant

as a coarse proxy for the frequency of inter-group contacts, we cannot explain the increase in interactions as an unavoidable outcome of a shift from residential to logistical mobility—other factors, such as procurement, can shape chances for interactions during such a shift.

We can rule out certain variables, including those linked to the organization of lithic technology. From AH VII to III, the lithic technology remained virtually unchanged: unidirectional reduction of small cores to make laterally retouched and backed bladelets. While we noticed subtle technological changes in the oldest layer, AH VII, the number of artifacts that deviate from this pattern is small. Furthermore, our ABM simulations reveal that factors such as lithic stock size and maximum use intensity have no effect on the frequency of inter-group contacts. The provisioning strategy—individual or place—had no effect on the inter-group contact frequency, so this, too, can be ruled out as a mechanism. Under restricted circumstances, a decrease in toolstone source abundance on the landscape can lead to more inter-group contacts. Note, however, that the proportion of cherts is, with the exception of AH VI, highest for AH III (14.3%; Table 2), suggesting a greater degree of flexibility in toolstone selection.

Two lines of evidence suggest that the A3C occupants increased their territory size between AH IV and III. The first, as shown in Table 3, is that a higher proportion of obsidian artifacts in AH III originated from more and farther obsidian sources than in
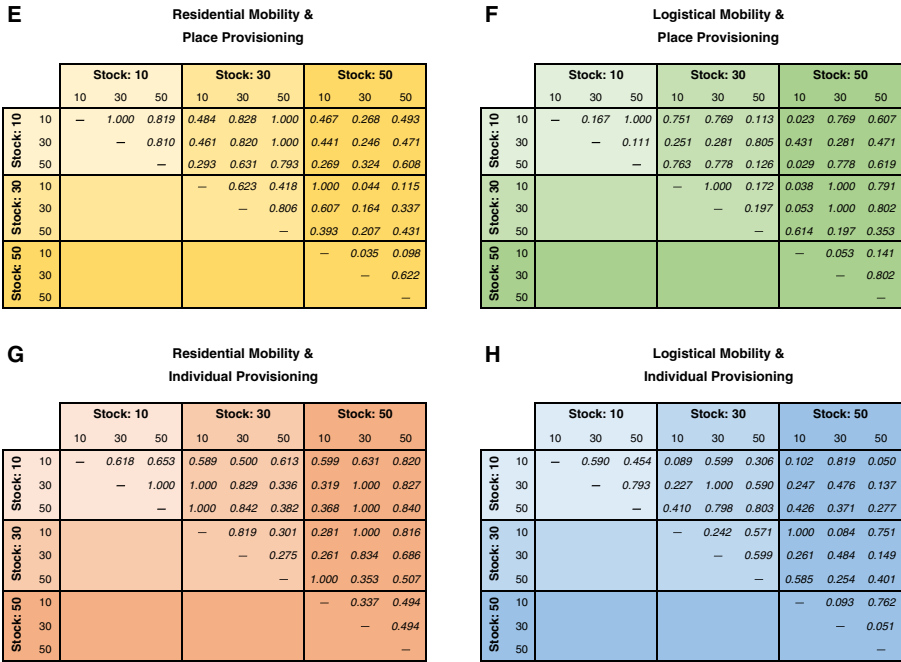
Direct Procurement

E — Residential Mobility & Place Provisioning

		Stock: 10			Stock: 30			Stock: 50		
		10	30	50	10	30	50	10	30	50
Stock: 10	10	—	1.000	0.819	0.484	0.828	1.000	0.467	0.268	0.493
	30		—	0.810	0.461	0.820	1.000	0.441	0.246	0.471
	50			—	0.293	0.631	0.793	0.269	0.324	0.608
Stock: 30	10				—	0.623	0.418	1.000	0.044	0.115
	30					—	0.806	0.607	0.164	0.337
	50						—	0.393	0.207	0.431
Stock: 50	10							—	0.035	0.098
	30								—	0.622
	50									—

F — Logistical Mobility & Place Provisioning

		Stock: 10			Stock: 30			Stock: 50		
		10	30	50	10	30	50	10	30	50
Stock: 10	10	—	0.167	1.000	0.751	0.769	0.113	0.023	0.769	0.607
	30		—	0.111	0.251	0.281	0.805	0.431	0.281	0.471
	50			—	0.763	0.778	0.126	0.029	0.778	0.619
Stock: 30	10				—	1.000	0.172	0.038	1.000	0.791
	30					—	0.197	0.053	1.000	0.802
	50						—	0.614	0.197	0.353
Stock: 50	10							—	0.053	0.141
	30								—	0.802
	50									—

G — Residential Mobility & Individual Provisioning

		Stock: 10			Stock: 30			Stock: 50		
		10	30	50	10	30	50	10	30	50
Stock: 10	10	—	0.618	0.653	0.589	0.500	0.613	0.599	0.631	0.820
	30		—	1.000	1.000	0.829	0.336	0.319	1.000	0.827
	50			—	1.000	0.842	0.382	0.368	1.000	0.840
Stock: 30	10				—	0.819	0.301	0.281	1.000	0.816
	30					—	0.275	0.261	0.834	0.686
	50						—	1.000	0.353	0.507
Stock: 50	10							—	0.337	0.494
	30								—	0.494
	50									—

H — Logistical Mobility & Individual Provisioning

		Stock: 10			Stock: 30			Stock: 50		
		10	30	50	10	30	50	10	30	50
Stock: 10	10	—	0.590	0.454	0.089	0.599	0.306	0.102	0.819	0.050
	30		—	0.793	0.227	1.000	0.590	0.247	0.476	0.137
	50			—	0.410	0.798	0.803	0.426	0.371	0.277
Stock: 30	10				—	0.242	0.571	1.000	0.084	0.751
	30					—	0.599	0.261	0.484	0.149
	50						—	0.585	0.254	0.401
Stock: 50	10							—	0.093	0.762
	30								—	0.051
	50									—

Fig. 17 **e–h** Calculated p values (Student's t test; $a = 0.01$) for changes in lithic stock and maximum lithic use intensity for different combinations of mobility (residential versus logistical) and provisioning (individual versus place) strategies with direct procurement. None of these p values are statistically significant

other layers. The second line of evidence is climatic and ethnographic data. Kelly (1983) showed that, in short, foraging populations living in colder climates must move farther in order to sustain themselves. Using the correlations reported by Kelly (1983) and rough temperature estimates for A3C, it is plausible to expect that, during the deposition of AH III, movements increased in distance on the order of two-thirds from those during warmer phases. Distance increases of double or triple seem less likely, although not impossible. ABM simulations, though, clearly establish that territory radius is not a simple, independent variable when it comes to the chances for inter-group contacts. Instead, its effect on contacts largely depends on two other variables: (1) procurement strategy (i.e., embedded versus direct procurement) and (2) territory separation distance.

The amount of cobble cortex on the AH III lithics indicates that the A3C occupants at this time favored, to some extent, collection from secondary deposits of water-worn obsidian nodules more than blocks from primary outcrops on Sevkar and Satanakar volcanoes. Recall that at Lusakert Cave 1, Frahm et al. (2016) interpret the collection of obsidian readily available in the adjacent river valley, rather than from primary outcrops up the slope of Gutansar volcano, as embedded procurement. Also trout (*Salmo* sp.) remains in AH III suggest not only more diverse subsistence activities in this cooler and drier phase but also more time spent along rivers during such activities. Embedded procurement during diversified subsistence activities might also correlate with the greater variability in obsidians in AH III, both of which may reflect a larger territory

size at this time. Brantingham (2003) has argued that, when considering the transport of toolstone, the null hypothesis should involve random movement and entirely embedded procurement, rather than exchange and direct procurement. Consequently, while we do not completely rule out other possibilities, our current working hypothesis is that, during the deposition of AH III, the A3C occupants principally practiced embedded procurement of, at least, obsidian.

Inter-group contacts increase as the territory separation decreases—this occurs regardless of the mobility, procurement, or provisioning strategies and their combinations. This relationship is not a linear one: as territory separation decreases, the frequency of inter-group contacts increases following a cubic function. This is the simplest relationship between our variables as a cause and the frequency of contacts as an effect. It also has complicated interplays with other variables—in particular, territory radius and procurement strategy—to affect opportunities for groups to interact. One mechanism that could account for smaller foraging territory separations during the deposition of AH III is an existing hypothesis that the Southern Caucasus served as a refugium during glacial conditions. If true, increasing population densities could be expected to have occurred as the climate cooled at the onset of the LGM.

Discussion

It may be a coincidence that far-traveled obsidians and evidence of clothing production and adornment occur in AH III, but we propose that both might be related to increased chances of interaction between different foraging groups on the landscape. The situation may have been roughly analogous to Hodder's (1977) findings in the Lake Baringo area of Kenya. He showed that ear decorations of Tugen, Njemps, and Pokot women were used as a highly visible means to assert tribal distinctiveness and affiliation. Kuhn and Stiner (2007) also have discussed the roles that Palaeolithic body ornamentation, especially shell beads, played as a technology that communicated social information and identification.

Over the course of A3C's occupation, lithic production was focused on unidirectional reduction of small cores to manufacture laterally retouched and backed bladelets. While this pattern remained more or less constant, WABI analysis indicates a trend from more expediency to more curation from AH VII to IV, followed by a strong shift back to expediency in AH III. As shown in Fig. 6, our data for the four oldest lithic assemblages appear to follow a fairly consistent trend over time. There is, however, a considerable change in AH III. Its volumetric density is an order of magnitude greater than that for any other horizon, but its retouch frequency is comparable to the two oldest horizons. The postulates of WABI suggest that AHs VII and III reflect higher logistical mobility, AH IV reflects higher residential mobility, and AHs VI and V fall in between. This would be consistent with other indicators, especially the occurrence of combustion features: AH VI had concentrations of lithics, fauna, and charcoal around small, isolated fireplaces while AH III exhibits evidence for more complex structures related to the use of fire. There is, though, clearly a behavioral difference between AH VII and III given their volumetric densities. A roughly analogous case occurs in UP assemblages at Üçağızlı cave in Turkey (Kuhn 2004). At that site, data for the older layers fell into consistent patterns for various proxies (i.e., proportion of non-pebble

cortex versus a disparity index, versus proportion of retouched pieces, versus ratio of blanks per core); however, the youngest layers (B and B1−B4) exhibited clear differences that indicate marked changes in lithic transport and use.

Previous research (Barton et al. 2011) has suggested that a change from residential to logistical mobility could increase opportunities for different foraging groups to encounter each other. Other work (Premo 2012) proposes that the opposite will occur. Our ABM simulations establish that both outcomes can occur, depending on variables such as procurement strategy, and that a residential-to-logistical shift has only a small effect unless the territories are or become closely spaced (≤ 50 patches). Territory size is another variable that does not have a consistent effect on the opportunities for intergroup encounters. An increase in radius can increase or decrease the frequency of encounters, depending on variables such as territory spacing and procurement strategy. Ethnographic data suggest that the A3C occupants were likely to have increased their foraging distances as the climate cooled, reducing the carrying capacity of the landscape and compelling a wider range of subsistence activities (e.g., fishing). If the territories were widely spaced, this change tends to slightly increase the chances of encounters.

Two variables have predictable and strong effects on the opportunities for encounters. First is procurement strategy. In our ABM at least, direct procurement increases the number of encounters under all circumstances (e.g., residential versus logistical mobility, small versus large territories). At present, we cannot explain our sourcing results in terms of changing procurement strategy. If anything, our data indicate that a greater degree of embedded procurement occurred during the deposition of AH III. If we interpret A3C consistently with Lusakert Cave 1, more cortex among the AH III lithics would support greater embedded procurement. At Lusakert Cave 1, Frahm et al. (2016) interpreted collecting obsidian readily available in the river valley, rather than from outcrops on the volcano slopes, as evidence of embedded procurement. Consequently, the amount of cortex on the AH III lithics implies that the A3C occupants at this point in time favored, to some degree, (1) collection from secondary deposits of water-worn cobbles and (2), in turn, embedded procurement of obsidian.

The second variable is foraging territory spacing. If, indeed, the Southern Caucasus served as a refugium during glacial conditions (e.g., Bar-Yosef 1994; Dennell et al. 2011; Finlayson 2004), increasing population densities would be anticipated as the climate cooled. This is not a linear effect. It follows a cubic function so that, as territories get closer, a small decrease in their spacing can yield large increases in encounters. This appears to be consistent with the simulations of Perreault and Brantingham (2011), although their exponential relationship takes a somewhat different form than ours. Consequently, this is a likely—but far from certain—cause of what we interpret as greater inter-group interactions, especially during the deposition of AH III. When based on archaeological data, claims for refugia commonly involve reported differences in material culture over large geographic scales, such as proposals by Banks et al. (2008) that the people producing Solutrean artifacts on the Iberian Peninsula were separated from people producing Epigravettian artifacts on the Italian and Balkan Peninsulas. Continental-scale biogeographical or genetic studies are also common (e.g., Yunusbayev et al. 2012; Platt et al. 2017). In this case, however, we advance such a hypothesis on the basis of a single archaeological site, stressing that we make

this suggestion as one part of an iterative process of model building and testing using archaeological datasets.

As noted by Kandel et al. (2017), archaeological sites contemporaneous with A3C are currently not known in the Armenian Highlands. Many of the open-air UP sites mentioned in the Soviet literature have been re-identified as Neolithic or Chalcolithic lithic workshops near obsidian sources (Gasparyan et al. 2014). The open-air site of Kalavan 1 in northern Armenia dates to the Late UP: 18–16 ka (Montoya et al. 2013; Tornero et al. 2016). Therefore, A3C remains, to date, the only known early UP site in Armenia. Of course, support for increasing population densities at the time of AH III is predicated on identification of further contemporaneous sites and their excavation to modern standards.

As we alluded to in the "Introduction," there are abstractions within the current iteration of this ABM model with room for improvement (with corresponding increases in the requisite computing power and time). For instance, at present, foraging territories within the current model are flat and featureless (with the exception of toolstone sources), so future versions might include features such as mountains or bodies of water within asymmetrical territories. One choice in the current model is that territory sizes are set by a user at the start of a simulation. Rather than the territory size being imposed in this way, a more sophisticated model might allow the territory sizes to emerge as a function of subsistence requirements and the carrying capacities of different ecological zones scattered across the landscape. Such a model would, in this regard, better reflect Premo's (2012) ABM, in which foraging agents moved their base camps only after the resources within a specified foraging radius had been exhausted. Many other behaviors could, in theory, be added to agents. For example, foraging agents could seek to optimize their spacing on the landscape or follow choices from game theory. Other potential additions to the model include the transmission of a trait that improves fitness and a trait that does not. This could show differences in transmission with and without selective pressure. For example, a trait of the agents could be exchanged either at random or only when sufficiently similar. It could also be advantageous to simulate different types of interactions, varying from chance encounters to exogamy.

We note that, especially in light of simulations by Perreault and Brantingham (2011) and others, it would be advantageous to model variables such as residential versus logistical mobility as continuous rather than discrete, as currently modeled. At present, the model permits foraging agents to spend, for example, 20% of time as residentially mobile and the other 80% as logistically mobile. Accordingly, in one of our 5000-tick simulations, the two agents could spend a total of 1000 ticks as residentially mobile and 4000 ticks as logistically mobile. This is the closest that the current model allows for mobility to exist on a continuum. During our initial tests, we did examine the effects of varying the proportion of ticks spent in each mobility strategy and found that the outcomes simply fit the arithmetical expectations from the two extreme conditions. That is, in the above example, the resulting values were simply weighted averages: a 20% contribution from the residential mobility dataset and 80% from the logistical one.

Would we expect our results to be radically different with the addition of such variables and an increased sophistication of the model? This is a difficult question to address at this point. However, in the case of Barton et al. (2011) and Premo (2012), who had differing interpretations as to whether a change from residential to logistical

mobility would increase or decrease opportunities for interactions, additional variables in our ABM reveal that both outcomes can occur. That is, a more sophisticated model was able to bring coherence to an apparent contradiction between Barton et al. (2011) and Premo (2012). Added variables in our model resolved this contradiction rather than brought about new ones. We expect that, when models continue to be iteratively tested against archaeological data, such a trend might continue. Additions to the model would not necessarily radically change the results we report here but, hopefully, add nuances that aid comparisons to archaeological sites and, consequently, further refine interpretations based on contrasting archaeological and simulated data.

Conclusions

Sourcing 1120 obsidian artifacts from A3C established that, between AH VII and AH III, the presence of obsidian from non-regional volcanic sources rose notably from 1% to 8%. Not only does AH III contain the highest proportion of obsidian from non-regional sources but also these obsidian artifacts originate from the greatest number of such sources. Five of the sources are distant (110–180 km), and the other two are long-distance sources ($\geq$ 270 km on foot) in different directions: Pokr Arteni to the northwest and Meydan Dağ to the west-southwest. AH III also included evidence of clothing production and adornment. The beads' concurrence with a variety of far-traveled obsidian artifacts might be coincidental; however, both of these phenomena could be explained by greater chances for interactions among different foraging groups as the climate cooled during the onset of the LGM.

As the climate cooled, the A3C occupants likely increased their foraging distances in response to the carrying capacity of their surroundings. Ethnographic data demonstrate that foraging populations in cooler climates must move farther to sustain themselves. Rough effective temperature estimates for the warmest and coolest phases at A3C suggest that foraging movements likely increased in distance on the order of two-thirds during the deposition of AH III. It might be that the five distant obsidian sources in AH III—all 110–180 km away and in roughly the same direction—reflect greater distances traveled by the A3C occupants during this phase. Obsidian from Pokr Arteni and Meydan Dağ, however, was transported over distances more consistent with the "social landscape" rather than foraging. Hence, we interpret our results as evidence that, during the AH III deposition, the A3C occupants not only moved farther distances during subsistence activities but also more frequently encountered neighboring groups.

Between AH VII and III, there is a shift from more natural fracture planes on the lithic artifacts to more cobble cortex. These data indicate that, while the occupants initially preferred obsidian collection from primary outcrops at the volcanoes, there was a change toward preferred collection from secondary deposits of water-worn nodules along river valleys. This also coincides with greater variability in toolstone raw materials (e.g., more cherts) and subsistence activities in AH III. Therefore, our working hypothesis is that the AH III assemblage largely reflects embedded procurement.

Lithic production at A3C was, throughout its occupation, focused on the unidirectional reduction of small cores to make laterally retouched and backed bladelets. WABI analysis, however, reveals a trend from more expediency to more curation from AH VII

to IV, followed by a strong shift back to expediency in AH III. This, in turn, suggests that there was an increase in the practice of residential mobility from AH VII to IV, followed by a considerable shift back to greater logistical mobility during AH III, which, unlike the other layers, exhibits evidence for abundant and complex combustion structures.

Past research (Barton et al. 2011; Premo 2012) has disagreed whether a change from residential to logistical mobility would increase or decrease opportunities for different foraging groups to encounter one another on the landscape. ABM simulations show that the relationships between mobility strategy and the frequency of inter-group interactions are nonlinear and largely depend on territory separation and procurement strategy. It is not as simple as logistical mobility leading to more or fewer opportunities for interaction than residential mobility. When foraging territories are both small and closely spaced, embedded or direct procurement makes the difference between either a drop or a rise, respectively, in contacts during a change from residential to logistical mobility. Otherwise, a residential-to-logistical shift has only a small effect. Additionally, territory size is not a simple, independent variable when it comes to the chances for inter-group contacts. Based on our simulations, we cannot explain the evidence of greater interactions in AH III as an unavoidable outcome of a shift from residential to logistical mobility. Certain variables (i.e., lithic stock, use intensity, provisioning strategy) can be excluded as increasing interactions, while other variables (i.e., decreased toolstone source density on the landscape, a change from embedded to direct procurement) appear inconsistent with the archaeological data for AH III.

Territory spacing, in contrast, has a clear and predictable effect. Perreault and Brantingham (2011) have called this relationship "mechanistic." Inter-group contacts increase as foraging territory separation decreases—this occurs regardless of changes in mobility, procurement, or provisioning. This phenomenon is also nonlinear—it follows a cubic function, so that a small decrease in spacing yields large increases in encounter opportunities. Furthermore, it has been hypothesized that the Southern Caucasus served as a refugium during glacial conditions. Assuming that foragers would preferentially move into more mild and stable environments at this time, such a phenomenon is one mechanism that can account for smaller territory separations during the deposition of AH III: increasing population densities would be expected as the climate cooled. Consequently, it appears that our analyses and data are pointing toward greater inter-group interactions during AH III as the outcome of closer foraging groups. Support for this hypothesis will require further archaeological data from contemporaneous Southern Caucasus sites.

Compliance with Ethical Standards

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