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Archaeomaterials, Innovation, and Technological Change

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ABSTRACT

The field of archaeomaterials research has enormous potential to shed light on past innovation processes. However, this potential has been only partially recognized outside its immediate practitioners, despite the fact that innovation and technology change are topics of enduring interest in archaeology and the broader social sciences. This review explores the relationship between archaeomaterials research and the interdisciplinary study of innovation, and maps out a path toward greater integration of materials analysis into these discussions.

To foster this integration, this review has three aims. First, I sketch the theoretical landscape of approaches to the study of innovation in archaeology and neighboring disciplines. I trace how theoretical traditions like evolutionary archaeology have influenced archaeomaterials approaches to questions of technological change while also highlighting cases where work by archaeomaterials researchers anticipated trends in the anthropology of technology. Next, I distill a series of core concerns that crosscut these different theoretical perspectives. Finally, I describe examples where archaeomaterials research has deepened scholarly understanding of innovation processes and addressed these core questions. The future of archaeomaterials research lies in engagement with these broader discussions and effective communication of the contributions that materials analysis can make to building a comparative understanding of innovation processes.

1. Introduction

In an era of archeological research with an ever-increasing emphasis on addressing big questions about the human past, archaeomaterials—a field lying at the intersection of archaeology, materials science, analytical chemistry, and earth sciences—must also claim a broad mandate. While previous generations of scholars working in the field of archaeomaterials were often based primarily in natural science departments, today these scholars are increasingly found within departments of anthropology and archaeology (Killick, 2015a:296). While this trend is not without its potential pitfalls (Killick, 2015b), one positive impact has been the improved integration of materials analysis into questions of broader archeological relevance. The present review makes the case that the study of ancient innovation and technological change deserves a key place in the disciplinary remit of archaeomaterials.

In its broadest sense, the field of archaeomaterials includes any approach to analyzing archeological material culture with the aim of reconstructing one or more aspects of the *chaîne opératoire*. This latter concept is most typically defined as the sequence of steps in the manufacture of an object, but the term is frequently expanded to include the full life history of an object, from manufacture to discard and even post-depositional transformation (e.g., Martinón-Torres, 2002:32–33; Schlanger, 2005:20–21; Sellet, 1993:106). Put more elegantly, if with less specificity, archaeomaterials is the study of human engagement with the material world. In terms of methodologies, this area of research typically involves the application of laboratory techniques drawn from materials science, analytical chemistry, and earth sciences. While one must recognize the smaller but nevertheless important branch of archaeomaterials research dealing with innovation in organic material technologies (e.g., Good et al., 2009; Shishlina et al., 2003), the overall orientation of the field toward inorganic materials, and pyrotechnologies in particular, is reflected in the research discussed in this review.

The last 20 years of archaeomaterials research have seen important methodological developments in nondestructive or minimally destructive analysis (Dussubieux et al., 2016; Shugar and Mass, 2012), as well as the development and systematizing of new chemical and isotopic systems of provenance (Charlton, 2015; Degryse et al., 2015; Degryse and Schneider, 2008; Haustein, 2010; Junk and Pernicka, 2003; Milot et al., 2016). Nevertheless, some of the most transformative archaeomaterials research has resulted less from the introduction of radically new analytical techniques and more through finding methodologically innovative ways of deploying existing techniques and synthesizing datasets to address topics of broad archeological and anthropological interest (e.g. Bray and Pollard, 2012; Erb-Satullo et al., 2017; Golitko and Feinman, 2015; Perucchetti et al., 2015).

Foremost among these topics is the study of innovation, a subject of intense interest far beyond the bounds of materials analysis (Barceló et al., 2014; Burmeister and Bernbeck, 2017; Fitzhugh, 2001;

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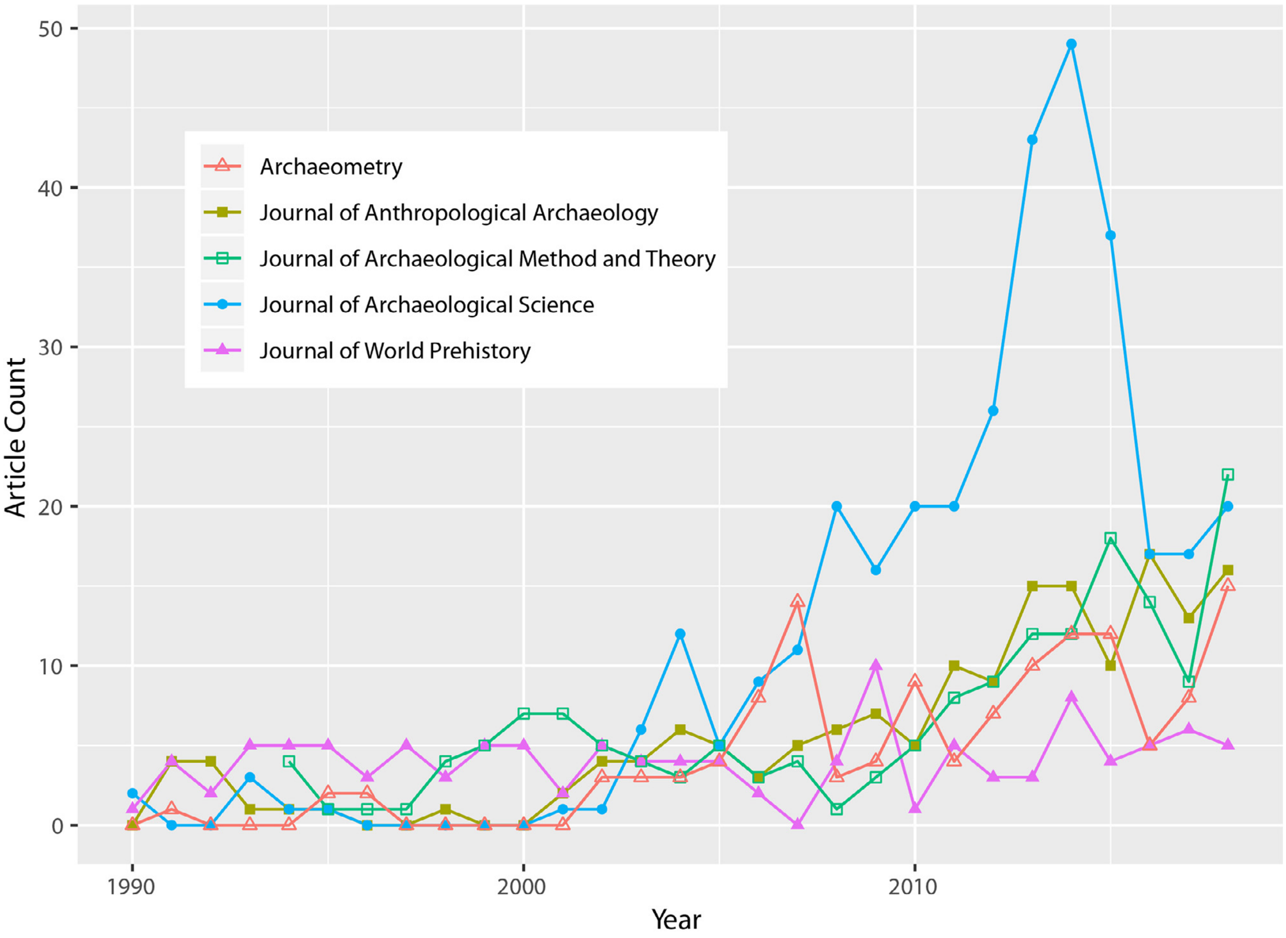

Fig. 1. Results of keyword searches for *innovation* in several prominent archaeology journals by year, 1990–2018. Absolute comparisons between journals are less meaningful, as search methodologies may differ between publishers and the total number of articles published per year varies between journals.

O'Brien and Shennan, 2010a; Potts, 2012; Schiffer, 2011; van der Leeuw and Torrence, 1989) and, for that matter, archaeology itself (Gladwell, 2000; Pelto and Müller-Wille, 1972; Rogers, 2003; Valente, 2005) (Fig. 1). Innovation and technology are fundamental elements of modern society, yet popular narratives about these topics have the potential to blind us to the underlying complexities of these processes (Pfaffenberger, 1992a; for a critique of the term *innovation*, see Leary, 2018:114–19). A primary contention of this review is that the field of archaeomaterials is fundamentally suited for analyzing innovation processes in the past. While there have been some recent promising moves to inject archaeomaterials research into broader disciplinary and transdisciplinary discussions of innovation (e.g., Charlton et al., 2010; Killick, 2015a:297–98; Radivojević, 2015; Roberts and Radivojević, 2015), archaeomaterials has yet to reach its full potential as a central player in archaeological studies of innovation.

This is not to say that archaeomaterials researchers have only recently started to work on the topic of ancient innovation. On the contrary, I will show that archaeomaterials research has had a major impact on our understanding of innovation in pyrotechnologies. Rather I argue that despite the long history of engagement with ancient technology and innovation, these contributions have not always been effectively communicated to, and recognized by, scholars beyond the subdiscipline. By situating that research within broader social science approaches to innovation, archaeomaterials can stake out a key position within these discussions.

This review begins with a broad sketch of how archaeologists and other social scientists have approached innovation in the past and traces the ways in which different theoretical traditions, particularly social constructionist and evolutionary approaches, have impacted archaeomaterials approaches to innovation. I trace patterns of influence and show that different theoretical traditions have had varying levels of impact, both geographically and in an absolute sense.

In the second part of the review, I distill a series of theoretical concerns that crosscut different theoretical approaches to innovation. One key theme in innovation research is the question of how inventions and innovations arise. This area of focus encompasses discussion of the social conditions that stimulate invention and innovation, the identification of diffusion and independent invention, and the question of how new technologies interact with preexisting traditions. This relationship between the new and the old is intimately bound up with discussions of "linearity" in technological change, a concept that frequently serves as a rhetorical foil in recent discussions of innovation but is often poorly defined. The discussion of linearity and technological sequences leads to an assessment of how scholars conceptualize the process of technological change, often through stage-based models. In essence, the value of stage-based models is their articulation, for each stage of relationships between different parameters of a sociotechnical system. Another key theoretical concern is how we assess consequences of innovation processes, both in terms of how innovations themselves transform as they are adopted and how they impact the societies that adopt them.

In the final section of the review, I discuss how archaeomaterials research has deepened our understanding of innovation processes. In doing so, I highlight research where archaeomaterials approaches have addressed or have the potential to address the core concerns of innovation studies outlined in the second part of the review.

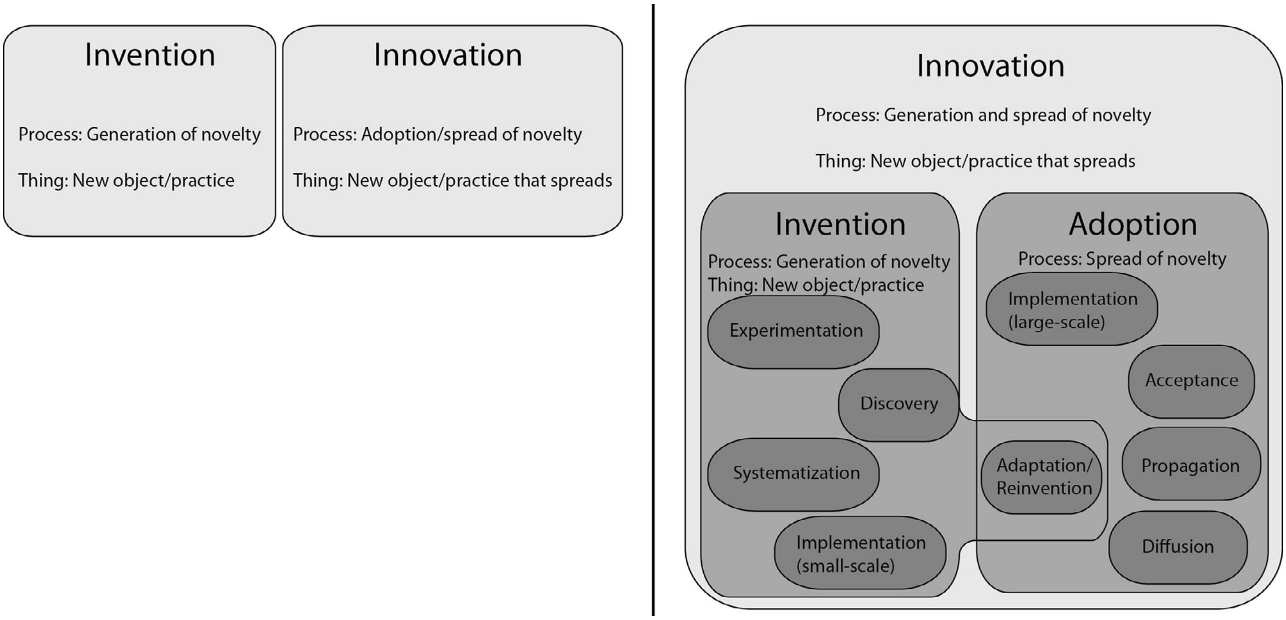

Fig. 2. Definitions of *invention* and *innovation* and their relationship with one another. The preferred schema is on the right; the alternative schema is on the left. Placement of activities (dark gray) within the categories of invention and innovation is not intended to imply a strict sequence; nor are they always present (for example, invention can occur without active experimentation). Adaptation/reinvention is a component of adoption but is also a form of invention.

2. Theoretical approaches to technology and innovation

Before discussing the potential of archaeomaterials research for the study of ancient innovation, it is worth exploring how different theoretical approaches to technology have percolated into the archaeomaterials literature. These investigations reveal some interesting asymmetries in the uptake of these approaches among archaeomaterials researchers.

2.1. *Defining invention and innovation*

The terms *invention* and *innovation* are often used in discussions of technological change. Scholars use these terms in varying ways (Fitzhugh, 2001:128–29; Godin, 2016; O'Brien and Shennan, 2010b:3–4; Roberts and Radivojević, 2015:300–301). Either word can be used as a verbal noun (the act of inventing or innovating) and as a reference to a specific thing (*an* invention or innovation), a dual aspect that has rarely been explicitly discussed when laying out definitions. One perspective, which has gained fairly widespread currency in archaeology, sees innovation and invention as discrete and fully separate from one another. Invention, in the verbal noun sense, is defined as the process of generating novelty, and innovation as the process of spreading novelties (Fitzhugh, 2001:128; Renfrew, 1978:90). Elements of this perspective are discernable in the pioneering work of Schumpeter (1939:84-86), who stresses the distinction between innovation (the primary subject of his analysis) and invention. Correspondingly, in the "thing" sense, inventions are new objects or technological practices, and innovations are inventions that spread, with the implication of some broader social impact (Killick, 2015c). The problem with the "activity" sense of this definition is that it essentially equates innovation with adoption, leaving no good shorthand for describing the full process of technological change.

Drawing on the work of Maclaurin (1949, 1950) and Utterback (1971), particularly as interpreted through Godin (2016:539), I see innovation (in the "activity" sense) as referring to the full process of initiating, systematizing, and transmitting technological change (Fig. 2). Invention, on the other hand, refers specifically to the portion of the innovation process in which a new technical behavior is initiated, recognized, and developed up to the point that it becomes systematic—in other words, where it moves from the realm of the accidental and fortuitous to the realm of the controllable and routine. I am sympathetic to views of invention as a process rather than a single moment, in large part because this conception of invention makes it more accessible to archeological investigation (Roberts and Radivojević, 2015; contra Fagerberg, 2006:5).

This definition of the relationship between invention and innovation is not necessarily in conflict with traditional Schumpeterian perspectives, as innovation still carries an association with the spread and, ultimately, social impact of new technologies. Maclaurin, who was among the first to articulate a stage-based model for innovation, was very much influenced by Schumpeter (Godin, 2008; Maclaurin, 1953). My perspective still defines *an* innovation (in the "thing" sense) as an invention that has been widely adopted but defines the verbal noun sense of innovation as a process encompassing invention rather than distinct from it. The shift in the relationship between invention and innovation, however subtle, is an important one. A key advantage of seeing invention as a component of rather than separate from innovation is that it recognizes that invention, in the form of adaptation or "reinvention" (Rice and Rogers, 1980), is often an integral part of the spread and adoption of technologies (Fig. 2). Particularly from an archaeomaterials perspective, which emphasizes reconstructing behavioral components of technological practice, it is useful to acknowledge that individual components may be transformed during the adoption process.

2.2. *Theoretical traditions and their impact on archaeomaterials research*

Among theoretical approaches to technology and innovation (Table 1), perspectives that see technology as fundamentally inseparable from its social and cultural context have had enormous influence on the field of archaeomaterials (Killick, 2004; Lechtman, 1977; Lechtman and Steinberg, 1979; Smith, 1965, 1981). Central to these perspectives is the idea that technological problems invite a range of different solutions, many of which are nonetheless, from a purely functional perspective, equivalent. A bronze cauldron can be made from riveted sheets of metal or through casting, just as a coil-built ceramic vessel holds water just as effectively as one shaped with the paddle-and-anvil method. Thus the sequence of behaviors and decisions made in the implementation of a

Table 1
Summary of major theoretical approaches to technology and innovation and their impact on archaeomaterials.

Theoretical Approach	Key Terms, Concepts, and Features	Major Figures (Selected)	Impact on Archaeomaterials
Social Constructionist	• sociotechnical systems • technological style • contextualized/holistic approaches	Lemonnier, Pfaffenberger, Lechtman, Hosler, Smith	Substantial and global. Impact on the specific topic of innovation more focused on adoption patterns (especially adaptation and rejection).
Evolutionary	• risk • bias (direct/indirect) • dual inheritance theory • cultural/technological transmission	Shennan, O'Brien, Boyd, Richerson, Henrich, Fitzhugh	Significant impact on archaeomaterials research in Europe. Impact on archaeomaterials more limited in North America.
Innovation Diffusion	• S-shaped diffusion curves • reinvention • opinion leaders • communication networks	Rogers, Granovetter, Valente	Limited, but increasing impact, often filtered through evolutionary approaches. Incipient influence through growing interests in network analysis.
Behavioral	• performance characteristics/matrices • social needs • adoption models	Schiffer, Skibo	Predominantly in North America. Limited impact on archaeomaterials overall.

Note: Theoretical cohesiveness and sharpness of boundaries vary significantly between these different traditions.

technology can be conceived as a series of technical choices influenced by cultural and social factors. Combinations of these choices form a distinctive technological style that is reflective of more than just material constraints. Some technical choices might be rationalized by geological, ecological, or materials science considerations, while others may not (Pfaffenberger, 1992b:282). Moreover, the ethnographic and archeological record reveals instances where technological behaviors seemingly contradict purely environmental, material, or techno-functional logics (Epstein, 1993:186–97; Lemonnier, 2002 [1993]:1–2), not to mention instances where technological variability occurs within the same environmental context (e.g., Lemonnier, 1986; Roux et al., 2017).

This somewhat loose collection of perspectives, which Killick (2004) terms "social constructionist," is difficult to characterize as a whole, but one common feature is that they place particular emphasis on the socially embedded nature of technological processes (Dobres, 2010). Cultural beliefs and social practices play an equal role with thermodynamic and material properties in the formation of technological traditions. Many scholars refer to the concept of a "sociotechnical system" to describe the web of relationships that comprises the implementation and practice of a technology (Hughes, 1991; Pfaffenberger, 1992a:493, 497). Social constructionist approaches are by no means unique in their consideration of the social dimensions of technology, but their highly contextualized or "holistic" approach to technology is a distinctive feature of this kind of research (e.g., Shimada and Craig, 2013).

One can follow the threads of these ideas very early in the development of archaeomaterials as a discipline. Indeed, in some instances, the early work on this topic by archaeologically oriented materials scientists (Lechtman, 1977; Smith, 1965) actually predates the major groundswell of interest in the social dimensions of technology in anthropology, sociology, and STS during the 1980s and 1990s (Lemonnier, 1986, 1992; Pfaffenberger, 1992a). This latter trend, particularly its European manifestation, was influenced by the *chaîne opératoire* approaches pioneered by French anthropologists of the mid-twentieth century (Audouze, 2002:284–85; Gosselain, 1992:559–60; Leroi-Gourhan, 1943, 1945). The social constructionist theoretical paradigm impacted archaeomaterials research by contextualizing technical choices and behaviors that are not fully determined by material or thermodynamic constraints. These ideas have had a particular resonance in archaeometallurgy (Childs, 1991a; Epstein, 1996; Gordon and Killick, 1993; Hosler, 1994; Lechtman, 1984, 2007; Thornton, 2009a), though their influence is clearly present in other branches of archaeomaterials research (e.g., Gosselain, 1992; Loney, 2000; Sillar and Tite, 2000).

With respect to the study of innovation, social constructionist approaches are quite effective at explaining some features of the process while remaining more or less silent on others. A robust understanding of technological traditions within their social context is crucial for tracking processes of adoption and diffusion. For instance, an understanding of early ceramic traditions in China is essential for understanding the rapid divergence of Chinese bronze-working from the metallurgy of the Eurasian steppes (Mei et al., 2017:237). The concepts of technological style and sociotechnical systems help explain the persistence of technological traditions and their influence on the development of new innovations.

The implicit mechanism for innovation in many of these studies is the idea that inventions are adopted because they reflect, or can be adapted to, preexisting economic networks, social structures, or cultural beliefs (Bernbeck and Burmeister, 2017:11; Pfaffenberger, 1988; van der Veen, 2010:3). A corollary is that the introduction or imposition of a technology into a foreign sociocultural system can result in outright rejection or other unintended outcomes (Pfaffenberger, 1990; Sharp, 1952). Adaptation to existing social conditions is undoubtedly a key factor in innovation processes, but many discussions of innovation from a social constructionist perspective emphasize persistence, continuity, and tradition. Less emphasis is placed on the processes of autochthonous invention or the processes by which the underlying logics of sociotechnical systems change, stimulating new processes of invention and innovation. In other words, social constructionist perspectives help us explain encounters with new technologies but provide less guidance for understanding how new technologies appear in the first place or why longstanding technological practices might be abandoned. Nevertheless, the success of this theoretical approach to technology and innovation is reflected in the diffuseness of its boundaries: many of its central ideas have been adopted broadly across archeological approaches to technology.

The study of technology and innovation has proven fertile ground for the application of evolutionary theory to archaeology (Kuhn, 2004; O'Brien and Shennan, 2010a). Nevertheless, assessing the impact of evolutionary theory in the study of technology is difficult, as its applications differ widely. One major set of approaches, often referred to as dual inheritance theory, draws an analogy between biological evolution and the repetition, replication, and transmission of cultural and/or technological practices. New cultural and technological behaviors are conceived as emerging from a variety of processes, include copy errors during learning, as well as fortuitous observation, unstructured play, and goal-directed experimentation. These variants are then recognized and subject to cultural and economic selection factors (Basalla, 1988; Boyd and Richerson, 1985, 1987; Eerkens and Lipo, 2008). Concepts such as direct bias (imitating behaviors that are most effective through direct observation) and indirect bias (the copying of behaviors of higher-status actors) were developed to account for the distinct nature of behavioral evolution in the cultural sphere. In contrast to many social constructionist approaches to innovation, evolutionary approaches often explore the mechanisms and conditions influencing invention directly (Fitzhugh, 2001).

Variations on these evolutionary approaches have had a particularly strong impact on archaeomaterials research in Europe, most notably in the cross-fertilization between evolutionary archaeologists and archaeomaterials researchers at University College London (Charlton et al., 2010; Radivojević, 2015; Roux, 2008). The merging of archaeomaterials research and evolutionary theory has provided focused contextual analyses of specific innovations, providing some welcome balance to the overall trend of applying evolutionary theory to long-term cultural and technological transformations. To those interested in analyzing and comparing specific, thoroughly contextualized cases of innovation, the mathematical foundations for theories of technological and cultural evolution can feel very much removed from the primary focus of research. Because archaeomaterials research produces detailed data on technological choices and behaviors, it has helped ground some of the more abstracted formulations of risk, bias, and transmission processes that dominate some evolutionary approaches.

The application of evolutionary theory to archaeology has elicited critiques from a number of different perspectives (e.g., Kristiansen, 2004; Loney, 2000; Pluciennik, 2012:39–42). Critiques of evolutionary approaches to technology derive not so much from the details of mechanics (that is, the idea that variation is introduced during transmission) or the idea that social factors exert selective pressures on the adoption of certain technologies over others. Indeed, the concept of selective pressures acting within cultural systems is not unique to evolutionary approaches, though other approaches formulate the process in different terms. Rather, one potential concern among critics is that evolutionary models reinforce the perception of technological change as gradual, inexorable, and unilineal (Loney, 2000). This is somewhat of a “straw man” critique, as a few studies drawing on evolutionary theory document technological loss and abandonment (Henrich, 2004; Roux, 2008), and some argue that evolutionary approaches strongly reject unilineal models (Schubert, 2017). The key here is to draw a clear distinction between what might be termed “evolutionary sequences,” such the Levantine Paradigm in Near Eastern archaeometallurgy critiqued by Thornton (2009b), and evolutionary logic of descent with modification applied to the innovation process. The former echoes nineteenth-century notions of Tylor (1881) and others that social and technological development follows a fixed linear progression, while the latter does not. Overall, in reviewing evolutionary approaches to technology and innovation and their critics, one is left with the distinct impression that the different sides are talking past one another.

A related class of theoretical and methodological approaches, diffusion research (also referred to as innovation diffusion research or diffusions-of-innovations research), has had a more indirect influence on the archeological study of technological change. Many references to this body of work have filtered into the archeological literature through the evolutionary approaches described above (Eerkens and Lipo, 2014; Henrich, 2001). Diffusion research encompasses a wide-ranging set of approaches with its origins in the mid-twentieth century, and it seeks to explain the processes by which innovations spread within and between different social groups (Rice and Rogers, 1980; Rogers, 2003; Ryan and Gross, 1943; Valente, 2005). Concepts such as S-shaped curves of adopters over time, identification and characterization of adopter categories (for example, early adopters versus “laggards”) (Rogers, 1958), and the impact of social communication networks on adoption/diffusion patterns (Granovetter, 1973; Rogers and Shoemaker, 1971; Valente, 2005) have been major contributions of this field of study (Fig. 3).

Much of this work has focused on relatively rapid diffusion processes in contemporary societies, contributing to an acknowledged “pro-innovation bias” in diffusion research (Rogers, 2003:106–7). Archeological studies of innovation have developed along a separate, though often parallel, track. Within archaeology, the concept of diffusion is still associated with grandiose and often highly problematic “hyperdiffusionist” claims of influence across wide ranges of time and space (see Storey and Jones, 2011:7–8; Trigger, 2006:219–23). Even in more nuanced approaches, the term *diffusion* is primarily associated with cross-cultural transmission rather than the full range of adoption, adaptation, and reinvention processes that occur both within and between sociocultural groups. Indeed, one critique of diffusion research, that innovations are conceptualized as discrete, unchanging packages, was addressed some time ago (Rice and Rogers, 1980). To be fair, one might still argue that the most visible and widely cited innovation diffusion concepts, such as S-shaped diffusion curves, are ill-suited to capture modification or adaptation of innovations during adoption. While some archaeologists dismiss diffusion research (Schiffer, 2011:17), recent archeological studies of innovation have displayed an increasing archeological awareness of these concepts (Barceló et al., 2014; Eerkens and Lipo, 2014; Kim, 2001; Shortland, 2004). The rise of interest in network analysis in archaeology (e.g., Collar et al., 2015; Knappett, 2013) has recently opened another route for ideas from innovation diffusion research to enter archaeology. These developments have resulted in recent work on materials innovation through the lens of network analysis (Östborn and Gerding, 2015), though this area of study has only recently begun to be explored.

In evaluating the potential contributions of innovation diffusion research to the study of archaeomaterials innovation, one must acknowledge that generalizations and models derived from modern Western contexts are not always applicable to ancient cases (Schubert, 2017; van der Veen, 2010:4). Indeed, the terminology and models can come across to archaeologists and anthropologists as value-laden (for example, “laggards” for late adopters) or overly specific to modern capitalist societies (for example, an approach to invention heavily focused on modern R&D contexts). Yet useful observations drawn from innovation diffusion theory abound, and engagement with these concepts both reinforces archaeology’s status as a key methodology for investigating innovation processes and builds a more robust set of tools with which to investigate technological change cross-culturally.

If evolutionary and diffusion approaches have had more influence on archaeomaterials research in Europe, behavioral approaches to innovation, developed primarily by Michael Schiffer and his colleagues, have had a greater impact in North America (Schiffer, 2004, 2011). Central to behavioral approaches to technological change is the concept of “performance characteristics,” or the attributes of a technological behavior as assessed through its particular sociocultural lens. Innovation is conceived as the process of developing and selecting materials or technologies with desirable performance characteristics. Performance characteristics range from specific material properties (for example, the hardness of a metal blade’s cutting edge) to environmental factors (such as the availability of raw materials) to more abstract attributes of social performance (such as the effectiveness of enhancing social prestige). More broadly, behavioral archaeology’s most significant contribution to the study of technological change is the elaboration of a wide variety of scenarios in which invention, innovation, and adoption occur (Schiffer, 2011). On the other hand, behavioral approaches to technological change have also been critiqued for developing a body of theory and a terminology isolated from broader interdisciplinary discussions of technological change (Eerkens and Lipo, 2014:23).

The potential attraction of behavioral approaches for the archaeomaterials specialist is that many performance characteristics can be empiri-

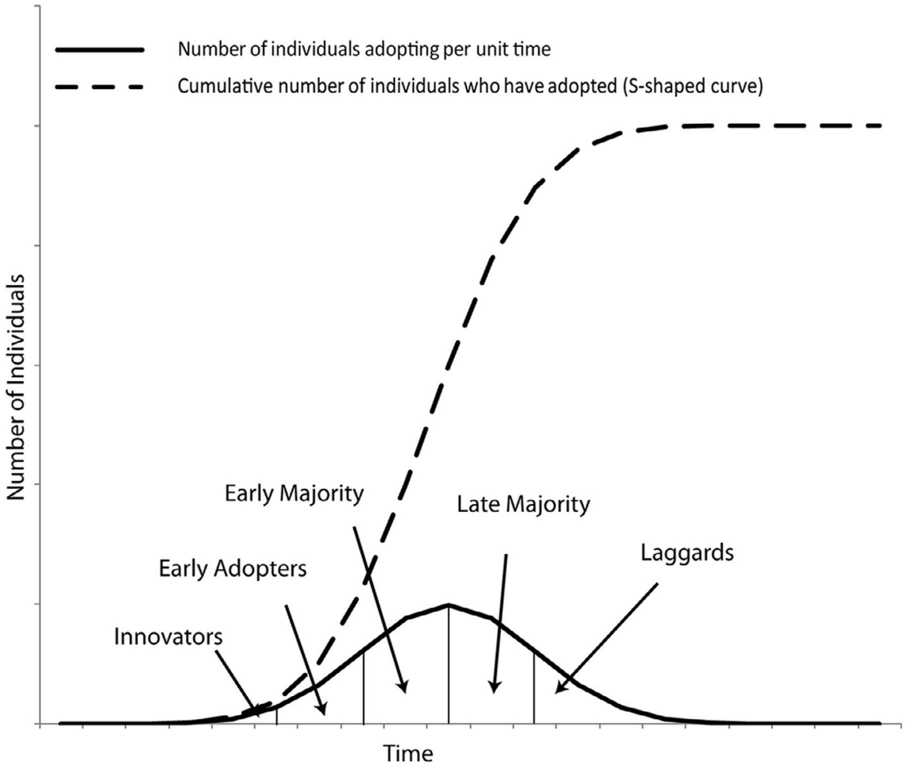

Fig. 3. S-shaped curve of cumulative adopters versus time and terms for adopter categories derived from innovation diffusion research.

cally investigated through the scientific analysis of finished objects, production residues, and experimental re-creations. The researcher therefore gains some insight into what performance characteristics were desirable and what trade-offs were considered acceptable. While archaeomaterials research is often interested in the material and functional properties of archeological artifacts (Eliyahu-Behar and Yalahom-Mack, 2018; Mathieu and Meyer, 1997; Mödlinger et al., 2017), relatively little archaeomaterials research has explicitly adopted the behavioral approach (for an exception, see Schiffer et al., 1994). The reasons for this are not entirely clear, but they may be attributable to the idiosyncrasies of academic geography. As a predominantly North American phenomenon, behavioral archaeology emerged in an area with fewer archaeomaterials specialists. Another possibility is that Schiffer's tendency to explore his behavioral approach through recent historic case studies made it less obviously applicable to the field of archaeomaterials, which predominantly focuses on preindustrial technologies.

3. Common concerns in the study of innovation

The theoretical approaches sketched above conceive of innovation in radically different ways. One index of these differences is the variety of attitudes toward the adage "Necessity is the mother of invention," ranging from unquestioned acceptance to a passionate opposition and including both inversions ("Invention is the mother of necessity") and reformulations (Basalla, 1988:5–7; Fitzhugh, 2001:126; Maddin et al., 1977:122; Pfaffenberger, 1992a; Rosen, 2002; Schiffer, 2011:43; Smith, 1981:325). Without pretending that these different theoretical perspectives can be fully homogenized, it is nonetheless worthwhile to draw out a series of common themes and considerations. Phrased as a series of questions, these core concerns will help focus the subsequent examination of how archaeomaterials research can best contribute to the study of innovation.

3.1. How do inventions and innovations develop?

A major common concern in many theoretical approaches is understanding how inventions and innovation develop and spread. The social conditions that are conducive to invention and adoption are of major concern across these theoretical traditions. Do innovations arise in societies with surplus time and abundant natural resources, or among social groups that are marginalized and under pressure (e.g., Flannery, 1969:76; Papousek, 1989)? How might invention and innovation differ in these instances? What is the relationship between centers of invention and areas of early widespread adoption?

Another oft-considered problem is whether an innovation has an endogenous origin in local invention or an exogenous origin in preexisting technologies elsewhere. Archaeologists studying technological change often frame this as a binary between diffusion and independent invention (Renfrew, 1969; Storey and Jones, 2011; Wertime, 1973a). *Diffusion* in these discussions almost always refers to the spread of a technology across cultural boundaries, often over large distances, a more restricted sense than the term's use in the innovation diffusion literature. However, framing technological change as a simple binary between diffusion and independent invention has limitations, which will be discussed further below.

When assessing causes for adoption, explanations must take into consideration the manner in which a technology spreads. Innovations spread at different rates, through different social groups, and through a variety of networks. Explanations much consider variability in adoption rates: Why does an innovation spread rapidly through certain social groups but more slowly through others? Technological boundaries can create shared communities-of-practice where new ideas and innovations spread easily within one group but fail to be adopted between groups (Roux et al., 2017). Likewise, it is important to understand that some inventions fail to become innovations and to explore possible factors underlying the lack of adoption (Killick, 2015c). These cases illustrate that conditions that promote inventive behaviors are not necessarily the same as those that promote adoption.

3.2. How do technologies build on preexisting knowledge?

A concern related to the origins of innovation is the relationship between new technologies and those that preceded them. To what extent does a given innovation build upon or derive from the prior sociotechnical system? In discussions of relationships between different technologies in a chronological sequence, the concept of linearity is a common point of discussion. Linear (sometimes also called unilinear or unilineal) models of technological change have been heavily critiqued in recent work (Cordani, 2016; Heskel and Lamberg-Karlovsky, 1980:230; Pfaffenberger, 1992a; Radivojević et al., 2013:1031; Schubert, 2017:4–5). Linearity as applied to technological trajectories is not always well defined in these critiques. While occasionally the concept is used to denote innovations that spread at a relatively consistent rate (Cordani, 2016), in most cases it refers more to the idea of technologies evolving along a prescribed, sequential, and universal path. Archaeomaterials research has proven particularly effective at documenting how technologies do not always follow identical developmental sequences and often undergo periods of retraction and abandonment (Lechtman, 1980:268–70; Radivojević et al., 2013; Shortland, 2012:169–73; Thornton, 2009b).

Most scholars critiquing linearity in innovation models would probably recognize some commonalities in the broad arc of human technological experience. Human ability to control and manipulate materials was greater in AD 2000 than it was in AD 1, and correspondingly greater in AD 1 than in 2000 BC. Likewise, when viewed on millennial time scales, general patterns in the development of pyrotechnologies can be discerned. In almost every region with a metallurgical tradition predating European colonialism, the use of copper and its alloys precedes the innovation of iron metallurgy, though parts of Africa are exceptions to this statement in at least some respects (see Childs, 1991b:37; Killick, 2009:408; Killick, 2016). The emergence of high-fired stoneware and porcelain ceramics is almost always preceded by the manufacture of low-fired earthenware ceramics. Many of these patterns are attributable to the fundamental chemical and thermodynamic properties of materials: iron oxides require higher temperatures and lower oxygen partial pressure to reduce than copper oxides do, and the firing of glazed porcelain and stoneware clays requires higher temperatures and better control of firing conditions than the firing of earthenware clays.

In essence, these broad linear patterns tell us more about the properties of materials than any universal pattern of human behavior. Moreover, linear sequential models of technological development hold true at only the most generalized level, and even then one can point to exceptions. Although in most places, the Bronze Age precedes the Iron Age, attempts to formulate a more detailed model for the development of copper alloys, from native copper working to complex sulfide smelting, fails to account for innovation trajectories in many areas (Thornton, 2009b). Finally, unilineal models essentially ignore the false starts, eddies, local divergences, and historically contingent factors that constitute the true appeal of examining humanity's experience with materials.

While critiques of unilineal models have made us attuned to the complexities of innovation and technological change, it is still worth considering how the emergence of new technological systems is influenced by preexisting ones. Experience in the implementation of one technology can play a key role in subsequent innovation processes (e.g. Schiffer, 2005). In this context, it is useful to invoke the concept of "path dependence" from economics (Kenney and von Burg, 2001), in the sense that the growth and transformations of sociotechnical systems are conditioned by prior developments, but the end results of these transformations are far from deterministic. One can speak of technological trajectories without the requirement that all trajectories will be identical everywhere. Because archaeomaterials research provides such a granular perspective on the techniques, decisions, and behaviors inherent in technological practice, it is uniquely positioned to probe the web of interactions and influences between different material technologies.

3.3. How do we describe and organize segments of the innovation processes?

Social scientists studying invention and innovation have generated a wide array of models to characterize these processes. Staged models are particularly abundant and influential (e.g., Pinch and Bijker, 1987:22–23; Shortland, 2004; Snodgrass, 1980; Spratt, 1982). Such models have been used to describe processes of invention (gestation, cradle, maturation) (Lienhard, 2006:157–58), the cognitive stages of individual adoption decision making (Rogers, 2003:169–70), and the entire process (invention, commercialization, adoption, senescence) (Schiffer, 2011:34–38). Stage-based models are often implicit in archeological research describing early experimentation and transitional periods.

Stage-based models of technological change may at first glance seem susceptible to accusations of linearity that are otherwise anathema (see Lechtman, 1980:268; Pinch and Bijker, 1987:22–23, 28). Indeed, there is some danger that an overly rigid application of stage-based models can grade into unilineal evolutionary sequences. However, if one understands these models as descriptive rather than prescriptive and partial rather than total, they can provide a reasonable basis for comparing instances of technological change.

Of particular interest in assessing different models is not so much whether innovation processes are best described in four stages or five but how each stage of a given model maps relationships between different parameters of a sociotechnical system and how those associations change as an innovation passes through different stages. These relationships generate expectations that can then be tested with archeological data. These parameters might include identities of practitioners, the degree of control over the technological process (that is, its maturity and stability), the contexts of production and use, the percentage of adopters in a society, the spatial patterning and pace of adoption, and many others. An "initial" or "experimental" stage might be characterized by correlations between a relatively low proportion of practitioners, a slower rate of adoption, and an unstable or somewhat variable technological repertoire.

Staged models of innovation processes vary along a spectrum of specificity to generality, particularly in the extent to which they correlate parameters of a sociotechnical system at each stage. Programs of archaeomaterials research that are well integrated with other archeological data can provide information about the parameters of a sociotechnical system and assess the extent to which a given model provides a viable approximation.

3.4. What are the consequences of innovation processes?

Assessing the consequences of technological transformations is a major concern across all social science disciplines studying innovation. Indeed, along with the determining causes of innovation, the assessing of the impact of innovation might be considered the most fundamental inspiration for research on the topic.

One of most important consequences of innovation is that technologies change as they are transmitted between individuals and adopted into new cultural contexts. Nearly all theoretical perspectives recognize these processes. In social constructionist perspectives, this concern manifests in an attention to how new technologies are incorporated into preexisting sociotechnical systems. The diffusion research tradition describes these processes as reinvention (Rice and Rogers, 1980), while evolutionary paradigms emphasize that humans are biased copiers. Technologies or groups of technologies that are adopted or imposed wholesale without much modification are the exception rather than the rule and require their own set of explanations (Schiffer, 2011:145–46). The behavioral units that make up a technological practice may each be adapted, modified, or rejected to such an extent that the adoption of a technology in two different contexts may look radically different. By offering a nuanced and detailed perspective on the *chaîne opératoire*, archaeomaterials provides a sensitive set of tools to analyze adaptation and modification of technological practices.

Most definitions of the concept of innovation carry implications of societal impact. Assessing the impact of an innovation is no easy task even for well-documented, recent innovations, and the challenges increase for innovation in the distant past. In the archeological investigation of prehistoric technological change, there is a possibility of significant interpretive slippage between discussions of the causes of innovation and their consequences. Innovations frequently result in a cascade of unintended consequences. Some of them may be desirable to early adopters while others may not (Bernbeck and Burmeister, 2017:8; Schiffer, 2005; Sharp, 1952). Yet archaeologists run the risk of retrospectively projecting unintended positive consequences backward onto the motivations of early adopters. Childe is well-known for stressing the social impact of widely available iron (Childe, 1951 [1936]:180), but it is far from clear when these impacts began to be felt. The desire for cheap farm tools was almost certainly not a driving factor in the earliest adoption of iron: early iron artifacts tend to be either decorative items or prestige weaponry (see Yahalom-Mack and Eliyahu-Behar, 2015).

When discussing the social impact of technological innovations, it is important to steer clear of the crude technological determinism that infused some early discussions of technological change. Material technologies such as metallurgy or ceramics, perhaps because of their archeological visibility, seem to be particularly susceptible to these lines of thinking. At the same time, it is important to recognize that many of these technologies did have a major social impact, though perhaps not immediately and often not in the ways early technological determinists might have predicted.

Archaeomaterials analysis can contribute to a more robust understanding of causes and consequences in several ways. It can uncover patterns of adaptation and incorporation in the generation of new innovations, identifying relationships between other technological traditions that may have influenced their development. It can map boundaries in technological traditions, exploring areas of homogeneity and discontinuity across cultural spaces. Often, materials analyses can narrow down the geographic origins and cultural context of technological innovations, either indirectly through analysis of artifact provenance or directly through the analyzing of residues of technological practice. Sometimes, such analyses can directly assess the material properties of archeological artifacts, testing whether certain performance characteristics ascribed to a technology were present in its earliest stages.

4. Assessing the contributions of archaeomaterials research to innovation studies

Having discussed the various theoretical approaches to technological change and identified common themes, I now turn to a more detailed assessment of the impact that archaeomaterials analysis has had on the study of innovation. The orientation of this section is partly retrospective, highlighting past research related to the core concerns outlined above, and partly aspirational, mapping out a central space for archaeomaterials research in the archeological study of innovation.

4.1. Mapping invention and innovation in time and space

At the most fundamental level, scientific analysis of material remains is essential to identify many inventions and innovations properly. The simple identification of new technologies may seem a rather basic contribution, but it is not a trivial one. Many material technologies leave complex or unclear residues, particularly in their earliest manifestations. The study of ancient innovations is replete with cases where key technologies have been initially misidentified and detailed analysis has resulted in a reevaluation (Erb-Satullo, 2018:44–45; Erb-Satullo et al., 2014, 2018; Pigott, 2003; Radivojević et al., 2017). Conversely, materials analysis has often played a leading role in the documentation of technological "firsts" (Radivojević et al., 2010; Thoury et al., 2016; Vandiver et al., 1989; Yahalom-Mack et al., 2015). As a result, almost any discussion of pyrotechnological innovation, from the development of lime plaster (Kingery et al., 1988) to the blast furnace (Buchwald and Wivel, 1998; Lam, 2014; Wagner, 1993; Williams, 2009), has been fundamentally dependent on archaeomaterials research.

It is worth considering how inventions and innovations are identified through archaeomaterials research. The earliest instances of a particular technology are by definition the rarest, but even if finding a true "first" seems an impossible goal, examining the process of invention is far more feasible. Archaeomaterials researchers can identify behaviors of play and experimentation where different elements of technological practices appear, disappear, or are rearranged. Detailed archaeomaterials research can locate a particular technological assemblage on the spectrum of inventive processes.

For example, in the study of early metallurgy, distinguishing between native (naturally occurring) metals and smelted metal is essential for identifying the inception of extractive metallurgy. New research on early iron has demonstrated with increasing certainty that iron artifacts were fashioned from rare meteorites for at least a thousand years before ancient metalworkers figured out how to extract metallic iron from the far more abundant deposits of terrestrial oxide ores (Jambon, 2017; Johnson et al., 2013; Rehren et al., 2013). Similarly, copper ores were used as ornaments and native copper was forged into artifacts for millennia prior to the first chemical reduction of copper from ore compounds (Maddin et al., 1999; Radivojević, 2015; Roberts et al., 2009). One may debate how and to what extent experience with ores and native metals contributed to the development of extractive metallurgy, but archaeomaterials research provides the fundamental data with which to approach this question.

Numerous innovations in production technologies result in artifacts that appear on cursory macroscopic examination to be indistinguishable, necessitating more careful compositional or microstructural analysis. This is especially relevant when an artifact has sustained weathering and corrosion that transforms or obscures its original condition. Research on early glass and other vitreous materials has demonstrated the importance of chemical analysis in identifying innovations in glass and glaze colorants, especially since alteration can change their color (see, e.g., Shortland et al., 2018:772). Early materials research on faience technologies used scanning electron microcopy to document a range of different manufacturing methods for this material, which consists of a glazed surface over a sintered quartz body (Tite and Bimson, 1986; Tite et al., 1983). Such differences could be properly identified only through the careful examination of the glaze-sintered quartz interface and the interstitial matrix between quartz grains at high magnification.

The production of high-carbon steel in crucibles in Central and South Asia represented a major innovation in iron metallurgy, producing a homogeneous material with considerable advantages over wrought and cast iron. Identifying this technology in the archeological record is dependent on scientific analysis to supplement ambiguous textual documentation (Alipour and Rehren, 2014; Craddock, 2003; Feuerbach, 2002; Gilmour, 2000; Rehren and Papachristou, 2003). Iron artifacts made from crucible steel display characteristic microstructures, while analysis of crucible remains has identified where and when this distinctive technology was developed. Indeed, analysis of iron artifacts from southern India has recently demonstrated the presence of crucible steel in contexts predating textual documentation by hundreds of years (Park and Shinde, 2013).

In the study of ceramic innovations, the use of the wheel to create vessels has long attracted significant attention (Baldi and Roux, 2016; Roux, 2008; Thér et al., 2017), and distinguishing between the different wheel-using techniques is both important and sometimes difficult using macroscopic techniques alone. Inclusion orientation and certain surface features have long been recognized as important distinguishing characteristics, which can be investigated using X-radiography, thin section petrography, and macroscopic observation (Rye, 1981:74–80). Recent work on vessel forming techniques has seen both the rise of digital radiographic techniques (Greene et al., 2017) and the development of systematic methods for quantifying inclusion orientation (Thér, 2016; Thér et al., 2017). These methods make it possible to differentiate between wheel-finished, wheel-shaped, and wheel-thrown vessels. A fine-grained understanding of precisely how the wheel was used in the vessel forming process is important for understanding the factors affecting the spread of innovations, since performance characteristics (such as speed of vessel manufacture) vary significantly between types of wheel use.

Materials analysis is often essential for determining consistency and intentionality in the production of artifacts. These two elements are important for distinguishing the tentative early stages of invention from a more established technological repertoire. A popular hypothesis for the origins of iron metallurgy is that the earliest smelted iron was initially an unintentional by-product of copper (or perhaps lead) smelting, which was eventually recognized and developed as a separate technology (Gale et al., 1990; Shell, 1997; Wertime, 1973b:885). Direct material evidence for this phenomenon might be early iron objects with significant copper content or finds of discarded lumps of metallic iron in copper slag heaps, but as of yet, no unequivocal examples have been found (Merkel and Barrett, 2000). More circumstantial evidence, in the form of small amounts of metallic iron in copper smelting slags (Erb-Satullo et al., 2014:157), shows that thermodynamic requirements for iron reduction were achieved in Bronze Age copper smelting but not that macroscopic, usable quantities were produced. While the debate has yet to be resolved, it is clear that careful chemical and microscopic analysis of early iron objects and production debris from both iron and copper smelting is the way forward (Erb-Satullo, 2019). Experimental work on smelting mixed copper- and iron-bearing ores, and analysis of the resulting slags, will further help to constrain possibilities and aid in the archeological identification of such processes.

Through an exploration of intentionality, some archaeomaterials research has revised interpretations of supposed earliest examples of key innovations. Recent archaeomaterials research has shown that while green copper-bearing minerals were reduced to metal at Çatalhöyük in the seventh millennium BC, this was likely an incidental process during the burning of the building (Radivojević et al., 2017). Thus the “slag” produced during this burning event was not, as had been suggested, the beginnings of extractive copper metallurgy. Similarly, a comprehensive program of slag analysis showed that claims for the world’s earliest iron smelting on the Black Sea coast were unfounded: all the earliest sites were copper smelting workshops (Erb-Satullo et al., 2014, 2018).

Materials analysis has also helped explain why developments in one technology may not lead directly to the subsequent innovations that, in retrospect, might seem obvious. Materials analysis of the earliest ceramic objects in the world, from Dolni Věstonice in the Czech Republic, showed that these objects were likely cast into a fire to make them explode. Their transformation into lasting objects may well have been incidental to the process, perhaps explaining why this early experimentation with ceramic materials did not lead directly to the development of pottery containers (Vandiver et al., 1989). The social context and perception of these materials—reflected by the ways in which they were manipulated and illuminated by materials analysis—was the determining factor in the development of this pyrotechnology.

Archaeomaterials research has led to the identification of technological behaviors that complicate narratives of linearity. One such “linear” model might view technology as moving smoothly from an initial experimental stage, with small-scale output, limited usage, poorer quality control, and a limited or incipient understanding of the properties of the materials involved, to a mature stage characterized by broader usage, higher outputs, consistency, and a high degree of facility with the relevant material properties.

The discovery of a refractory crucible in a fourth-millennium BC context complicates this model (Thornton and Rehren, 2009). Chemical and scanning electron microscopy demonstrated that the crucible was constructed from composite materials that included a magnesium-rich, talcose fabric selected for its resistance to the high temperatures present in metallurgical processes. Unlike most early crucibles, it was heated from the outside rather than internally. Refractory metallurgical ceramics (that is, those highly resistant to heat and melting) achieve wide usage only during the Roman era, so the crucible is exceptional among contemporary technical ceramics. Yet the crucible reflects a clear understanding of ceramic refractoriness that predates other refractory, externally heated examples by thousands of years. Not all inventions, even ones that are quite effective from a material properties perspective, achieve widespread adoption.

Materials analysis has uncovered intriguing divergences in technological trajectories that further counter unilinear models of technological development. Comparative analysis of transformations in the gold and bronze industries of the Caucasus between the Middle Bronze Age and the Early Iron Age illustrates this point effectively. In the late third and early second millennia BC, the South Caucasus is known for a number of spectacular gold artifacts with complex wirework, granulation, and composite constructions involving stones and other materials (Lordkipanidze, 1989:Plates II, VI–VIII). Yet between about 1500 and 800 BC, when the bronze industry experienced a massive increase in the scale of production and the complexity and diversity of artifact types (see, e.g., Akhvlediani, 2005; Erb-Satullo et al., 2017, 2018; Maisuradze and Inanishvili, 2006; Picchelauri, 1997), there seems to be a significant decline in the quantity and complexity of gold artifacts in some areas of the South Caucasus (Japaridze, 1999:64; Kuftin, 1941:132) (The area of modern-day Armenia seems to be an exception (Kalantarian, 2007).) This decline lasted until about the eight to sixth centuries BC, when gold working reemerged, eventually reaching another high point of technological sophistication during the Classical–Hellenistic period (see Kacharava and Kvirkvelia, 2008).

The apparently divergent trajectories of gold and bronze working are even more puzzling when looking at the chemical composition of copper alloys from the late second and early first millennium (Abesadze and Bakhtadze, 2011 [1988]). These reveal that gold-*colored* tin bronzes were highly sought after for prestige weapons and items of body adornment. These patterns suggest that the decline or abandonment of gold working occurred even as the demand for gold-colored objects was high and copper-alloy metallurgical expertise was increasing.

Further investigation is needed to define the chronological and geographical scope of this apparent abandonment and to assess its possible causes (for example, exhaustion of key gold deposits or social changes affecting the integrity of craft transmission). Where a unilineal model would predict a consistent increase in metallurgical expertise over time, and a correlation between metallurgical expertise in one metal and expertise in another, the data suggest the opposite. While a large body of evidence on cross-craft interactions reveals that experience in one material can lead to innovations in another (Fenn, 2015; Goldstein and Shimada, 2007; Li, 2007), this is clearly not always the case.

4.2. Rethinking exogenous and endogenous influences on innovation

While the impact of archaeomaterials research in identifying technological “firsts” is undeniable, determining where and when an innovation first appears is only the initial step in understanding how and why those innovations spread. Archaeomaterials research has made profound contributions to discussions about exogenous diffusion versus endogenous independent invention. While this binary may be a reasonable first approximation and a useful rhetorical shorthand, the dynamics of innovation and technological change are often more complicated. Research on the spread of metallurgy into China has suggested that the initial ideas of smelting metal were likely transmitted through contact with metal-using peoples of the Eurasian steppes, probably through the Gansu corridor. At the same time, the ways of making and using metal in the central plains of China are so radically different from those of the “donor” regions that a simple model of diffusion is woefully unsuited to explain the patterning of archaeometallurgical evidence (Mei et al., 2015, 2017). Indeed, the diffusion-independent invention binary subsumes a wide variety of interactions that represent radically different mechanisms of technological spread. In the Chinese example, what does diffusion mean if the basic idea of metal smelting derived from external contacts but the core of the technological style bears little or no resemblance to those external traditions?

The diffusion-independent invention binary is tied to an implicit assumption of technologies as discrete and unchanging behavioral units. In this conception, copper-alloy metallurgy, for instance, is viewed as a package rather than a complex of technical challenges, including mining and processing ore, building furnaces, smelting raw metal, and manufacturing artifacts, each of which invites a range of different solutions. One of the greatest contributions of archaeomaterials research has been to illustrate the richness and variation of technologies as they are adopted in different social contexts and incorporated into prior sociotechnical systems. Indeed, it is precisely the reconstructing of these concatenated technological behaviors that has allowed scholars to break down this binary and reveal complexities of interaction between different technological systems.

Materials analysis documents interaction, adaptation, and transmission of technologies in several key ways. Perhaps the most straightforward of these is by studying the provenance of raw materials used to make a particular set of artifacts. If the earliest appearance of a material made from nonlocal resources derives from an area where the technology is already established, a strong case for exogenous origins can be made. Conversely, if an object made from local resources predates its appearance in neighboring regions, independent invention is more probable. In addition to the source of raw materials, one can also consider the geographical attribution of particular techniques of manufacture: Do aspects of the production process follow local or foreign traditions?

Many archeological case studies defy straightforward assessment: either chronological resolution makes it difficult to determine primacy, or the mechanism and extent of interregional interaction are unclear. Yet even in cases where such information is known, many instances of innovation diverge from the “endmember” cases of fully endogenous or fully exogenous origins. For instance, some distinguish between “complete” and “conceptual” transfer, with the former referring to the wholesale transplantation of a technological practice, whereas the latter describes a process where the idea for a technology is exogenous but the implementation and realization of the idea are locally derived (Frankel, 2012). Frequently, innovation and technological transfer involve the import substitution, the development of local imitations of imported goods, as has been documented in Late Bronze Age pottery production in the Mediterranean and sub-Saharan primary glass production (Babalola et al., 2017, 2018; Buxeda I Garrigós et al., 2003; Lankton et al., 2006; Sherratt, 1999). In both instances, the presence of desirable foreign products—Mycenaean pottery from Greece in the former instance and glass from the Islamic Middle East in the latter—stimulated innovation in local pyrotechnologies reliant on local resources. While import substitution focuses on the imitation of foreign products, foreign techniques and processes can also replace local traditions, even if they do not impact the final macroscopic form of the object. Analysis of technology and provenance of archeological materials are ideally suited to untangle the variety of interactions inherent in technological change.

The emergence of metallurgy in West Mexico provides a classic example of how a broad suite of materials analyses can illuminate the patterns of adoption, incorporation, selection, and imitation in the process of technological transfer. While theories of South American origins for pre-Columbian metalworking in West Mexico have a long history (Meighan, 1969), metallographic, chemical, and experimental materials research provided the most compelling case for the exogenous influences on early Mesoamerican traditions (Dewan and Hosler 2008; Hosler 1988a, 1988b, 1994:87–124). This body of research showed that while much of the metal in these artifacts was local to West Mexico, the specific traditions of shaping and working copper alloys derived from several distinct metalworking traditions in southern Ecuador and Colombia. Crucially, materials analyses were able to show how these different strands of influence were selectively integrated and modified in the development of a new West Mexican metallurgical tradition.

Debates about the rise of iron production in sub-Saharan Africa illustrate the importance of considering the technological style in potential source regions as an adjunct to chronological considerations. The emergence of iron into Africa has often been framed as competing theories of diffusion and independent invention (Alpern, 2005; Chirikure, 2015:20–28; Holl, 2009; Killick, 2009). Chronological considerations have loomed large in this debate due to the publication of some surprisingly early radiocarbon and thermoluminescence dates (e.g., Darling, 2013). Subsequent revisions and reevaluations have narrowed down the crucial period to the Halstatt radiocarbon plateau of 800–400 BC, making it difficult to resolve conclusively whether the earliest well-dated sub-Saharan smelting sites predate the introduction of iron into Egypt/Sudan (Killick, 2009:405–6). For all the attention to chronology, there has been relatively little opportunity to compare the technological style of iron smelting in sub-Saharan Africa and the regions from which the technology may have originated (Killick, 2009:405–6). Far fewer iron smelting and other iron metallurgical sites have been investigated in the Near East, particularly in the crucial intermediate area of Egypt (Erb-Satullo, 2019). Recent work on iron metallurgical remains at Meroe in Sudan and Carthage in Tunisia, while not (as yet) resolving the question of origins, illustrates the potential of integrating dating and materials analysis programs to build a robust technological chronology (see Charlton and Humphris, 2019; Humphris and Rehren, 2014; Humphris and Scheibner, 2017; Kaufman et al., 2016).

Recent archaeomaterials research on the origins of glass also illustrates how a detailed examination of technological practices can clarify directionality in innovation and adoption. Large quantities of glass first appear in both Mesopotamia and Egypt during the Late Bronze Age. Much research has focused on determining whether glasses found in Egypt and the Near East come from different production centers, as well as whether the major mid-second-millennium BC expansion in glass production may have originated in one area before spreading to the another (Degryse et al., 2010; Moorey, 1999:193–94; Shortland, 2012). While some scholars suggested that core-formed glass vessel technologies were introduced from Mesopotamia to Egypt (Bryan, 2000:75), reevaluation of the chronology at the important glass-containing site of Nuzi (Stein, 1989) and a review of wider evidence have led scholars to question the chronological primacy of Mesopotamian glass (Shortland et al. 2018). This same research stresses the greater variability in the color palette of Egyptian glass and points out elements of Mesopotamian glass working (namely, the technique of applying and scoring rods of colored glass on core-formed vessels) that appear to be imperfect imitations of techniques from Egyptian glassmaking practice. Chemical and isotopic analysis of glass strongly supports the existence of multiple distinct glassmaking centers in Mesopotamia and Egypt (Degryse et al., 2010; Shortland et al., 2007, 2018).

The debate over the origins of glass is not yet fully resolved, but archaeomaterials research on Bronze Age glasses offers several possible interpretations. Was Near Eastern glass innovation the result of import substitution, whereby Near Eastern glassmaking emerged to produce local versions of imported Egyptian glass vessels? Import substitution may have taken place in other crafts within Late Bronze Age Syro-Mesopotamia (e.g., Erb-Satullo et al., 2011). Alternatively, could the spread of glassmaking technology have moved in the opposite direction, with the arrival of Near Eastern glass in Egypt stimulating a cascade of radiative innovation? Given the high degree of the contact, interaction, and imitation in the formation of the Late Bronze Age artistic koine (Feldman, 2006), it seems possible that multiple streams of influence flowed back and forth between Egypt and Mesopotamia. Analyses of glass colorants, provenance, and working techniques are essential in tracing the chronology and directionality of influences in such a highly connected world.

The study of early glass innovation is not the only example of how material analysis has revealed new complexities that defy simple narratives of unidirectional influence. The appearance of opacified white-glazed ceramics in the Islamic world during the eighth century AD has played an important role in historical narratives about interaction between China and the Middle East. While traditional perspectives framed the emergence of opacified white glazes in terms of local imitation of imported Chinese stoneware and porcelain, recent work has begun to complicate this picture, pointing out the influences of preceding local glazed ceramic traditions (Watson, 2014). This new work rejects models that cast the Islamic world as passive receptors by showing how demand for Islamic pottery styles influenced Chinese ceramic production through the Middle Eastern commissioning of Chinese-made pottery. Analysis of glaze chemistries and opacifying technologies has played a key role in this reevaluation, illuminating a complex web of interaction between East Asian high-fired ceramics and preceding Middle Eastern glazed ceramic and glassmaking traditions (Matin et al., 2018; Tite et al., 2015).

It would be impossible to discuss questions of exogenous and endogenous influences without mentioning the considerable body of research examining the material dimensions of colonial encounters between Europeans and indigenous peoples of the New World (Bradley and Childs, 1991; Capone, 2004; Ehrhardt, 2005; Martinón-Torres et al., 2012; Thomas, 2018; Ting et al., 2018; VanValkenburgh et al., 2017). These studies have illustrated the remarkable diversity in the patterns of adaption, incorporation, and negotiation that characterized these interactions. In several cases, careful materials analysis has overturned prior interpretations of certain classes of material that appear in contact-period and early colonial sites. Based in part on metallographic analyses, Bradley and Childs (1991) demonstrated that while the distinctive contact-period metal spirals in eastern North America were largely smelted copper and brass of European origin, the working methods indicate that the metalsmiths themselves were Native Americans. Similarly, SEM analysis combined with re-firing experiments on Early Green Glazed wares from the North Coast of Peru suggests a series of complex interactions between indigenous Andean and Iberian firing technologies, vessel forms, and glazing techniques (VanValkenburgh et al., 2017). The variability in innovations documented in colonial contexts prompts archaeologists to probe questions of technological interaction and hybridity in colonial contexts more deeply.

Taken together, these examples illustrate the enormous potential of materials analysis to move the theoretical debates over endogenous and exogenous origins of technologies beyond well-worn binaries of diffusion and independent invention. Indeed, this work has documented in rich detail the processes of imitation, adoption, reinvention, and recombination that characterize the spread of innovations.

4.3. Explaining technological change

Archaeomaterials research has played a fundamental role in testing hypotheses about why innovations spread. Distinguishing foreign imports and local imitations is one approach to identifying potential external impetuses for change, as discussed above. Another class of approaches examines the material properties (performance characteristics) of archeological materials to understand how they may have been perceived and to identify which properties of an innovation were considered desirable, replicated, and optimized. When combined with chronological data, this aspect of archaeomaterials research has played an important role in sorting out cause from consequence.

The investigation of the origins of iron metallurgy is an instance where the delineation of causes and consequences has been somewhat muddled (see discussion in Erb-Satullo, 2019). Perhaps in part because of iron and steel's status as the premier industrial metals, early investigations of iron placed particular emphasis on its geological abundance, cheap cost, and the potential (if carburized and quenched) for dramatic improvements in hardness relative to most Bronze Age copper alloys. Yet it is very unclear how much these aspects of the technology were major factors in the initial adoption of iron. In the 1970s and 1980s, during the first wave of metallographic studies on early iron artifacts in the Near East (Davis et al., 1985; Maddin, 1982; Muhly et al., 1985; Stech-Wheeler et al., 1981; Tholander, 1971), some scholars expressed the view that the discovery of consistent carburization, quenching, and tempering made iron artifacts far superior to those of bronze, stimulating the major expansion in the use of the metal in the late second and early first millennium BC (Maddin et al., 1977).

More recent metallographic work has challenged this theory, pointing out that few artifacts show evidence of quenching and that one of the best examples likely dates to a later period (Eliyahu-Behar and Yahalom-Mack, 2018; McConchie, 2004; Yahalom-Mack and Eliyahu-Behar, 2015). While acknowledging that the parts of an object most likely to show evidence of quenching are the first areas to corrode, there is at present little evidence that consistent carburization, quenching, and tempering were regular features of early iron metallurgical repertoire. Rather it seems more likely that systematic carburization and quenching techniques emerged as "cascade" innovations that followed the wide adoption of iron.

Archaeomaterials research has also played a central role in recognizing that aesthetics and color played a far greater role in the spread of metallurgical innovations than had previously been appreciated. Indeed, one can trace the evolution of these ideas through generations of archaeomaterials specialists, from pioneering work by archeological materials scientists at MIT (Hosler, 1994; Lechtman, 1984:14–15; Smith, 1965) through more recent discussions of metallurgical innovation (Radivojević, 2015; Roberts et al., 2009:1012). Recent years have seen more systematic exploration of the colors of ancient alloys, which are often obscured by corrosion (Mödlinger et al., 2017; Radivojević et al., 2018). Given that hardness testing of archeological artifacts has been a regular part of the archaeometallurgical repertoire for some time, it is encouraging to see color receive similarly rigorous attention.

It is worth pointing out that performance characteristics may also be viewed from the perspective of primary producers rather than the ultimate consumers, who may be none the wiser. Innovation in iron smelting technologies in medieval Wales seems to have been driven by a desire on the part of the smelters to increase flexibility to respond to changes in fuel supply and iron prices (Charlton et al., 2010). Likewise, the innovation of local material technologies to provide import substitutes is predicated on the consumer being minimally aware of the difference between a product made from local materials and a foreign import.

5. Conclusions

As the above case studies have shown, archaeomaterials research has exceptional potential for the archeological study of innovation processes. While this observation could hardly be considered a revelation for archaeomaterials specialists, the future of this field lies in effectively communicating this potential to a wider audience within archaeology and beyond. Indeed, materials analysis has contributed directly to addressing the common concerns that infuse wider discussions of innovation. Yet while there are some notable cases where archaeomaterials has successfully permeated these theoretical discussions, and archaeomaterials as a field is moving in the right direction, as others have noted (e.g. Killick and Fenn, 2012:565–66), the overall level of integration remains unsatisfactory.

In part, this can be achieved through better engagement with key concepts in one or more of the theoretical traditions in innovations studies. Given the existing diversity of terminologies and theoretical approaches to technological change, it would be naive to call for a unified terminology. Yet there is something to be said for presenting archaeomaterials data in ways that are intelligible to these broader theoretical conversations. By situating archaeomaterials research on innovation in relation to existing theoretical terminologies, we can build a common frame of reference and make archaeomaterials research a leading player in archeological study of innovation. Archaeomaterials specialists must take an active role in connecting their work to these larger transdisciplinary debates. The result of these efforts will be a more robust and comprehensive archeological approach to the topic of innovation, as well as cross-fertilization of ideas across subfields. After all, zooarchaeologists and paleobotanists studying domestication engage with similar technological questions of experimentation, adaptation, manipulation, invention, and innovation. Despite these commonalities, there has been surprisingly little engagement between the subfields of ancient biotechnologies (that is, plant and animal manipulation) and material technologies.

In engaging with theoretical issues in innovation studies, it is important to emphasize that archaeomaterials research can do more than map existing theoretical concepts onto analytical data. It can contribute to recursive model building. To take one example, the innovation diffusion research tradition has an acknowledged emphasis on successful, rapidly spreading innovations, while comparatively little work has been done outside archaeology to explore slower adoption processes, rejection of innovations, and/or the formation of durable boundaries between coexisting technological traditions (Rogers, 2003:106ff). By contrast, archaeomaterials research has investigated numerous examples of such processes. Thus the scientific analysis of ancient craft production technologies is well situated not just to adapt various theoretical traditions in the study of innovation but also to interrogate, revise, and extend them.

Given the increasing concentration of archaeomaterials specialists within archaeology and anthropology departments, we can expect these approaches to become increasingly prevalent in the discipline. One indication is the increasing number of archaeomaterials research articles appearing in widely read general archaeology journals (for example, *Journal of Anthropological Archaeology, Journal of Archaeological Research, Journal of World Prehistory, Antiquity,* and *Journal of Archaeological Method and Theory)* in addition to those targeted specifically to archaeometric topics. This increase occurred at different times for these journals; some have a long history of publishing archaeomaterials research while others have seen a more recent uptick in archaeomaterials-related articles. Nevertheless, the overall trend is fairly recent, with an important shift in the late 2000s to early 2010s. I see a clear link between these developments and a recent position piece arguing for the merging of archaeology and archeological science and an end to the “two cultures” paradigm of earlier decades (Martinón-Torres, 2018; compare with earlier assessment in Jones, 2004). One can debate how far along archaeomaterials is in this integrative process, but the trend is undeniable.

At the same time, the observation that hiring in archaeomaterials has not, to a large extent, kept up with the broader expansion in archeological science positions (see Killick, 2015a:296), underscores the urgency of clearly articulating the value of archaeomaterials research. One way of doing this is to orient the discipline around major themes of broad archeological and anthropological interest. This approach has worked well for other archeological sciences. Themes like resilience, sustainability, and climate change adaptation have invigorated paleobotanical research in recent years (e.g., d’Alpoim Guedes and Bocinsky, 2018; Marston, 2015). The theme of innovation offers analogous direction and coherence for archaeomaterials research.

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