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On-Site Recording of Excavation Data Using Mobile GIS

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Archaeologists have embraced new technologies in many aspects of research, but reliance on paper-based recording has impeded development of excavation recording methods. The digital recording of spatial provenience for artifacts and features, together with complex attributes during excavation, while not problem-free, provides a streamlined recording process. This article describes a digital interface that links precise spatial provenience with digital forms and geo-referenced photographs during excavation at a colonial site in highland Peru. A customized version of ESRI ArcPad provides the means to create and to explore spatial and attribute data in the field and laboratory as GIS data, which in turn can be integrated with ArcGIS for post-field visualization and analysis.

Keywords: GIS, spatial analysis, Andes, colonial period, mobile computing

Introduction

In recent years, digital technologies have permeated archaeological practice to the point where fieldwork planning and orchestration, and post-fieldwork analysis and data dissemination, are facilitated by computers and digital instruments. However, the act of excavation recording—the key stage of primary data collection—remains less often integrated into a digital workflow. This article describes a rapid digital recording system developed with mobile Geographical Information System (GIS) software customized for use in excavations at a late prehispanic and early colonial era site in highland Peru that we believe will improve data recording procedures.

During excavation archaeologists must record the three-dimensional spatial location of thousands of artifacts, features, and samples, and connect these records with other data such as written descriptions, photographs, and soil characteristics. Among GIS specialists, the on-site registry of excavation data is not a novel method, but it has yet to become widespread in practice. Adjusting or overhauling the system by which the primary observations of archaeological excavation are recorded is not to be taken lightly, and archaeologists have been conservative in their data registry practices. Because excavation is irreversible, careful recording is critical, but the resolution of the data recorded ultimately represents a compromise between ideals of precision and detail on one hand, and real-world time and resource constraints on the other.

Increasingly accessible GIS packages, combined with continuing advances in portable and rugged computing equipment, have lowered costs and computer literacy barriers to the point that many archaeologists are switching from paper forms and maps to a GIS system. While these techniques require archaeologists to be adept with digital resource management and problem solving, the tools provided by GIS improve speed and precision that benefit data management and analysis. We suggest that a GIS/paper data registry system like the one we developed for our work in Peru can be implemented to improve the precision of data collection and streamline the work from field collection to analysis and publication.

There are good reasons why many archaeologists have been reluctant to incorporate computers into excavation recording, and paper excavation forms have worked well for generations, especially those customized for each excavation project (Kipfer 2007: 53–148; Wheeler 1954: 69). Making the transition to a digital system may entail giving up tangible means of recording data—hand-plotted plan and profile maps and provenience registries for objects and associated features in three-dimensional space. Equipment costs, battery life, screen legibility in sunlight, harsh field conditions, the complexity of archaeological data structures, and the need for secure backups during the excavation process have been obstacles preventing many projects from adopting a digital recording system (Dibble et al. 2007; McPherron and Dibble 2002; Searcy and Ure 2008). Fortunately, we have found that written notes on paper forms can remain a core part of excavation observations along with GIS for mapping and basic attribute data collection in digital forms.

Our goal was to create a system in which digital field recording methods are used to maximize efficiency and precision, while paper recording methods are used where digital ones would create interface-type impediments to the speed or mechanics of the process. Thus, hybrid digital/paper systems can accommodate some records on paper (long-form narrative observations), while a digital registry can accommodate standardized excavation observations (for example, soil color and texture, or collection inventories) and precise measurements.

Digital documentation of excavation is one of the largest ongoing transformations of how archaeologists register and manage their field data. Perhaps because of the fundamental importance of a three-dimensional data registry, digital data entry for excavation has lagged behind that of survey (Ryan et al. 1999; Ryan and van Leusen 2002; Tripcevich 2004; Wagtendonk and De Jeu 2007). At the regional scale, GIS-based field methods are established in survey research design and execution, and are distinguished from traditional methods primarily by greater precision and scale of documentation.

The system described here allows archaeologists to document excavation work in a rapid and efficient manner by integrating vector and raster spatial data sources with a digital provenience system. This gives excavators the ability to work with the data at many different scales (Craig 2000). It permits integration of much of the recorded information with existing digital databases and expedites analysis with statistical packages and GIS software, while allowing rapid map and report generation during the field season. Using the system described below, excavation recording occurs directly in projected coordinate space and features can be mapped in both vector (point, line, and polygon) and raster (photomap) data, using a flexible array of techniques (FIG. 1, TABLE 1). These include provenienceing features or artifacts with an existing polygon such as a grid cell or locus boundary, direct hand-plotting with handheld computers using XYZ offset values from local datums, photomapping through geo-referenced vertical digital photographs, and precise mapping using a total station. This system brings the core functionality of GIS to the field by permitting immediate connection between digital spatial data and observational (attribute) data through links between the cartographic entities (features, artifacts, etc.) and a database. Here, we discuss the benefits and costs of this system, and provide an overview of how it was implemented in our Peruvian excavation at a terminal prehispanic and early colonial settlement in a remote highland location.

Approaches to Digital Excavation Recording

After a decade of experimentation, a dedicated community of technologically inclined archaeologists has explored the possible advantages of real-time computer based excavation recording methods (Lock 2003; McPherron and Dibble 2002; Richards 1998). A variety of approaches have been described in the literature including in-field GIS approaches emphasizing 3D recording with complex stratigraphy (Katsianis et al. 2008), use of a GIS on a laptop or tablet together with orthorectification software (Craig 2000; Craig et al. 2006; Doneus and Neubauer 2004), commercial software dedicated to interfacing with a total station on a pocket PC or tablet PC (Bradley 2006; Levy and Smith 2007; Ziebart et al. 2002), and customized database software written for handheld computers (Skousen 2004; Tasic and Jevremovic 2004; Powlesland 2010: 104). Archaeological applications also benefit from advances in digital field methods in related disciplines like field geology (Apel 2006; Whitmeyer and Nicoletti 2010).

Digital excavation recording systems

Software options for the management and analysis of spatial data have grown with the expansion of GIS and CAD applications. The national antiquities departments in some European countries have promoted the use of GIS with standardized data models, spurring the development of excavation systems (García Sanjuán and Wheatley 2002; Richards 2009). One excavation system, Intrasis by the Swedish National Heritage Board, is a commercial digital data acquisition system that stores data in several ESRI file formats and provides tight integration with total station provenienceing. Open source GIS packages (in which source code can be freely distributed and modified) with modules dedicated to scientific field applications are evolving rapidly and becoming easier to use. Existing digital fieldwork approaches can be generally considered in a few groups: a general GIS or mobile component of a larger geospatial system, geospatial software written specifically for archaeological data recording, and an enhanced total station recording interface. The ESRI ArcPad approach described here falls into the first group and has the advantage of being a mobile component of a widely used GIS system, ESRI ArcGIS, a system that is familiar to many users and will be part of future improvements to the larger ArcGIS suite.

GIS-based recording uses vector and raster data models for documenting archaeological features and a field system can integrate these models with excavation methods. Vector data are discrete objects (usually points, lines, or polygons) with associated attribute tables, and vectors are commonly used to delimit discrete phenomena like artifacts and features. Raster data, in contrast, consist of evenly-spaced cells of a regular size, and are suitable for representing continuous phenomena like topographic
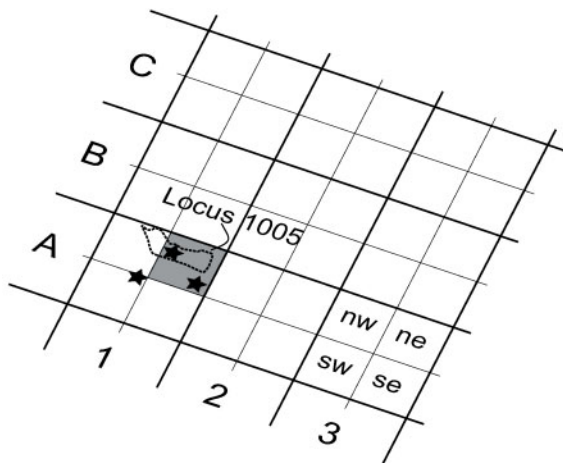
1. Nominal Attribute: items are provenienced in aggregate to a locus or grid cell by name.
In this example, a 1 m grid was divided into quadrants, and items derived from cell A1ne and from locus 1005. Error: depends on cell or locus size, speed: Fastest.
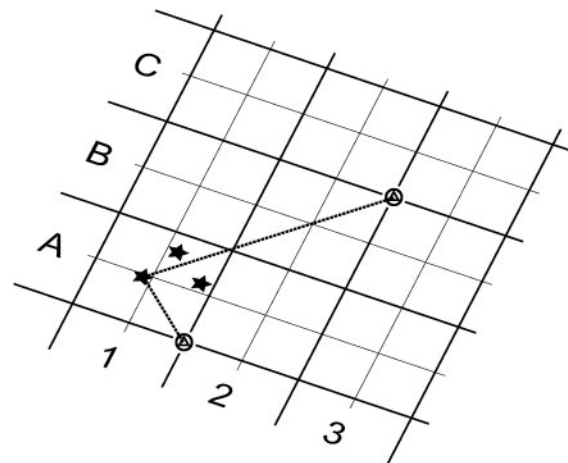
2. Offset mapping: distance from two accurately positioned grid corners are measured using tapes and Arcpad calculates point location from these values. Error: ~2 cm, speed: medium.
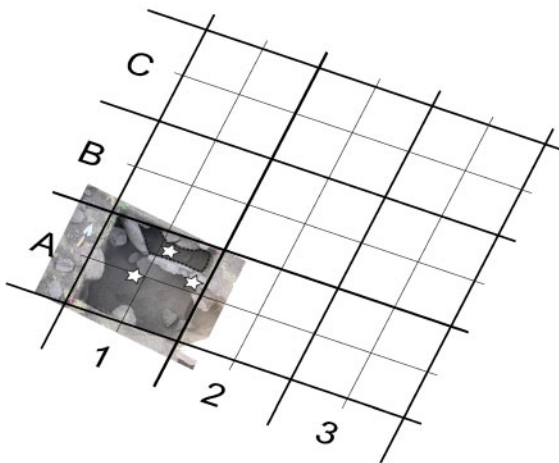
3. Photomapping (tracing): digital photos are shot from overhead (near-nadir) and geo-referenced to grid system in Arcmap using string intersections. Error: ~3–5 cm, speed: medium.
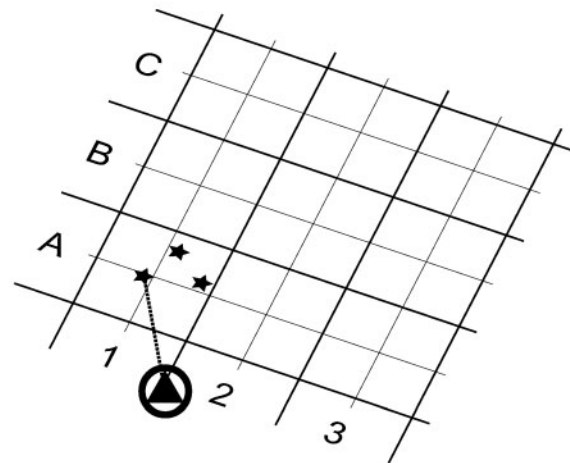
4. Point provenience: items are mapped individually using a total station established on site datum. Error: <1 cm, speed: slowest.

Figure 1   Four proveniencing methods in ArcPad.

Table 1   Principal mapping methods for on-site GIS.

| Method	Horizontal accuracy	Vertical accuracy	Time investment	Description
Nominal attribute	Low, depending on cell or locus size.	Low, by level or surface	Low	Assign to existing locus or arbitrary grid cell by referencing name.
Offset mapping	ca. 2 cm	Medium, by excavation surface or level or using string with a line level and a tape measure.	Medium	Positioning in ArcPad using horizontal offset measurements from two known grid corners to artifact/feature in situ.
Photomapping	ca. 3–5 cm, depending on quality of image geo-referencing, and rectification	Medium, by excavation surface or level or using string with a line level and a tape measure.	Medium	Digitized from photograph geo-referenced to grid cell; useful for delimiting features using polygons and when artifacts appear in photographs of surface levels.
Total station	High	High	High	Feature/artifact is delimited or point provenienced using total station.
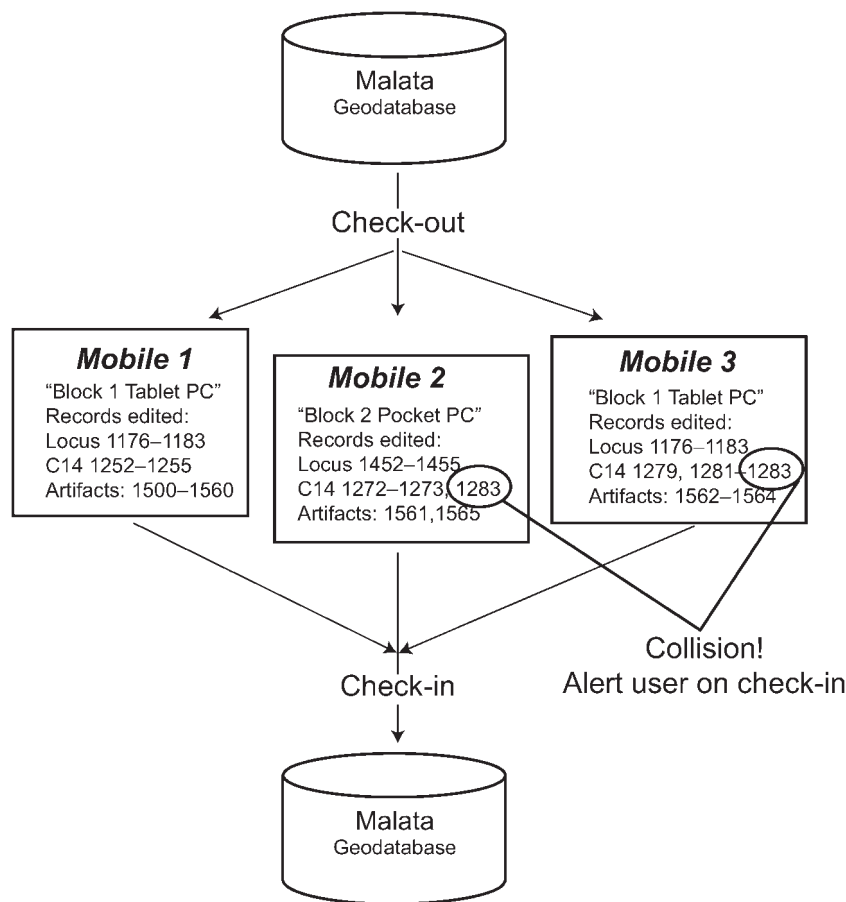
Figure 2   Excavation GIS workflow.

surfaces or imagery. Digital photographs and remote sensing data are integrated into an archaeological GIS as raster data. With three-dimensional recording, other kinds of vector data, such as the Triangulated Irregular Network (TIN) representation, can be important. In the system described below both vector and raster data models are used for recording an archaeological excavation.

Preparing the Interface and GIS Database for Use in the Field

Digital recording systems for archaeological excavations must be adaptable to a great variety of recording formats, while necessity forces archaeologists to work within the limitations of these digital recording systems. We negotiated these requirements and constructed a recording system for excavating a terminal prehispanic and early colonial *doctrina* (mission settlement)—known today as Malata—in southern highland Peru (Wernke 2007a, 2007b, in press).

Data preparation

Just as paper forms have long been used to provide consistency and comparability for archaeological feature recording, GIS attributes and digital forms structure how features are documented in digital recording system. To ensure consistency in the field, decisions must be made at the beginning of a research project concerning what observations (attribute fields)

will be gathered for each record, and what types of geographical entities (point, polyline, or polygon) will be used for each type of data. These decisions often have their basis in the research design, the scale of research, and the funding and time available.

The GIS system we employed was based on customized versions of ESRI ArcPad, which is a commercial mobile GIS application for use on inexpensive handheld computers running either Windows Mobile (PocketPC) or on tablets and laptops running Windows. This seemed the most feasible within the time and budgetary constraints of this project, especially considering that the excavations were not conducted in a single area (where more capable but costly laptop computers could be shared by excavation teams) but instead required multiple widely-spaced excavation areas. ArcPad permits data to be "checked-out" from a larger GIS (geodatabase managed via ArcGIS) and then later reintegrated (FIG. 2), allowing each mobile GIS unit to be dedicated to a particular spatial zone (e.g. the area excavated by a single crew) or to a particular topic such as a carbon sample log. As a mobile component of a larger GIS software package, ArcPad offers several advantages over existing digital record keeping solutions. These include the ability to synchronize files at the level of the record and providing a simple interface for customization. More sophisticated alternatives to check-out/check-in are available

for remote editing of GIS datasets. These take the form of database versioning provided by Structured Query Language servers and, in the case of ESRI products Enterprise Geodatabase, versioning and "disconnected editing." These approaches are typically costly or more complex and would have been excessive in our circumstances, but in projects with elaborate configurations of users and equipment and a need to be able to return to older views of the database, a versioning approach is recommended.

Finally, if a reliable wireless network could be established at the excavation area and the portable units could have real-time, shared access to the excavation GIS database, the need for the synchronization process described below could be avoided. Establishing a wireless computer network between instruments in a remote field site without a source of electricity or cellular reception will, however, require more energy use and confine networked computers to the unobstructed Wi-Fi reception range of approximately 100 m from a 802.11n transmitter or 10 m using a Bluetooth wireless connection.

Check-out/check-in

ArcPad is primarily a data acquisition package and consequently the editing and analytical tools are kept to a minimum. Rather, data acquisition and integration with a larger GIS database are emphasized through a periodic "check-out/check-in" process (FIG. 2). The underlying principal with check-out/check-in is that independent digital recording of fieldwork is possible as features are checked-out from the larger GIS database for "disconnected editing." A new Boolean field for changed records is created and for every record containing a TRUE in the Changed field, the record in the mobile GIS unit overwrites the older record on the main GIS. Thus, several devices running ArcPad can be used even without continuous networking and the GIS units can contribute to the same spatial database. With proper use there will be few instances of a conflict between systems where new data are overwritten and lost: new records are flagged and if more than one instance of a record in a file has been modified in two or more places the administrator is alerted of a synchronization problem. By synchronizing at the level of the record, the same spatial file can be modified by multiple devices on a given day provided that the same records in the database have not been altered by two different teams on that day. Each time that the units are synchronized with the main database (perhaps nightly) individual records, rather than a whole file, are over-written by new content from each portable GIS device. This is much improved over other systems where entire files are modified by a given portable device and the structure of the file system is predicated on over-writing entire files every night because of a few records that were changed.

Custom ArcPad forms

A second advantage of the ArcPad system is its facility for customization. Prior to beginning fieldwork, archaeologists can modify their input forms (FIG. 3) for recording observational data. The major considerations are workflow, maximizing the use of space on the small screens of handheld PCs, and the uses and limitations of each input device. The GIS devices we used at Malata ranged from inexpensive handheld PDA devices with 320×240 pixel screen resolution, to tablets and laptops with 1024×768 pixel or greater resolution. We designed the input forms for the smallest screen-size. Thus, multiple pages were required, each easily accessible by tapping on its corresponding tab.

The resulting custom ArcPad forms we developed were organized into six tabbed pages. The example in Figure 3 shows the attribute pages, which in turn are linked to a polygon delimiting a "Surface" feature during excavation. The first of these tabbed pages, called "Locus," records the basic provenience (locus posit-fields information), including the locus number, locus type, a ordinal scale code of interpretive confidence for the locus type, architectural context, range of grid units covered by the locus (see below), and metadata (excavator initials and date). The next page, called "Spatial," includes topological references to surrounding loci, the mapping subdatum, bucket count of soil, and excavation depths. The "Soils" page includes Munsell color categories and soil characteristics. This is followed by the "Collections 1" and "Collections 2" pages for in-field inventories. On the final page, feature photos are logged by referencing ranges of photo JPEG file numbers per camera, and an unstructured "Digital Notes" field provides a text field 254 characters long for other observations or for indicating the path to additional notes taken digitally or on paper. Such notes were considered supplemental to handwritten notes, which were entered into a corresponding database (MS Access). These handwritten notes could then be linked to the GIS by the unique identifying code for each excavation context, as discussed below.

Spatial reference and grid system

Archaeologists have traditionally excavated in site-specific coordinate space by setting their site datum XYZ at an arbitrary starting point. Our use of GIS at Malata, however, enabled direct recording of provenience data in real-world projected coordinates—in this case, the metric units of Universal Transverse Mercator (UTM) coordinates. If a local coordinate system and projection with an ellipsoid applicable to

Figure 3   ArcPad forms designed for handheld screen (320 × 240 pixels). This form was designed for recording surface areas or lenses into polygon geometry during excavation.

large scale mapping is available then this may be preferable to the UTM system used here.

Early in the first season at the site, a primary site datum was established and coordinates were determined using a single geographical point that a Trimble GeoXT GPS receiver generated from the average of 1800 positional measurements. These measurements were post-processed in Trimble Pathfinder Office using correction data from the International GPS Service AREQ base station in Arequipa, Peru, approximately 100 km distant. The horizontal azimuth for the total station was established by first sighting to a distant peak of known coordinates (Mount Hualca Hualca), and then by shooting in a second local reference point, which was subsequently used for setting the horizontal angle. All

mapping at Malata was conducted in real-world coordinates that were gathered relative to these UTM coordinates for a single GPS-derived point at the site datum. Next, since the site has standing fieldstone architecture, it was important to be able to align local grids to the primary axis of each structure to be excavated, rather than to the cardinal directions, as is common practice at sites without visible architecture. The arbitrary provenience system we developed was thus organized by "grids," "cells," and "units." A grid refers to a given matrix of 1 × 1 m cells. Each grid was identified with a Roman numeral. Each cell within a grid was referenced by a letter and number address (or "geocode") in its southwest corner (letters by column, numbers by row). The cell geocoding system was used for artifact proveniencing, as well as

geo-referencing and archiving photomaps and other field data (see below). Finally, a "unit" referred to a contiguous group of cells opened for excavation by a single crew. Units were identified by their southwest and northeast cell geocodes. Thus, a 3 × 3 unit spanning the cells F9 to H11 in grid I was referred to as "I/F9–H11."

The cultural units of provenience were organized by spatial scale: the site boundary, as defined by systematic pedestrian surface survey; architectural context, defined by standing structural walls (usually structure number) and/or other architectonic features; and locus, defined as any discrete volume of excavation matrix within an excavation unit and any cultural materials found therein. Loci were excavated by natural or cultural stratigraphy (i.e. until a change in matrix was detected), thick loci were subdivided by arbitrary 10 cm levels until a change was detected. Within loci, artifacts could also be piece-plotted using a single log of artifact numbers. The locus system (similar in scale to the "unit" of many European provenience systems) was employed for a number of reasons: it provides greater analytical flexibility in the field than a level and feature system; it enables excavation of culturally-defined contexts without forcing them into a binary "level" or "feature" classes as minimal units of provenience; and it facilitates database design by providing a single minimal unit of provenience with a unique identification number (key field) for structuring databases. In the case of a large locus—for example, a general layer that covers an entire excavation unit, or a lens larger than a 1 × 1 m grid cell— excavated matrix was screened and bagged by 1 × 1 grid cell within the locus.

Excavation proceeded by declaring a locus, which entailed assigning it a four digit number. A master locus number log was maintained, starting at Locus 1001, and locus numbers were checked out to crew chiefs in groups of ten (e.g. 1001–1010). The locus was either hand-plotted using an offset from cell corners or sketched into ArcPad as a polygon, and then its ArcPad attribute form was filled out. If the polygon was sketched as a "dummy polygon," the total station would be used to shoot points to outline and take elevations of the locus surface and the polygon was later reconnected to the total station-derived geometry by locus number. Photomapping would also take place at the top of each locus. In total, mapping operations for a locus ranged from 5–20 minutes, depending on the size, complexity, and mapping method used.

Mapping and attribute recording techniques

The flexible mapping system we developed at Malata allowed investigators to devote a greater amount of time to documenting high priority items during excavation, while logging the location of lower priority items using one of the more expedient methods (FIG. 1, TABLE 1). For example, general soil samples or items retrieved from the screens could be simply provenienced to their grid cell or locus number, while important diagnostics or discrete pieces of carbon suitable for radiocarbon dating could be piece plotted with the total station. Likewise the outlines of loci could be mapped in a variety of ways, though most locus mapping was conducted with a total station. Alternatively, an excavation crew chief could delimit the items on a photomap or hand plot the information using the offset function in ArcPad (Method 2, TABLE 1). This works in the same way as offset plotting using paper methods: by measuring the distances to a point from a pair grid corners (or any other two known points) using two tapes and a plumb bob at varied intervals. The advantage in plotting it using on-site GIS is that the feature is mapped in real projected coordinates on the screen, rather than in an arbitrary grid on paper. Artifact or feature edges can therefore be precisely plotted without a total station more quickly than could a comparable method on paper.

Photomapping

Almost all loci were documented at varied scales of precision through "photomapping," that is, by taking a digital photograph vertically at near-nadir and then geo-referencing the photograph. Photomaps provide map-correct, very low altitude high resolution visible light imagery of excavation features and artifacts (Craig 2000; Craig et al. 2006). Photomapping was done at three scales and levels of precision, depending on the subject of the photo, workflow considerations, and level of detail desired in the resulting photomap. In ascending order of precision, these were by entire excavation unit, by 1 × 1 m cells, or by feature, using a set of custom-plotted reference points (usually nails). Each entailed compromise in terms of precision, time investment, and clarity of resulting imagery. Photomaps of entire excavation areas, while the least precise and detailed, are very useful for providing a visualization of an entire surface—for example, the entire floor of a building with its features exposed. By contrast, cell or feature-specific photomaps are more accurate and detailed, allowing high resolution documentation of artifact scatters, but are also more time consuming to take and geo-reference, and produce a choppy mosaic of images if a large area is displayed. In important contexts, a mix of techniques can be used for different modes of viewing. In all cases, photographs for geo-referencing were renamed by their locus number(s) and stored in a folder structure organized by the hierarchical grid-unit-cell geocoding scheme. Each photomapping technique is described below.

Photomapping of entire excavation units was accomplished by using a 2.25 m camera boom with a ball-type mount. A digital SLR camera (8 megapixel resolution) was set to a 10 second timer and then hoisted with the boom over the center of the excavation unit. A wide angle lens (10–22 mm) was used to capture a maximum extent with minimal height. Several attempts were usually needed to obtain a properly aligned and focused vertical image, but the results could be quickly previewed using the screen on the camera. Using this method, we were able to capture up to a 4×4 m unit with the boom. Some of the distortion introduced by the wide angle lens was corrected in the geo-referencing process (called "rubbersheeting," since the image is warped into coordinate space according to the reference points). At least four, but usually six or more control points (nailheads demarcating the local cell corners) were used to geo-reference the image. As with any technique, there was a compromise between scale and representation in these "big picture" photomaps: they were very useful for showing spatial relationships between features in architectural context, but, because of the distortions introduced by the wide angle lens, they were not accurate enough or of sufficient image resolution for precise piece plotting of small artifacts. These compromises could be lessened by orthorectifying the images, and through the use of a higher resolution camera, though each would bring higher time and financial costs. For our purposes—showing whole excavation areas and their features *in situ* with most wide-angle distortion removed, with minimal time investment in the rectification process—simple georectification was quite satisfactory.

When more accurate mapping was desired, lens distortion was minimized by shooting individual cells by standing over a cell, holding the digital camera high over the center of the cell, and shooting straight down. To facilitate quick orientation and geo-referencing in the lab, flagging tape was used to highlight the nail heads of the cell corners, with the northwest corner flagged in a different color from the others.

Finally, feature-specific photomaps were sometimes taken when high precision was desired—for example, in the case of a burial. In these cases six or more nails were distributed around the feature of interest and their coordinates plotted with the total station. Vertical photos were then taken of the feature. In some cases, we would also shoot a high number of surface topography points of the feature in question, which could then be used to create a high resolution Digital Elevation Model (DEM) surface over which the georeferenced photo could be draped to produce a 3D image of the feature, as will be discussed below. Alternately, high resolution DEMs can be generated through close-range stereo photogrammetry (Remondino and El-Hakim 2006). Though

it sometimes took 15–20 minutes to shoot a full unit with the boom, or to document an entire unit cell-by-cell at higher resolution, we found it ultimately less time consuming and the results more data-rich than hand-plotting feature outlines on paper, and more analytically useful than traditional oblique photographs. Once the photographs are batch-renamed and transferred to their spatially-designated folders, geo-referencing them to the excavation grid in ArcMap was a straightforward and relatively quick task. Our experience has shown that most photographs can be geo-referenced in about three minutes, and we were able to geo-reference most of them on a same-day basis in the field. With a person dedicated to managing data in the field, geo-referencing can remain on schedule with excavation. Accuracy of geo-referencing varies depending on factors such as the stability of the control points (which can shift subtly as the excavation deepens), the vertical distance between the control points and the feature surface, and the height, angle, and position of the camera relative to the feature surface. Most unit-scale images used for overall visualization of large areas provided a range of less than 8 cm range of error, while cell-level and feature-specific images provided accuracy within 1–2 cm as determined by comparing items visible in geo-referenced images against positions mapped with the total station.

Loci can be thus documented in two complementary formats: as vector data plotted via total station or by hand (and in turn linked to their attribute data in the GIS) and as images via geo-referenced digital photos. Features can be viewed in both formats in the GIS as separate layers in the same coordinate system, enabling various types of overlay and visualization otherwise nearly impossible using traditional analog methods. The benefits of this enriched and efficient visualization capability, coupled with in-field digital registry of attributes associated with the spatial representations of features and artifacts, greatly outweigh their costs relative to traditional analog methods.

Stratigraphy and digital recording

Stratigraphic analysis remains one of the greatest challenges in digital recording of archaeological excavations, but it is also an element of excavation practice that stands to benefit from digital data acquisition and storage. The Harris Matrix approach (Harris 1979) is a common topological method of representing the logic of superposition of events in an archaeological site, and while several computerized Harris Matrix tools have been developed, these programs are primarily visualization tools and they have yet to integrate fully with a GIS.

While tools for generating and editing 3D polygons in most GIS packages are limited, they are improving

rapidly (Abdul-Rahman and Pilouk 2008; Katsianis et al. 2008); and this remains a domain in archaeological applications where Computer-Aided Design software remains superior.

The weak support for storage and analysis of complex stratigraphy in most current GIS software may be the principal reason why digital field methods and GIS for excavation lag behind survey. Working around the limited 3D support in current GIS software is often necessary. For example, archaeologists have long tallied bucket counts to estimate soil volume during excavation, and bucket counts can be logged as an attribute with a locus and these values can be compared with volumetric estimates from the GIS after the excavation season ends. Furthermore, a 2D GIS assigning artifacts to discrete "levels" (an ordinal variable) during excavation is still an excellent recording system, and the data can always be "dumped" to paper for more traditional analyses of excavation contexts after the conclusion of the field season. A well-integrated future system would use a total station to record 3D data together with the ability to designate stratigraphic relationships between loci in schematic form akin to the Harris Matrix. These are stored together as primary evidence during the course of fieldwork. Subsequently, in the interpretation of archaeological contexts, a true 3D GIS model of an excavation with corresponding geostatistical tools that can exploit these rich data will be the breakthrough that will fundamentally change both excavation and analysis interpretation in the near future.

Approaches to stratigraphic recording in GIS
Different types of deposits and excavation styles demand different ways of recording stratigraphy (Katsianis et al. 2008: 83). Omitting the technical details, a few principal methods are available for generating 3D GIS vectors ranging from simple manual methods to the integration from precise total station data into 3D datasets.

MANUAL ATTRIBUTE METHOD
Top and bottom excavation heights for a given 2D locus or feature are logged as numerical attributes and these values are later used for extruding a 3D polygon. This low-technology approach is suitable for digital data entry where a total station is not available at all times and it corresponds to the nominal attribute method of proveniencing described in Figure 1.

TOP AND BOTTOM SURFACES
Topographic surfaces are interpolated from XYZ points acquired with a total station across an entire excavation level, or from close-range stereo photogrammetry and stored as Triangulated Irregular Network (TIN) files. These interpolated surfaces can then be used to derive Z values for use as top and bottom "caps" on extruded 3D polygon solids (Katsianis et al. 2008: 83). This method is particularly suitable to horizontal excavations where discrete levels extend across large areas.

3D MODEL GENERATION
XYZ points are shot as nodes on locus boundaries during excavation. This approach is time consuming and may result in gaps in resulting 3D volumes unless vertex snapping is incorporated, but it represents the most accurate recording method and with instrumentation improvements this recording method will be sufficiently rapid for consistent use during excavation.

VOXEL BASED APPROACH
Representing subsurface 3D features as *voxels* (volumetric pixels) is an approach developed in the earth sciences and available in both commercial products that link to GIS (e.g. RockWorks) and CAD software, as well as non-commercial projects based on open-source GIS (Cattani et al. 2004; Lieberwirth 2008; Losier et al. 2007; Nigro et al. 2002, 2003). Voxel based approaches are limited by the fixed resolution and potentially large file sizes of a given dataset, and the relative difficulty of joining voxels to the complex attributes of archaeological stratigraphy.

There are other approaches that permit the logging of 3D data, or 2D GIS data with topographic surfaces generated for each excavation level. Nathan Craig (2005: 506) combined 2D vector feature photomapping with topographic data represented as a 10 cm resolution DEM for every level. As described under the top and bottom surface mapping (above), Craig was able to calculate volumes per level for an entire excavation block by subtracting the DEM of the top of one level from the DEM of the top of the level above.

In short, excavations can be recorded as a simple 2D data model together with depth attributes that the GIS model does not attempt to represent, or the excavation features can be logged as true 3D polygons and surfaces that are faithfully represented in the GIS. In both cases, the depth values of loci or features are logged and stored digitally, and will be available for more sophisticated stratigraphic analyses. By incorporating digital excavation methods today, researchers are anticipating the appearance of interpretive tools along the lines of Harris Matrix software that exploits the precision and rich attributing of 3D GIS data, and will be in a better position to use these interpretive tools in their analyses of excavation data as the software evolves.

Implementation: An Example from Highland Peru
We implemented this on-site GIS system for excavations (directed by Wernke) at the site of Malata, a
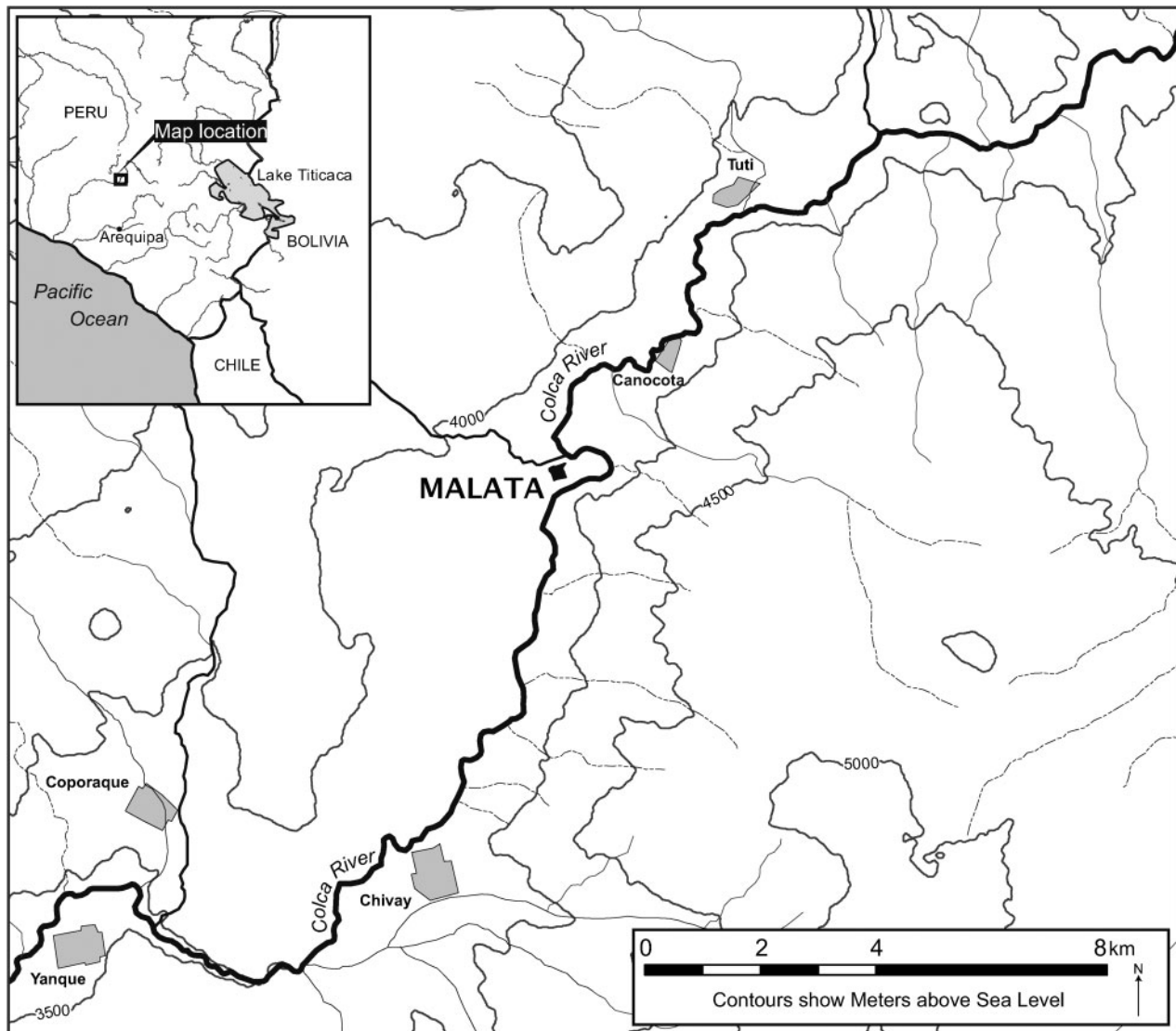
Figure 4   Location of Malata in the Colca Valley and south central Andes.

terminal prehispanic and early colonial era settlement in the Colca Valley of southern highland Peru (FIG. 4). Located at 3850 masl, the village occupies the head of a *quebrada* (ravine) above the deep inner gorge of the Colca River. During late prehispanic times, Malata was a small Inka provincial settlement with houses constructed in the local architectural style with a Inka great hall building and plaza at the west end of the site. During early colonial times, the site was transformed into an early *doctrina* (doctrinal settlement). Ecclesiastical memorials state that this and other settlements documented by Wernke were established by Franciscan friars between the 1540s and 1560s, and administrative documentation indicates that it and other doctrinas like it were forcibly abandoned during the 1570s, when planned colonial towns were founded here and throughout the viceroyalty under the *reducción* (literally, "reduction") program of the viceroy Francisco de Toledo (Wernke 2003, 2007a, 2007b). The site assemblage is entirely consistent with this occupational timeframe. It is

dominated by local variants of Late Horizon (A.D. 1450–1532) ceramics, with an overlay of colonial artifacts, of which the diagnostics (including Nueva Cádiz glass beads and caret head iron nails) date to the mid-16th century and earlier, with no colonial diagnostics from later periods recovered *in situ* (see Wernke in press). Excavations at Malata—which total 300 sq m—were aimed at documenting change and continuity in ritual and domestic practices from terminal prehispanic to early colonial times.

Mapping during 2006 produced a topographic and architectural map of the remarkably-preserved standing fieldstone architecture at the site (FIGS. 5, 6). The site's habitational area of 1.6 ha occupies a draw surrounded by colluvial slopes. Most domestic structures are located to the east at the lower end of the draw, while a public and ceremonial sector is located in the upslope end of the site to the west (FIG. 6).

Excavations in 2007 focused on the Franciscan chapel at Malata, identifiable by its curved apse and prominent location overlooking the rest of the
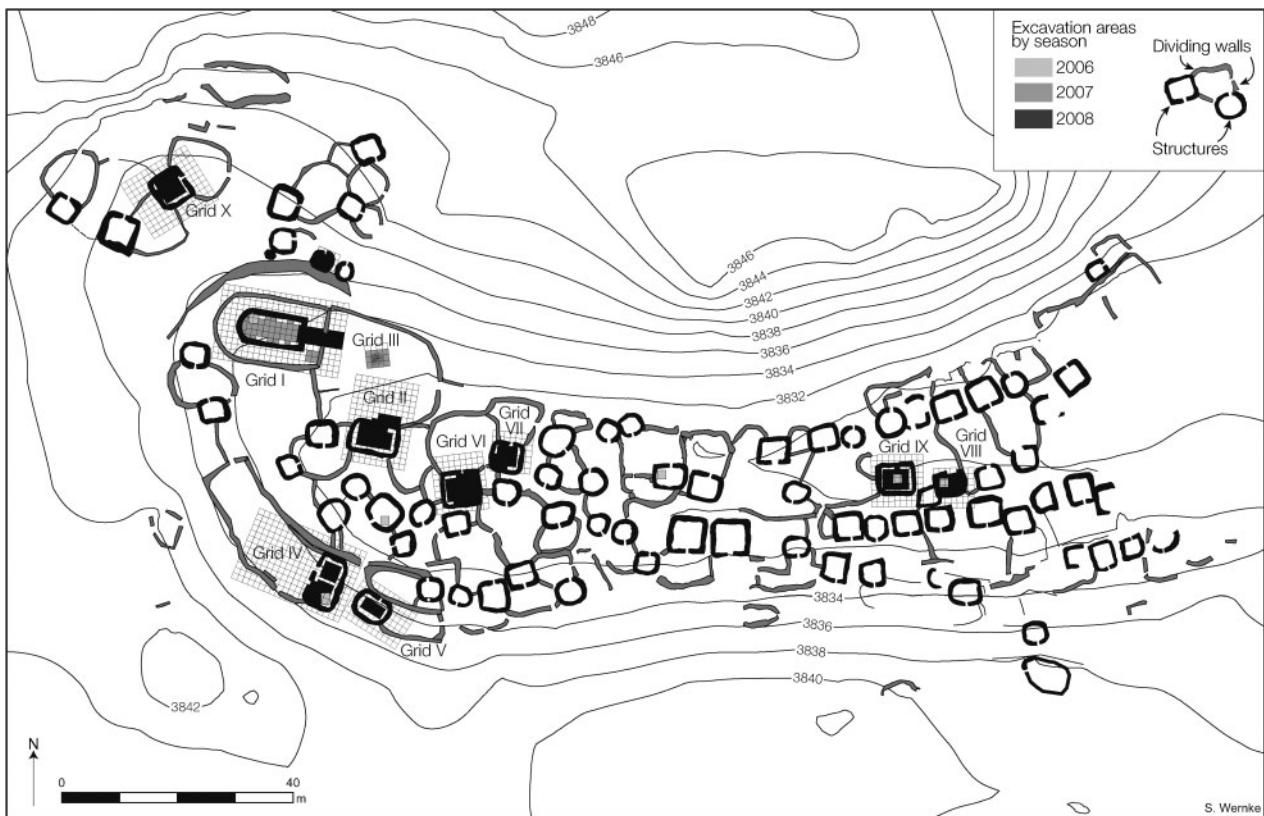
Figure 5   Architectural map of Malata, showing local grids and areas excavated.

settlement (FIGS. 5, 6). It is enclosed in a terraced atrium with fieldstone walls and an entryway aligned with that of the chapel. Excavations in 2008 were conducted in a variety of contexts, including several domestic structures, the Inka great hall structure, and a colonial structure on the south side of the plaza, adjacent to the chapel and atrium. The project thus included excavations of some depth in the chapel (around 1 m) and broad, shallow, areal excavations in other contexts. Each of these presented different challenges and solutions for the in-field excavation GIS system. Below, the provenience and mapping systems are discussed, followed by an example of

Figure 6   The site of Malata, from the northwest. The chapel and plaza are in the foreground, overlooking the main residential area to the east. The Inka structure and plaza (center right, with two doors) faces the opposite direction.

their implementation in a domestic structure and in the chapel. The focus is on how the GIS documentation and visualization work, rather than on the results themselves.

Vector- and raster-based mapping: an example from a domestic context

The database for reconstructing domestic practices is derived from excavations in 7 of the 73 domestic structures at Malata. In all but one of these, the entire interior of the structures was to be excavated, leaving small (ca. 50 cm) perimeter buffers inside the wall to protect from collapse. The structure discussed here (Structure 26) is a large (elite) domestic structure. In fact, it is the largest domestic structure at the site, with an interior area of 28.79 sq m.

As with other excavation contexts, the first step for excavation was to establish a grid oriented along the dominant axis of the building. The grid (denoted by its Roman numeral: Grid VI) was extended beyond the interior of the structure in all directions in case excavations were extended to the exterior. Distinct provenience codes for each scale of arbitrary provenience enabled quick mental visualization of the location of a given excavation context, and a corresponding directory hierarchy on the computer for archiving photomaps and other data. Cell corners were shot inside the building with the total station, and the reference grid in the GIS was shifted and rotated into place to fit the real-world orientation of the grid. Next, the grid was divided between two

2×5 m units (E4–F8 and G4–H8). Surface and overburden layers, which covered the entire surface of each unit, were assigned locus numbers and plotted by hand using the offset function in ArcPad (Method 2, TABLE 1).

The top of the packed earth floor of the structure contained ceramics, lithics, animal bone, and carbon embedded in it. This top floor stratum was denominated locus 1573 in E4–F8 and 1583 in G4–H8. With the top of the floor level exposed, vertical photographs were shot with the boom and wide angle lens to capture an entire unit in one frame; these were then geo-referenced (FIG. 7).

Stone features were partially exposed in the center of the south edge of E4–F8 and in the northeast corner of G4–H8. Extensions were then opened in the cells adjacent to the walls to fully expose these features, denominated locus 1579 and locus 1585. Detailed vertical photographs were taken for these features to ensure high resolution photomap documentation, so that each stone could later be traced from the photomap; thereby saving field time (as would be the case in traditional hand-plotted plan view maps—locus 1579; FIG. 7). Soil samples for chemical analysis were taken at 50 cm intervals, with the location of each sample plotted via total station. To provide data for later distributional analysis, we used a piece plotting strategy for the ceramics embedded in the floor. Plotting every sherd was not feasible given time constraints, and so only sherds 3 cm or larger were mapped with the total station. All other artifacts were bagged by cell within their respective locus to provide provenience. Though not without compromise, this combined piece-plot and cell-specific locus collection strategy made possible later density plots of a subsample, and generalized cell-density calculations.

Each evening, the locus photographs for geo-referencing were renamed by adding the locus number in front of the frame number (so that they could later be sorted by locus) and then moved to their folder in a directory organized by grid, unit, and cell. The photomap of a locus could be quickly located by navigating through the spatially-organized folder system. Geo-referencing of photos was conducted each evening and kept apace with the daily generation of photos. The results—in both photomap and vector formats—are seen in Figure 7. The distributions from the piece plotting were immediately visible in the GIS after downloading the data from the total station in the evening. Figure 7C shows the sherd plot. A density plot such as Figure 7D can also be generated in a matter of minutes in the field laboratory. Though this visualization simply plots all ceramic types without any laboratory analysis, such visualization can nonetheless inform hypotheses and decision-making in the field about on-going excavation strategy in an iterative manner. Subsequent loci were excavated and documented in similar fashion. This example illustrates how on-site GIS provides expedient and precise documentation of horizontal excavations using both vector and image-based methods. Though photomapping and total station mapping of key loci were time consuming, they were less so than traditional hand-plotting and drawing on graph paper, and are as precise. They recorded real-world coordinate space with more data-rich vector- and raster-based (photomap) representations, allowing the integration of observational and spatial data.

Documenting and visualizing stratigraphic relationships: an example from a colonial chapel

The chapel at Malata presented different circumstances for incorporating the in the field GIS approach, since the excavations were deeper and involved more stratigraphic complexity than did the domestic structures. Excavations involved first exposing the floor of the congregation area and chancel platform, and then excavating through the floor and subfloor fill to expose a series of burials. The altar platform was also sectioned and excavated (FIG. 8). Excavation ended with exposure of sterile sediments and bedrock around 1 m below present surface. Excavations in the chapel provide an example of how features can be documented and visualized in stratigraphic relation to one another.

After establishing the grid (Grid I) and three 3×3 m units (F6–H8, F9–H11, and F12–H14) and excavating a thin layer, the top surface of the floor was exposed. The top of the floor, which was intact, was composed of a packed earth in the congregation area and a chancel platform fronted by two stone-faced steps running the width of the building where the curved apse meets the side walls. A fieldstone altar was also exposed on the chancel platform in its expected location: centered against the apse wall. The floor topography, including the chancel platform steps and altar, was shot in greater detail using the reflectorless function of the total station for later interpolation to a DEM. The chancel platform was then excavated to reveal that the floor originally extended in one level all the way to the foot of the altar, and the platform was added in a remodeling episode. The floor was then excavated to reveal subfloor fill of abundant pebble to boulder size rocks interspersed by loose sediments. The ovoid outlines of most of the interments became evident at the base of that fill layer. These shallow pits were filled with river sand and were easily distinguishable from the surrounding matrix. All were mapped with total station and photomaps, and a sample of the burials was selected for more detailed micro-topographic mapping for later interpolation to DEM. Traditional wall profiles in the excavation units were
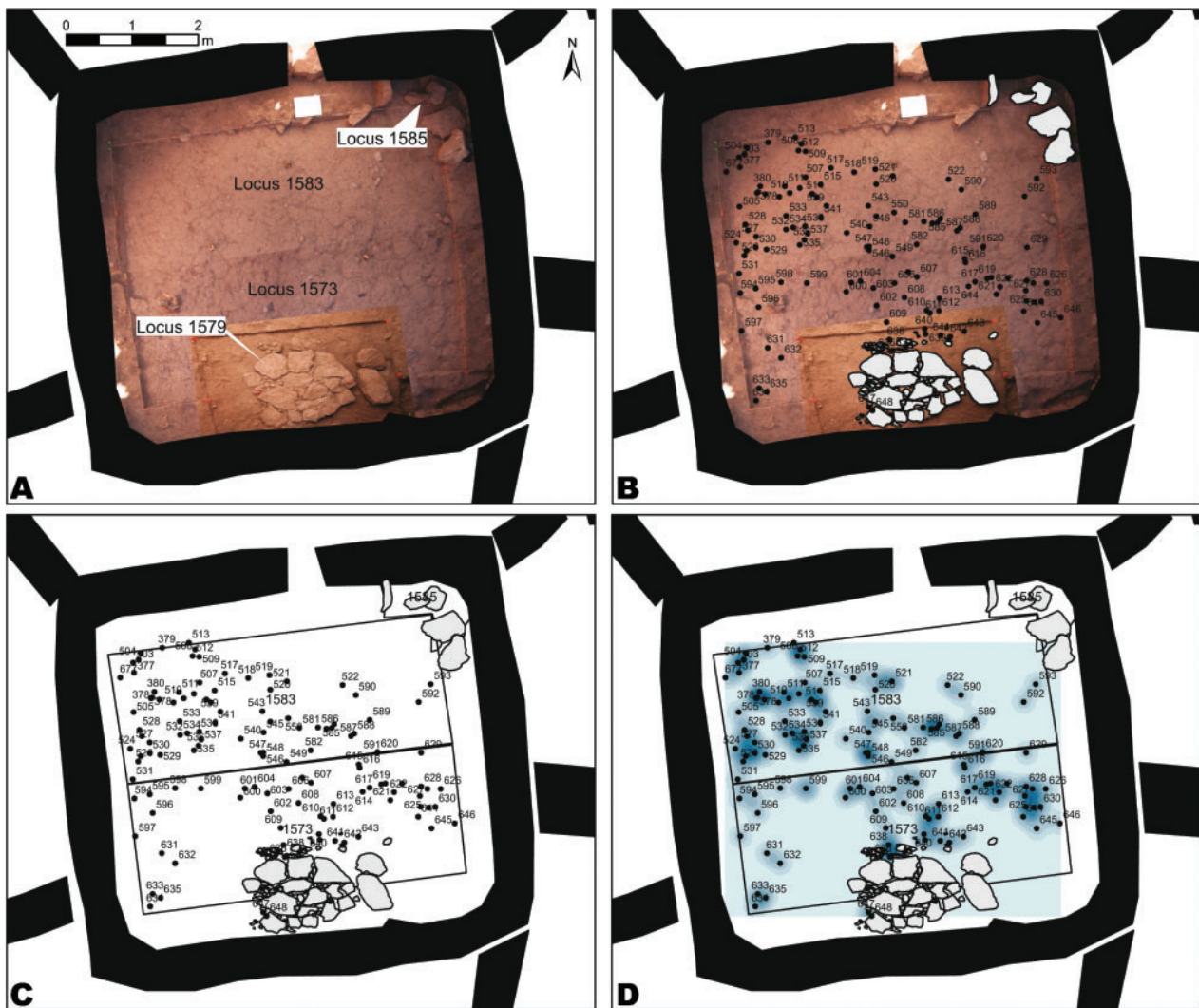
Figure 7   Four ways of viewing a floor and artifact densities in a domestic structure at Malata.

also completed at the end of excavations. We elected to use traditional profiles because of the dispersion of the multiple simultaneous excavations at the site (each with several profiles to map), made digital registry (e.g. by shooting with the total station) logistically infeasible.

Stratigraphic sequences can be visualized in a number of ways in the GIS that are complementary, and often superior to the traditional profile view. Most simply, loci can be grouped into strata and seen in plan view as a series of superimposed layers. However, the potential of the digital data format for visualizing stratigraphic relationships is more fully realized in ArcScene, a 3D visualization application (included in the ArcGIS suite). In ArcScene, points from the total station can be viewed in 3D, as well as any DEM interpolated surfaces derived from the total station points. Even loci for which only the corners and center of the unit were recorded can be viewed as a DEM surface. Photomaps and locus polygons can then be overlaid on their respective locus DEM for 3D viewing. In other cases, points were taken at the top, approximate middle, and bottom of the pit feature. For example, locus 1136—a

burial feature under the chapel floor just in front of the entry—was selected for micro-topographic documentation to produce a DEM for photomap overlay. The resulting visualization (FIG. 8 B–D) shows the outline of the chapel with the floor DEM, and the burial feature below. A selection of burial feature outlines is displayed with the locus of interest, 1136, shown in further detail. The scene can be rotated and manipulated, and attributes can be queried and displayed as well. Precise elevations can be obtained by clicking the information tool on DEM surfaces.

Visualizations such as this are advantageous in that they come close to reproducing the excavation context in digital format and provide a detailed excavation record. They also provide a means for viewing continuous surfaces in three dimensional space, rather than moving back and forth between plan and profile view to obtain stratigraphic relationships in traditional mapping techniques.

Discussion

These examples illustrate the main advantages of an on-site GIS system for excavation. First, in terms of
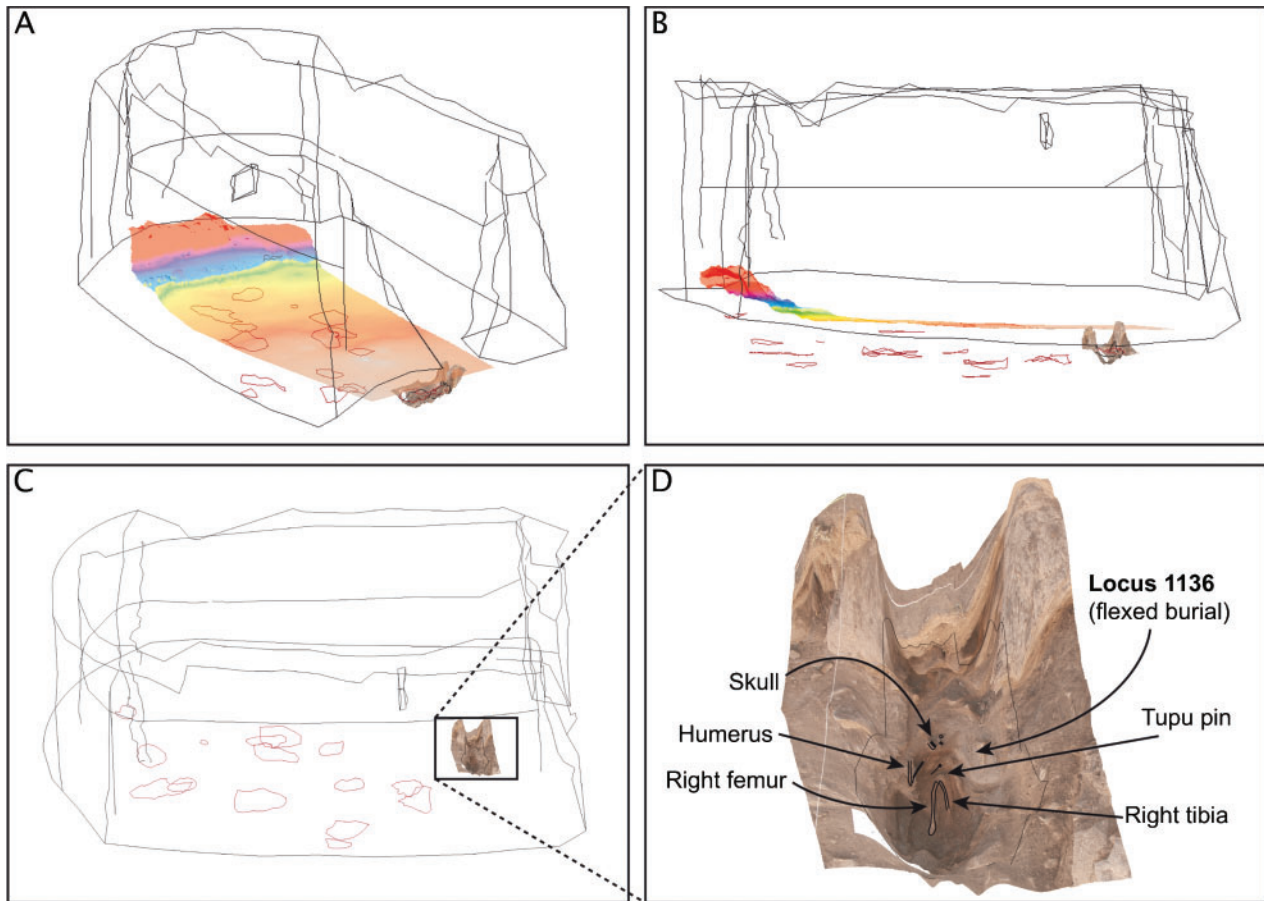
Figure 8 Three dimensional locus registry in the chapel at Malata, with a vertical photograph draped over DEM.

spatial documentation and representation, on-site GIS allows fast and precise recording of contexts and artifacts in multiple formats employing both raster (varied resolutions of photomaps and DEMs) and vector (points, lines, and polygons) representations. It also facilitates rapid production of distributional and 3D visualizations that would be impossible in the field using traditional methods. In terms of observational data, the system allows co-registry of the spatial features with standardized data registry in connected data tables via intuitive forms, while maintaining handwritten notes where appropriate. Below we discuss each of these aspects in further detail and explore some of the opportunities and obstacles for on-site GIS.

Rapid results: efficiency in data management, analysis, and time to publication

Data post-processing, analysis, and report generation is one of the strengths of adopting a GIS-based excavation recording system. As studies have found (Wagtendonk and De Jeu 2007), prior to and during fieldwork a GIS-based recording system generates additional preparatory work, but it significantly speeds analysis during the post-fieldwork phase. While data may have to be transferred from instruments such as cameras and total stations, this process (together with necessary backups) can become a

nightly routine such that the larger GIS remains current as work proceeds.

Summary statistics such as counts, means, and variance are available in ArcPad immediately during fieldwork, and further analyses can be generated rapidly in the GIS laboratory. The immediacy of summary reports results in better information guiding excavation. When excavation and laboratory work are occurring concurrently, the rapid production of excavation reports signifies that artifacts can be brought in for laboratory analysis together with up-to-date figures and charts reflecting the current state of excavation and artifact provenience. Such streamlining of workflow between excavation, analysis, and reporting ultimately enables faster publication.

Integration

While mapping instruments like total stations and digital cameras are now commonplace at excavations, most archaeologists use paper forms for context recording and excavation records. Our position is that paper notes should be used where a computer interface might be a hindrance. It has been our experience that opening a laptop in the field or turning on a handheld computer and navigating to the correct screen, then pecking out notes with a stylus or typing them out in the elements act as deterrents to taking good longhand notes compared

to the ease of opening a clipboard and handwriting them. It is a matter of matching appropriate technologies to the tasks—paper for longhand notes, computers for managing locus and collection inventories, photographic logs, total station data, and standardized observational data from excavation contexts *together with* precisely located spatial objects (points, lines, and polygons). This is different from the more common hybrid analog/digital systems where digital instruments are used but the minutia of spatial location are hand-written on paper forms and transferred to databases or spreadsheets. This enables increased data collection (total station points quickly pile up) but puts the burden of data management on the excavators, while creating unneeded redundancy between paper and digital records, which can also lead to error propagation during paper-to-digital transfer. In contrast, a well designed system relieves archaeologists from many of these data-management burdens, allowing investigators to focus on archaeological contexts. While our approach makes use of widely available hardware, at the front of this type of integration are systems, such as the Swedish Intrasis system, that link robotic total station proveniencing with attribute forms available on a small touch-screen attached to the prism pole.

A principal benefit of a digital excavation strategy is simplified data acquisition and analysis workflow. ArcPad can be customized relatively rapidly by non-programmers to meet the needs of archaeologists, and the GIS can be used analytically to link laboratory results from survey and surface collection with excavated contexts (Tripcevich 2004, 2007: 421). The approach described here is amenable to collaboration by numerous specialists because it consists of a smaller mobile sub-set of the mature and widely-used ArcGIS platform.

Smart forms

A further advantage of digital data entry is that the time spent filling out record forms can be streamlined when the software provides sensible default values, and forms can provide error checking of entries. Data entry in ArcPad forms can be confined to "attribute domains" from the geodatabase, which restrict data entry to particular values, such as valid Munsell color values, and ensures data comparability. A list of possible values for a particular field are typically shown through a drop-down menu—however, such lists will also contain a "See Notes" option for the rare exceptional value.

An elaboration of this approach is the concept of semantic plausibility controls (Pundt 2002; Ryan et al. 1998). It is possible to design input forms that test for logical consistency between attributes and save time by automatically populating fields with reasonable values, or simply flag inconsistencies and thus reduce error. For example, one design might alert users when the depth of locus A is lower than locus B, but the topological relationships indicate that locus A should be higher than B.

Multiple forms of media

Digital excavation methods also allow for greater integration within archaeological project planning, site interpretation, and laboratory analysis. A digital excavation workflow with GIS allows for digital integration with geophysical prospection data, such as ground penetrating radar and magnetometer data, so that anomalies detected by remote sensing data are available in the digital interface during excavation (Kvamme 2007; McCoy and Ladefoged 2009; Neubauer 2004). Additionally, laboratory results from previous excavation seasons can be incorporated as optional layers in the digital excavation interface facilitating interpretation "at the trowel's edge" and providing for a more informed fieldwork experience (Hodder 1997; Ryan et al. 1998). In fact, any historical or preexisting spatial data can be made available as reference layers in a digital excavation GIS, provided that scans of maps, diagrams, or photographs include the necessary spatial reference information.

In addition to photographs, media in other forms can be linked to digital provenience and summarized or retrieved on-demand according to provenience, feature type, or other attribute. Most handheld computers can record audio clips, and it may be useful to have a vocal description of observations during excavation, linked to provenience through a unique identification number system. Video media can also be linked, and such media can be browsed by context or attribute.

Opportunities and Obstacles

As digital technologies are being widely adopted in archaeological practice, it is worth considering the larger context in which these technologies will contribute to, and perhaps hinder, development in the discipline.

Backups, archives, and data security

The volatile nature of digital storage of data and media is cause for concern. Mismanagement can result in digital photographs and data being over-written or lost, and the possible confusion associated with training and developing new excavation techniques is a situation when mistakes can be made. While digital data can disappear, they can also be duplicated readily. For example, paper records and photographs can be ruined by water; whereas digital data may be protected by regular backup to CDs or to small hard drives for safe-keeping. Thus, if daily workflows are developed that include secure backup with redundancy (most of which can also be automated), digital

recording should not be inherently more risky than analog methods. It is recommended that backup strategies should always include a version with the unmodified data straight from field instruments in case errors during initial processing steps corrupt or otherwise irretrievably degrade data.

The generation and curation of digital excavation records is increasingly important to managers and institutions (Kintigh 2006, 2009; Richards and Robinson 2000), and a GIS-based registry is an efficient means of achieving digital archives. Digital archiving standards have been developed in various countries, and the longevity of media and of file formats must be considered. Curation issues include the short lifespan of proprietary data formats, and the fact that most CDs and DVD media used for burning from personal computers are not of archival quality.

Fragility of equipment and power supply issues

One hindrance to adopting digital excavation methods is that they involve substantially increasing the number of delicate electronics present at an excavation. Costs are going down for most rugged instruments, and with proper backup strategies the chances of losing a significant amount of data are slim. Nonetheless, equipment failures can be a problem in settings where technical support services are unavailable. Regular users of such equipment become competent at solving a variety of technical problems, and such training is now common for graduate students in archaeology. There is no easy solution to these problems besides thorough testing of systems and software prior to beginning fieldwork, collecting all software installers and reference documentation (perhaps in digital form) for emergency use while in the field, and, whenever possible, purchasing essential hardware in duplicate.

Compromises are necessary in instrumentation where access to electricity is limited as digital excavation methods place greater demands on power for portable devices. Applications like ArcPad can be used either on PDA or on larger field computers like tablets, notebooks, and laptops, but in their current form PDA operating systems (built for devices lacking hard drives) cannot run full GIS software. Thus, ArcPad gives investigators the option of running one copy of the data entry system on a simple, energy efficient PDA for basic tasks such as maintaining a carbon sample log. For more elaborate applications where the larger screen size is advantageous one could use the same software on a tablet PC or laptop and re-sync the system databases at the conclusion of each day.

Ensuring an adequate power supply is another concern. Flexible solar panels used as shade awnings

Figure 9 Powerfilm PowerShade awning. Staked dimensions: 11.5 × 10.9 m. These awnings charge a 12-volt battery at a rate of 1 kW per hour. Current cost is $24,000.

and tents are becoming available that provide both shelter and 12 volt power to archaeological excavation projects (FIG. 9), as well as improving the visibility of computer displays in outdoor settings by providing shade. Rapid improvements in solar cell technology will have a beneficial effect on digital field methods, but nevertheless many archaeologists will likely become familiar with generator-based 12-volt power systems (Dibble et al. 2007).

Conclusion

We have outlined a practical system for GIS in the field that is within the technical and financial reach of the majority of archaeologists. GIS does require some pre-fieldwork preparation and training, but it provides a number of advantages. Portable computers are increasingly resilient and inexpensive, and geospatial software interfaces are becoming easy to use and can be customized for applications like archaeological excavation. Shifting to a primarily digital GIS-based recording system will simplify data organization because it combines precise spatial coordinates, attributes, and digital media in a single system and enables more comprehensive data registry and analysis in the field. The system we described is simple and inexpensive, and combines the strengths of digital and analog systems. Moreover, the strengths of digital technology are apt to improve, while its limiting aspects for field archaeology are lessening. In sum, "digging digitally" is now moving from a specialist frontier to common practice, and this is a change that all archaeologists should embrace.

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References

Abdul-Rahman, A., and M. Pilouk. 2008. *Spatial Data Modelling for 3D GIS*. Berlin: Springer.

Apel, M. 2006. "From 3d Geomodelling Systems Towards 3d Geoscience Information Systems: Data Model, Query Functionality, and Data Management," *Computers & Geosciences* 32: 222–229.

Bradley, M. 2006. "Archaeological Survey in a Digital World," in T. L. Evans and P. T. Daly, eds., *Digital Archaeology: Bridging Method and Theory*. London: Routledge, 29–42.

Cattani, M., A. Fiorini, and B. Rondelli. 2004. "Computer Applications for a Reconstruction of Archaeological Stratigraphy as a Predictive Model in Urban and Territorial Contexts," in K. F. Ausserer, W. Börner, M. Goriany, and L. Karlhuber-Vöckl, eds., *Enter the Past: the E-way into the Four Dimensions of Cultural Heritage CAA 03 Computer Applications and Quantitative Methods in Archaeology (Vienna). BAR International Series* 1227. Oxford: Archaeopress, 299–303.

Craig, N. M. 2000. "Real-Time GIS Construction and Digital Data Recording of the Jiskairumoko Excavation, Peru," *SAA Bulletin* 18: 24–28.

Craig, N. M. 2005. The Formation of Early Settled Villages and the Emergence of Leadership: A Test of Three Theoretical Models in the Rio Ilave, Lake Titicaca Basin, Southern Peru. Ph.D. dissertation, University of California, Santa Barbara. Ann Arbor: University Microfilms.

Craig, N. M., M. S. Aldenderfer, and H. Moyes. 2006. "Multivariate Visualization and Analysis of Photomapped Artifact Scatters," *Journal of Archaeological Science* 33: 1617–1627.

Dibble, H. L., S. J. P. McPherron, and T. McPherron. 2007. "12V," *The Archaeological Record* 7(4): 35–41.

Doneus, M., and W. Neubauer. 2004. "Digital Recording of Stratigraphic Excavations," in K. F. Ausserer, W. Börner, M. Goriany, and L. Karlhuber-Vöckl, eds., *Enter the Past: the E-way into the Four Dimensions of Cultural Heritage CAA 03 Computer Applications and Quantitative Methods in Archaeology (Vienna). BAR International Series* 1227. Oxford: Archaeopress, 113–116.

García Sanjuán, L., and D. Wheatley, eds. 2002. *Mapping the Future of the Past: Managing the Spatial Dimension of the European Archaeological Resource*. Sevilla: Universidad de Sevilla.

Harris, E. C. 1979. *Principles of Archaeological Stratigraphy*. London: Academic Press.

Hodder, I. 1997. ""Always Momentary, Fluid and Flexible": Towards a Reflexive Excavation Methodology," *Antiquity* 71: 691–700.

Katsianis, M., S. Tsipidis, K. Kotsakis, and A. Kousoulakou. 2008. "A 3D digital Workflow for Archaeological Intra-site Research Using GIS," *Journal of Archaeological Science* 35: 655–667.

Kintigh, K. 2006. "The Promise and Challenge of Archaeological Data Integration," *American Antiquity* 71: 567–578.

Kintigh, K. 2009. "The Challenge of Archaeological Data Integration," in A. Velho and H. Kamermans, eds., *Technology and Methodology for Archaeological Practice: Practical Applications for the Past Reconstruction. BAR International Series* S2029. Oxford: Archaeopress, 81–86.

Kipfer, B. A. 2007. *The Archaeologist's Fieldwork Companion*. Malden, MA and Oxford: Blackwell.

Kvamme, K. L. 2007. "Integrating Multiple Geophysical Datasets," in J. R. Wiseman and F. El-Baz, eds., *Remote Sensing in Archaeology*. New York: Springer, 345–374.

Levy, T. E., and N. G. Smith. 2007. "On-site GIS digital archaeology: GIS-based excavation recording in Southern Jordan," in T. E. Levy, P. M. M. Daviau, R. W. Younker, and M. Shaer, eds., *Crossing Jordan: North American Contributions to the Archaeology of Jordan*. London and Oakville, CT: Equinox Publishing Ltd., 47–58.

Lieberwirth, U. 2008. "Voxel-based 3D GIS: Modelling and Analysis of Archaeological Stratigraphy," in B. Frischer and A. Dakouri-Hild, eds., *Beyond Illustration: 2D and 3D Digital Technologies as Tools for Discovery in Archaeology*. Oxford: Archaeopress, 85–94.

Lock, G. R. 2003. *Using Computers in Archaeology: Towards Virtual Pasts*. London: Routledge.

Losier, L. M., J. Pouliot, and M. Fortin. 2007. "3D Geometrical Modeling of Excavation Units at the Archaeological Site of Tell Àcharneh (Syria)," *Journal of Archaeological Science* 34: 272–288.

McCoy, M., and T. Ladefoged. 2009. "New Developments in the Use of Spatial Technology in Archaeology," *Journal of Archaeological Research* 17: 263–295.

McPherron, S. J. P., and H. L. Dibble. 2002. *Using Computers in Archaeology: A Practical Guide*. Boston, MA: McGraw-Hill.

Neubauer, W. 2004. "GIS in Archaeology—The Interface Between Prospection and Excavation," *Archaeological Prospection* 11(3): 159–166.

Nigro, J. D., W. F. Limp, K. K. Kvamme, D. J. de Ruiter, and L. R. Berger. 2002. "The Creation and Potential Applications of a 3-Dimensional CIS for the Early Hominid Site of Swartkrans, South Africa," in G. Burenhult and J. Arvidsson, eds., *Archaeological Informatics: Pushing the Envelope CAA 2001. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 29th conference, Gotland, April 2001. BAR International Series* 1016. Oxford: Archaeopress, 113–124.

Nigro, J. D., P. S. Ungar, D. J. de Ruiter, and L. R. Berger. 2003. "Developing a Geographic Information System for Mapping and Analysing Fossil Deposits at Swartkrans, Gauteng Province, South Africa," *Journal of Archaeological Science* 30: 317–324.

Powlesland, D., and K. May. 2010. "DigIT: Archaeology Summary Report and Experiments in Digital Recording in the Field," *Internet Archaeology* 27: http://intarch.ac.uk/journal/issue27/2/1.html

Pundt, H. 2002. "Field Data Collection with Mobile GIS: Dependencies Between Semantics and Data Quality," *GeoInformatica* 6: 363–380.

Remondino, F., and S. El-Hakim. 2006. "Image-based 3D Modeling: A Review," *The Photogrammetric Record* 21(115): 269–291.

Richards, J. D. 1998. "Recent Trends in Computer Applications in Archaeology," *Journal of Archaeological Research* 6: 331–382.

Richards, J. D. 2009. "From Anarchy To Good Practice: The Evolution of Standards in Archaeological Computing," *Archeologia e Calcolatori* 20: 27–35.

Richards, J. D., and D. Robinson. 2000. Digital Archives from Excavation and Fieldwork: A Guide to Good Practice. Woodbridge, CT: Oxbow.

Ryan, N., J. Pascoe, and D. R. Morse. 1998. "Enhanced Reality Fieldwork: The Context Aware Archaeological Assistant," in V. Gaffney, S. Exon, and P. M. van Leusen, eds., *CAA: Computer Applications and Quantitative Methods in Archaeology 1997. BAR International Series* 751. Oxford: Archaeopress, 269–274.

Ryan, N., J. Pascoe, and D. R. Morse. 1999. "FieldNote: Extending a GIS into the Field," in J. A. Barceló, I. Briz, and A. Vila, eds., *New Techniques for Old Times CAA98. Computer Applications and Quantitative Methods in Archaeology. BAR International Series* 757. Oxford: Archaeopress, Unpaginated CD-ROM.

Ryan, N., and P. M. van Leusen. 2002. "Educating the Digital Fieldwork Assistant," in G. Burenhult and J. Arvidsson, eds., *Archaeological Informatics: Pushing the Envelope. CAA 2001. BAR International Series* 1016. Oxford: Archaeopress, 401–412.

Searcy, M., and S. Ure. 2008. "Laptops in the Sand," *SAA Archaeological Record* 8(4): 43–46.

Skousen, H. 2004. "Between Soil and Computer—Digital Registration on a Danish Excavation Project," in K. F. Ausserer, W. Börner, M. Goriany, and L. Karlhuber-Vöckl, eds., *Enter the Past: the E-way into the Four Dimensions of Cultural Heritage CAA 03 Computer Applications and Quantitative Methods in Archaeology (Vienna). BAR International Series* 1227. Oxford: Archaeopress, 110–112.

Tasic, N. N., and V. Jevremovic. 2004. "ArcheoPackPro! A Software System for Digital Data Management for Archaeologists," in K. F. Ausserer, W. Börner, M. Goriany, and L. Karlhuber-Vöckl, eds., *Enter the Past: the E-way into the Four Dimensions of Cultural Heritage CAA 03 Computer Applications and Quantitative Methods in Archaeology (Vienna). BAR International Series* 1227. Oxford: Archaeopress, 125–127.

Tripcevich, N. 2004. "Flexibility by Design: How Mobile GIS Meets the Needs of Archaeological Survey," *Cartography and Geographic Information Science* 31: 137–151.

Tripcevich, N. 2007. *Quarries, Caravans, and Routes to Complexity: Prehispanic Obsidian in the South-Central Andes.* Ph.D. dissertation, University of California, Santa Barbara. Ann Arbor: University Microfilms.

Wagtendonk, A. J., and R. A. M. De Jeu. 2007. "Sensible Field Computing: Evaluating the Use of Mobile GIS Methods in Scientific Fieldwork," *Photogrammetric Engineering and Remote Sensing* 73: 651–662.

Wernke, S. A. 2003. *An Archaeo-History of Andean Community and Landscape: The Late Prehispanic and Early Colonial Colca Valley, Peru. Ph.D. dissertation, University of Wisconsin. Ann Arbor:* University Microfilms.

Wernke, S. A. 2007a. "Analogy or Erasure? Dialectics of Religious Transformation in the Early Doctrinas of the Colca Valley, Peru," *International Journal of Historical Archaeology* 11: 152–182.

Wernke, S. A. 2007b. "Negotiating Community and Landscape in the Peruvian Andes: A Transconquest View," *American Anthropologist* 109: 130–152.

Wernke, S. A., in press. "Convergences: Producing Early Colonial Hybridity in Highland Peru," in M. Liebmann and M. Murphy, eds., *Enduring Conquests: Rethinking the Archaeology of Resistance to Spanish Colonialism in the Americas.* Santa Fe, NM: School for Advanced Research.

Wheeler, M. 1954. *Archaeology from the Earth.* Oxford: Clarendon Press.

Whitmeyer, S. J., and J. Nicoletti. 2010. "The Digital Revolution in Geologic Mapping," *GSA Today* 20(4–5): 4–10.

Ziebart, M., N. Holder, and P. Dare. 2002. "Field Digital Data Acquisition (FDA) Using Total Station and Pencomputer: A Working Methodology," in D. Wheatley, G. Earl, and S. Poppy, eds., *Contemporary Themes in Archaeological Computing.* Oxford: Oxbow Books, 58–64.