The effects of secondary recycling on the technological character of lithic assemblages

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Abstract: Recycling of lithic artifacts, including both lithic scavenging and secondary recycling, is a widely recognized phenomenon in the Paleolithic archaeological record, in some instances creating tools with morphological signatures characteristic of multiple time periods or technological systems. These types of tools often define transitional industries including those at the Middle-to-Upper Paleolithic transition, suggesting a variety of behavioral interpretations for the supposed evolution of Middle Paleolithic toolkits to Upper Paleolithic toolkits. Here we test an alternative hypothesis that transitional assemblages formed via secondary recycling of stone artifacts produced by two technologically divergent populations. Results from the application of an agent-based model indicate how ordered sets of assemblages resembling archaeological transitional sequences can result from the combination of simple recycling behaviors and periods of sediment deposition and erosion. This implies that some transitional assemblages could have formed without the interaction of different populations and/or without technological evolution.

Keywords: Lithic recycling, lithic scavenging, transitional industries, agent-based modeling

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Lithic artifacts were recycled throughout prehistory in many areas of the globe (Amick 2007, 2015; Assaf et al. 2015; Baena Preysler et al. 2015; Barkai 1999; Barkai et al. 2015; Belfer-Cohen and Bar-Yosef 2015; Camilli 1988; Gravina and Discamps 2015; Hiscock 2009, 2015; Shafer and Hester 1991; Shimelmitz 2015; Turq et al. 2013; Vaquero 2011; Vaquero et al. 2012, 2015; Whyte 2014). However, because of difficulties in identification, recycling as a process receives comparatively little attention in the archaeological literature (Vaquero 2011). This is problematic because recycling has the potential to affect chronological and compositional assessments of assemblages by creating misleading associations between items that were not used together in the same space or time (Amick 2015; Camilli and Ebert 1992). Recycling can also cause a spatial displacement and fragmentation of reduction sequences, sometimes with preferential selection of specific shapes and sizes for recycling (Belfer-Cohen and Bar-Yosef 2015; Vaquero et al. 2015).

Secondary recycling (as distinguished from *reuse*) involves a functional change to an object often coinciding with a cultural or technological break and a period of discard between episodes of use (Baena Preysler et al. 2015; Barkai et al. 2015; Vaquero et al. 2015). Secondary recycling of archaeological lithic artifacts by comtemporary people is a well-recognized phenomenon ethnographically (Amick 2007; Holdaway and Douglass 2012), with examples ranging from the reuse of prehistoric arrowheads in North America, the reliance on archaeological material for hide scrapers in Africa, and the reuse of ancient stone tools in Australia (Amick 2007; Gould et al. 1971; Holdaway and Douglass 2012; Weedman 2005). Demonstrating time depth between instances of reuse during the Paleolithic is harder (Amick 2014; Barkai et al. 2015). Usually, the presence of double patina or other surface alterations is used to demonstrate timelapse between multiple flaking events (Turq et al. 2013; Vaquero 2011; Vaquero et al. 2012), although not all recycled artifacts will necessarily display these features and some patinas can form in a relatively short time span (Belfer-Cohen and Bar-Yosef 2015).

One important consequence of lithic recycling is that it questions the intentionality behind identifiable lithic types because recycling may involve the transformation of an object into a new form (Barsky et al. 2015; Vaquero et al. 2015; Whyte 2014). Belfer-Cohen and Bar-Yosef (2015), for example, identified double patinated tools displaying Upper Paleolithic morpho-types on Levallois-produced blanks in two Aurignacian contexts, Kebara and Hayonim cave sites in Israel. Similarly, in Sefunim cave, retouched Middle Paleolithic blanks occur in Aurignacian contexts (Ronen 1984). Given the spatio-temporal ubiquity of documented instances of recycling, it is safer to assume that recycling was common rather than rare in prehistory even when it is impossible to detect. Therefore, we should include it in explanations regarding the character of assemblages.

Industries labeled ‘transitional’ in the literature constitute one particularly salient example. These contain tool forms with characteristics intermediate between those of earlier and later periods (e.g. Kuhn 2003; Kuhn et al. 1999; Kuhn and Zwyns 2014). One interpretation of *transitional* in such situations involves the hypothesis of technological evolution where industries contain mixtures of characteristics from both a preceding and a subsequent period, and/or features that are intermediate between the two because of changing cultural norms through either invention or adoption (Kuhn 2003; Tostevin 2000). However, an alternative hypothesis proposes that transitional forms are the outcome of secondary recycling rather than the presence of a single, mixed technology.

In this paper, we test the utility of the secondary recycling hypothesis for explaining the appearance of transitional industries using agent-based computer simulation. As with any simulation of complex behavior, such models are usually too simplified to map directly onto a real system, specifically systems with cultural components (Breitenecker et al. 2015; André Costopoulos 2015). Instead, agent-based models provide an environment for experimentation to understand the feasibility of possible hypotheses for the formation of the archaeological record (Barceló and Del Castillo 2016; Barton and Riel-Salvatore 2014; Davies et al. 2016; Dean et al. 2000; Kowarik 2012; Premo 2006, 2010). Agent-based models simulate the process of creating phenomena emergent in the archaeological record (Crabtree and Kohler 2012).

The simulation presented in this paper implements a simplified theoretical model of secondary recycling by two technologically distinct populations in an environment experiencing episodic erosion and deposition to see how these phenomena might affect the formation of transitional industries. The two populations recycle visible artifacts by applying retouch to available blanks. We stress that the model does not determine the actual processes that occurred in the past but instead constitutes a tool to test the secondary recycling hypothesis. We show that secondary recycling is capable of producing site stratigraphies and assemblages resembling those described for transitional industries. This means that secondary recycling is a potential explanation for the formation of these industries.

Methods

Model description and basis

The model presented here simulates simplified secondary recycling behaviors on a landscape that undergoes erosional and depositional events. The model simulation described was developed in R 3.6.1 (R Core Team 2019) and is available as an RScript (Online Resource 1). Model description following the ODD protocol (Grimm et al. 2006, 2010) is also available as a supplement (Online Resource 2). A new model was created that combines methodologies from Barton and Riel-Salvatore (2014) and Davies, Holdaway, and Fanning (2016) to examine how recycling behaviors affect the formation and subsequent interpretation of an archaeological assemblage. The process of erosion and deposition of sediments used for this model (described below) comes from Davies and colleagues (2016) in their modeling of the effects of these geological processes on the formation of archaeological surface records. Deposition of sediment causes artifacts to become invisible on the surface, whereas erosion either removes surface artifacts or exposes previously discarded artifacts. The majority of agent behavior (explained below) comes from Barton and Riel-Salvatore's (2014) model of the formation of lithic assemblages. Agents have the ability to move between specific locations, and to carry, make, and retouch artifacts in both models. Our model differs from that of Barton and Riel-Salvatore (2014) by allowing for unlimited retouching of artifacts, since we are interested in the final form of these artifacts instead of their intensity of retouch. Additionally, the agents in the model presented here do not need to collect raw materials but instead collect lithic resources from previously discarded artifacts to mimic the lithic scavenging and secondary recycling behaviors of interest.

Model entities

The model has three interacting parts: a landscape that contains artifacts and undergoes erosional and depositional events, mobile agents who move between designated sites to manufacture and discard lithics, and the lithic artifacts themselves that are subject to collection, retouch, and deposition.

Each element of the landscape array (hereafter, patch) contains a number to represent the arbitrary “age” of the sedimentary layer at a place in the environment and step in the model run. Each patch also has an associated list of artifacts (described below) associated with the particular place and time step of the model.

An agent represents a mobile foraging group with an identification number, a random starting location, a specific technology type, and an artifact list. The agents move between sites, randomly selecting a new destination from their previous location. The groups have *two distinct technologies*, with half having technology type 1 and the other half type 2. If there is no temporal overlap or only half overlap between the two technology types, only the type 1 groups are present on the landscape to start with; otherwise, both populations exist for the duration of the model run. For no overlap, halfway through the model run, type 2 groups replace the type 1 groups. For half overlap, after a third of a model run, type 2 groups appear on the landscape, with type 1 groups disappearing after two-thirds of a model run.

The artifacts in this model are objects represented by a number that denotes the current stage of manufacture, an ordered list of the groups who have retouched the artifact, an ordered list of the technology types used to make retouch, and a number corresponding to its current location in the storage container. Any artifact at manufacture stage 1 is a blank. An episode of retouch occurs through modifications performed by a group to the artifact beyond stage 1. Any artifact that has experienced at least one retouch event, and therefore has a manufacture stage of 2 or more, is considered a tool. At initialization, some locations on the landscape have blanks of technology type 1; this allows recycling behaviors to start immediately using the assumption that the events in the model would occur on a landscape previously occupied by populations with technology type 1.

Model process overview

At each step of the model run, all agents move to a random location in the environment. Agents perform behaviors at a constant rate, choosing between two courses of action. The model prioritizes recycling behaviors, so these happen 75% of the time. During the other 25% of the time, agents will produce blanks of that agent’s technology type. If recycling behaviors occur, the agent collects artifacts if any are currently visible, retouches any artifacts it is holding according to the agent’s technology type, and then randomly drops some of its artifacts. Any artifacts not dropped move with the agent to its next location.

Only the uppermost layer at a site provides collectable artifacts. The agent may collect artifacts until there are up to 30 in its possession, following the maximum use intensity set by Barton and Riel-Salvatore (2014). Collection occurs without regard for any previous retouch; the only rule for collection is that artifacts with the lowest stage numbers are collected first, following observations that secondary recycling involves preferential selection of thicker elements (Belfer-Cohen and Bar-Yosef 2015). Artifacts that experience more retouch will reduce in size, so modeled artifacts at lower manufacture stages have larger dimensions. This collection behavior allows for recycling to occur.

After collection, each artifact currently held is retouched; the retouch stage increases by 1, with the technological type and identification number of the group recorded. At the end of a model run, assemblage analysis involves only the first and last technology types of an artifact. Following this, the agent randomly drops artifacts until it is carrying only 10 artifacts, the maximum number that any group can take to a new destination.

Geological events – either erosion or deposition of sediment – occur randomly at each patch with the frequency of these events varied to determine its effect on the patterns produced by the model. When deposition occurs, the particular landscape array element acquires the current age of the model, with each time-step representing an arbitrary increment in time units. When erosion occurs, the particular landscape array element acquires the age of the chronologically preceding layer.

Model initialization and experimental parameters

The model runs with an environment of 6 x 6 size for 2000 time-steps on New York University's high-performance computing clusters. Each time-step represents 100 arbitrary time units with the starting point set at 250,000. Time units distinguish simulated layers and assemblages based on their contemporaneity.

For this study, we investigated how the overlap of groups and the relationship between agent behaviors and geological events structured assemblage composition. Additionally, we looked at how population density, calculated as the number of total groups over environment size, and frequency of erosional and depositional events affects these patterns. The model runs used varying numbers of total groups, varying frequencies of geological events, varying proportions of sediment erosion and deposition, and varying overlap parameters.

Each experiment ran 20 times to capture variability of the simulation experiments. At the end of the model run, artifact type (see Table 1) count data was collected for each assemblage and step of the model, in every site. Artifacts are described as blank type/final retouch type; therefore, an artifact whose blank technology is type 1 and whose final retouch technology is also type 1 would be described as a 1/1 tool. Transitional industries are said to have tools with a mix of Middle Paleolithic and Upper Paleolithic characteristics; for example Middle Paleolithic blanks with Upper Paleolithic retouch. These tools are comparable to the 1/2 tools produced by the model.

Table 1. Artifact type descriptions

Artifact type	Description
type 1 blanks	artifacts in stage 1 of technology type 1
type 2 blanks	artifacts in stage 1 of technology type 2
tools	artifacts in stage 2 or greater
mixed artifacts	artifacts in stage 2 or greater with a different blank type and final retouch type
1/1 tools	tools with blank type 1 and final retouch type 1
2/2 tools	tools with blank type 2 and final retouch type 2
1/2 tools	tools with blank type 1 and final retouch type 2
2/1 tools	tools with blank type 2 and final retouch type 2

Model output and assemblage analysis

After the completion of a model run, analysis proceeded by location on the landscape (hereafter, site), each of which had its own stratigraphy of layers. Layers at a site defined assemblages if they contained tools, meaning an artifact at stage 2 or above. Coding for each assemblage used the presence of tool types as described in Figure 1.

Figure 1. Assemblage codes and visualization. The ovals represent retouched tools, and the colors correspond to technology type. Blank type is indicated by the outline color; retouch type is indicated by the cross-hatch color as specified by the key to the right of the table.

Results

Each set of experimental parameters produced between 30 and 36 sites for each model run. Sites contained between 1 and 59 assemblages. Using the assemblage codes explained in Figure 1, Figure 2 shows the proportions of assemblage types by experimental parameters. Type A assemblage have only tools with type 1 technological signatures, type B assemblages have tools with type 2 technological signatures, and type AB assemblages have a mixture of both 1/1 and 2/2 tools. The mixed typology tool assemblages are of either type M1 with only 1/2 tools, or type M2, with 2/1 tools. In the figure, larger dots correspond to larger proportions. Pure technology type assemblages (type A and type B) are relatively rare in full overlap conditions; since full overlap has high proportions of mixed typology assemblages (type M1 and type M2). In no overlap conditions, M2 assemblages are absent. The overall rarity of assemblages with a mix of 1/1 and 2/2 tools (type AB) is an artifact of the model that emphasizes recycling behaviors.

Figure 2. Proportions of assemblage types by experimental parameters. Size of the dot is proportional to the proportion of each assemblage type out of the total assemblage count.

Assemblages with type 1/2 tools (type M1 assemblages)

Every set of experimental parameters produces some proportion of sites with one or more M1 assemblages that contain type 1/2 tools (i.e. blank type 1 with retouch type 2), the equivalent of intermediate tool types used to define some transitional assemblages (Figure 3). This suggests secondary recycling as a viable explanation for the production of transitional stone tool forms.

Figure 3 indicates how the interaction of the frequency of agent behavior (x-axis), population density, and the overlap of the technological populations has impacts on the prevalence of sites with this type of mixed typology assemblage. The frequency of agent behavior relative to frequency of geological events has different effects on the proportion of sites with M1 assemblages depending on the overlap conditions. Secondary recycling of archaeological deposits depends on geological processes of erosion and deposition which allows for access to previously discarded artifacts (Camilli and Ebert 1992). For no overlap conditions, when geological events are more frequent there are fewer sites with M1 assemblages. The modeled geological events reduce the ability of populations to recycle by burying or removing previously discarded artifacts. Conversely, in full and half overlap conditions, when geological events are more frequent there are more assemblages with M1 assemblages. More geological events mean a greater chance for preserving M1 assemblages through burial, instead of leaving them exposed and available for further recycling resulting in the introduction of type 2/1 tools (see below).

Population density amplifies all these trends because high population densities are effectively a proxy for increased intensity of recycling behaviors, which result in more locations in the model world preserving assemblages.

Figure 3. Proportions of sites with presence of at least one assemblage that have tools of type 1 blanks with type 2 retouch. A visualization of the assemblage is given to the right of the boxplots. The ovals represent retouched tools, and the colors correspond to technology type. Blank type is indicated by the outline color; retouch type is indicated by the cross-hatch color as specified by the key.

Production of type 2/1 tools (type M2 assemblages)

In full and half overlap conditions, the production of tools of blank type 2 and with retouch type 1 always occurs, whereas this type of tool is absent when the populations do not overlap. This is because in no overlap conditions it would be impossible for populations with technology type 1 to retouch a tool with blank type 2 as those blanks do not occur until the population with technology type 2 is on the landscape. This phenomenon is most common in full overlap conditions and in half overlap conditions with high population densities (see Figure 4).

Figure 4. Proportions of sites with presence of at least one assemblage that have tools of type 2 blanks with type 1 retouch. A visualization of the assemblage is given to the right of the boxplots. The ovals represent retouched tools, and the colors correspond to technology type. Blank type is indicated by the outline color; retouch type is indicated by the cross-hatch color as specified by the key.

"Transitional" sequences

"Transitional sequences" exhibit M1 assemblages with type 1/2 tools preceded by any number of A assemblages with only type 1/1 tools and/or followed by any number of B assemblages with only type 2/2 tools in stratigraphic order.

Model runs of the no overlap condition produce the most "transitional" stratigraphies. The half and full overlap conditions do produce full transitions, or sites with M1 assemblages preceded by A assemblages and followed by B assemblages, but only very rarely. Within the no overlap results, larger numbers of geological events reduce the frequency of "transitional sequences", because, as stated, these geological events reduce the possibility for recycling by burying or removing previously discarded assemblages.

In full overlap conditions, transitional sequences are rare for any frequency of geological events because 1) the majority of sites produced in full overlap conditions only have assemblages with mixed typology tools, and 2) the full overlap conditions produce on average the longest stratigraphic sequences allowing for more variation in the sequence structure. Half overlap conditions do not produce very many full "transitional" sequences either but do produce varying numbers of sequences with either a preceding type A assemblage with only type 1/1 tools or a subsequent type B assemblage with only type 2/2 tools depending on the frequency of geological events. When geological events are less frequent, there are more sequences with B assemblages following a M1 assemblage. Conversely, when geological events are more frequent, M1 assemblages are more often preceded by an A assemblage. Type A assemblages are preserved when geological events are more frequent because they are not available for recycling by populations with technology type 2. Less frequent geological events expose A assemblages for potential recycling for longer, reducing the frequency of preceding pure type A assemblages.

Figure 5. Proportions of "transitional" sequences by experimental parameter settings. Each color represents a different "transitional" sequence as visualized by the stratigraphies given in each black box to the right of the boxplots. The ovals within the black boxes represent retouched tools, and the colors correspond to technology type. Blank type is indicated by the outline color; retouch type is indicated by the cross-hatch color as specified by the

key. Assemblages are separated within the black boxes by dotted lines to indicate relative stratigraphic positions as they would appear archaeological, with the oldest assemblage on the bottom and youngest on the top.

Reverse "transitions"

Reverse "transitions" occur where M1 assemblages with type 1/2 mixed typology tools are *preceded* by B assemblages with only type 2/2 tools or *followed* by A assemblages with only type 1/1 tools. However, in no cases did a site have both these conditions even though in all overlap conditions type M1 assemblages preceded by type B assemblage were produced (Figure 6). Because these transitions were created in all parameter conditions, if recycling played a role in assemblage formation, assemblages conforming to the patterns of either an M1 assemblage preceded by a type B assemblage or followed by a type A assemblage with only type 1 technology signatures should be expected.

Figure 6. Proportions of reverse "transitional" sequences by experimental parameter settings. Each color represents a different reverse "transitional" sequence as visualized by the stratigraphies given in each black box to the right of the boxplots. The ovals within the black boxes represent retouched tools, and the colors correspond to technology type. Blank type is indicated by the outline color; retouch type is indicated by the cross-hatch color as specified by the key. Assemblages are separated within the black boxes by dotted lines to indicate relative stratigraphic positions as they would appear archaeological, with the oldest assemblage on the bottom and youngest on the top.

Sensitivity to type of geological event

The final analysis investigated the sensitivity of the results to the predominant type of geological event, either sediment deposition or erosion. Because the results described above are similar for full and half overlap conditions, sensitivity analysis used only the half and the no overlap conditions (Figure 7). When there is overlap, more deposition amplifies the patterns described because layers are not exposed, allowing for greater preservation (e.g. the "transitional" sequences described above). When there is no overlap, more deposition reduces the frequency of recycling overall by obscuring layers more quickly, which means that "transitional" sequences are less likely to form. Conversely, more erosion has the opposite effects. When there is overlap, more erosion allows for exposure of layers for more recycling to occur which results in fewer stratigraphic sequences of a "transitional" nature because assemblages are more likely to have mixed characteristics. However, when there is no overlap, more erosion exposes layers for the later type 2 populations to recycle, allowing for higher frequency of "transitional" sequences.

Figure 7. Proportions of "transitional" sequences by predominant type of geological event. Each color represents a different "transitional" sequence as visualized by the stratigraphies given in each black box to the right of the boxplots. The ovals within the black boxes represent retouched tools, and the colors correspond to technology type. Blank type is indicated by the outline color; retouch type is indicated by the cross-hatch color as specified by the key. Assemblages are separated within the black boxes by dotted lines to indicate relative stratigraphic positions as they would appear archaeological, with the oldest assemblage on the bottom and youngest on the top.

Discussion

Can recycling result in "transitional" assemblages?

The simulations reported here tested the hypothesis that secondary recycling can produce transitional assemblages (i.e. those with intermediate technological signatures). Results show the production of artifact assemblages with signatures of both technologies for every set of experimental parameters. This supports the hypothesis that recycling behaviors are a potential explanation for the mixed/intermediate character of transitional forms. Furthermore, secondary recycling frequently produces "transitional" sequences that appear to progress from technology type 1 into a mixed technology type and/or from a mixed technology type into technology type 2 when there is a clear chronological relationship between these two technologies, as when the populations do not overlap or overlap for part of the time. When there is not a chronological relationship between the two technological systems and both populations overlap completely in time, transitional sequences are less common.

Results also show how secondary recycling produces sequences that depart from the assumed chronological relationship between earlier technology type 1 and later technology type 2 sequences. Model results show technology type 2 assemblages preceding, or technology type 1 assemblages following intermediate assemblages. This is most common when there is full overlap of the technologies. This model also demonstrates that the frequency and predominant type of geological events influences "transitional" sequence formation. Erosion or deposition events, and the time between such events leads to more or less exposure time for previously discarded assemblages. As exposure time increases, recycling becomes more likely (Camilli and Ebert 1992; Vaquero 2011). Additionally, the way in which these factors influence the types of sites created is dependent on whether or not there was overlap between the two technologically divergent populations. This relationship needs further consideration when assessing the archaeological record in different contexts (cave/rockshelters vs. open-air sites). Additionally, intensity of recycling affects the patterns produced by simple secondary recycling approximated in the model by increased population density (i.e. more groups practicing recycling behaviors). This also needs consideration when assessing the formation of archaeological assemblages.

The results of this model demonstrate how secondary recycling introduces complexity into the archaeological record by iteration of a small number of parameters. With a model of two chronologically related populations with distinct technologies, secondary recycling produces five types of assemblages with distinctive technological signatures depending on the degree of mixture between two technological systems. In the model, three of the five assemblage types are palimpsest phenomena. This suggests that secondary recycling may lead to overestimating the number of unique technological systems in the archaeological record. Additionally, secondary recycling produces stratigraphic sequences that complicate chronological relationships between technological types, at times suggesting chronological relationships between two technological systems that may not have existed. This is of course not just an issue with what are termed transitional assemblages; if secondary recycling occurred at any time in a stratigraphic sequence, outcomes like those simulated in our model likely had some impact on assemblage composition and therefore lithic industry definitions.

In the following, we consider the results of the simulation model for an archaeological case study, the Middle-Upper Paleolithic transitional industry labelled the Initial Upper Paleolithic (IUP).

Case study: implications for interpretation of the Middle-Upper Paleolithic transition record

At the transition from the Middle Paleolithic to the early Upper Paleolithic in Eurasia, many lithic industries are labeled as "transitional" to designate their intermediate nature (Kuhn 2003; Kuhn and Zwyns 2014; Riel-Salvatore 2009). These industries, called by different names and located in different regions, date to approximately 50 – 35 ka, at the time modern humans moved into new areas (Bednarik 2009; Hublin 2015; Kuhn 2003; Zilhão and D'Errico 2003).

One of these transitional industries, the Initial Upper Paleolithic (IUP), shows obvious technological connections with the antecedent Middle Paleolithic (through the use of Levallois-style reduction) and subsequent Upper Paleolithic (through the creation of characteristically Upper Paleolithic tool types) (Kuhn 2018; Kuhn et al. 1999; Kuhn and Zwyns 2014). The term, IUP, was coined to describe the lithic industries from layer 4 at Boker Tachtit, characterized by a method of blade production that combined Levallois and Upper Paleolithic volumetric core reduction behaviors (Kuhn and Zwyns 2014). Additionally, the layer 4 assemblage demonstrated the production of artifacts resembling Levallois blades and points, but these do not appear at the end of the reduction sequences, suggesting another end form was intended (Kuhn and Zwyns 2014). Subsequent revisions of the term have expanded the IUP to describe any assemblages dominated by Upper Paleolithic retouched tool forms, where many are made on Levallois-style blade as indicated by features of Levallois in blank production (Kuhn 2018; Kuhn et al. 1999; Kuhn and Zwyns 2014; see Table 2 and references therein for examples). This, in addition to further analysis of Boker Tachtit, has also led to reclassification of Boker Tachtit layers 1 through 3 as IUP and Boker Tachtit layer 4 as Upper Paleolithic (Škrdla 2003). Because the IUP combines Levallois-style blank production with Upper Paleolithic-like tool types, these assemblages are often characterized as an evolution of technology based on Levallois technique toward blade technologies and blade-based retouched tools, therefore representing a logical link between Middle and Upper Paleolithic technological strategies (Hublin 2015; Kozlowski 2000; Kuhn 2018; Rybin and Khatsenovich 2018).

Typically, acculturation, independent *in situ* development, or an adaptive response based on interaction/observation with Upper Paleolithic populations provide behavioral explanations for transitional industries (Bednarik 2009; Clark 2009; Clark and Riel-Salvatore 2006; Harrold 2009; Riel-Salvatore 2009; Roussel et al. 2016; Zilhão and D'Errico 2003). Such explanations require that the Middle Paleolithic technologies necessarily evolved into Upper Paleolithic technologies. They also assume knowledge of technological behaviors distinguishing Middle Paleolithic and Upper Paleolithic from those that were continuous across the periods.

The secondary recycling hypothesis makes no such assumptions requiring only the visibility of artifacts and their selection for recycling. The simulation results show how secondary recycling might permit IUP-like assemblage formation through behaviors that mimic a culturally mediated process of lithic industries transitioning from one steady state to another. Recycling of stone tools is a strategy that occurs in the periods preceding and following the Middle-Upper Paleolithic transition (Amick 2007; Belfer-Cohen and Bar-Yosef 2015; Gravina and Discamps 2015), supporting the likelihood that this behavior was used between 50 and 35 ka. Although recycling is not necessarily the only explanation for the creation of these intermediate tool forms, it deserves consideration.

In the simulation, most sets of parameters produced a small number of assemblages that contained a mixture of type 1 and type 2 technology tools. In the context of the Middle-Upper Paleolithic transition, this is a mixture of Middle and Upper Paleolithic tools, but not intermediate forms. These types of assemblages typically occur above and/or below "transitional" layers with intermediate tool forms. This phenomenon does not occur during the Middle-Upper Paleolithic transition; however, greater scrutiny of stratigraphic sequences may indicate typological classifications of assemblages conforming to the simulation expectations.

Another phenomenon that must be examined, if we assume overlap of Middle and Upper Paleolithic populations, is the appearance of artifacts with Middle Paleolithic retouch on an Upper Paleolithic blank, represented as 2/1 tools in the model. Every set of experimental parameters with some overlap between the two populations produced assemblages with 2/1 tools. This means that if two populations are simultaneously recycling each other's stone tools, both types of mixed typology tools should occur. Among IUP sites, there is one potential example of such an occurrence from Temnata Cave in Bulgaria, where refitted pieces suggested the presence of a technological sequence that began with Upper Paleolithic preparation and core reduction and changed to a recurrent Levallois technique when the core had flattened in a later phase of reduction (Kozlowski 2000). Although not exactly the phenomenon modeled in the simulation, the reduction sequence example from Temnata Cave has a similar pattern to the intermediate tool forms: initial manufacture under one technological system and final manufacture under a different one. Again, the possibility of artifacts that began with Upper Paleolithic technology and ended with Middle Paleolithic technology is an archaeologically testable hypothesis suggested by the model that could help increase our confidence in the secondary recycling model for transitional industries.

Similarly, model runs with overlap produced sites that had type A assemblages (representing Middle Paleolithic) overlaying the mixed typology "transitional" layers. Because IUP sites represent a transition from the Middle to the Upper Paleolithic, nothing in the literature describes an overlying layer classified as anything besides Upper Paleolithic or later. However, one site from Russia, Barun-Alan-1, may have a Middle Paleolithic-like industry over an assemblage of mixed characteristics (Rybin and Khatsenovich 2018; Tashak and Antonova 2015). Barun-Alan-1 is an open air site just north of the Russian-Mongolian border that has nine lithological units (Tashak and Antonova 2015). Layer 7 is similar to the IUP in central Asia due to its concurrent use of Levallois and prismatic core reduction methods; however, in the overlying layer 6, flakes are the primary blank type and blades are scarce; additionally, the primary knapping technique in layer 6 seems to be parallel reduction (Tashak and Antonova 2015). These characteristics do not fit with the typical definition of the Upper Paleolithic as blade-based with a unidirectional prismatic reduction sequence. As such, Barun-Alan-1 could be a site that does not follow the typical Middle Paleolithic, IUP, Upper Paleolithic order, similar to some of the sites produced by the model. If this is true, there might exist other sites that demonstrate the reverse "transitions" like those created under many of the modeled parameter values.

Table 2. Initial Upper Paleolithic (IUP) archaeological sites

Site	***Country***	***Preceding Layer***	***Subsequent Layer***	Context	***Source(s)***
Temnata	Bulgaria	Middle Paleolithic	Gravettian?	cave	Kozlowski 2000; Kozlowski 2004
Stranska Skala III	Czech Republic	none	Aurignacian	open air	Svoboda 2003; Škrdla 2003
Boker Tachtit	Israel	none	Upper Paleolithic	open air	Škrdla 2003; Sarel 2004
El Wad	Israel	Middle Paleolithic	Aurignacian	cave	Garrod 1951
Emireh	Israel	none	none	rockshelter	Garrod 1955; Barzilai and Gubenko 2018
Raqefet	Israel	Mousterian	Aurignacian	cave	Sarel 2004
Tor Sadaf	Jordan	none	Ahmarian UP	rockshelter	Fox and Coinman 2004
Ushbulak	Kazakhstan	none	Upper Paleolithic	open air	Shunkov et al. 2017
Abou Halka	Lebanon	none	Ahmarian UP	rockshelter	Copeland 2000; Leder 2016
Antelias	Lebanon	none	Aurignacian	cave	Copeland 2000
Ksar Akil	Lebanon	Mousterian	Ahmarian UP	rockshelter	Ewing 1947; Copeland 2000; Leder 2016

Chikhen Agui	Mongolia	none	none	rockshelter	Brantingham et al. 2001; Rybin and Khatsenovich 2018
Kharganyn Gol 5	Mongolia	terminal MP	Late UP	open air	Rybin and Khatsenovich 2018
Podzvonkaya	Mongolia	none	non-Paleolithic BA		Rybin 2015
Tolbor 16	Mongolia	none	EUP?	open air	Zwyns et al. 2014
Tolbor 21	Mongolia	terminal MP	UP	open air	Rybin and Khatsenovich 2018
Tolbor 4	Mongolia	Middle Paleolithic	EUP/UP	open air	Derevianko et al. 2013; Rybin and Khatsenovich 2018
Tsagaan-Agui	Mongolia	Levallois-Acheulean	Upper Paleolithic	cave	Derevianko et al. 2000; Rybin and Khatsenovich 2018
Brno-Bohunice	Moravia	none	nondiagnostic	open air	Škrdla and Tostevin 2005; Richter, Tostevin, and Škrdla 2008
Kamenka	Russia	none	non-Levallois	open air	Zwyns and Lbova 2018
Kara Bom	Russia	Mousterian	Upper Paleolithic	open air	Goebel 1993; Brantingham et al. 2001
Khotyk	Russia	Mousterian	Upper Paleolithic	open air	Kuzmin et al. 2006
Shlyakh	Russia	Middle Paleolithic	Upper Paleolithic	open air	Hoffecker 2011; Hoffecker et al. 2014
Ust Karakol	Russia	Mousterian	Upper Paleolithic	open air	Goebel 1993; Otte and Derevianko 2001
Jerf Ajlah	Syria	Mousterian	Aurignacian	cave	Richter et al. 2001
Um et'Tlel	Syria	Mousterian	Ahmarian/Aurignacian	open air	Richter et al. 2001; Ploux and Soriano 2003
Yabrud II	Syria	Mousterian	Aurignacian	rockshelter	Pastoors, Weniger, and Kegler 2008
Kanal Cave	Turkey	Mousterian	Upper Paleolithic	cave	Kuhn, Stiner, and Güleç 1999
Ucagizli	Turkey	Middle Paleolithic	Upper Paleolithic	cave	Kuhn, Stiner, and Güleç 1999; Kuhn, Stiner, and Güleç 2004
Korolevo	Ukraine	Mousterian	none	open air	Gladlin and Demidenko 1989; Demidenko and Usik 1993; Nawrocki et al. 2016
Kulychuvka	Ukraine	none	UP	open air	Meignen et al. 2004

Conclusions

By simulating simple secondary recycling behaviors, it is possible to produce assemblages with intermediate tool forms under a variety of conditions. The results reported here raise questions concerning explanations for a transition between two different lithic technocomplexes, relating to the assumption that any given technocomplex should evolve into another. Recycling can produce sequences documenting gradations without an evolutionary relationship. Although recycling can be difficult to identify confidently in the archaeological record, it likely occurred throughout prehistory and it is therefore relevant to examine the potential of recycling behaviors creating “transitional” sequences. Recent studies attempt to quantify the minimum significance of secondary recycling in Paleolithic contexts (Peresani et al. 2015; Vaquero et al. 2012). Based on the results presented here, we suggest the application of these methods to transitional assemblages in order to understand the significance of recycling behaviors. The results of this model also suggest archaeologically testable hypotheses about the types of stratigraphic sequences (i.e. reverse “transitions”) and assemblage characteristics (i.e. type 2/1 tools) that indicate secondary recycling behaviors.

Lithic recycling is a widespread phenomenon in the Paleolithic record, but it continues to assume only an ancillary role in explanations for archaeological findings due to the difficult nature of identification. The results presented here demonstrate that this can no longer be the case. Assemblages are not necessarily created as entire units at one instance in time and then deposited as a single event (Binford 1981; Dibble et al. 2017; Kuhn and Zwyns 2018; Miller-Atkins and Premo 2018; Perreault 2018; Rezek et al. 2020). This means that a single assemblage can contain artifacts that were never used contemporaneously and that were deposited by different groups of people (Dibble et al. 2017; Kuhn and Zwyns 2018; Rezek et al. 2020). The secondary recycling of previously deposited artifacts adds an additional aspect by allowing different groups of people to modify previously discarded materials. As such, archaeological phenomena, like transitional industries, that are traditionally ascribed important cultural evolutionary significance may have emerged from one group recycling another group's leftover tools. Furthermore, this model demonstrates the complex tool characteristics and stratigraphic sequences that recycling behaviors can produce, highlighting the need for archaeologists to consider how this behavior affected the formation of the archaeological record.

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