

# Digital Vacone: The Upper Sabina Tiberina Project's Transition from 2B Pencils to 3D Mesh

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Between 2016 and 2018, excavations at the Roman villa of Vacone, carried out by the Upper Sabina Tiberina Project, transitioned to completely digital recording practices. The methodological shift was accompanied by a three-year campaign of backfill removal and cleaning, which allowed most of the villa's extant architecture and décor uncovered since 2012 to be digitized. Moreover, a new documentation protocol was established that employs photogrammetry in lieu of scale drawing to model the three-dimensional spatial characteristics of every archaeological context. Notable artifacts were also modeled to facilitate off-site study. The excavation's experiences with this conversion offer valuable lessons for other long-term archaeological projects contemplating a similar shift amid active fieldwork. The project's digital recording team developed a methodology for layer-by-layer modeling that ensures precise alignment between stratigraphic contexts using fixed markers. From these, standard 2D products (orthomosaic plans and digital elevation models [DEMs]) were produced. A similar technique was used for generating 2D orthomosaics of vertical features (such as walls and stratigraphic sections) without the need to take numerous measurements on the vertical surface (e.g., with a prismless total station). Similarly, the generated data can create 2D sections along any arbitrary line even after the strata have been removed. Beyond simply replicating traditional two-dimensional records, the 3D data have proven essential for visualizing the interrelation of above and below ground spaces, and for analyzing a terraced structure built on several levels. Composite 3D models, hosted online, are also an effective tool for public outreach with stakeholders in the local community, as well as the general public.

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## Keywords:

Photogrammetry, 3D Modeling, Archaeological Recording, Field Methodology, Roman Archaeology.

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## 1. INTRODUCTION

Over the course of the last decade, photogrammetry has become a standard instrument in the archaeologist's toolkit, driving a veritable revolution in field recording methodology [e.g., De Reu 2014; Roosevelt et al. 2015; Opitz 2015; Willis et al. 2016; Koenig et al. 2017; Garstki et al. 2018; Taylor et al. 2018; Garstki 2020]. Rapid advancements in software based upon the Structure from Motion and Multi View Stereo techniques have made the process progressively automated and cost-effective, while more user-friendly interfaces allow non-specialist practitioners with minimal training and expertise to take advantage of its many benefits. Concurrently, more efficient algorithms and constantly advancing hardware have cut down on processing times even on thin and light laptops suitable for use in the field. The latest generation of photogrammetry software is also increasingly foolproof, reliable, and easy to use. This limits the need for projects to invest in professional photographers, expensive cameras or photographic equipment, or even to commit precious time towards mitigating shadows or other lighting issues, and still achieve quality results. Consequently, archaeological recording practices have seen significant progress in quality and efficiency [Sapirstein 2016]. Many projects are now generating gigabytes of accurate, three-dimensional data each season, along with their associated two-dimensional rasters, orthomosaic images and digital elevation models (DEMs), which can be integrated with existing GIS projects.

Nevertheless, the pace of change in field recording practices has been uneven. Long-standing projects with entrenched methodologies might be reluctant to alter procedures. Old and new methods are sometimes practiced concurrently until confidence is gained with digital methodologies, leading to a doubling of labor, rather than an increase in efficiency. Questions may linger about how to incorporate new digital data with legacy records, or how to deal with a significant backlog of earlier-excavated remains, and how such mismatched records might affect publications. Plans must also be made to address the long-term stability and accessibility of digital records in comparison to their analog predecessors, and comprehensive publications with 3D data are still rare [e.g. Opitz et al. 2016; Counts et al. 2020]. In addition, photogrammetric methodologies in archaeology are far from standardized, unlike those for measured scale drawings, and exhortatory calls for best practices are progressively growing [e.g., Barnes 2011; Sapirstein and Murray 2017; Borrero and Stroth 2020]. This paper details how one project navigated some of these concerns in order to provide a roadmap for similar excavations contemplating such a change amid active fieldwork.

The excavations of the Roman villa at Vacone, carried out by the "Upper Sabina Tiberina Project" (USTP), implemented photogrammetry as a systematic field recording technique during the 2016 season. We decided to test the applicability of photogrammetry initially on the villa's architecture and associated *in situ* mosaics and wall plaster. These could be recorded digitally, multiple times if necessary, without the potential risk of data loss were we to begin with ephemeral features such as stratigraphic units. After establishing the suitability, effectiveness, and accuracy of the

photogrammetric process, the project implemented a fully digital recording protocol that replaced measured scale drawings of stratigraphic units during the 2017 season. Since that time, 3D models have also formed a powerful visualization tool for analysis of the villa's architecture, especially for interpreting the relationship of above- and below-ground spaces as well as stratigraphy. Moreover, a selection of small finds have been digitized to facilitate their study during the off season.

## 2. THE ROMAN VILLA AT VACONE

The Upper Sabina Tiberina Project, in operation since 2011, is a collaboration between Rutgers University and the Joukowsky Institute for Archaeology and the Ancient World of Brown University (formerly with the University of Alberta, 2017-2019, and the University of Edinburgh, 2015-2017) [<https://ustproject.org>; Bloy et al. 2014, 2016; Rice et al. 2017; Pollari et al. 2018; Franconi et al. 2019;]. Its objective is to understand the long-term development of rural settlement and economy in the northern portion of the Sabina Tiberina region of Lazio, located about 55 km north of Rome between the Tiber river on the west and the Monti Sabini on the east (Fig. 1). The project has conducted survey and geophysical prospection at 15 sites within a study area that is roughly equivalent to the territory of the ancient settlement of Forum Novum (modern Vescovio). Most effort, however, has been focused upon the excavation of a late-republican to mid-imperial villa located in the town of Vacone, which has been carried out for eight consecutive seasons.

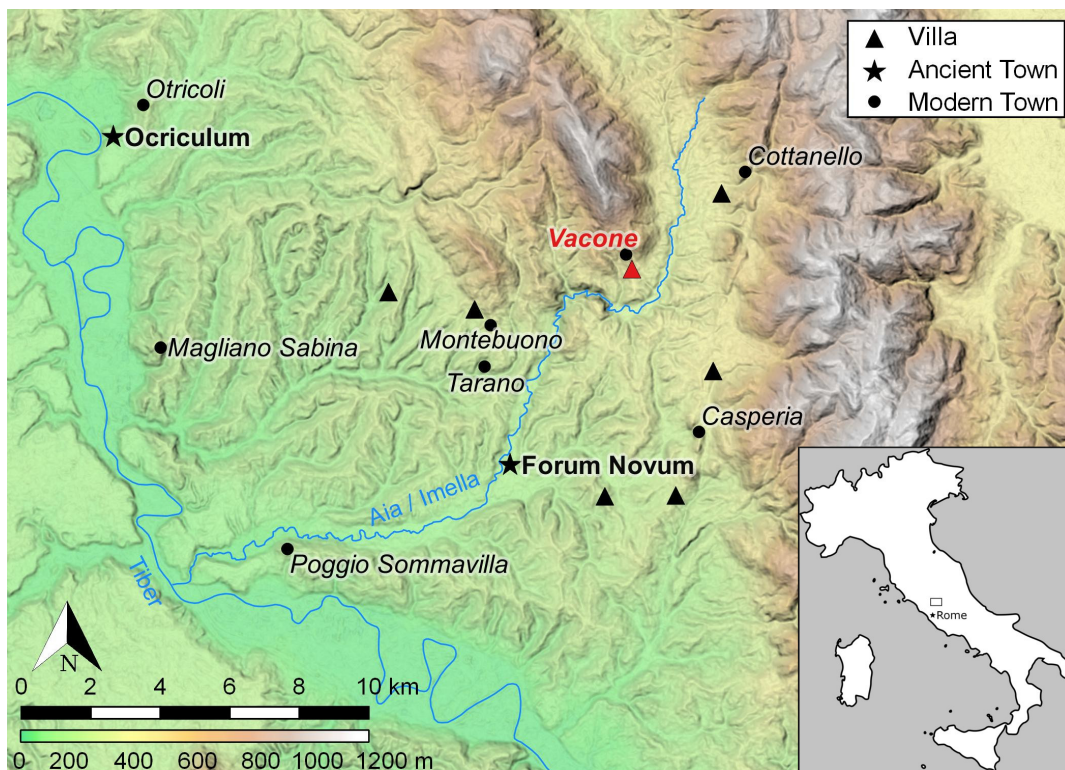


Figure 1. Map of the Upper Sabina Tiberina indicating the location of the Vacone villa (in red) and a selection of other neighboring villas.

The villa was built upon a large concrete vaulted terrace facing the valley of the seasonal stream (*torrente*) Aia (also called Imella), on the southeastern slopes of Monte Cosce. Known colloquially, though without proof, as Horace's villa, its remains have been known to humanists and antiquarians since at least the 15<sup>th</sup> century, though were later overlooked [Notarian et al. 2016]. The villa was rediscovered during road construction in the 1970s and subsequently restored and minimally excavated by the Soprintendenza per i Beni Archeologici del Lazio in the 1980s [Alvino 2009]. After brief geophysical prospection in 2011, the USTP began full archaeological exploration in 2012.



Figure 2. Orthomosaic plan of the Vacone villa in the imperial era, as of the 2018 excavation season.

The excavations have revealed a substantial villa (Fig. 2), 62 by 42 meters in size, with some 50 rooms identified as of 2018, organized around a central peristyle with 5 by 5 colonnade (room 29 on the plan). The main residential zone of the villa was built upon an artificial terrace buttressed by an L-shaped cryptoporticus in *opus incertum*, 43 meters long on the south, and 21 meters on the east, dating to the second half of the 2<sup>nd</sup> century BCE. The cryptoporticoes supported two colonnaded porticoes with probably 6 columns along the east (Room 37) and 12 along the south (Room 2). At the rear of the villa another vaulted *opus incertum* structure (Rooms 22 and 17), probably a cistern, buttressed a higher terrace that supported the productive sector of the villa with at least four olive presses and three

settling tanks. All but one of these presses were converted into treading platforms for grapes, probably in the early 2<sup>nd</sup> century CE. The villa's opulent decor testifies to the fact that the owner was quite wealthy. Its western sector contained a bath complex, only discovered in 2018. Moreover, the project has excavated over 30 mosaic pavements to date, about half of which are polychrome, and many walls were decorated with colored frescos, molded stucco, and even some marble revetment [e.g., Rice et al. 2017; Pollari et al. 2018]. It underwent at least two phases of redevelopment throughout its lifetime: one during the late-Augustan or early-Tiberian era (to which the vast majority of the extant rooms, mosaics, and frescos belong), and another in the early 2<sup>nd</sup> century CE. The villa was abandoned around 200 CE or shortly thereafter, probably due to structural problems perhaps stemming from an earthquake. The site, however, remained in use almost immediately following its structural collapse in the early 3<sup>rd</sup> century, as evidenced by burials, sporadic pottery finds, and two overlying ovens built near the former productive zone. Through 2018, five human burials radiocarbon dated to the 7<sup>th</sup> century CE, testify to a significant, though yet little understood, Lombard-era reuse. Intermittent finds from the post-Lombard era indicate limited activity within the southern cryptoporticus between the 11<sup>th</sup> and 14<sup>th</sup> centuries. Finally, the terrace was redeveloped for a vineyard in the 16<sup>th</sup> century as shown by long agricultural trenches dug through the imperial era rooms of the villa across the site, which coincide with the villa's reference in antiquarian sources between the 15<sup>th</sup> and 18<sup>th</sup> centuries.

### 3. DIGITAL RECORDING TRANSITION

In the first years of the USTP, between 2012 and 2015, the excavation employed mostly analog (paper-based) documentation methods. Trench supervisors logged paper forms with informal sketches of context plans. All stratigraphic contexts were recorded with digital photography using a photo board, north arrow and scale bar. A total station was used to record elevations, the locations of small finds, and basic site planning for the GIS. Measured scale pencil drawings (plans and sections) were done at the end of the season to record the final state of excavated trenches, or for particularly noteworthy features such as burials. Photographs were also taken again to record the final state of excavation trenches. Since the USTP operates as a field school, contextual drawing was taught as part of the educational process. While this is a critical skill for students to learn, the process is slow and requires heavy oversight from trench supervisors. The addition of photogrammetric documentation allowed for accurate and efficient recording without compromising the educational process.

#### 3.1 Software, Hardware, Equipment, and Methods

Beginning in 2014, the project incorporated very limited photogrammetric documentation of standing architecture such as the above-ground cryptoporticus at the northern end of the site. Photogrammetry promised a much quicker, accurate, and state-of-the-art methodology for preparing publication-quality imagery, especially for mosaics, but integrating photogrammetry more fully required additional expertise in digital recording and new computing equipment and software. In 2016, the project invested in the incorporation of systematic photogrammetry into our field recording techniques. We brought on board additional staff members to form a "digital team" (see acknowledgments). An educational license for Agisoft Photoscan (now Metashape), a proprietary software, but arguably the most widespread photogrammetry application thanks to its ease of use,

and a laptop capable of running Photoscan were provided by the University of Edinburgh. Grants from Hiram College and the University of Alberta provided the funds for additional computers and software licenses. The relative low cost of photogrammetry, especially in comparison to other forms of 3D recording technology such as laser scanners, is one of its prime attractions. A full educational license of Metashape professional edition currently costs \$549 while a laptop with a dedicated video card, multi-core CPU and at least 16 GB of RAM can be obtained for less than \$1500 [for current hardware requirements, see <https://www.agisoft.com/downloads/system-requirements/>]. In terms of photographic needs, most standard digital cameras are adequate, although a camera with a full-frame CMOS sensor will deliver the highest quality results. Thankfully the USTP already owned a 22.3 megapixel full-frame dSLR camera (Canon EOS 5D Mark III), as well as a total station (TOPCON GTS-310 with Omni Prism), which is needed for georeferencing the 3D models. Finally, a crucial need is an adequate supply of digital storage since both the volume of high-quality photographs produced for photogrammetry (especially if shooting in RAW) as well as the size of the 3D models themselves are quite demanding. Moreover, no project can afford to lack adequate backups of data, so multiple external drives with several available terabytes are an absolute necessity.

The learning curve for using Metashape to produce 3D models is low, largely thanks to its simple, user-friendly interface and improvements in the Structure from Motion algorithms. Numerous tutorials are available on Agisoft's webpage and other online sources such as the nonprofit Cultural Heritage Imaging [Cultural Heritage Imaging 2020], which also offers guidance on proper photography for photogrammetry. Nonetheless, quality models can even be produced under less-than-optimal conditions, such as uneven lighting, blurry photographs, unstable lens focal distance, and the like, which are sometimes encountered in field archaeology. Beyond Metashape, there are also many open-source programs available that can be used for post-processing or visualizing data, such as Blender, a powerful 3D modeling software (although with a much steeper learning curve, but with a large online community and numerous free tutorials). Other open-source programs for viewing and analysis of 3D data include Meshlab and CloudCompare. The USTP also came to rely upon the web-based platform Sketchfab [<https://sketchfab.com/>], which hosts 3D models online for sharing, and provides "professional" level licenses to educators free of charge. Moreover, Sketchfab, based on the WebGL standard, enables most anyone to view 3D models in any capable browser, even smartphones and tablets, without the need for external plugins or specialized applications. 3D models hosted on Sketchfab can also be embedded on any webpage, a potent outreach tool for archaeological projects (e.g., <http://ustproject.org/sketchfab-models/>).

### 3.2 Emergency Documentation: The Eastern Cryptoporticus

Initial trials with photogrammetry in excavation trenches during the 2016 season quickly proved its utility. However, unexpected circumstances soon gave the project an opportunity to realize its full potential for rapid and accurate documentation under challenging circumstances. Mechanical brush removal by local authorities partway through the 2016 excavation season led to the unexpected discovery of a 21-meter long cryptoporticus (i.e. the eastern buttress of the villa's terrace, introduced in Section 2 above). The interior could be accessed via a narrow opening through rubble collapse, but the interior was spacious enough to stand within. Unfortunately, part of the vaulting near the entrance had collapsed, and heavy stones precariously hung off the edge. The structural integrity of

the rest of the vault was in doubt in the initial days after its exposure. Cracks were visible in the interior vaulting and sections of *opus incertum* stonework had fallen, revealing the concrete core. The floor of the cryptoporticus was full of stones, large equid bones, and scattered sherds of early-modern pottery.



Figure 3. Recording of ground control points with a total station in the eastern cryptoporticus in 2016.

Since the last time the tunnel had been used was unknown, our priority was to document the structure and its artifact scatter on the floor as completely as possible. Photogrammetry was the quickest and safest option, minimizing the amount of time any individual had to be present inside the cryptoporticus, in comparison to conducting a detailed scale drawing of the floor surface. Illumination within the completely dark interior was provided by a lamp connected via extension cords to a neighboring property (Fig. 3). Ground control points were recorded with the total station on coded targets attached to rocks via adhesive putty or soil via nails (a technique later revised, as discussed in Section 5), and additional targets were placed on the walls to aid in pair alignment. These conditions were still less than ideal for photography. We attempted to minimize sharp contrasts in lighting by moving the lamp adjacent to the camera for every shot, but this had to be

accomplished by moving the power cords so as not to disturb the artifact scatter or coded targets. Similarly, any movement on the floor risked disturbing the arrangement of objects or targets, and damp conditions within the tunnel quickly curled the paper targets. Nonetheless, after two sets of photos were taken, a total of almost 2,500 separate exposures, we were able to successfully produce an extremely detailed 3D model of the structure, as well as orthomosaics and DEMs of its floor and walls (Fig. 4).

All images to scale: 2 mm pixels (500 pixels/meter)

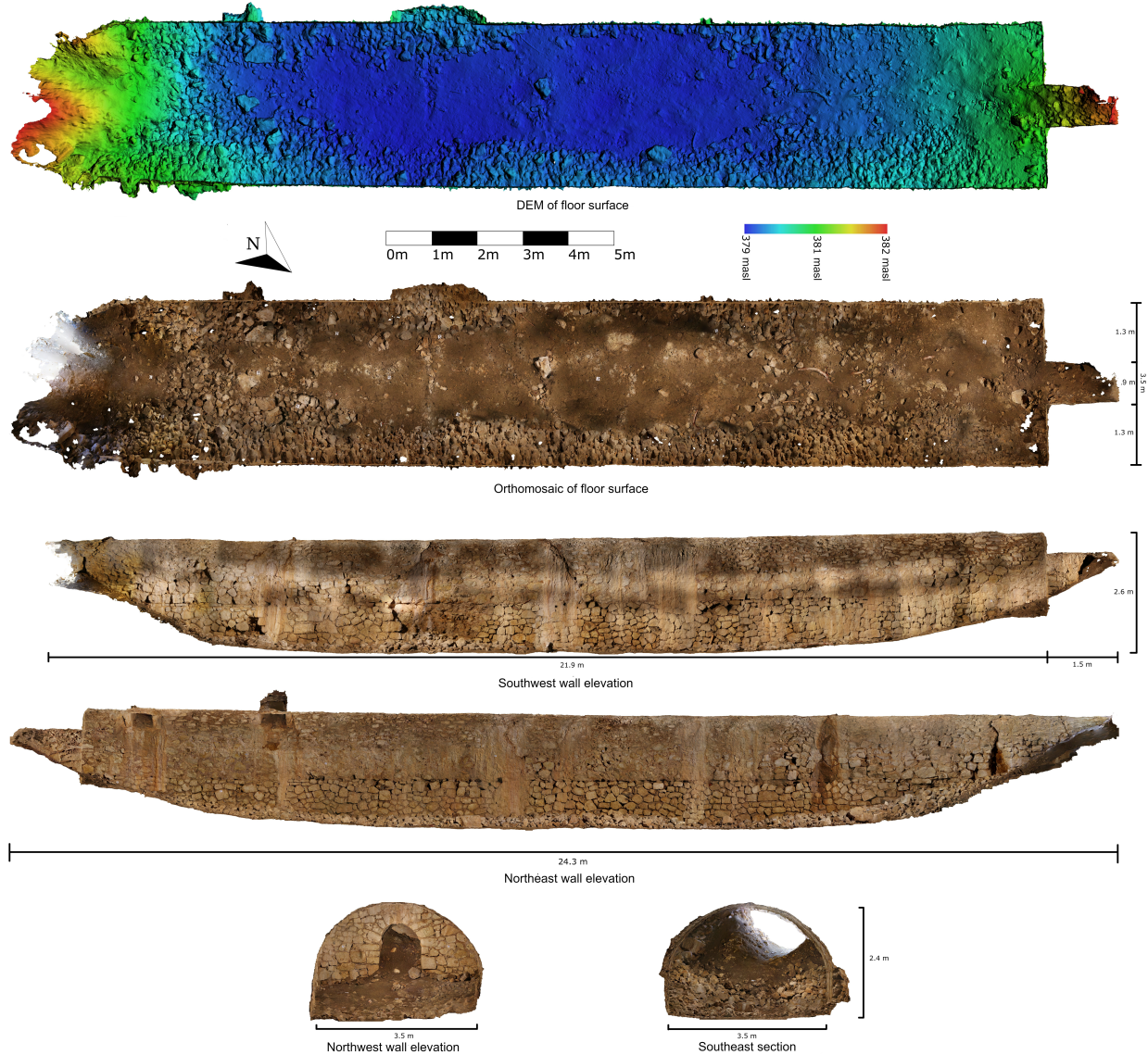


Figure 4. Eastern cryptoporticus of the Vacone villa. Orthomosaic and DEM plan of floor surface. Sectional elevations of four walls (southeast wall missing where it presumably connected to the southern cryptoporticus).

#### **4. RETROACTIVE DIGITAL MODELING CAMPAIGN: 2016-2018**

The success with the eastern cryptoporticus modeling convinced the project to digitally record all the villa's extant architecture and décor, uncovered since 2012, by removing the sand and geotextile backfill from all previously excavated trenches. This was also an opportunity to check the conservation of each room and to repoint loose mortar. The process of cleaning each trench was laborious, especially since care also had to be taken to trim and remove vegetation that would appear in the digital products. Finally, to minimize shadows, photographs were taken either in the early morning after sunrise, or in the late evening before sunset, and the mosaics were lightly watered to highlight their vibrant color. This last procedure could be very challenging since drying would occur almost instantaneously, especially after being heated by the sun all day, leading to color unevenness. As a result, the work unfolded piecemeal over the course of three excavation seasons. Nevertheless, the digital recording team was able to perform these tasks concurrently with the documentation of new stratigraphic units in active trenches (discussed in section 5 below).

A mixture of terrestrial photography (i.e., handheld photography walking around the trench) and pole photography was used. However, the dSLR camera was too heavy to mount elevated without an expensive boom. Therefore, we used a lighter digital camera (Sony a5100) with a smaller but still adequate APS-C sensor and a prime wide-angle lens (16 mm). The near perpendicular angles provided by pole photography were particularly useful for producing quality orthomosaic images of mosaics (discussed later). Drone photography was limited to brief use in 2017, but better results were provided at the necessary scale by handheld cameras. Some interior architecture was photographed using a tripod to facilitate long exposures using only ambient light.

After three years, almost every excavated room was digitized. In addition, we modeled the villa's architectural facades and interior, underground, spaces. The result is a near complete digital record of the villa which is integrated into the project GIS with the site vector plan (Fig. 2). This is an invaluable photographic dataset that allows the entire structure to be visualized free of backfill. Relationships can be observed between different rooms, or buried walls from earlier phases, that are difficult to note on site when all but the active trenches are covered.

#### **5. A NEW DOCUMENTATION PROTOCOL: LAYER-BY-LAYER MODELING OF ARCHAEOLOGICAL STRATA (2017 – PRESENT)**

Beginning in 2017, a new recording protocol was initiated in which every single context is recorded digitally. This was a relatively easy transition for the project to make since our previous methodology called for trenches to be cleaned and photographed with each new context. Very little additional time is required to take a series of photos for photogrammetry at the same time. However, care must be taken to ensure that models, orthomosaics, and DEMs of each successive context from a trench will align in GIS and other 3D modeling software. It is therefore imperative that stable ground control points (GCPs) are used for every context. The GCPs obviously need to be placed within a feature that will not be removed during excavation (such as a wall) or they can be placed just outside the trench along the edges. The USTP uses colored bottle caps secured to the side of the trench by very long nails. The colored bottle caps enhance visibility in the photos and the nails ensure that they will not

shift even if stepped upon by field workers or run over by a wheelbarrow. The GCPs only need to be surveyed once with the total station. These same coordinates are then input to every model from the same trench, assuring a very close alignment between each stratigraphic unit. Although the use of nails, which must be manually entered into Metashape, results in variable GCP residual root mean square errors (RMSE) up to a centimeter between unit models, at the typical scale of analysis there is no (or extremely minor) visible misalignment when different units are visualized together. Machine-readable targets are no longer used for this purpose since they are far less durable than nails or caps. They also frequently cannot be detected by the software in low or overexposed light conditions, or if they are bent, too blurry, too small, or even too large in terms of pixels within the photo. They also tend to be pierced by the pointed end of the total station prism pole, rendering them useless. As targets on walls, however, they do retain value as they can be located with much greater accuracy by the photogrammetry software and can improve image alignment [Sapirstein 2016]. They can also be used on a scale bar as a more accurate scale control in comparison to the total station readings, whose error under normal field conditions can approach a centimeter or more [Sapirstein 2016; Sapirstein and Murray 2017:345]. Even a block of wood can suffice for such a scale bar, with the targets placed at any measured interval (accurate to about a millimeter if done manually), which is then entered into the photogrammetry software.

One disadvantage of this method is the need to photograph the entire trench, or at least much of it, for every context model, even if the context in question only extends across part of the excavated area. This is due to the need to capture the GCPs along the edges for the purposes of georeferencing, scaling, and aligning. This increases the total number of photos taken, exacerbating issues of storage and archiving. For this reason, the USTP tried to wait until multiple contexts were ready for photography to cut down on the need to model an entire unit for a context that only covers a small area. A related issue is the fact that context boundaries often only extend across part of a trench and are frequently not easily discernable in the models. For this reason, a polygon shapefile is drawn onto the model (more precisely, onto the orthorectified plan view, discussed in the next section) indicating the boundaries of the context. This can be done either directly in Metashape or in a GIS program.

## 1.1 2D Products: Plans and Sections

Orthomosaics are orthorectified, meaning that they have been corrected for distortion (such as lens, perspective, or geographic distortion) and are thus scaled and measurable. They are also georeferenced using ground control points registered with the total station. The coordinates of each ground control point are converted to a projected coordinate system, so each orthomosaic can be loaded into the site GIS in their correct location with respect to preexisting vector data. The DEMs are also orthorectified and georeferenced, but additionally each pixel contains elevation data that can be represented through a color ramp, to create contours at any chosen interval, or to take the elevation of any point in the image at any time. In Fig. 5, which displays an orthomosaic and DEM of a *cubiculum* (bedroom) adjoining the villa's peristyle side by side, differences in elevation such as those created by the collapse of the mosaic floor in the middle of the room appear more clearly in the elevation model than in the orthomosaic. Moreover, full resolution orthomosaics can be extremely detailed, given that they are derived from high quality digital photography. The orthomosaic of Room 10, for example, is built from pixels that represent 0.49 mm at full scale. This means that an individual tessera in the mosaic floor, about 8 mm square, is composed of over 16 pixels in the image, more than

enough to be zoomed in for observation and measurement. The full resolution orthomosaic of the eastern cryptoporticus floor (Fig. 4) has an even higher resolution: 0.35 mm pixels. A 10 cm long artifact is composed of almost 300 pixels, enough for a sharp appearance. The sharpness of the resultant orthomosaic is also high dependent upon the focus, distance, and angle of the original photographs, hence the USTP's focus on detailed zenithal photos over mosaic floors. Their utility as research tools notwithstanding, orthomosaic files, especially if saved in an uncompressed lossless format such as GeoTIFF, present significant challenges for storage and viewing on less graphically capable systems. Downsampled imagery (e.g., 2 mm pixels, as in Fig. 4) are more than sufficient for traditional publication or public presentation.

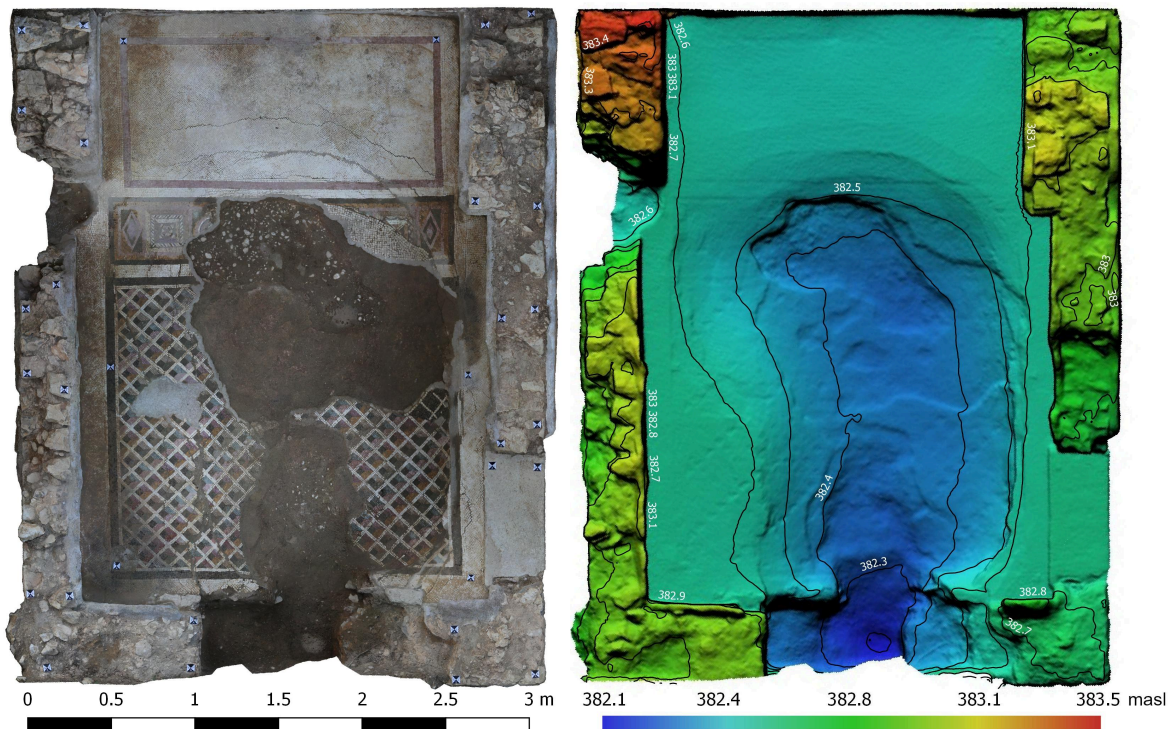


Figure 5. Room 10, cubiculum: orthomosaic (left) and digital elevation model with 10 cm contours (right).

Digital models can also be used to create orthomosaics of stratigraphic sections (Fig. 6) and elevations of any vertical feature (Fig. 7) within a 3D model, even without the use of a prismless total station or vertical control points on walls or trench edges. This can be achieved in Metashape by creating two markers, roughly horizontal to each other, directly on the face of the vertical surface to be rendered in the model. Then a third marker is manually created with the same x and y (or northing and easting) coordinates of one of the two other points, but a "z" (i.e., elevation) coordinate at an arbitrary distance higher. These three points define a plane that is perfectly vertical and aligned with the wall or trench edge to be rendered, which the software uses for a planar projection orthomosaic. These elevations have the added advantage of being able to represent below and above ground features simultaneously, provided that obstructing portions of the model are removed prior to the creation of the orthomosaic.



Figure 6: Orthomosaic section of fill of underground passage (S2) near its northwest end.

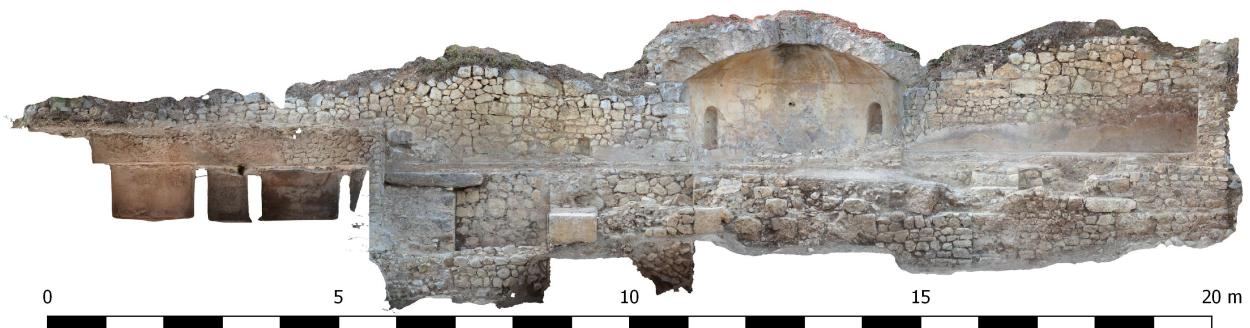


Figure 7. Sectional elevation orthomosaic of the villa's pressing terrace, with semicircular domed structure from the earlier Republican phase. Note the views of the three settling vats (left) below ground level.

While the orthomosaics themselves are invaluable records, they can also easily be converted into more traditional scale vector plans by simply tracing their features in any vector-based illustration or GIS program. These plans are potentially more accurate since their production is largely automated by computer algorithms, unlike pencil drawings taken from dozens of hand measurements converted to scale. For the sake of comparison, Fig. 8a is a measured scale plan of the

portico of the villa's peristyle drawn in 2016, the last year we produced pencil drawings on site concurrently with limited photogrammetry. The stylobate of the peristyle's colonnade can be seen along the lower end of the plan, with one *in situ* column base in the lower right corner. Fig. 8b is an orthomosaic produced from photogrammetry of the same area. Fig. 8c is a vector plan created by tracing the walls, pavements, cuts, and stones on an iPad Pro with a stylus in the app Adobe Illustrator Draw. While the two plans appear similar, there are significant differences that underline the difficulties of producing a very accurate scale drawing. The orthomosaic, on the other hand, has a RMSE of less than 2 cm between the input coordinates of the ground control targets, recorded with the total station, and their position in the model. Switching to photogrammetry therefore has not only improved the accuracy of our records, but it has also increased our efficiency dramatically, leaving more time for excavation each season that would otherwise have been devoted to measured drawing.

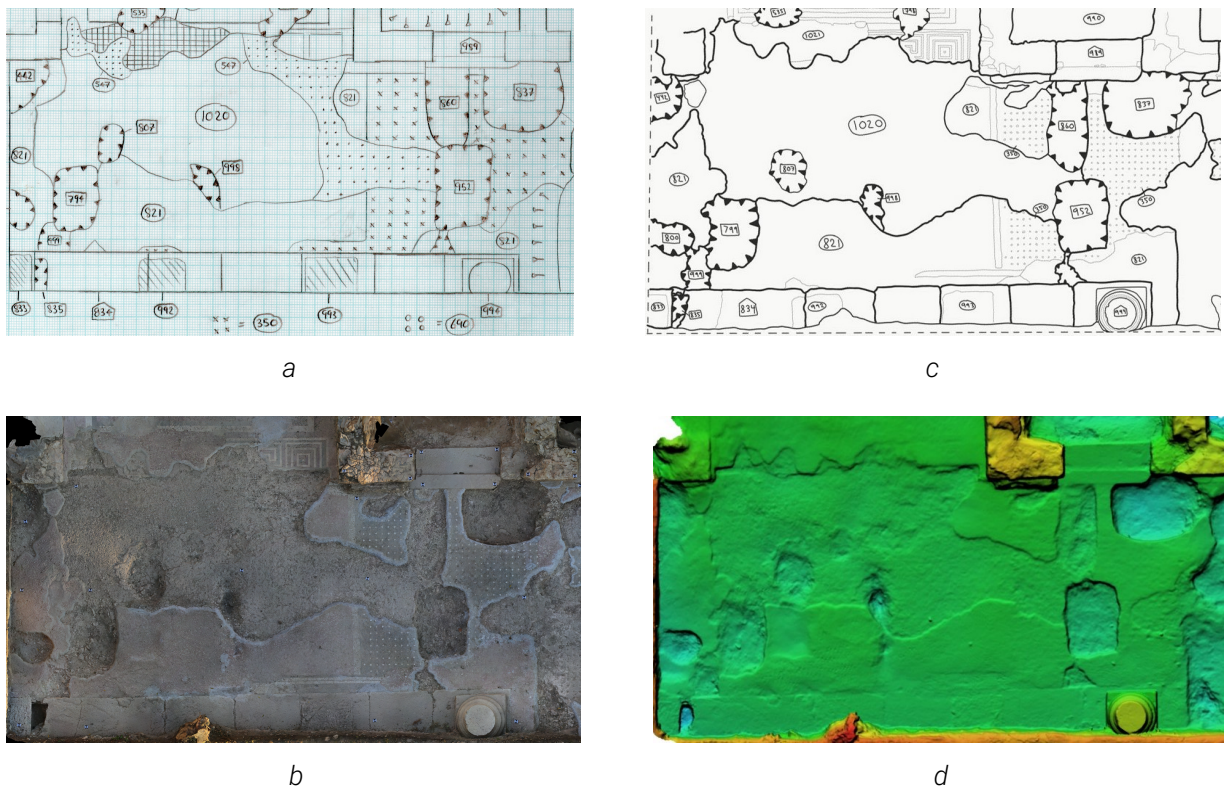


Figure 8. Northeastern sector of portico of the villa's peristyle: a) hand-drawn measured plan (1:20 scale); b) orthomosaic; c) plan traced from orthomosaic; d) digital elevation model (red-yellow=high elevation, green=middling, blue=low)

One can also create stratigraphic sections of any trench across any plane even after the excavation is complete (Fig. 9). This can be achieved using the DEMs of the individual contexts. In Metashape, a polyline can be drawn across the DEM along the plane to be sectioned. Since a DEM records elevation data in every pixel, it is easy for the software to export a 2D shapefile along this polyline which

records the elevation of each pixel as a profile line. This can be imported into a GIS in the same project coordinate system as the model. The original polyline (in plan) can then be exported as a shapefile and reimported in Metashape into each context DEM from the same trench. The resulting 2D profile shapefiles are then iteratively exported and imported into the GIS, forming a stratigraphic section. In ArcGIS, each context can be rendered into a polygon with a “feature to polygon” transformation. Elevation and scale bars can be added, and the section polyline can be represented on the DEM for reference (Fig. 9b).

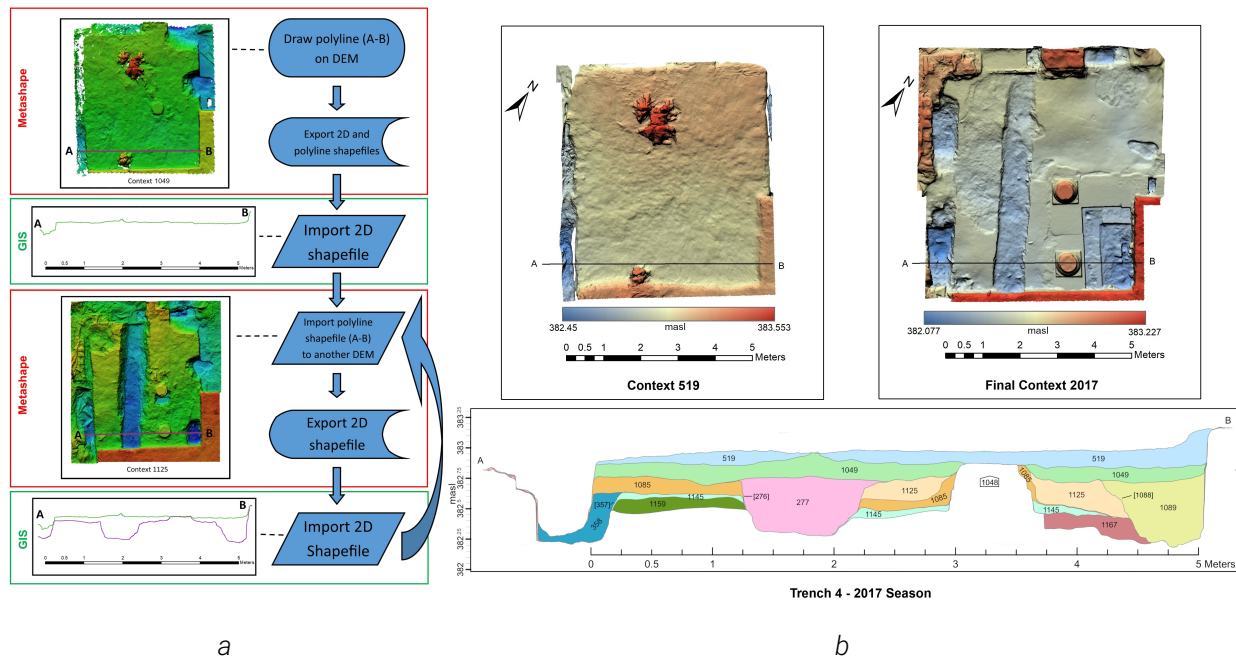


Figure 9. a) Iterative workflow for building up a stratigraphic section (A-B) in GIS from successive DEMs of overlying contexts; b) Stratigraphic section with first and last context DEMs above. NW corner of villa peristyle with two in situ column bases.

## 6. THREE-DIMENSIONAL VISUALIZATION AND ANALYSIS

The two-dimensional products derived from photogrammetric data are the most frequently discussed or reproduced in publications because they are essentially digital surrogates for conventional paper-based documentation. They can easily substitute for traditional plans and sections or be used to rapidly mimic them. The 3D models themselves, however, should not be neglected since they form a far more visually powerful representation of the spatial relationship between archaeological features. Stratigraphic context models have a range of uses. Processes exist for converting 3D models of contexts into volumetric 3D shapefiles in a 3D capable GIS such as ArcScene or ArcGIS Pro [Gavryushkina 2018; Ostrowski et al. 2018; Landeschi 2019]. A similar process for calculating layer volumes can be achieved by performing a raster calculation in QGIS that subtracts DEM values of the bottom of a unit from those of the top of a unit (similar to the Cut Fill tool

in ArcGIS [Koenig et al. 2017:65]). Such analysis, although taking advantage of the three-dimensional properties of the DEM, is still based upon a two-dimensional abstraction of the data ("2.5D"), which lacks the immediate comprehensibility of the 3D models with their photographic textures. Moreover, 2.5D imagery such as DEMs cannot represent overhanging or vertical features since these occupy the same x and y coordinates with different elevation values - an impossibility in raster datasets. Fully 3D models, on the other hand, can easily visualize all types of complex topography and architecture. To take advantage of this quality, trenches can be virtually "re-excavated" in any 3D capable program or GIS by simply loading all the relevant unit models at once and selectively turning their visualization on or off. They can even be rendered into time-lapse videos which show the successive removal of contexts, or the layers can be animated to "expand" upwards as they were removed, which serve as useful teaching tools to illustrate the process of stratigraphic excavation (for an example, rendered in ArcScene, see: <https://youtu.be/jQk3rGgSWFM>).

The Roman villa at Vacone offers a compelling case study that illustrates the potential paradigm shift in archaeological data represented by fully 3D data. Their three-dimensionality has more potential for unlocking structural relationships that cannot be observed unassisted in the field. These include the relationship of above and below ground features, or the interface of archaeological contexts that are no longer extant. The creation of 3D models throughout the course of fieldwork has even altered, to a certain extent, the project's approach to the process of excavation. An example of each scenario will be discussed in the following sections.

## 6.1 Above and Below Ground Architecture

Since the Vacone villa is a terraced site with extensive underground features such as cryptoporticoes, tunnels, and cisterns, 3D modeling has opened entirely new avenues for the project to visualize and analyze how these various spaces connect and interact within the villa's architectural space.

### 6.1.1 Eastern Porticus and Cryptoporticus

The villa's eastern porticus (Room 37), for example, sits directly on top of the eastern cryptoporticus. When the cryptoporticus was first found in 2016, it indicated that the villa extended further to the northeast than previously realized. At that time, most of this area was under 2 to 3 meters of modern fill created for a roadway that was partially constructed in the 1970s before work was halted with the rediscovery of the villa. Furthermore, we had long hypothesized that the southern cryptoporticus (Room 1) originally supported an overlying porticus overlooking the Aia valley to the south, evidence of which had long since eroded away. In 2017, a trench was opened above the northern end of the eastern cryptoporticus to test whether the eastern cryptoporticus supported a similar, hopefully intact, porticus.

Thanks to layer-by-layer modeling of archaeological strata, we knew exactly how much fill had to be removed before reaching any anticipated archaeological remains. We were even able to monitor our progress during the excavation with single-context models that were superimposed upon the cryptoporticus model, visualizing and measuring how close to the underground architecture the excavations had come. The result confirmed the existence of an eastern portico, complete with an *in*

*situ* column base and pilaster with fluted stucco, remarkably intact frescos, and a well-preserved mosaic of the same design as that lifted by the Soprintendenza from the southern portico in the 1980s.

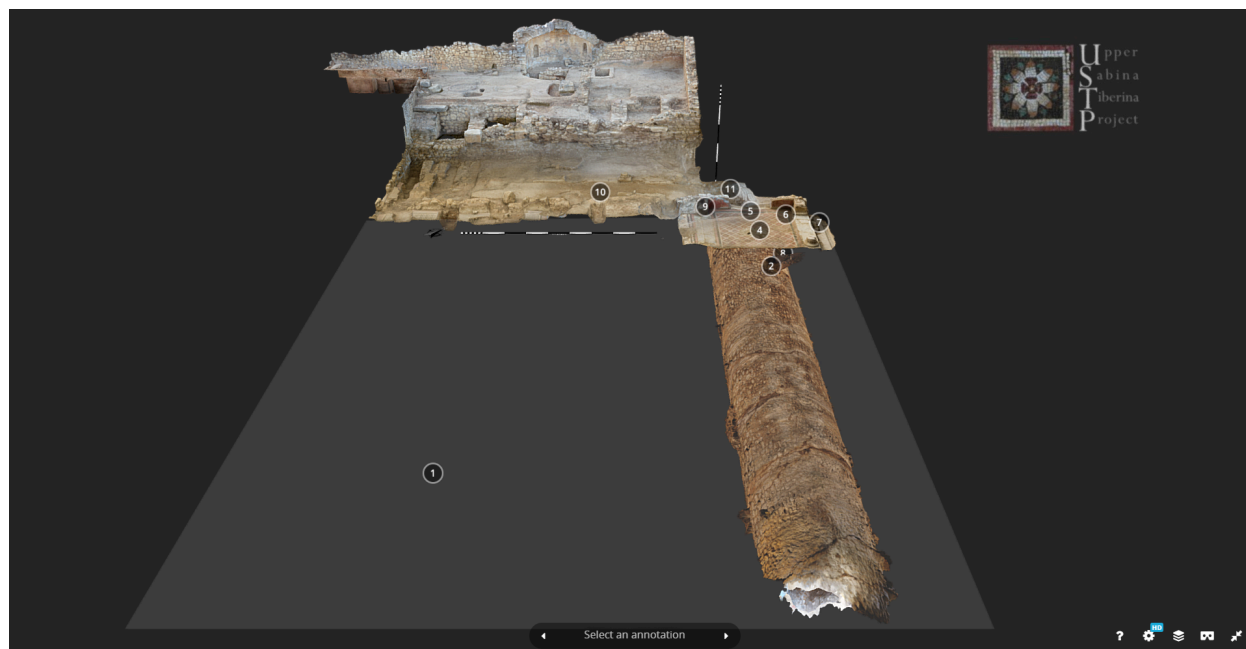


Figure 10. Composite 3D model of the villa's eastern porticus / cryptoporticus with annotations (hosted on Sketchfab: <https://skfb.ly/6KFSH>). The villa's agricultural pressing terrace (at rear) can also be explored.

A composite model (Fig. 10) created from the end-of-season 3D models and hosted on Sketchfab (<https://skfb.ly/6KFSH>), visualizes the relationship of the porticus to the cryptoporticus below, including windows and the passageway that connects to the villa's upper level. This model confirmed, for example, that an unusual u-shaped drain on the exterior of the porticus corresponded to one of the interior windows within the cryptoporticus. The composite model was created in Blender where a transparent plane was added to indicate the approximate ground level in antiquity. Since Sketchfab lacks measurement and orientation tools, 3D scalebars (vertical and horizontal) and a north arrow were also rendered in Blender to orient the viewer and provide a sense of scale. One particularly useful feature of Sketchfab, on the other hand, is the ability to add numbered annotations. These can not only provide didactic text but also form a curated virtual "tour" through the model when a user clicks through them sequentially. Of course, the models can also be freely navigated by the user, unlike a video walkthrough. It is this ability to interrogate the models by zooming in on features or viewing them from multiple angles that sets 3D data apart from its 2D counterparts. With hosting provided free of charge by Sketchfab, models can either be shared privately with staff members and or they can be set to public for outreach efforts.

As with all 3D data, it is also possible to convert such composite 3D models to conventional 2D representations for traditional print publications. By combining several models of the villa's

architecture, for instance, it is possible to create an orthometric 2D sectional elevation of the entire villa and its terraces, including the underground features (Fig. 11).

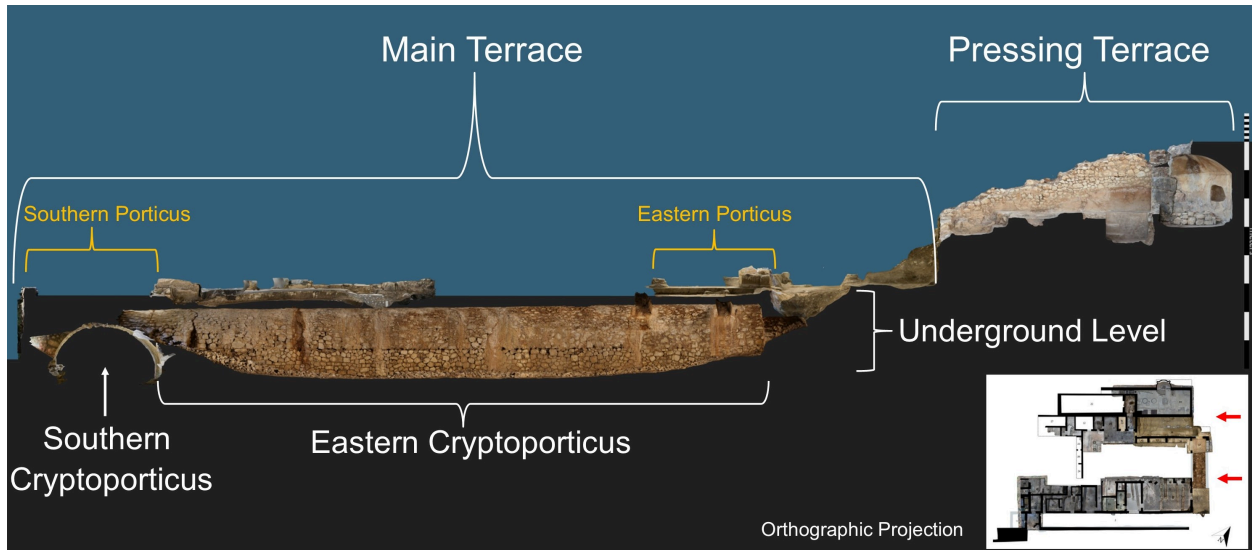


Figure 11. Sectional elevation of the Vacone villa, viewed toward the southwest (as indicated by red arrows in cutout plan), in an orthographic projection. Created in Blender.

### 6.1.2 Tunnel-Well System

Another part of the multi-level villa is the southern sector of the main terrace. Here a descending subterranean vaulted passageway was built directly through the villa's innermost southern cryptoporticus wall, creating a corridor which also had access to a well that opens into the *pars urbana* above. Another composite model (Fig. 12) created in Blender and hosted on Sketchfab (<https://skfb.ly/6KFSM>) visualizes the relationship of the tunnel, cryptoporticus, well, and mosaic paved rooms above. As with the previous composite model, this also combines architectural spaces captured in various years. Room 30, for example, was digitized in 2016 after the removal of backfill, while Room 32, the well, and access tunnel were done in 2017. Room 35 was only excavated in 2018 and added to an earlier rendering of this zone, as was the southern cryptoporticus. Furthermore, the success of photogrammetry within the narrow access tunnel and well is indicative of the reliability of the latest generation of software, further reducing the need for a laser scanner even under such cramped and poorly lit scenarios. This was accomplished using nothing more than a wide-angle prime lens (16 mm), handheld, with natural ambient lighting. The space itself was too narrow for a tripod or artificial lighting.

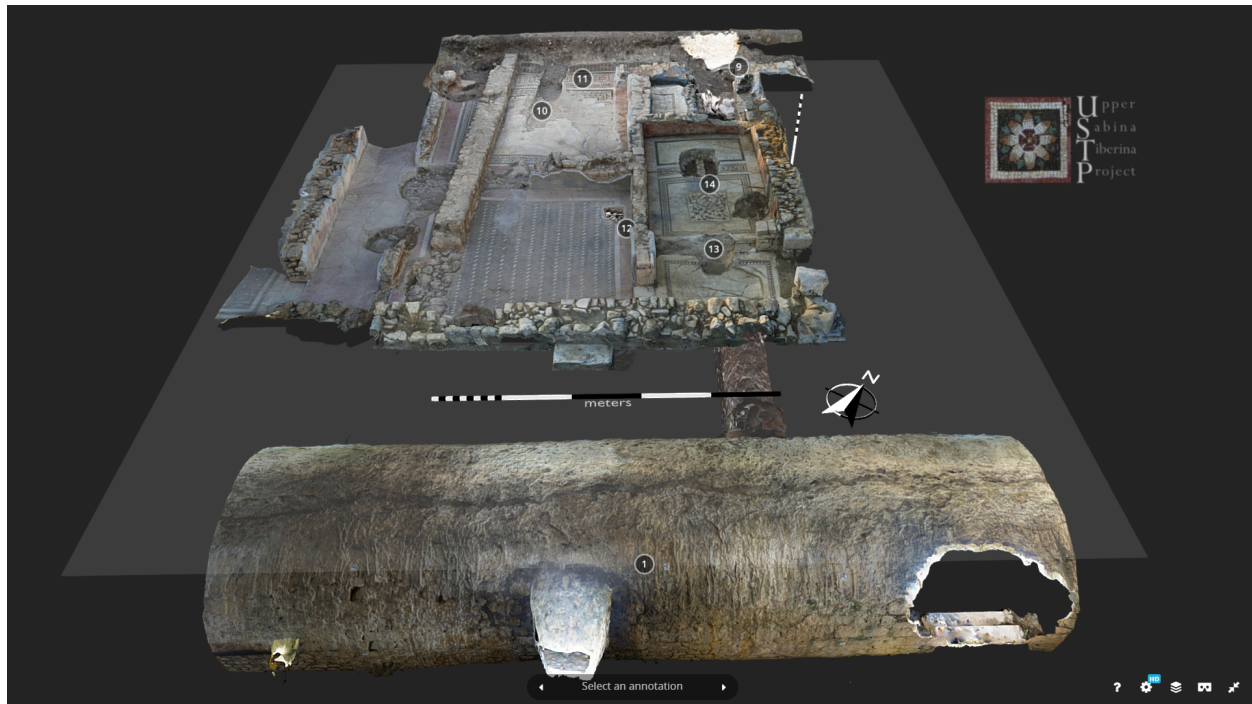


Figure 12. Composite 3D model of the villa's tunnel and well system, and its correspondence with features on ground level, with annotations (hosted on Sketchfab: <https://skfb.ly/6KFSM>)

## 6.2 Burials, Small Finds, and Conservation

Photogrammetry has also proven invaluable in instances where speed and accurate documentation are a necessity. It has, for example, revolutionized the speed and accuracy with which we can record human burials. With photogrammetry a perfectly scaled model can be generated in just a couple of hours. These models also document the exact location of grave goods, such as a bronze ring found *in situ* on individual G5.1's left hand, that can be measured and interrogated for further study by specialists long after the burial's removal. It is also useful for documenting conservation efforts on site. 3D models provide a superior record of the original location and condition of mosaics and wall paintings before treatment than simple photographs. For example, in 2018 a small circular section of mosaic that had collapsed into a void was lifted. When this mosaic section is eventually restored to its original location, the 3D model will serve as a useful guide to its original orientation. Photogrammetry has also enhanced our ability to accurately record the original context of small finds, such as an iron hinge found *in situ* within the pivot hole of a stone threshold in 2017. By rotating the view of the 3D model, a future researcher can observe the position and orientation of the hinge in 360 degrees, as opposed to mere photographic documentation that might only capture a handful of angles.

### 6.3 Artifact Modeling

A limited selection of notable artifacts has also been digitized using photogrammetry. Since objects remain in storage in Vacone during the off season, 3D models facilitate continued study back home. They can either be explored digitally or 3D printed for physical manipulation. They can also be shared with colleagues seeking comparanda or identification, or they could form the core of a virtual museum hosted on the project's webpage. On select objects, digital models can also be enhanced to help distinguish subtle details in their surface décor or texture. The process to create artifact models is slightly more time intensive than trench photogrammetry since it must be done with a turntable in a photo tent with the camera mounted on a tripod [Porter et al. 2016]. Moreover, both sides of the artifact must be modeled separately and then joined in Metashape. Once complete, however, these models are extremely accurate because of the controlled conditions of their photography, with RMS errors often less than a millimeter.

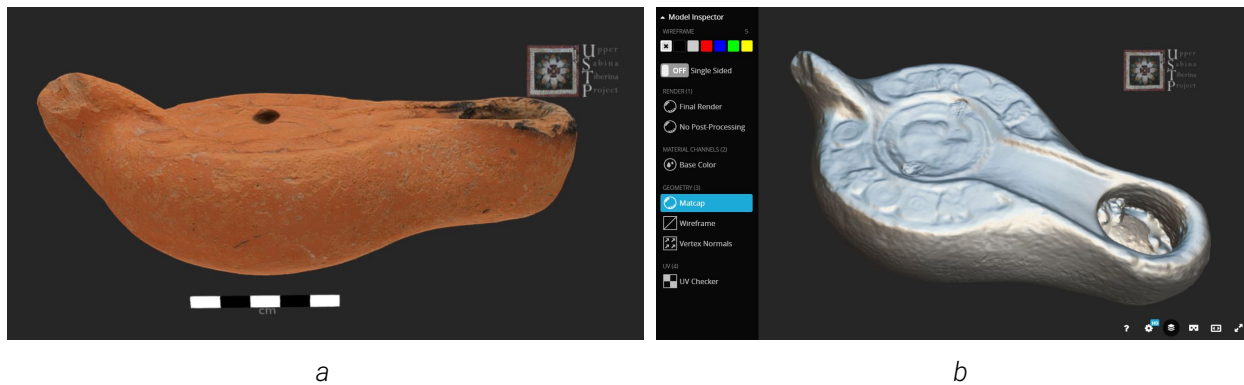


Figure 13. 3D model of a late antique ARS lamp (c. 500 AD), viewed in Sketchfab (<https://skfb.ly/6PLSz>): a) Photographic texture; b) MatCap shader in the Model Inspector view.

One example (Fig. 13) is a late antique ARS oil lamp (Hayes IIA, Bailey Q1837), dating to c. 500 CE, found in a fill layer in the southern cryptoporticus [Franconi et al. 2019, 129]. Although difficult to discern, the discus, framed by a braided border, contains a female bust facing left with hair wrapped into a bun. The shoulder is framed by a motif of inscribed circles, squares, and palmettes. The nozzle is charred from use. When viewed on Sketchfab (<https://skfb.ly/6PLSz>), the Model Inspector feature can be activated, which offers various shaders in addition to the default photographic texture. In particular, the MatCap (Material Capture) option, which replaces the object's real colors with a singular color whose tint varies with the model's surface angle relative to the viewer's perspective (i.e., vertex normal), is especially useful for observing surface contours on objects. With this shader activated, the lamp's decoration can be easily studied while rotating the object to capture individual details. Since Sketchfab lacks functionality for measurement, a 3D scalebar was added in Blender. 3D models of other artifacts from the USTP, such as a well-preserved *fritillus* (<https://skfb.ly/6OS9D>) and a modern ceramic sherd bearing a forged inscription (<https://skfb.ly/6PLTF>), are also available online.

## 6.4 Complete Site 3D Model

After the conclusion of the three-year retroactive digital modeling campaign and with the implementation of the new digital recording protocol, there is now an almost complete 3D model of the entire site excavated to date (Fig. 14). The model can be continuously updated, as well, as new spaces are revealed by future excavation seasons. Rendered in Blender, it includes many of the same elements as the composite models discussed above, such as scalebars, a north arrow, and various transparent planes that indicate ground levels while allowing underground architecture to be seen. It is an invaluable resource for study conducted in the off season, and even serves as a convenient reference during fieldwork when questions arise related to adjacent backfilled zones. It permits continued interrogation of the villa's spaces in ways that are simply impossible even when present on site because the rooms are covered for conservation, and because the site itself is composed of various terraces and underground spaces that cannot be viewed simultaneously in person. The full model includes most of the villa's exterior and interior architectural spaces. At present, the model can only be viewed and manipulated in Blender on a computer with capable graphics hardware, however, animations rendered in Blender from the model can be more easily distributed as video files (a fly-through video is available at: <https://youtu.be/aFlbzUhDqtI>). Future iterations could include an associated VR capable model for an immersive experience at real scale. A publicly available model located in the town of Vacone would also allow the local community greater access to the site than can currently be experienced on site given current conservation practices. The reception of 3D data by this kind of non-specialist, but heavily invested, audience has gained significant traction [Rabinowitz 2019].

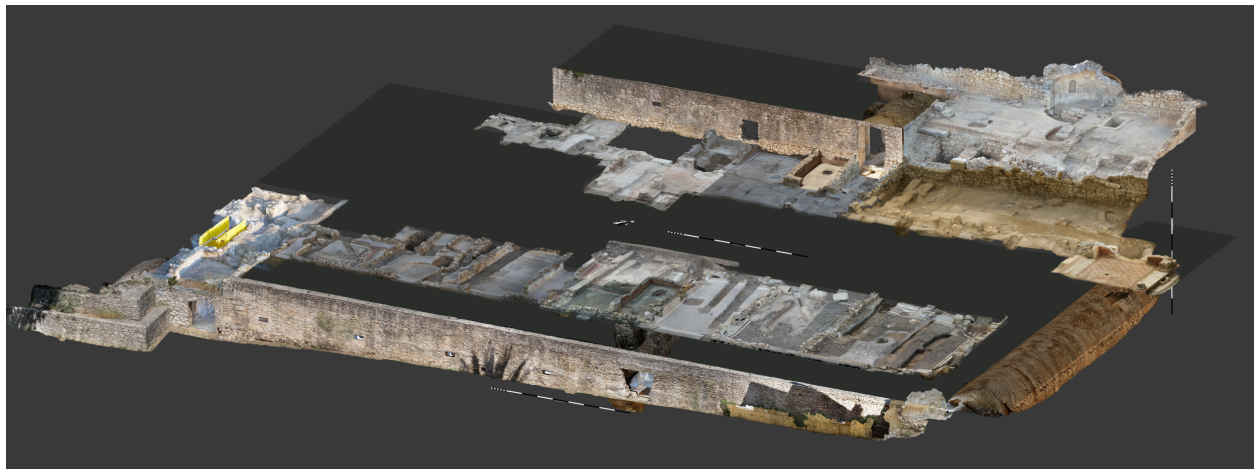


Figure 14. Complete 3D model of the villa's remains as of the 2018 excavation campaign. Viewed in Blender.

## 7. CONCLUSIONS

### 7.1 Impacts, Challenges, Missteps, and Recommendations

The implementation of photogrammetry at Vacone revolutionized the quality and efficiency of recording and documentation of the project's excavations. It was achieved, moreover, with no disruption to fieldwork. Analog records, such as trench sketches, paper forms, and notebooks, still form an important component of the excavation's documentation protocols. Photogrammetry complements these traditional practices. Pencil and paper documentation maintains crucial attentiveness to details that allow trench supervisors and excavators to accurately interpret stratigraphy [Caraher 2016; Morgan and Wright 2018; contra, see now Sapirstein 2020]. Paper records also provide added context for the digital data. Most importantly, they constitute an extra layer of long-term archival security given the precarity of digital data. Current prices for storing the large amounts of data generated by 3D recording in digital repositories such as the Digital Archaeological Record [tDAR.org] or OpenContext [opencontext.org] are unfortunately prohibitive. This means individual projects must develop responsible backup procedures until more standardized and affordable long-term solutions emerge. Cloud-based solutions (e.g. Dropbox, Box, Google Drive, OneDrive, etc.) are a possible archival stopgap, but require renewable subscriptions for larger storage capacities (typically up to 2 TB). In addition to long-term preservation of digital data, issues of data sustainability and accessibility also remain largely unresolved [e.g. Clarke 2015; Richards-Rissetto and von Schwerin 2017; Hardesty et al. 2020], and individualized solutions must be identified. Unfortunately, current practices tend towards customized software that are either not distributed for wider access or remain difficult to implement for budget strapped projects without support from technology specialists.

Moreover, the USTP's digital transition was not accomplished without missteps and inefficiencies typical of any new methodology. Documentation of difficult areas, such as poorly lit, narrow, underground spaces, often required two or more rounds of photographs when the first set failed to render correctly. Early experimentation with drone photography was also misguided given the scale of recording, and the propellers often blew dirt and vegetation onto pristinely cleaned surfaces, resulting in additional time and labor. Much time was also lost to cleaning spaces used for storage of excavation equipment so that it could be photographed for photogrammetry. Time was also spent on mundane tasks such as locating bottle caps, nails, and printing services to create more machine-readable targets when the initial supply was damaged or exhausted. Lack of electricity on site in the first two years meant that all model processing had to be done in the evening, and a significant backlog of photos built up, pushing a lot of processing into the post-season. Fortunately, this did not slow down excavation. Stratigraphic context models proved to render reliably and without problems, so we did not feel it necessary to wait until these were processed to remove layers. Significantly, however, this meant that orthomosaics of contexts were unavailable to supervisors until much later in the season and there was no adequate workflow for recording vector polygons of context boundaries into the site GIS. The division of the digital recording team from trench supervisors and excavators meant that those processing the digital data lacked detailed understanding of stratigraphic boundaries and sequences. Context boundaries, then, needed to be drawn over orthomosaics using notes from field journals, often in subsequent years.

In retrospect, a unified plan with a clear vision for the format of final products should be established from the beginning of any such digital transition. This needs to include not just procedures for cleaning and photographing the trenches, but also a timeline for processing models and then ensuring that context boundaries are added. This could be as simple as having a color printer and supply of ink so that printouts of orthomosaics can be drawn on by hand by trench supervisors with detailed stratigraphic insight. It could also include a small supply of tablets so that context boundaries can be digitally drawn. This can be accomplished with minimal technological expertise using, for example, built in image annotation tools in iOS. Technologically savvy, bespoke, solutions (using apps like iDig [Boyd et al. 2021] or field enabled wireless client-servers [Roosevelt et al. 2015; Taylor et al. 2018]) are inspirational but impose steep challenges for low budget projects without expert technological staff. Simpler, “out-of-the-box” solutions, are more cost-effective, flexible, and less likely to lead to technological breakdowns and delays.

Ideally, the digitization of all data, from 3D models down to GIS vector files, should be completed before the end of the season so that questions of interpretation can be addressed with access to the field. This might mean investing in multiple computers for more efficient evening processing or creating a workflow with on-site electricity or transferal of photos to an off-site processing lab. The physical separation of digital and excavation teams, however, should be avoided because both need to have a mutual understanding of the processes involved in each realm of work. A strategy that integrates excavation and digital team members (i.e., all are engaged in both activities) is recommended to ensure effective collaboration, avoid “technological elitism,” and foster a democratized interpretative process [Taylor et al. 2018].

## 7.2 Future Directions

Three-dimensional data still have untapped potential to unlock new forms of analysis. For instance, single context orthomosaics might be able to assist in the identification of stratigraphic changes since these are sometimes more clearly visible in digital form, especially with color enhancement, than on site. Single context models can also be used to calculate the volumes of excavated layers, leading to the computation of artifact densities, for example. The locations of small finds, already recorded with the total station, could be represented in a 3D GIS by a 3D point to pinpoint their exact provenience within a stratigraphic unit. Finally, the full site 3D model could form the basis of a computer-generated reconstruction of the villa’s architecture. By integrating the photogrammetric models with reconstructed walls, it is possible to create a reconstruction that more honestly represents what is extant and what is conjectured. Such a model will illuminate the possible connections of interior spaces within the villa and reveal aspects of lighting and sight that are currently unclear. Furthermore, building a digital reconstruction directly onto an accurate 3D model of the existing remains has been shown to assist in the interpretative process (as done, for example, by the Swedish Pompeii Project with data derived from laser scanning [Dell’Unto et al. 2013], or using the Extended Matrix methodology [Demetrescu 2015, 2018; Ferdani et al. 2019]).

Most importantly, the digital dataset represents a significant advancement in the volume of information recorded each excavation season. As archaeology is a destructive process, archaeologists are ethically bound to transmit as much evidence as possible to future generations

[Koenig et al. 2017:67]. With each passing year, technological upgrades will ensure that future researchers have ample data with which to assess the USTP's conclusions.

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## 9. REFERENCES

- Giovanna Alvino. 2009. Vacone, Forma Urbis, n.9, Roma: E.S.S. Editorial Service System.
- Adam Barnes. 2011. Close-range photogrammetry: a guide to good practice. In *Archaeology Data Service / Digital Antiquity Guides to Good Practice*. Archaeology Data Service, University of York, UK. Retrieved December 3, 2020 from [https://guides.archaeologydataservice.ac.uk/g2gp/Photogram\\_Toc](https://guides.archaeologydataservice.ac.uk/g2gp/Photogram_Toc)
- Dylan Bloy, Giulia Masci, Gary Farney, and Matthew Notarian. 2014. The Upper Sabina Tiberina Project: prima campagna di scavo a Vacone (2012). In Elena Calandra, Giuseppina Ghini, and Zaccaria Mari, eds. *Lazio e Sabina 10, Atti del Decimo Incontro di Studi sul Lazio e la Sabina (Roma, 4-6 giugno 2013)*. Roma: Soprintendenza per i Beni Archeologici del Lazio, 57-62.
- Dylan Bloy, Gary Farney, Tyler Franconi, Giulia Masci, Candace Rice, and Matthew Notarian. 2016. The Upper Sabina Tiberina Project. I risultati della seconda campagna di scavo a Vacone (RI), in Giuseppina Ghini, Zaccaria Mari, and Alfonsina Russo Tagliente, eds. *Lazio e Sabina 11, Atti dell'Undicesimo Incontro di Studi sul Lazio e la Sabina (Roma, 4-6 giugno 2014)*. Roma: Quasar.
- Michael J. Boyd, Rosie Campbell, Roger C. P. Doonan, Catherine Douglas, Georgios Gavalas, Myrsini Gkouma, Claire Halley, Bruce Hartzler, James A. Herbst, Hallvard R. Indgjerd, Ayla Krijnen, Irini Legaki, Evi Margaritis, Nathan Meyer, Ioanna Moutafi, Nefeli Pirée Iliou, David A. Wylie, and Colin Renfrew. 2021. Open Area, Open Data: Advances in Reflexive Archaeological Practice, *Journal of Field Archaeology* 46, 2 (2021), 62-80. <https://doi.org/10.1080/00934690.2020.1859780>
- William Caraher. 2016. Slow Archaeology: Technology, Efficiency, and Archaeological Work, in Erin W. Averett, Derek Counts, and Jody Gordon, eds. *Mobilizing the Past: Recent Approaches to Archaeological Fieldwork in a Digital Age*. Grand Forks: The Digital Press at the University of North Dakota, 421-441.

- Mary Clarke. 2015. The Digital Dilemma: Preservation and the Digital Archaeological Record, *Advances in Archaeological Practice* 3, 4 (2015), 313–30. <https://doi.org/10.7183/2326-3768.3.4.313>
- Derek B. Counts, Erin Walcek Averett, Kevin Garstki, and Michael K. Toumazou. 2020. *Visualizing Votive Practice: Exploring Limestone and Terracotta Sculpture from Athienou-Malloura through 3D Models*. Grand Forks: The Digital Press at the University of North Dakota. <https://thedigitalpress.org/vvp/>
- Mario Borrero and Luke Stroth. 2020. A Proposal for the Standardized Reporting of Error and Paradata Regarding Structure from Motion (SfM) 3D Models Used in Recording and Consolidating Archaeological Architecture. *Advances in Archaeological Practice* 8,4 (2020), 376–388. <https://doi.org/10.1017/aap.2020.11>
- Cultural Heritage Imaging. 2020. Photogrammetry. Retrieved January 13, 2020 from <http://culturalheritageimaging.org/Technologies/Photogrammetry/>
- Nicoló Dell'Unto, Anne-Marie Leander Touati, Matteo Dellepiane, Marco Callieri, Daniele Ferdani, and Stefan Lindgren. 2013. Digital reconstruction and visualization in archaeology: Case-study drawn from the work of the Swedish Pompeii Project. In *2013 Digital Heritage International Congress (DigitalHeritage)*. IEEE, 621–628. <https://doi.org/10.1109/DigitalHeritage.2013.6743804>
- Emanuel Demetrescu. 2015. Archaeological Stratigraphy as a Formal Language for Virtual Reconstruction. Theory and Practice. *Journal of Archaeological Science* 57 (2015), 42–55. <https://doi.org/10.1016/j.jas.2015.02.004>
- Emanuel Demetrescu. 2018. Virtual Reconstruction as a Scientific Tool: The Extended Matrix and Source-Based Modelling Approach. In Sander Münster, Kristina Friedrichs, Florian Niebling and Agnieszka Seidel-Grzesińska, eds. *Digital Research and Education in Architectural Heritage*. Cham: Springer, 102–116.
- Jeroen P. De Reu, Philippe De Smedt, Davy Herremans, Marc van Meirvenne, Pieter Laloo, and Wim De Clercq. 2014. On Introducing an Image-based 3D Reconstruction Method in Archaeological Excavation Practice. *Journal of Archaeological Science* 41 (2014), 251–262. <http://dx.doi.org/10.1016/j.jas.2013.08.020>
- Daniele Ferdani Emanuel Demetrescu, Marco Cavalieri, Gloriana Pace, and Sara Lenzi. 2019. 3D Modelling and Visualization in Field Archaeology. From Survey to Interpretation of the Past Using Digital Technologies. *Groma* 4 (2019), 1–21. <http://10.12977/groma26>
- Tyler Franconi, Candace Rice, Dylan Bloy, and Gary Farney. 2019. Excavations at the Roman Villa of Vacone (Lazio) by the Upper Sabina Tiberina Project, 2012–2018. In Carla Sfameni and Monica Volpi, eds. *Oltre la Villa: Ricerche nei siti archeologici del territorio di Cottanello, Montasola, Configni e Vacone*. Roma: Arbor Sapientiae, 109–136.
- Kevin Garstki. 2020. *Digital Innovations in European Archaeology*. Elements in the Archaeology of Europe. Cambridge: Cambridge University Press. <http://dx.doi.org/10.1017/9781108881425>
- Kevin Garstki, Marcus Schulenburg, and Robert A. Cook (2018): Practical Application of Digital Photogrammetry for Fieldwork in the American Midwest: An Example from the Middle Ohio Valley. *Midcontinental Journal of Archaeology*(2018), 1–18. <http://dx.doi.org/10.1080/01461109.2018.1452364>
- Marina Gavryushkina. 2018. *Layer by (3D) Layer: 3D GIS Stratigraphic Analysis of Chlorakas-Palloures, Cyprus*. Master's thesis. University of Leiden, Leiden, Netherlands.
- Juliet Hardesty, Jennifer Johnson, Jamie Wittenberg, Nathan Hall, Matt Cook, Zack Lischer-Katz,

- Zhiwu Xie, and Robert McDonald. 2020. 3D Data Repository Features, Best Practices, and Implications for Preservation Models: Findings from a National Forum. *College & Research Libraries* 81, 5 (2020), 789. doi:<https://doi.org/10.5860/crl.81.5.789>
- Charles W. Koenig, Mark D. Willis, Stephen L. Black. 2017. Beyond the Square Hole: Application of Structure from Motion Photogrammetry to Archaeological Excavation. *Advances in Archaeological Practice* 5, 1 (2017), 54–70. <https://doi.org/10.1017/aap.2016.8>
- Colleen Morgan and Holly Wright. 2018. Pencils and Pixels: Drawing and Digital Media in Archaeological Field Recording. *Journal of Field Archaeology* 43, 2 (2018), 136-151. <http://dx.doi.org/10.1080/00934690.2018.1428488>
- Matthew Notarian, Dylan Bloy, and Gary Farney. 2016. Forgery and the Antiquarian Tradition: The Identification of Horace's Sabine Villa at Vacone, *Memoirs of the American Academy in Rome* 61 (2016), 41-58.
- Giacomo Landeschi. 2019. Rethinking GIS, three-dimensionality and space perception in archaeology. *World Archaeology* 51, 1 (2019), 17-32. <http://dx.doi.org/10.1080/00438243.2018.1463171>
- Rachel Opitz. 2015. Three-Dimensional Field Recording in Archaeology: An Example from Gabii, in Brandon Olson and William Caraher, eds. *Visions of Substance: 3D Imaging in Mediterranean Archaeology*. Grand Forks: Digital Press, University of North Dakota, 73-86.
- Rachel Opitz, Marcello Mogetta, and Nicola Terrenato. 2016. *A Mid-Republican House from Gabii*. Ann Arbor: University of Michigan Press.
- Wojciech Ostrowski, Lukasz Miszczak, and Weronika Winiarska. 2018. Three-Dimensional Stratigraphy Reconstruction and GIS - Postprocessing Issues in Archaeological Field 3D Documentation, *Studies in Ancient Art and Civilization* 22 (2018), 219-40. <https://doi.org/10.12797/SAAC.22.2018.22.10>
- Federica Pollari, Candace Rice, Gary Farney, and Tyler Franconi. 2018. Villa Romana di Vacone (RI): Nuovi mosaici dal settore urbano della villa, in Claudia Angelelli, Daniela Massara, and Andrea Paribeni, eds. *Atti del XXII Colloquio dell'Associazione Italiana per lo Studio e la Conservazione del Mosaico*. Narni: Edizioni Scripta Manent di Tipografia Mancini s.a.s., 805-809.
- Samantha Porter, Morgan Roussel, and Marie Soressi. 2016. A Simple Photogrammetry Rig for the Reliable Creation of 3D Artifact Models in the Field: Lithic Examples from the Early Upper Paleolithic Sequence of Les Cottés (France). *Advances in Archaeological Practice* 4, 1 (2016), 77-86. <http://dx.doi.org/10.7183/2326-3768.4.1.71>
- Adam Rabinowitz. 2019. Communicating in Three Dimensions: Questions of Audience and Reuse in 3D Excavation Documentation Practice. *SDH* 3, 1 (2019), 100-116. <https://doi.org/10.14434/sdh.v3i1.25386>
- Candace Rice, Federica Pollari, and Gary Farney. 2017. I mosaici imperiali della villa romana di vacone (RI), in Claudia Angelelli, Daniela Massara, and Andrea Paribeni, eds. *Atti del XXII Colloquio dell'Associazione Italiana per lo Studio e la Conservazione del Mosaico, Matera 16-19 marzo 2016*. Tivoli: Edizioni Scripta Manent di Tipografia Mancini s.a.s., 303-311.
- Heather Richards-Rissetto, Jennifer von Schwerin. 2017. A Catch 22 of 3D Data Sustainability: Lessons in 3D Archaeological Data Management & Accessibility. *Digital Applications in Archaeology and Cultural Heritage*. 6 (2017), 38-48. <https://doi.org/10.1016/j.daach.2017.04.005>
- Christopher H. Roosevelt, Peter Cobb, Emanuel Moss, Brandon R. Olson, and Sinan Ünlüsoy. 2015.

- Excavation is Destruction Digitization: Advances in Archaeological Practice. *Journal of Field Archaeology* 40 (2015), 325–346. <http://dx.doi.org/10.1179/2042458215Y.0000000004>
- Philip Sapirstein. 2016. Accurate Measurement with Photogrammetry at Large Sites. *Journal of Archaeological Science* 66 (2016), 137–145. <http://dx.doi.org/10.1016/j.jas.2016.01.002>
- Philip Sapirstein. 2020. Hand Drawing versus Computer Vision in Archaeological Recording. *SDH* 4,2 (2020), 134-159. <https://doi.org/10.14434/sdh.v4i2.31520>
- Philip Sapirstein and Sarah Murray. 2017. Establishing best practices for photogrammetric recording during archaeological fieldwork. *Journal of Field Archaeology* 42, 4 (2017), 337-350. <https://doi.org/10.1080/00934690.2017.1338513>
- James Taylor, Justine Issavi, Åsa Berggren, Dominik Lukas, Camilla Mazzucato, Burcu Tung and Nicoló Dell'Unto. 2018. 'The Rise of the Machine': the impact of digital tablet recording in the field at Çatalhöyük, *Internet Archaeology* 47 (2018). <https://doi.org/10.11141/ia.47.1>
- Mark D. Willis, Charles W. Koenig, Stephen L. Black, and Amanda M. Castañeda. 2016. Archaeological 3D Mapping: The Structure from Motion Revolution. *Journal of Texas Archeology and History* 3 (2016), 1-36.

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