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Geographic Visualization in Archaeology

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Abstract: Archaeologists are often considered frontrunners in employing spatial approaches within the social sciences and humanities, including geospatial technologies such as geographic information systems (GIS) that are now routinely used in archaeology. Since the late 1980s, GIS has mainly been used to support data collection and management as well as spatial analysis and modeling. While fruitful, these efforts have arguably neglected the potential contribution of advanced visualization methods to the generation of broader archaeological knowledge. This paper reviews the use of GIS in archaeology from a geographic visualization (geovisual) perspective and examines how these methods can broaden the scope of archaeological research in an era of more user-friendly cyber-infrastructures. Like most computational databases, GIS do not easily support temporal data. This limitation is particularly problematic in archaeology because processes and events are best understood in space and time. To deal with such shortcomings in existing tools, archaeologists often end up having to reduce the diversity and complexity of archaeological phenomena. Recent developments in geographic visualization begin to address some of these issues, and are pertinent in the globalized world as archaeologists amass vast new bodies of geo-referenced information and work towards integrating them with traditional archaeological data. Greater effort in developing geovisualization and geovisual analytics appropriate for archaeological data can create opportunities to visualize, navigate and assess different sources of information within the larger archaeological community, thus enhancing possibilities for collaborative research and new forms of critical inquiry.

Keywords: Geovisualization; GIS; Maps; Interpretation; Computational and Digital Archaeology; Cyber-infrastructures

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The Practice of Archaeology in a Globalized World

Geospatial technologies such as geographic information systems (GIS), Global Positioning Systems (GPS), remote sensing images and Light Detection and Ranging (LiDAR) are now routinely used in archaeology. Archaeologists are not only thought of by their colleagues in the social sciences and humanities as frontrunners in employing GIS, but are sometimes looked upon with envy for their apparent embrace of the ‘spatial turn’ several decades ahead of most other disciplines (Bodenhamer et al. 2010). Over the last three decades, a growing number of archaeologists have adopted GIS technologies, as illustrated in the works of Allen et al. (1990), Lock and Stančič (1995) and Aldenderfer and Maschner (1996). Many subsequent publications (e.g. Lock 2000; Wheatley and Gillings 2002; Conolly and Lake 2006; Mehrer and Wescott 2006) took the form of instructional manuals or teaching aids aimed at a non-specialist audience, highlighting what-not-to-do when using GIS technologies, thus reflecting an awareness of critiques of environmental determinism in archaeology prevalent at that time (Gaffney and van Leusen 1995: 367).

A common argument in many early works was that GIS should allow more than just making "pretty pictures" (Ebert 2004: 320). In this context, GIS applications were thought of as a three-component hierarchy consisting of analysis, management, and visualization or representation of archaeological data in map forms (Ebert 2004: 320-321). In this conceptualization (Fig. 1), the complexity of the tasks had a direct relationship with prestige, where analytical tasks provided the greatest prestige of all three components. The traditional simple map visualization capabilities of GIS, while readily acknowledged as "vital" (Ebert 2004: 320), were quickly downplayed as "output and display" or the "read-only mode of GIS" (Ebert 2004: 319-320). GIS

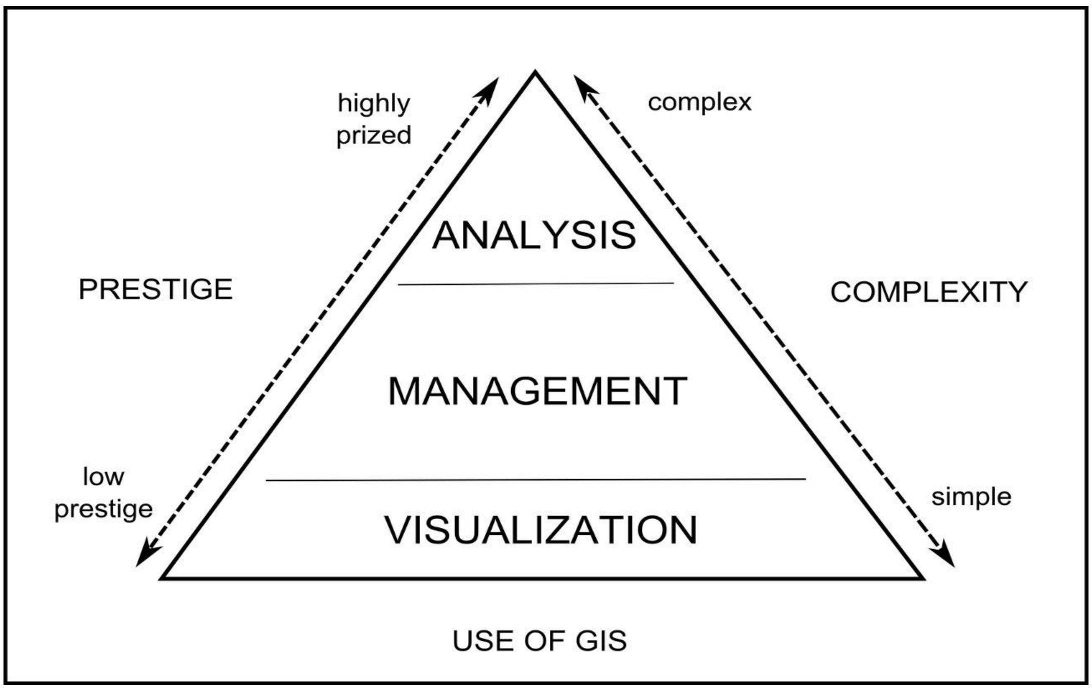

Fig. 1 The conceptualized hierarchy of GIS tasks. The left axis represents prestige and the right axis represents complexity. Visualization is at the bottom of this hierarchy where it is considered simple and has low prestige as an "output" for complex tasks like analysis

visualization was considered a communication tool, while data analysis offered ways to explore and generate new knowledge. This tripartite view of GIS, representative of how GIS was perceived in other fields, precluded the recognition of information visualization as a process for generating knowledge, a key role now acknowledged in the recent geovisualization and geovisual analytics literature (Fairbairn et al. 2001; Dykes et al. 2005; Andrienko et al. 2007; Andrienko et al 2010; Lloyd and Dykes 2011). This shift in focus on the benefits of geographic visualization for knowledge creation has not yet gained much traction in the archaeological community but can offer opportunities to analyze the complex spatial and temporal data inherent to the field of archaeology.

In this paper, we will review ways that conventional GIS map outputs have been used in archaeology and will discuss how recent developments such as geovisual analytics can offer opportunities for deeper insights into the past. We argue that advanced geovisual analytics systems can go beyond the limits of traditional GIS technologies, offering new forms of research that support knowledge generation in archaeology. Within this framework, we demonstrate that existing geospatial tools and technologies such as GIS fall short for archaeological phenomena, not because of a lack of computing performance, or limited memory size, but rather because these tools are often inadequate in facilitating an understanding of complex real-world processes and events. Specifically, time-dependent spatial phenomena that archaeologists study are not easily captured in algorithms for automated processing. As a result, archaeologists too often reduce phenomena in size and complexity to match the capabilities of existing tools. Furthermore, while maps are primarily meant to communicate results, maps and visualization have great potential in heuristic methods that facilitate information processing in archaeology.

In addition to their temporal dimension, archaeological data have a clear spatial component. It should then come as no surprise that, despite some of its limitations, archaeologists often described GIS as an ideal technology for storing, managing and analyzing archaeological field data (Ebert 2004: 319). As recently as 2011, Scianna and Villa (2011: 337, emphasis added) remarked that when "limited to data inventory and management, or *more simply* to visualization", the potential of GIS is constrained, as "it is above all a spatial analysis tool supporting decision making". This view of GIS was also common in other disciplines such as geography (Maguire 1991).

While most archaeologists acknowledge that GIS can help support decision making, the situation is decidedly more complex when it comes to the management of the temporal dimension. Despite a significant body of research on temporal GIS (Langran 1992; Peuquet and Duan 1995; O'Sullivan 2005), most current commercial GIS packages still fail to easily manage complex temporal data (Lock and Harris 1997; Green 2011). This limitation often results in the reduced scope of research questions and constrains the examination of change through time. This situation is particularly problematic in archaeology as it deals with diverse and complex data on time-dependent spatial phenomenon and because archaeologists have great interest in examining change through time. Archaeologists are aware that GIS typically offer a static 'snapshot' (Maschner 1996: 303-304) and some have sought out ways to represent time through techniques such as time-stamping and map animation, which we will discuss in detail in a later section.

In his call for an Archaeological Information Science, Llobera (2011: 218) remarks that archaeologists tend to "reduce" technical skills in information systems to an "add-on to their bag of tricks" (2011: 217). He observes that archaeologists have made little effort to "integrate" information technologies "within current archaeological discussions", a state Llobera believes is reflected in the lack of appropriate training that could enable the development of "new IT tools" in archaeology (2011: 217). Llobera refers only briefly to geographic visualization or to digital visual media and technology that promotes a spatial understanding of archaeology. Most crucially, however, he states that visualization can "precipitate new forms of doing archaeology" (2011: 219).

Cognizant of the dramatic growth in information and increasing graphics capabilities, McCoy and Ladefoged (2009: 264-265) have encouraged archaeologists to create 2D or 3D GIS representations in order to perform "exploratory spatial data analysis". The authors remark that visual exploration is particularly useful in identifying historic and archaeological features of interest on remotely collected (aerial and geophysical) imagery. McCoy and Ladefoged (2009: 266) refer briefly to visualization on the Web, remarking that these technologies can "facilitate public outreach". While fruitful, this view of visualization falls within what has been described as a communication-based approach (MacEachren 1995).

Geographic visualization relies on the broader research in cartography and information visualization. Recent developments in cartographic representation of information are premised on two key changes in the field, namely, that there are "new things" to represent and "new methods" to represent them (Fairbairn et al. 2001: 1). In this context, Fairbairn et al. (2001: 2) define cartographic representation as the transformation of information into perceptible forms that "[encourage] the senses to exploit the spatial structure of [the portrayed information] as it is interpreted". Put simply, advanced visualization methods encourage use of our cognitive abilities (rather than equations and algorithms) to process information and generate new knowledge. This field is now referred to as visual analytics or geovisual analytics when it focuses on geographic information. Such representations are thus distinguished from traditional maps meant solely for communication of information.

Visualizations, such as maps, are used to communicate information and can be studied in the more general context of the communication or information transmission model (Fig. 2). Under this model, measurement of the transmission of information through a unidirectional communication system is of key interest, with a particular focus on assessing the loss of information upon reaching non-specialists. This is in contrast with a representational approach in which maps are a "graphic summary of spatial information" (MacEachren 1995: 12), a visualization tool that promotes exploration and questions about what still remains unknown (MacEachren and Ganter 1990). In the representational model, a map-form is not solely a static communication device. Rather, maps and map-forms can facilitate dynamic interaction and identification of unknown spatial patterns and relationships in complex data (MacEachren and Kraak 1997: 338). Thus examination of how the content of a map facilitates spatial understanding of complex phenomena, and how and why these representations acquire meaning, are of greatest interest (Dodge et al. 2008).

This situation however, does not mean that maps and map-forms are not used to present knowledge claims or that they do not reflect the scholars' values, beliefs and interests (Harley 1988). Rather, geographic visualization (geovisual) methods draw attention to, and harness human cognition for information processing through pattern recognition. To facilitate these capabilities, geovisualization methods aim to create display environments such as multiple linked views that enable visual investigation through interaction with information (Andrienko et al.

2011). Geovisualization includes in this context any graphic that enables a spatial understanding of the time-dependent phenomenon or process of interest. These methods are a form of information processing, as well as a way to communicate information.

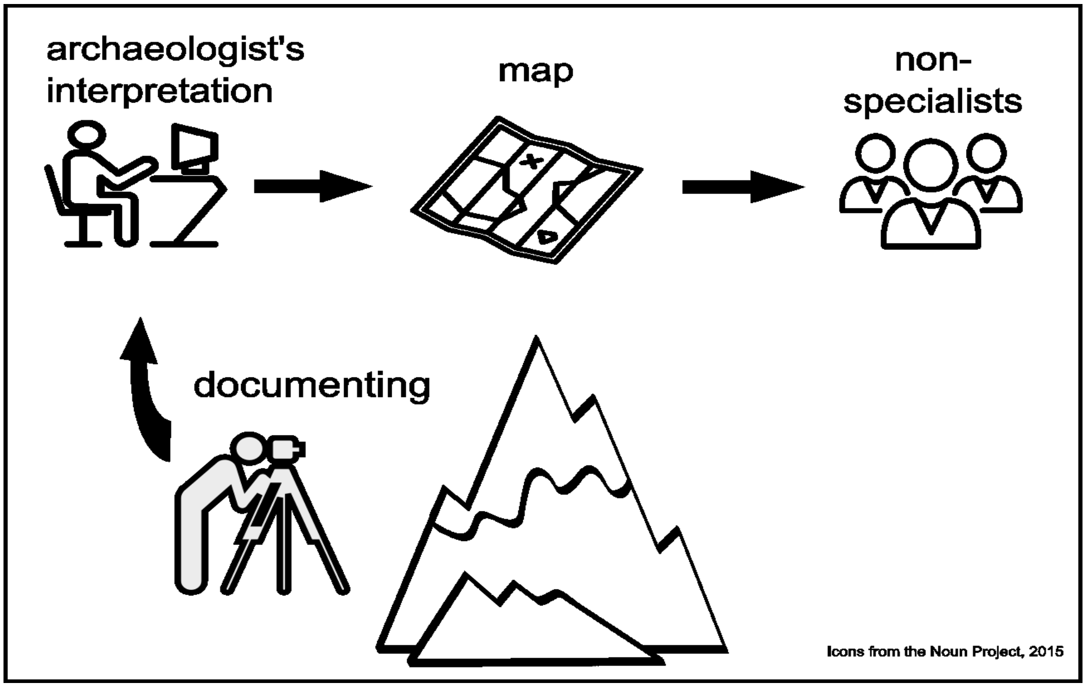

Fig. 2 A depiction of the information transmission model in which the map is typically considered a communication device for outreach to non-specialists. The model is unidirectional and emphasizes the loss of information at each stage until it reaches the final non-specialist recipients (adapted from MacEachren 1995)

Visual analytics, for example, is a recent field of research focusing on the development of visual interfaces that enable "knowledge discovery" through a visual exploration of information (Keim et al. 2008; Deufemia et al. 2012). "Geovisual analytics" (Andrienko et al. 2007) leverage the spatial dimension in data, including location information that can pose privacy and security concerns. This suggests that scholars can gain meaningful insights into complex phenomena even where data contain sensitive location information, a situation to which archaeologists can certainly relate. Moreover, these methods are being employed in an increasingly wide range of scenarios particularly where scholars and policy makers have to deal with information that is heterogeneous and voluminous. These recent developments can benefit archaeologists as we routinely deal with heterogeneous data that are increasingly computationally processed (Bevan and Lake 2013), which we will discuss in a later section.

We begin by briefly discussing the nature of archaeological data with a view on their heterogeneity and uncertainty. Next, using landscape and settlement archaeology as examples, we examine how GIS have been used for producing maps and visualizations in archaeology. Landscape and settlement archaeology are of particular interest as both approaches integrate a unique class of archaeological data that are sources of spatial, temporal and thematic information on material culture and physical landscapes. Up until very recently, maps represented a synchronous or snapshot view of the past, where an examination of change through time was limited. Through careful examination, we show how maps and other traditional geographic visualizations have been used as a communication tool and we discuss what insights are gained through conventional static maps when examining complex archaeological phenomena. Next, we discuss how archaeologists have sought to examine change through time in GIS, as well as geovisualizations that can offer perspective on complex archaeological data. Finally, we will discuss current themes and trends in geovisualization that are particularly relevant for archaeology.

Nature of Archaeological Data

In this paper, we distinguish between two related concepts: the *archaeological record* and the *archaeological database*. The former refers to all material culture which exists, whether it has been recovered or awaits investigation, whereas archaeological database refers specifically to material that archaeologists have successfully recovered during field investigations to shed light on human history. The archaeological database then consists of collections that different archaeologists have made at different times and places. An archaeological collection encompasses portable artefacts, skeletal material, and soil, wood, botanical samples and faunal material, along with photographs, drawings, imagery, maps and field journals describing an archaeologist's field methods. Archaeological documentation of features such as hearths, camps, dwellings, rock images, monuments and earthworks and their spatial relationship with other recovered material can be viewed as imperfect models of a complex reality. Subsequent evaluation of such heterogeneous collections would therefore be best considered an analysis of geographically-referenced historical information.

Often termed legacy data, archaeological collections in local and national repositories are increasingly being digitized and integrated with new archaeological data for combined analysis (Kintigh et al. 2015). Because repositories, physical or otherwise, are themselves a product of the society in which they were created, they are influenced by their social, political, cultural and historical circumstances (Cox and Wallace 2002). For example, how and why particular collections are chosen for digitization and which classes of data within them are preserved in digital format can impact subsequent study. Investigations that integrate new data with existing collections then take on their assumptions and limitations (Atici et al. 2013), in addition to uncertainties in the new data (Allison 2008). Imperfections in geo-referenced historical information can be described as having three components; spatial, temporal, and thematic (Plewe 2002).

Time, as a concept, is a vital subject of research in archaeology that generally focuses on how archaeological data enhance or constrain understandings of the past (Murray 1999; Lucas 2005, 2012; Bailey 2007; Holdaway and Wandsnider 2008). Archaeological data are by their nature both spatial and temporal. They can result from temporal averaging (Llobera 2007) or 'flattening' processes (Rabinowitz 2014) and their spatial, temporal and thematic components are characterized by varying kinds and degrees of uncertainty or imperfections. This has two important implications for archaeology. First, imperfections in archaeological data, particularly in the temporal component are complex, and this uncertainty is not unique to archaeology. Fields such as history (Knowles 2008) and geology (Bárdossy and Fodor 2001) have similar temporal uncertainty. Second, commercial GIS do not easily handle uncertainty (Devillers and Jeansoulin 2006). The widespread use of GIS in archaeology thus can result in the mismanagement and propagation of uncertainty. However, specific methods and tools can be developed to model and visualize data-centric imperfections in archaeology.

In an increasingly digital environment, these imperfections are rightly of great interest as is suggested by recent research on temporal uncertainty in archaeology (Green 2011; Crema 2013; Bevan et al. 2013), including simulation approaches (Llobera 2007; Crema 2012; Barton 2013) and "spatio-temporal" uncertainty (de Runz et al. 2007; de Runz and Desjardin 2010; Crema et al. 2010; Zoghlami et al. 2012; Yubero-Gómez et al. 2015; Kolar et al. 2015). Specifically, archaeologists have sought to address assumptions of synchronicity in spatial analysis especially where temporal information is coarse, as is often the case with archaeological data (Johnson 2004; Crema et al. 2010). These works propose statistical techniques such as fuzzy logic and probabilistic approaches to model imperfections in temporal aspects of archaeological geo-referenced information. While fruitful, they lack discussion on visualization of these imperfections (Thomson et al. 2005; Zuk and Carpendale 2007) or on how visualizing uncertainty enhances reasoning and decision making (Retchless 2014; Kinkeldey et al. 2014).

Recognizing the complexity of the temporal component within archaeological data, Green (2011: 213) remarks that archaeological time has "two forms", namely, the chronology archaeologists create, and the "perceived temporality of persons in the past". Green (2011: 213) rightly observes that conventional GIS are "temporally-frozen", a situation that is unacceptable to archaeologists. He further suggests that GIS software packages such as STEMgis (Discovery Software®) that are temporally-precise, are generally built on a modern calendar and clock time that is inappropriate for archaeological data. Most crucially, Green (2011: 214) acknowledges that "temporal needs" of archaeologists differ from those of other specializations, and he therefore encourages the development of tools appropriate for the discipline (see Rabinowitz 2014 for a non-spatial example).

Katsianis et al. (2008: 656) remark on the uniqueness of excavation data, arguing that they "represent events or durations" that an archaeologist must organize in "a relative or absolute manner" with "more or less interpretative certainty". The authors argue that this situation is distinct from "dynamic temporal phenomena" that they believe represent constantly changing events in the present (2008: 656). While the authors rightly observe varying degrees of certainty in archaeology, this view overlooks time as a continuous entity, and the complexity of studying time-dependent spatial phenomena including taphonomic processes (Waters and Kuehn 1996). Under this model, the life and death of organisms, and societies are of greatest interest, broadening the scope of investigation to include differences in both the preservation of archaeological material and the manner of their subsequent recovery. We argue that it is possible to accurately associate material culture with the Bronze Age, for instance, without continuous data with high temporal precision. In archaeology, time-dependent spatial phenomena can refer to material culture archaeologists have successfully recovered through field investigation and the practice of archaeology itself in the present. Given the inability to repeat or reproduce an archaeological investigation, subsequent study of an archaeological collection must consider all resulting imperfections in such geographically-referenced historical information.

While both Green (2011) and Katsianis et al. (2008) develop user-interfaces, neither discusses how visualization promotes insights into archaeological phenomena. We argue that advanced geovisual analytics systems have the potential to go beyond the limits of traditional GIS technologies, creating opportunities for new forms of research in archaeology that can support knowledge generation. Placing visualization as one stage in the cyclical process of archaeological practice (Fig. 3) can give insights into field methods from both ʻtop-downʼ and ʻbottom-upʼ perspectives, which in turn can revitalize the relationship between the collection and interpretation of archaeological data. Reconceptualizing maps within the process of knowledge

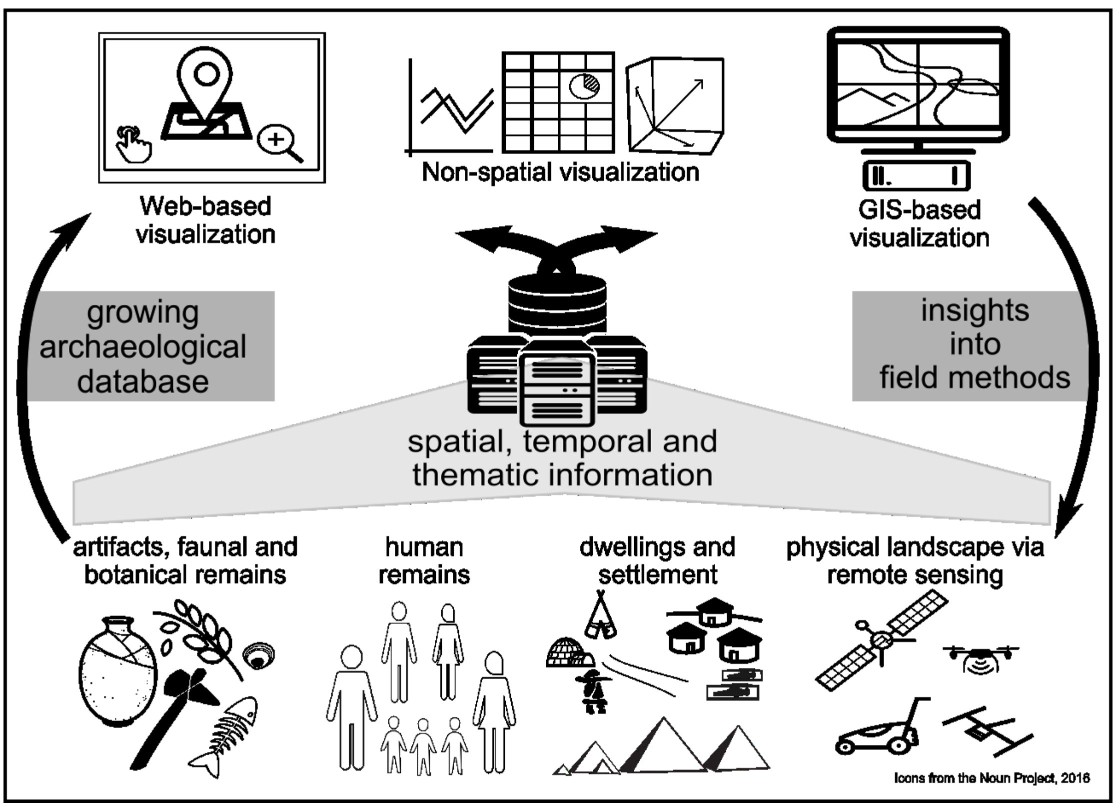

Fig. 3 A representation of the cyclical relationship between archaeological field collection, information integration, and data visualization and interpretation. As the archaeological database continues to grow, greater volumes of spatial, temporal and thematic information (with varying degrees of imperfections) are accumulated in digital repositories. These complex data can enable ʻtop-downʼ and ʻbottom-upʼ perspectives. Visual analysis can facilitate deeper insights that inform archaeological field methods

creation can shift intellectual and analytical focus to developing visualization tools that draw out unknown spatial patterns and relationships in large, diverse and complex data that can deepen our understanding of archaeological phenomena. Moreover, developing these methods on Web-based platforms can create opportunities to link across different sources of information, greatly enhancing search-ability, visualization and insights that in turn can promote engagement between specialists and across varied intellectual communities (Fig. 4). This kind of collaborative research is necessary for studying complex global phenomenon such as climate change.

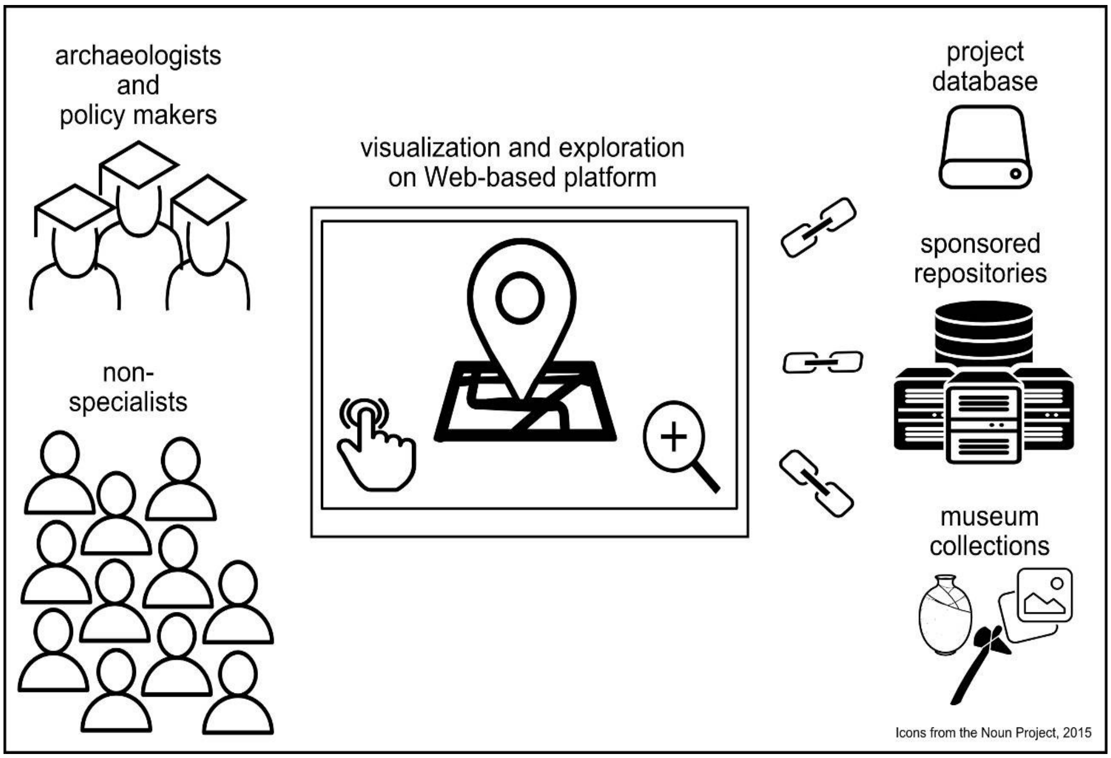

Fig. 4 An overview of geographic visualization. Visualization encourages use of human cognitive abilities to process information on a Web-based platform. This conceptualization underscores the collaborative nature of archaeological research and emphasizes visualization and interaction with different sources of information. Geovisualization tools can be employed by archaeologists, policy makers, other specialists and the general audience, albeit for different aims

Through the example of landscape and settlement archaeology we will now discuss how traditional maps have been used and how heuristic methods can facilitate deeper understanding of archaeological phenomena.

The Place of Maps in Landscape and Settlement Archaeology

A review of geographic visualization in archaeology must include map use in landscape and settlement archaeology, field-based approaches that refer to the study of the terrestrial environment and how societies in the past modified, organized and distributed themselves across that space.

A theme common in landscape and settlement archaeology is the collection of archaeological data with particular focus on extensive, non-invasive field surveys to record constructions visible above ground, such as dwellings, monuments, field walls and earthworks, and to a lesser degree, buried ones identified through archaeological excavations. These field collections are complemented with terrestrial imagery (e.g. ground penetrating radar, aerial and satellite imagery) and the surface recovery of portable artefacts such as potsherds, and tools (e.g. stone, bone, metal), and skeletal material. In the 21^{st} century, such complex archaeological data are often recorded, accessed, analyzed and shared in a digital environment.

Collection in hand, the most common unit of post-field analysis of archaeological data in a GIS is a point, a single location defined by a set of geographic coordinates (i.e. longitude and latitude or easting and northing). Information on the surface area of a dwelling, monument or artefact scatter is also typically collected. Detailed field data are often generalized to enable GIS-based techniques, such as viewshed analysis and least cost path analysis, both computational procedures that often can yield surprising results. These results are typically represented as static 2D maps. Yet our overall understanding of the human past is impacted by the *interpretation* of these results, which reflect an archaeologist′s beliefs and values and can offer insight on the use of maps in archaeology.

While a large number of landscape and settlement archaeology studies use maps to communicate their results (e.g. Clark et al. 1997; Bevan and Conolly 2004; Doyle et al. 2012), we describe in more detail three recent studies that illustrate how maps and other geographic visualizations are used in those approaches to provide synchronic views of the past. We acknowledge that the studies examined here were primarily focused on GIS analysis and not visualization. However, at present, archaeologists generally do not distinguish between maps meant to present results of GIS-based techniques and geovisualizations that enable insights into complex data and promote the generation of new knowledge. The reviewed studies exemplify the limited use of maps by archaeologists and a general reduction of archaeological phenomena (i.e. limiting of the temporal dimension). This situation does not mean that landscape and settlement approaches cannot enable insight into change through time (Chapman 2006; Crema 2013). Rather, we argue that while GIS-based techniques and maps are fruitful, deeper understandings of the past are possible within a heuristic approach.

In their recent article, ″Mapping the Political Landscape: Toward a GIS Analysis of Environmental and Social Difference″ in Inka society, Kosiba and Bauer make explicit that landscape is more than a physical space. They argue that landscapes are political spaces ″constituted by social categories and spatial boundaries″ (Kosiba and Bauer 2013: 67). They use a combination of field survey and GIS-based viewshed analysis, a measure of the visibility of the physical landscape and settlement features as a reflection of the ″systemic decision-making process″ that facilitates ″surveillance″ in a local space (2013: 64). Visibility thus, is a proxy for perceptions of the Inka landscape.

The authors present large scale (1:834; 1:1000; 1:4285) maps showing what Kosiba and Bauer (2013: 84) call "micro-scale" topography of the towns of Wat'a and Paqpayoq, including standing architecture in the two towns, agricultural terraces and platforms (Fig. 5).

Fig. 5 Copyrighted Image See Kosiba and Bauer 2013 (Figs. 2, 5, 9)
On the left, a small scale map that shows the location and sizes of the towns of Wat'a and Paqpayoq discussed in the study. On the top right is a large scale map that shows the "micro-scale" topography of Wat'a, including the locations of buildings represented as polygons, draped over a digital elevation model of the survey area. The bottom right image shows the range of visibility (in blue shading) at Wat'a from one viewer point on a 3D surface. While the authors have represented buildings as polygons on the map, the GIS-based analytic technique calculates visibility based on point locations (Kosiba and Bauer 2013)

Additionally, small scale (1:625,000 and 1:200,000) maps show the location of other settlements using points, their distribution across local topography and proximity to areas of maize production. The range and extent of production areas is based on prior analysis of multi-spectral imagery. The resulting maps effectively convey the distance between potential agricultural fields and settlements. However, the maps also give the unfortunate impression that maize agriculture and by implication, the pattern and distribution of settlements did not change through time. Furthermore, in their study, "environmental features" refer solely to glaciated mountain peaks (Kosiba and Bauer 2013: 81), the precise locations of which are indicated neither on the small scale nor large scale maps. The authors remark that mountain peaks were "most likely revered or attributed cultural importance" and therefore proximity to these features reflect "claims to divine authority" (Kosiba and Bauer 2013: 81). They also use photographs of stone houses (scale not indicated) to argue that elite Inkas perceived power differently from common people. The criterion for measuring authority is limited to one variable: range of visibility from each recorded residence.

Viewshed analysis on elite residences, however, did not show a preference for commanding views (2013: 77). Rather, Kosiba and Bauer found that commoner residences often had views of "more elaborate" elite buildings, including ceremonial architecture (2013: 82). Surprisingly, the authors conclude that elite residences were "built in places that maximize surveillance of commoners' residences" (2013: 82). Next, Kosiba and Bauer measure visibility of glaciated mountain peaks from residences and they conclude that a greater proportion of elite residences compared with commoner ones have line-of-sight to those physical features. They explain that the pattern reflects a "pronounced link" that enhanced Inka elite claims to social authority (2013: 81-82). Yet elsewhere, Kosiba (2011: 139-140) has remarked that the Ollantaytambo area "constituted a regional social landscape", where local people "experienced, imagined and perceived their social and physical environment" in a "common way". In this instance, Kosiba concluded that social authority was expressed through specific places such as towns where elites "directed a program of localization" and that "a perceived need for increased settlement proximity" influenced its density and distribution (2011: 139, 127-128).

A key issue with Kosiba and Bauer′s study is the assumption that all residences, civic and ceremonial buildings were co-terminal, which implies that the settlement did not change through time. This assumption is reflected in their use of static maps to communicate the output of particular techniques, a result that does not necessarily support their interpretation of archaeological data. The authors rightly note that theirs is a ″synchronic study″ of the ″accreted Inka landscape″ (2013: 69, Footnote 2) and therefore offer a spatial analysis of this past society. However, Llobera (2007: 57) has remarked that visibility patterns are ″complex″ because they are ″linked to movement″ and ″change as the landscape [is] transformed″, suggesting the need for greater attention to change through time. Reducing archaeological data to its spatial component, with limited attention to the temporal dimension can thus have unfortunate interpretive consequences. Most crucially, however, Kosiba and Bauer do not discuss how they integrated data that have different resolutions, nor do the authors visually represent uncertainty in their data (e.g. dwelling size, height, and proximity to neighbours′ dwellings), or discuss its sources and causes. Thus they miss the opportunity to explain how these imperfections impacted their interpretation of archaeological data.

Challenges in managing the temporal dimension in GIS and the reduction of archaeological phenomena is further reflected in measurements of movement over space. In this context, Surface-Evans (2012: 128) proposes using least-cost analysis to characterize the influence of the physical landscape on the ″movement of past peoples″. Critical discussion on the algorithm used for generating cost paths, including issues regarding calculation of direction of travel are available in Herzog (2013, 2014) and are not examined here.

In her evaluation of the ″position of shell mound sites in the Ohio Falls landscape″, Surface-Evans (2012: 141) presents a combination of small scale and large scale maps. She considers how terrain and hydrology constrained movement of prehistoric peoples through Ohio River Falls, remarking that shell mounds in this area have not been well researched and lack ″temporal control″ (2012: 129). Thus like Kosiba and Bauer (2013), the author considers the spatial component of archaeological data and uses maps to communicate the results of an analytical technique. To model the prehistoric landscape, Surface-Evans uses a digital elevation model at a 10m cell-resolution and a hydrology layer at an unspecified resolution. The author does not discuss how she integrated the two sets of data, or the impact of their potentially differing resolutions on understanding prehistoric travel paths. This oversight on data integration is striking because the author aims to use the resulting cost paths as heuristic devices. Surface-Evans (2012: 139) generates cost paths between 29 known archaeological shell mounds to compare time costs of travelling over land and along the Ohio River. The resulting cost paths are presented on static maps where the start and end locations are indicated using points and the path between them is represented as a line.

While a fruitful first step, these highly simplified maps miss opportunities to incorporate what Branting (2012: 219) calls ″interaction variables″, such as group walking that can alter the speed and direction of travel. For example, the GIS model does not offer a chance to visually assess the cost of travel in segments along paths, overlooking potential stops or breaks and diversions in travel between two points, or how these paths might differ seasonally (e.g. Scheidel 2015) or when transport animals and technologies are used. Visually representing different scenarios, including when data with different resolutions are computationally processed, can give archaeologists opportunities to better evaluate generated cost-paths, and this in turn can broaden our understanding of social landscapes. Moreover, such a heuristic approach can open conceptual space to discuss complexities of data integration and uncertainty in modeling prehistoric travel paths, a situation that can deepen insights into archaeological phenomena.

Jones (2010) uses viewshed and discriminant analysis to examine the impact of warfare on Haudenosaunee settlement pattern and distribution between 1500 AD and 1700 AD in the lower Great Lakes region. He draws upon published archaeological reports, archival research, including a trail map, and field collection using Global Positioning Systems (GPS) for geographic coordinates at 125 known Haudenosaunee villages. Jones (2010: 10) compares historic sites against a set of computer-generated points and concludes that "transportation" or proximity to overland trails was a key factor in settlement distribution such that the Haudenosaunee placed "themselves near overland transportation routes or vice versa". Furthermore, Jones remarks that defensibility was not a significant factor in the pattern and distribution of historic settlements.

Interestingly, Jones does not visually present results of the viewshed analysis, nor does the author perform spatial analysis on distance to overland trails. This is particularly surprising as he remarks that "Oneida and Onondaga villages gravitated toward inaccessible physiographic locations more than other nations" (2010: 9). Rather, Jones presents three small scale maps to situate the reader in New York State. On these maps, he uses points to show the location and distribution of 125 known sites occupied during the two hundred year study period and overland trails that he represents as lines. Jones (2010: 9) stresses the "positive spatial correlation" between villages and overland trails, and notes the influence on settlement distribution of the "unique political arrangement of Northern Iroquoian confederacies" during the 16th century (2010: 10). Indeed, the map (Fig. 6) does suggest close proximity

Fig. 6 Copyrighted Image See Jones 2010 (Fig. 3)
The inset situates the reader in the southern shore of Lake Ontario, in New York State. The small scale map shows the locations of Haudenosaunee villages represented as points and their proximity to overland trails and canoe-navigable waterways, both represented as lines. Of interest (arrows) is the extent of the overland trails and waterways and the apparent absence of archaeological sites along them (Jones 2010)

between villages and trails. Yet Jones fails to explain why villages are not located throughout the extensive trail network. This oversight casts doubt on his statement (2010: 4) that there are "likely few undiscovered village sites". Furthermore, Jones' assessment that defensibility was not a significant factor in settlement pattern and distribution is unexpected, given that elsewhere, the author has remarked that Iroquoians often relied on clear lines-of-sight (Jones 2006). In this case, Jones stressed the importance of "mutual visibility" to communication between villages and for their "mutual defence", and stated that the Iroquois were "likely making an effort to maintain" such visibility (2006: 537). Such a practice could be reflected in the pattern and distribution of settlement.

In his examination of post-contact Haudenosaunee society, Jones uncritically uses historical and archaeological data collected by scholars who employed different methods, which is clearly problematic. For example, the trail map upon which Jones bases much of his analysis is adapted from Henry Lewis Morgan's publication of 1851. Jones makes no mention of the scale of the historic map, nor does Jones contextualize Morgan's work with informants or weigh the map's value in terms of behaviors that ethnographers can and have observed (Wobst 1978). Moreover, Jones compiles names of historic communities, their locations and dates of occupation from 35 reports dating from 1714 through to 2006. While he remarks on technical issues with viewshed analysis, Jones does not discuss potential methodological concerns when integrating a wide range of sources of historical information. For example, what were the scale of historical maps, and the geographic extents of previous field studies? How did the methods archaeologists employed differ from one other, such as estimates of the size and density of settlements? How did archaeologists date villages and how confident were they in dating occupations at different villages? Such variability is an important consideration for any archaeological interpretation. In the absence of such contextual information, however, and with limited attention to the issue of data scale, data resolution and uncertainty, we effectively reduce previous archaeological studies to lists of point locations, oversimplifying archaeological phenomena and our overall study of the social and political organization of past societies. Visual representation of spatial, temporal and thematic information can enable assessment of the nature of archaeological data and can shed light on the strengths and limitations of particular sources of information. This in turn, can better inform subsequent archaeological field methods and deepen our understanding of change through time.

Visualizing Change through Time in Archaeology

The previous section described examples of studies that used GIS to provide a 'snapshot' or synchronic view of the past, and how maps function within the communication model. While such an approach can be appropriate in some contexts, it can reduce the size and complexity of archaeological phenomena, limiting its explanatory potential with regards to how and why past human societies changed. These interests cannot be overlooked or marginalized when employing computational methods and digital sources of information.

In this section, we will examine visualization techniques that go beyond conventional GIS tools, yet are supported by computational databases that enable dynamic views of change through time. These developments reflect a reorientation in the field of cartography over the last decade towards what MacEachren and Kraak (1997: 337-338) call the "map use-based approach" that juxtaposes private and public use of maps. Specifically, the authors define public use as that meant for a general audience who extracts specific information from a map, whereas private use is generally reserved for "an individual or small group", often researchers, interested in generating specific hypotheses (MacEachren and Kraak 1997: 337). This model draws attention to the relationship between static maps as communication devices in the public sphere and dynamic exploration of information in the private sphere. As Cartwright (1997) argues however, interactivity offered on Web-based maps potentially narrows gaps between private and public use, as well as intellectual distance between specialists and the general audience. "Web 2.0", as Kansa (2011: 3-4) has remarked, offers ways to encourage collaboration and broad engagement in archaeology via Web mapping, blogging and social media.

Recent years have witnessed a growing interest in computational and digital archaeology including themes such as movement over space (White and Surface-Evans 2012; Polla and Verhagen 2014), space and spatial approaches (Robertson et al. 2006; Salisbury and Keeler 2007; Bevan and Lake 2013), visualization (Llobera 2003, 2011), simulation and agent-based modeling (Costopoulos and Lake 2010), information and communication technology approaches (Evans and Daly 2006; Bimber and Chang 2011), digital culture studies (Huggett 2013, 2015) and Web-based collaboration (Kansa et al. 2011). Terminology used in these works underscores the ways that computational tools and technologies are currently employed in archaeology, as well as highlighting variability in contemporary practices. More fundamentally, these works reflect an expanding archaeological database, the exponential increase in digital data and acceleration in the development of analytical tools to process them.

Up until very recently, archaeologists tended to overlook visualization of change through time for similar reasons they overlooked traditional GIS visualizations. The prevailing perception was that visualization only represents something already known from the data and does not enable knowledge creation, i.e. seeing change through time does not help explain that change. This longstanding oversight on the part of archaeologists is underscored in Aldenderfer's (2010) call for the development of more effective technologies to visualize spatial patterns that change through time. In the following section, we examine this theme in detail. The cases examined here were chosen for their foci on handling imperfect temporal information in archaeology and the visualization of archaeological data. Of the four examples critically reviewed, three (Johnson 1999; Katsianis et al. 2008; Tsipidis et al. 2011) were conducted by archaeologists, and one (Huisman et al. 2009) is by information scientists working with archaeological data. In each case, we present background studies to contextualize recent developments. Katsianis et al. (2008) and Tsipidis et al. (2011) both offer a 'bottom-up' perspective that emphasizes digital recording in the field and further processing of those data in a digital environment (e.g. 3D models, multiple linked views) customized for visualization of archaeological data. Huisman et al. (2009) and Johnson (1999) describe the challenges and potential of 'top-down' approaches when navigating archaeological data that another scholar has collected through the 'space-time-cube' and through temporal animation.

(1) *3D recording and temporal visualization*

In her discussion of the temporal dimension in spatial databases for archaeological research, Constantinidis (2007: 408) conceptualizes archaeological sites as "mines containing a wealth of information concerning cultural changes". Under this model, archaeological stratigraphy and the documentation of the excavation process through "spatio-temporal databases" are of greatest interest (Constantinidis 2007: 408). Archaeological stratigraphy, of course, refers to the physical order and chronological sequence of cultural modifications and deposition of soils. Recording stratigraphy (including depth measurements) enables archaeologists to work out the order and relative sequence of natural deposition and cultural modifications within an excavation unit. This situation gives a reader the impression that depth and the temporal dimension are typically synonymous.

Some scholars have focused on developing digital documentation during excavations including three-dimensional (3D) recording of geo-referenced archaeological stratigraphy. For example, Katsianis et al. (2008: 656) propose a "digital workflow" that enables 3D representation of stratigraphic contexts for intra-site analysis within a GIS. Recognizing that excavation documentation in traditional GIS often simplifies archaeological data, the authors emphasize "temporal data" and correlate "temporal sequences" with stratigraphy (2008: 656-657). They offer an example of their workflow approach through archaeological field excavations at Paliambela in Greece. The authors focus on linking attribute information to "discrete objects" (Katsianis et al. 2008: 657), which they define as both recovered material culture and excavation units, or what they (2008: 658) call the "conceptualization of archival events" in the process of archaeological recovery. In their model, Katsianis et al. include six distinct "temporal categories": the date of excavation, the date when a new event was created in the information system, the cultural affiliation of artefacts, the absolute and radiocarbon dates, and the excavation phase (2008: 661).

The authors do not explain how an archaeologist not involved in the model's creation might use it, nor do they present any kind of diachronic analysis using their data. However, Katsianis et al.'s distinction between 'time attributes' (see also Koussoulakou and Styliandis 1999) reflects an awareness that computational queries on change through time are best served when multiple temporal values are recorded. Most crucially, the person who collected data in the field often also encodes these sources of information for further use, particularly where recording is in both analog and digital formats. In such cases, the encoder has pre-existing knowledge of spatial relationships in the data that enable the archaeologist to link individual field records. Therefore these geo-referenced sources can differ from information collected and stored directly from location-based technologies, or information extracted from digital archaeological repositories, for example. In the latter scenario, the researcher processes existing time-dependent geo-referenced information to potentially identify unknown spatial patterns and relationships, as we will discuss in the next sub-section.

(2) *Linked views and the space-time-cube*

In their study, Huisman et al. (2009) analyzed archaeological records within a geovisual analytics environment. Many spatial-temporal geographic visualizations are influenced by the space-time-aquarium framework (Hägerstrand 1970), more commonly referred to as a space-time-cube.

Space-time cubes allow visualizing changes in a given location (x, y) of phenomena through time (z) (Kraak and Koussoulakou 2005; see Mlekuz 2010 for time-space aquarium). Kraak and Koussoulakou (2005: 194) emphasize three key elements in any space-time cube: interaction, dynamics, and alternate views. Specifically, the authors discuss how simultaneous combination of different 2D and 3D views in an interface can enable users to navigate and examine linked variables (Kraak and Koussoulakou 2005). A synchronization of the different views (e.g. 2D map and timeline of events) allows users to discover patterns and relationships in the data that contribute to generating insights into complex phenomena. In the 'cube', it is possible to visualize the cumulative time paths of individuals and/or objects and enable tracing of their movement across space. As Kraak and Koussoulakou (2005: 194) remark, these movements can be explored diachronically because time is "always present". Periods of stay or stations are represented on extruded vertical lines where their length corresponds to their duration at a particular location.

As Huisman et al. (2009) show, a station might be a single archaeological site that corresponds to more than one archaeological culture and their relative chronologies. The authors present a case study in which they visually examine patterns and relationships in a database of 900 archaeological sites collected by the Natural Resource Department in Puerto Rico. The authors examine only a small subset of the existing data, focussing on four archaeological cultures that date between 850 AD and 1200 AD. Huisman et al. (2009) do not discuss in detail the nature of archaeological data or how the data were collected and encoded, remarking only that temporal classification was based on ^{14}C dating. The authors developed the space-time-cube as a plug-in for User-friendly Desktop Internet GIS (uDig GIS), an open source software package.

Attribute information for Huisman et al.'s (2009: 230) analysis include geographic coordinates, name of culture period, "maximum and minimum temporal value" of recovered artifacts (cultural affiliation) and "duration of given culture" at a station (i.e. an archaeological site), elevation, slope, aspect and agrarian capacity. In their visualization environment, the authors group archaeological events by cultural affiliation, and use color to distinguish between different archaeological cultures. Each station is shown with an extruded vertical column that corresponds to its cultural identity, and where the column's height represents the start and end time of that culture. Interaction (i.e. temporal overlap) between archaeological cultures is represented as a linking horizontal line between co-terminal sites. These "network clusters" highlight where a "certain degree of interaction" could have existed between different cultures (Huisman et al. 2009: 233). The authors (2009: 228) note additional grouping features within the analytical environment, including "data manipulation functions" such as "brushing" that enable an archaeologist to explore data with other linked representations. Tools such as filtering using query operations, and point-and-click highlighting, as well as the ability to select and display different attributes, can greatly facilitate user interaction with archaeological information.

Huisman et al. (2009) do not offer specific insights into archaeological phenomena, nor do they discuss how summarization and classification impacts our understanding of spatial relationships. However, the visualization environment has functionality that enable different ways of clustering or 'grouping' complex data can offer an archaeologist opportunities to visually analyze complex spatial patterns and relationships in existing archaeological collections. This opens possibilities for further research, particularly where another scholar has collected the data and where the spatial coverage and temporal granularity of those data are not well understood.

Drawing upon excavation data from Paliambela, Greece, Tsipidis et al. (2011: 88) have designed a visualization system that enables archaeologists to "review-revisit the excavation site and its inclusions, inspect their actions in the field, [and] compare, synthesize and analyze the complex archaeological information". The authors conceptualize field excavation diaries as a "highly detailed archive of observations" of an activity that cannot be repeated (2011: 86). This archive, along with photographs and topographic information collectively represent the primary source of information available to the archaeologist for post-field analysis. The authors thus aim to formulate a "workflow for dynamic investigation and analysis of [the] excavation archive" (2011: 87).

In their study, Tsipidis et al. (2011) design techniques that enable visual analysis of complex archaeological data within a customizable visualization environment. The authors argue that traditional GIS assume user expertise and familiarity, a limitation they believe prevents further development in visualization. To address this issue, the authors (2011: 90) offer a simplified and customizable GIS interface that enables 3D visualization of "temporal characteristics and relationships", querying, and dynamic presentation to aid interpretation and enhances user interaction with data.

The interface articulates multiple linked windows with a main viewer and a "temporal graph" (Tsipidis et al. 2011: 103). The temporal graph is a chart with dynamic buttons corresponding to particular archaeological periods, such as Neolithic, and "excavation time", which is the date of the field investigation. In distinguishing between these two time attributes, Tsipidis et al. (2011) employ a workflow framework previously developed by Katsianis et al. (2008). The interface includes a slider that enables the user to define start and end time (archaeological period). Selecting a time range will filter results in the database and will display corresponding objects in the main viewer.

The authors (Tsipidis et al. 2011: 107) remark that an understanding of "temporal diversity across space" is important for archaeological interpretation, and is enhanced by "[linking] temporal graphs with the actual spatial elements of reference in 3D space". Through these links it is possible for an archaeologist to query for a specific artefact, such as fish bones that were recorded within a user-specified buffer distance in an excavation unit and/or dated to a particular archaeological period. Users can define parameters such as "type of query" (thematic, spatial, temporal) and "finds type" (material, category). While informative, this functionality assumes the archaeologist has prior knowledge of terms to search for. Although the authors do not offer any specific insights derived from their intra-site analysis, or understandings of how users evaluated their interactions with the system, Tsipidis et al. (2011) offer a customized platform that other archaeologists can potentially employ.

(3) *Time-stamping and map animation*

Animated maps, as Harrower and Fabrikant (2008: 50) define them, are “sequences of static graphic depictions” that when “shown in rapid succession”, enable the graphic content to “[move] in a fluid motion”. As such, animations can assume both temporal and non-temporal forms. Non-temporal animations include ‘fly-throughs’ in a 3D terrain where the viewer’s perspective changes (Peterson 1995). Temporal animations are those that explicitly represent the passage of time. Like static maps, animated maps can be used to disseminate knowledge to a wide audience and to enable exploratory data analysis by scholars and scientists. However, unlike a static map where it is possible to carefully examine details and specific places, an animated map frame is on screen only briefly. Thus, animated maps are orientated towards general patterning with emphasis on “change between moments” and to gain “overall perspective on the data” (Harrower and Fabrikant 2008: 50). Temporal animated maps therefore can be effective in depicting processes or “representing dynamic geographical phenomena” (Ogao and Kraak 2002: 23).

Characteristics of animated maps include a “temporal scale” that is expressed as a ratio between real-world time and animation time, the temporal granularity or the finest temporal unit possible, and the pace or the amount of change per unit time (Harrower and Fabrikant 2008: 54-55). The temporal scale has been visualized as cyclic and linear legends and builds on awareness that different kinds of legends can support understanding of varied phenomena; for example, a cyclic wheel is more informative than a liner bar for understanding recurring seasonal events. The key advantage of a temporal legend is the capability to visualize both the “current moment” and the “relation of that moment to the entire dataset” (Harrower and Fabrikant 2008: 55). Moreover, Kraak (2005: 5) has remarked that a timeline can improve “[access] to the data” and furnish “options to explore the data”. It is no surprise then that such timeline representations accompany most maps and have been developed as a module in open source GIS software such as QGIS, and Geographic Resources Analysis Support System (GRASS) GIS 7 (Kratochvílová 2012), and in commercial ones such as Environmental Systems Research Institute’s ArcGIS® (version 10.x). This, however, does not mean that animation is an ideal representation form for all data that have a temporal component.

Time-stamping is a technique in which each record in a spatial database has at least one time-value, and these are arranged in chronological sequence. The resulting arrangement can be visualized on a horizontal timeline that runs between the earliest temporal-value through to the most recent in a given set of data. Time-stamping can be employed to visualize both image and feature-data layers where temporal information is available. This functionality can enable an examination of landscape changes through visual exploration of a time-series of aerial imagery, for example.

In this context, *Time*Map®, a map visualization tool developed by Ian Johnson at the University of Sydney enables users to generate "complete interactive maps" without knowledge of computer programming (*Time*Map® 2015). Johnson (2002: 1) points out that archaeologists may locate a place with accuracy, but often have "a vague notion of time", an uncertainty that can lead to incorrect generalizations. The author rightly remarks that glossing over temporal resolution impacts the interpretation of archaeological phenomena, and he addresses this challenge through visualization of primary data. Such visualizations, Johnson (2002: 1) argues, can enable users to "assess the data for themselves" and gauge the strengths and limitations of particular arguments.

The *Time*Map® project began in 1997 with the aim to develop methodology and software for "recording, visualizing and eventually, analyzing features that evolve through time", or what Johnson (1999; 2008) calls "mapping the fourth dimension". *Time*Map® was developed from a desktop application into a Web browser-based applet that enabled a user to query and display information on the Electronic Cultural Atlas Initiative (ECAI) clearinghouse. The applet features a timeline bar that filters layers by period, such that those with a specific date span can be activated when they fall within a user-selected time range (Johnson 2002: 5). Once selected, the time-stamped data will display in the *Time*Map® viewer (Johnson 2002: 2).

Time-stamped spatial layers can also be used to generate a map animation through "snapshot-transitions" that encompass "the history of features" (snapshots) and the "series of transitions" that fall between the snapshots (Johnson 1999: 2.3). In this case, map animation would likely illustrate important changes over short intervals of time, and long periods of no change. While potentially visually compelling, Johnson does not make explicit how an interpolated value for transitions is calculated, and to what degree the visualization of such transitional states serves the interests of archaeologists, nor does he give specific insights into the ECAI clearinghouse. More crucially, improper use of animation can give an incorrect view of the passage of time that potentially underestimates the impact of archaeological recovery, and thus can influence our understanding of the past. For example, an interpolation generally assumes a linear transition between events, a situation that can simplify rapid changes characteristic of human history, which would not be accurately represented using such methods.

However, Johnson's overall platform does open possibilities for the integration and visual exploration of different sources of archaeological information on the Web. In the next section, we will discuss in detail recent developments in archaeology that intersect with current trends in geovisualization, a combination that can offer a 'top-down' perspective on archaeology.

Current Themes and Trends in Geovisualization for Archaeology

The term 'geovisualization' has been used in many publications in archaeology (e.g. Koussoulakou and Stylianidis 1999; Stine 2000; Kraak and Koussoulakou 2005; Watters 2006; Huisman et al. 2009; Pérez-Martína et al. 2011; Tsipidis et al. 2011; Gupta 2013; De Roo et al.

2013). The range of themes that these publications cover is as wide as the venues in which they were published, reflecting the intrinsic complexity of contemporary archaeology.

A number of geovisualization works have used the Web as a platform to communicate information (Prinz et al. 2014; McCool 2014; but see von Groote-Bidlingmaier et al. 2015). Much of the existing research on Web-based tools in archaeology has focused on development of architecture and server-side functionality (Djindjian 2008), data services (Richards et al. 2012), knowledge management (Watrall 2012), data publishing (Kansa and Kansa 2014), participatory crowd-sourcing (Bevan et al. 2014; Keinan 2014), and social media (Beale 2012). These developments reflect changes in the way archaeology is practiced in the 21st century. As Kansa (2012: 7) has remarked, "digital forms of archaeological communication differ from traditional paper-based media" and "require examination and rethinking of knowledge production processes". This brings into focus efforts in collecting archaeological data, how these heterogeneous data are structured, how they are integrated with other existing sources of information and then further analyzed for greater insights into the past (Kansa 2005). Similar efforts are necessary to allow for more effective geovisualizations. The Web thus requires that scholars and scientists ask different questions and develop appropriate tools to answer them.

Archaeologists are in general agreement that geo-referenced sources are currently at a magnitude where traditional forms of analysis fall short (Bevan 2012). Bevan and Lake (2013: 18) have remarked that the past ten years have been "unusually important" in developing and enhancing new "techniques" in archaeology such as "Digital Archaeology", and "explicitly model-based or spatial analytical approaches". They argue that these developments reflect a "wider democratization process in computational archaeology" (2013: 18; see also Costa et al. 2013). As Bevan and Lake (2013: 18) explain, the developments result from a "growth in modern computing", the availability of "sharply increased amounts of digital data" and a "wider climate of more open access to both data and software source code".

In this context, Kintigh (2006: 567) has stressed the "pressing need for an archaeological information infrastructure" that enables the integration of data from different sources. Likewise Snow et al. (2006) have envisioned cyber-infrastructures or consolidated Web-based computational databases for the integration and preservation of digital archaeological collections. Such consolidated databases can assist in the analysis of vast amounts of geo-referenced data, including those stored in archives and other government-sponsored repositories, as well as archaeological collections and computer databases on personal computers. These sources vary in size, in content and complexity, in formats, and in availability, and thus, their integration poses significant challenges. To address these concerns, Snow et al. (2006: 959) propose a distributed Web-based resource that emphasizes interoperability and is shareable. While informative, these efforts tend to maintain focus on a narrow range of sources and themes, overlooking opportunities for collaboration and the generation of new forms of research in archaeology, including geovisualization. Most critically, however, Web platforms in archaeology can promote 'top-down' perspectives that facilitate an examination of the overall practice of archaeology.

These perspectives are necessary as current efforts have generally overlooked the significant variability in archaeological practices across nations and around the world, a situation that impacts our overall view of human history.

As most archaeologists acknowledge, the life of archaeological data does not end at trowel′s edge or in a repository. Rather archaeological information are readily the source material for ′top-down′ analysis such as Bevan′s (2012) study of large-scale artefact inventories or Evans′ (2015) assessment of grey literature in British archaeology and Cooper and Green′s (2016) examination of archaeological ′Big Data′ via the English Landscape and Identities Project. ″Characterful archaeological data″ as Cooper and Green (2016: 271) call them, have ″diverse histories, contents and structures″ and are ″riddled with gaps, inconsistencies and uncertainties″ (2016: 294). In this context, we examined recent efforts (in published works) along three axes: temporal navigation (static-dynamic), interaction with information (low-high) and platform (desktop-Web). While several authors use maps to communicate results, visualization tools for generating new knowledge in archaeology, particularly for the Web, have been neglected (Fig. 7).

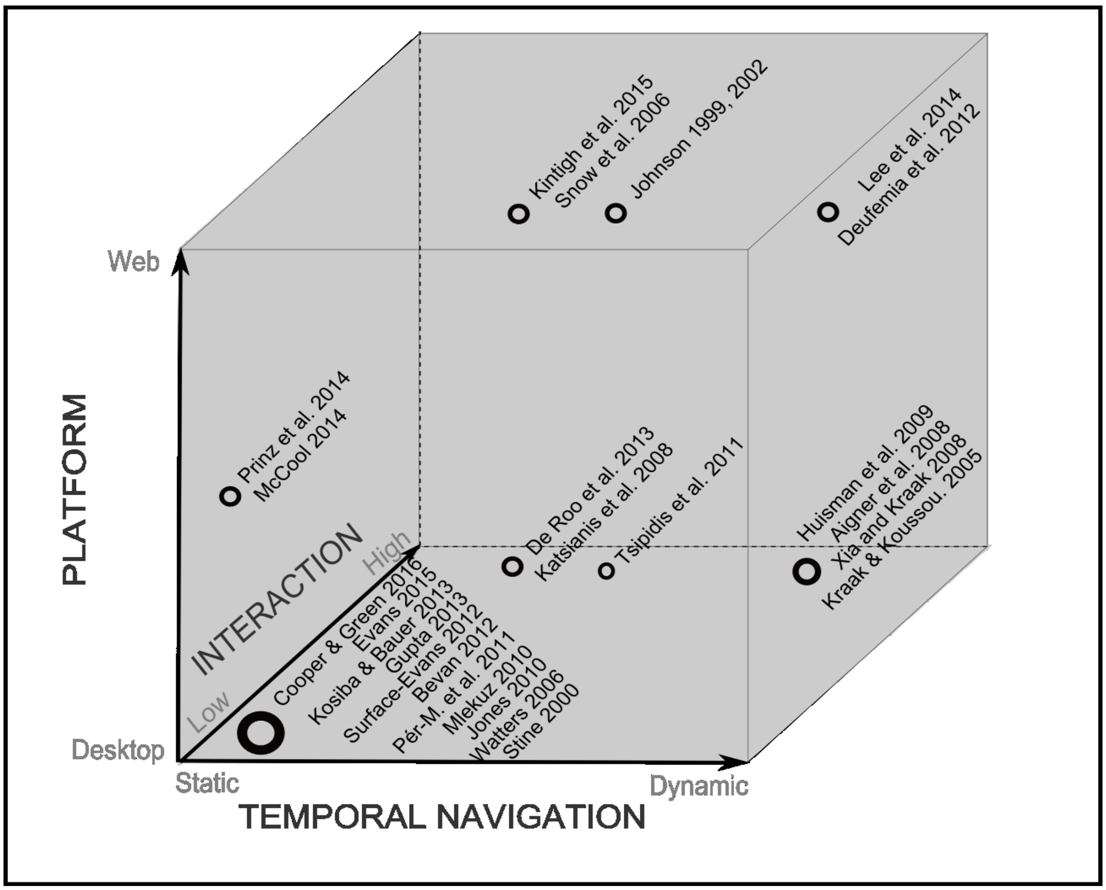

Fig. 7 A cube with three criteria: temporal navigation (static-dynamic), interaction with information (low-high), and platform (desktop-Web). The graph shows how reviewed articles deal with temporal navigation and whether tools facilitate (or are intended to facilitate) exploration through querying and data mining, and whether they are primarily desktop centered or Web-based. e.g. Deufemia et al. (2012) develop a geovisualization tool that is

Web-enabled, provides high interaction with information, where temporal navigation is dynamic

In the following sub-sections, we highlight different challenges that require further work in order to improve geovisualization as an analytical tool in archaeology.

(1) *Integration of sources of heterogeneous geo-referenced information*
To enable the creation of new knowledge, geovisualization tools have to access structured collections of data, a challenging situation due to the diversity of data that can be visualized. The potential of cyber-infrastructures or a consolidated computational database lies in its promise for shedding light on human history through the analysis of vast amounts of geo-referenced information (Snow et al. 2006). Kintigh (2006: 573) similarly proposes a cyber-infrastructure that will enable archaeologists to "contribute substantially to scientific understandings of long-term social dynamics". Kintigh et al. (2015: 5) draw attention to the complexities in integrating collections of "many different classes of items" that enable analysis ranging from "microscopic examination of a portion of a single object to archaeological sites and regional settlement patterns". Surprisingly, the authors remark only briefly on a "[t]emporally sequential visualization" and a "map-based tool" that can facilitate insights into past societies (Kintigh et al. 2015: 8).

While archaeologists recognize the potential for Web-based data sources in archaeology (e.g. Snow et al. 2006), greater attention is required on the specific challenges involved in merging existing collections with new ones. 'Born digital' collections differ from digitized ones that were originally preserved in analog format and subsequently are scanned or reproduced as digital documents. Combining digital and digitized sources requires what the digital librarian Donald Waters (2007: 9) calls "informatics of standards and practices" used to "identify, mark up, manage, preserve, and develop the algorithms for exploring large volumes of digital information". Kintigh (2013: 585) sheds some light on creating "adequate semantic metadata", which he defines as information on the "meaning of the observations represented in a database". Such efforts are coupled with the extraction of relevant information from digitized sources through automated procedures such as natural language processing (Kintigh 2015). Doerr et al. (2010) discuss the integration of complementary sources on Roman era inscriptions and iconography, whereas Wells et al. (2014) discuss indexing and publication of historic property inventories managed by different government offices. Most importantly, these developments reflect awareness of the highly variable nature of archaeological data and the opportunities that exist for linking across diverse sources of information in meaningful ways.

In this context, Atici et al. (2013)'s study offers insight into using data collected by other scholars. The authors designed a blind test in which three specialists analyzed an "orphaned" zooarchaeological collection consisting of over 30 000 animal bone specimens, identifications of which were preserved on paper, then on punch cards and subsequently transferred onto a spreadsheet (Atici et al. 2013: 664), a situation that is not uncommon with old archaeological collections. The animal bone specimens however, are no longer available to scholars for examination. In the blind test, Atici et al. (2013: 666) asked three zooarchaeologists to independently analyze and interpret the preserved identifications using "their own approach" but document the "full process, from data cleaning to interpretation". Interestingly, in the absence of contextual and methodological information on the collection, all three participants decided that the data were best used for examining economic changes through time as reflected in changing relative proportions of taxa and demographic profiles (Atici et al. 2013: 667), a situation that underscores the strengths and limitations of digitizing older archaeological collections.

The authors do not refer specifically to standards for geo-referenced information or definitions for the temporal component in archaeological data that would be required for more effective geovisualizations (see PeriodO for an example of period definitions that enable linkages across sources). However, Atici et al. (2013) highlight the need for ontologies that can enable data discoverability and linkages across diverse sources. The authors (2013: 668) define ontologies as "formalized conceptual, data organization and classification systems" developed for data sharing. Atici et al. (2013: 673) thus consider "data integration" as the consolidation of data within a "common ontology" that is subsequently employed for "comparison across multiple datasets". Data integration therefore requires efforts to structure and document data, and similar efforts are necessary to allow for more effective geovisualizations. With greater control over metadata, there are growing opportunities for archaeologists to develop visualization tools appropriate for massive amounts of diverse archaeological data.

Stringent control over metadata in archaeology, and by implication, enhanced data usability can create possibilities for visual analysis of archaeological information on Web-based platforms. New publication venues, such as the *Journal of Open Archaeology Data* (JOAD), explicitly encourage the documentation of data or metadata in archaeology. In its mission statement, the editors of JOAD (2016) note that they seek a "description of a dataset, and where to find it". These data may include "geophysical data, quantitative or qualitative data, images, notebooks, excavation data, software," among others (JOAD 2016). The aim of a "data paper" is to create awareness of available data and outline methods by which they were created, a process that potentially offers transparency in metadata creation and data archiving. As a prerequisite to publishing in the journal, authors must deposit or publish their data in one of the journal's recommended partners, such as United States-based the Digital Archaeological Record (tDAR) or Open Context, and the United Kingdom-based Archaeology Data Service (ADS) or other similar repository. The data must be published with an open license that enables unrestricted access, although they may be "partially redacted for legal reasons" (JOAD 2016).

In the same vein, the data publisher Open Context has partnered with the Digital Index of North American Archaeology to develop protocols for the integration of archaeological information (particularly 'gray literature') from state- and federal-level agencies in the United States (DINAA 2016). These efforts therefore can enable interoperability, exploration, and visualization of archaeological information that have wide geographic coverage and deep temporal spans, not unlike those utilized in landscape and settlement approaches. The combination of linked archaeological data and visualization tools customized for such data can promote insight into the practice of archaeology and deepen our understanding of archaeological phenomena.

(2) *Visualization of geo-referenced sources*

Archaeologists recognize their data are often best (although not exclusively) represented visually (Llobera 2011). Visualization has long played a role in archaeology (Molyneaux 1997; Smiles and Moser 2005; Alberti et al. 2013) and is generally conceptualized within a communication model i.e. communicate results to a non-specialist audience. Archaeological visual media broadly refer to "illustrations, drawings, maps, photos, models, videos, exhibitions", as well as 2D and 3D "analogue and digital graphic productions" (Perry 2013: 281). These representations have clear overlap with cultural heritage displays. Visualization can also be a "bridge" between specialists (Perry 2013: 283).

Geovisualization however, is generally underrepresented in archaeological practice (Miller and Richards 1995) and this oversight impacts the development of effective visualization tools and technologies appropriate for digital archaeological data. There are two implications of this marginalization in archaeology. First, maps are underestimated in the process of knowledge-making as we have argued, and they are thus overlooked as a source of spatial information. Examining the interpretation of archaeology through maps is a step towards more rigorous and effective (geo-) visualization in archaeology. Second, while maps are primarily meant to communicate results, they and other visualizations can facilitate information processing in archaeology. Given that archaeological data have spatial, thematic and temporal components and that we are interested in visualizing archaeology, archaeologists are uniquely positioned to develop appropriate geovisual methods and technologies that enable insights into archaeology.

Placing maps within the wider practice of knowledge-making broadens the scope of visualization research in archaeology. This reorientation can enable archaeologists to shift intellectual and analytical focus to developing appropriate visualization tools and can revitalize the relationship between the collection and interpretation of archaeological data. In so doing, we simultaneously create spaces to collaborate with scholars in disciplines such as geography, cognitive science, anthropology, sociology, computer science and history and philosophy of science. Such collaborations can have broader implications on the process of knowledge-making in the social and historical sciences.

By reconceptualizing maps within the framework of knowledge-making, we begin to engage with current developments in geovisualization that channel intellectual focus from data structures to data navigation. Asking how maps work draws attention to the interaction between them and human cognition (MacEachren 1995). In so doing, we stimulate intellectual interest in how and why this relationship influences decision making. Understanding this relationship is at the heart of developing advanced visualization tools that enable user interactivity with data, and by implication, promote insights into complex human phenomena (Roth and Harrower 2009).

Harrower and Sheesley (2008) have developed a framework for evaluating how well a map works based on what users can do with the map and how effectively those tasks are supported through map interfaces. What design for panning and zooming, for instance, can be implemented to improve user experience and why are particular implementations more effective than others?

Traditional GIS software typically enables navigation of the spatial and thematic dimensions, but it does not offer effective exploration of the temporal dimension. Where temporal navigation capabilities are available, they are often in the form of a simple time slider. Greater efforts (Aigner et al. 2008; Xia and Kraak 2008; Lee et al. 2014) have recently been made to facilitate temporal navigation. Lee et al. (2014) for instance, developed temporal pan and zoom, much in the way we use them in any spatial context. With temporal zoom, we can examine geo-referenced sources at different temporal granularities, potentially giving insight into the timespan of different classes in an archaeological collection. Moreover, the authors offer recommendations based on user-testing on tablets in which users interact with these visualization techniques in a multi-touch environment, thereby extending the range of application from desktop mapping to Web-based platforms and mobile technologies.

Similarly, interaction with the temporal component in archaeological data is a central theme in Deufemia et al. (2012)'s "Indiana Finder"[1]. The visualization system includes a map summary through which an archaeologist can navigate spatial and thematic components of the data. The temporal component is represented as a "chronological symbol view" which is a ring with sectors that correspond to the distribution of chronological dates (e.g. 4200 – 3600 B.C.) (Deufemia et al. 2012: 544). Cognizant that more than one period can be highlighted for a single carved object, the authors offer a second level of investigative tools that includes the temporal co-occurrence with another carved object. The 'symbol view' rotates accordingly when two objects co-occur in a particular time period. This visual analytics system potentially supports investigation into the rock carvings database that can facilitate detection of 'anomalies' and unexpected insights into archaeological phenomena. It is clear that recent interest in visualization of the temporal dimension can be beneficial for navigating archaeological data.

In addition to efforts to collect, manage, structure and document data, effective geovisualization in archaeology requires explicit focus on developing visualization tools appropriate for archaeological data. To this end, archaeologists must expand our range and scope of training to include computing technologies in the 21st century (Wells et al. 2015). Given known constraints on public monies for archaeology, we must invest available resources wisely so as to ensure we elicit the maximum amount of value for archaeologists. We cannot repeat, for instance, the unfortunate practices of the past that showered 'black-box' resources upon archaeology such as described by Miller and Richards (1995), and that did not enable archaeologists to directly encode, model and visually analyze their data. Rather, it is clear from recent efforts that archaeologists, with our interests in time-dependent spatial phenomena have as

[1]The cited URL, http://indianamas.disi.unige.it, does not yet have the full visualization interface for experimentation, although individual demonstrations are available (June 2016).

much expertise to offer in the development of advanced visualization tools as we have to gain from them.

Conclusions

Geospatial technologies, such as GIS, are routinely employed in archaeology. However, up until recently, the use of GIS in archaeology largely focused on data collection, management, spatial analysis and modeling. Visualizations, like maps, were often downplayed and largely considered as a tool for displaying outputs from analysis, failing to contribute to the creation of new knowledge. In addition, the nature of archaeological data and more specifically their uncertainty (e.g. spatial and temporal) have challenged the use of traditional commercial GIS for more advanced visualizations. While geography and computer science scholars have started to adopt advanced geovisualization and geovisual analytics approaches that can help generate knowledge and handle uncertain data, archaeology has not yet embraced these developments. Our paper reviewed ways that conventional GIS map outputs have been used in archaeology and discussed recent developments in geovisual analytics that go beyond the limits of traditional GIS. We argued that in the context of an increasing abundance and diversity of data in archaeology, the use of geovisual methods can contribute to knowledge creation from archaeological data.

Archaeologists generally agree that GIS can offer decision-support but have sometimes underestimated the limitations of GIS and their impact on the practice of archaeology. Like most computational databases, traditional GIS tools do not easily support a temporal dimension, and archaeologists sometimes reduce the size and complexity of archaeological phenomena to accommodate these shortcomings. Through examples, we have first shown how maps used in landscape and settlement archaeology present a synchronous view of the past and that emphasized the spatial dimension in archaeological data. While such approaches can be appropriate in some contexts, they neglect an examination of change through time. This is particularly problematic in archaeology because by definition our discipline deals with time-dependent spatial phenomena and archaeologists are therefore very interested in examining change through time.

While some archaeologists rightly acknowledge the limitations of GIS technologies, criticisms are often based on what commercial GIS software packages can (or cannot) do, a situation that overlooks customized geovisualization platforms that can better handle the temporal dimension and uncertain data. Geographic visualization methods offer opportunities to address inadequacies in existing tools. Shifting focus to developing tools that enable identification of and insights into, unknown spatial patterns and relationships in diverse and complex data can deepen an understanding of archaeological phenomena that is not easily captured in automated processing. To harness human cognition for information processing through pattern recognition, archaeologists can develop visual environments that enable navigation of the temporal component in archaeological data in new ways. We can benefit from interaction with data through multiple linked views, and systems that set a given temporal granularity and a temporal scale. These visual systems can help address temporal ‘flattening’ issues in archaeology.

In an era where data resources and availability far exceed the technical skills required to process spatial patterns and relationships in geo-referenced information, archaeologists concurrently face the challenge of studying complex phenomena that require collaborative research across different intellectual communities. With greater availability of archaeological data and more stringent control over their metadata, there are growing opportunities to develop geographic visualization tools on Web-based platforms. Such tools can greatly enhance search-ability, and visual navigation of large, diverse and complex geo-referenced information. Greater efforts are necessary to formally encourage archaeologists to fully intellectually engage with computational and digital methods in new ways. Such efforts are reflected in the National Endowment for the Humanities-sponsored “Advanced Challenges in Theory and Practice in 3D Modeling of Cultural Heritage Sites” and “Institute for Digital Method and Practice”, both initiatives that promote digital practices and offer training for graduate students and professionals in archaeology. More, similar opportunities are necessary to expand the range and scope of training for archaeologists.

As growing amounts of digitized information become available through nationally-sponsored Web-based repositories such as tDAR, the Archaeology Data Service and data publishers such as Open Context, archaeologists have become increasingly aware of variability in the nature and organization of archaeological collections, highlighting issues in data sharing and integration. These developments are encouraging discussion about the challenges and opportunities in merging digitized collections with ‘born digital’ ones. Greater attention to developing appropriate visualization tools and technologies for processing this information can enhance our understanding of archaeological phenomena. Orbis, a Web-based geospatial network model developed at Stanford University offers an example of this potential.

Recent efforts in computational and digital archaeology have also increasingly characterized the practice of archaeology as a social activity, drawing attention to the process of knowledge-making. These efforts highlight the identity of the archaeologist and composition of investigating teams as a key source of variability in the collection of archaeological data and its subsequent interpretation. In addition, reorienting our view of maps as spatial representations that facilitate the generation of new knowledge broadens the scope of computational and digital archaeology. This reorientation can significantly expand possibilities for working with scholars from disciplines such as geography, cognitive science, computer science, history and philosophy of science, and anthropology, collaborations that can have wider implications on knowledge-making in the social and historical sciences.

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Software referred to:

Environmental Systems Research Institute ArcGIS®: http://www.esri.com/software/arcgis/arcgis-for-desktop

Geographic Resources Analysis Support System (GRASS): https://grass.osgeo.org/grass7/

QGIS: http://www.qgis.org/en/site/

STEMgis: http://www.discoverysoftware.co.uk/STEMgis.htm

*Time*Map®: http://sydney.edu.au/arts/timemap/

User-friendly Desktop Internet GIS (uDig): http://udig.refractions.net/