

The Impact of Structure from Motion on Archaeological Fieldwork Practice: Experiences of the Via Consolare Project in Pompeii

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The last decade of advances in Image-Based Modeling (IBM) data acquisition based on Structure from Motion (SfM) have made it possible as never before to record excavated archaeological deposits, historical architectural remains, artifacts, and geographical surroundings in the field. Armed only with digital cameras and low-cost or open-source software, researchers can now produce accurate point clouds of millions of points, capturing archaeological information in high-resolution detail. But what changes will IBM really bring to the standards, requirements, and expectations of practical field methodology for projects operating on shoe-string budgets? Since 2010, the Via Consolare Project, a small archaeological research project from a State level University, has employed an entirely open-source and “free for academic use” IBM pipeline to record a variety of archaeological features in Insula VII 6 and the “Villa delle Colonne a mosaico” in Pompeii. Ranging from surviving architecture, to rubble fill layers, to the interiors of inaccessible cisterns and drains, this work has been carried out in preparation for the eventual coordination of these data into a 3D GIS of all recorded stratigraphy. Rarely were sufficient resources available for dedicated equipment or personnel to be devoted to this task. While practical implementation, even in a low-budget excavation environment, has confirmed that this technology can indeed augment archaeological field documentation and provide investigation opportunities that would otherwise be impossible, it failed to replace traditional hand-drafted recording techniques and was found to present significant challenges and a number of hidden costs. This emphasizes a need for appropriate and cautious planning in implementation, especially in projects with limited means.

Key words:

Structure from Motion (SfM), Image Matching (IM), Free and Open-Source, Photogrammetry, Excavation Methodology.

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1. INTRODUCTION

The acquisition and analysis of 3D data has been an indispensable aspect of archaeological field methodology for more than 20 years at a variety of scales, from digital surface models (DSMs) of sites, to total station surveys of architecture or excavations, to the laser-scanning of artefacts recovered. The last decade, however, has witnessed something of a revolution in the acquisition of 3D data that holds the potential to transform the very core of archaeological field practice. From its origins in the field of computer vision, visual perception, and image matching, Structure from Motion/Image Matching (SfM/IM), belonging to the image-based modelling (IBM) category of methods, makes it possible for researchers to capture point clouds of 3D data from unordered sets of digital photographs acquired with mass-market digital cameras, and processed on consumer-grade computer systems for comparatively low cost as opposed to alternatives such as terrestrial scanning or LiDAR. Initially requiring some computing expertise and comfort with command-line interfaces, these techniques are now available in a number of “free for academic use,” open-source, and commercial packages featuring user-friendly graphical user interfaces (GUIs). This has made structure from motion 3D data capture more accessible than ever and has encouraged its use at a variety of scales, from the production of localized DEMs with unmanned aerial vehicles (UAV) photography to the digitization and modeling of artefacts and other small finds. [Pollefeys et al. 2000, 2003, 2004; Doneus et al. 2011; De Reu et al. 2013, 2014; Olson et al. 2013; Green et al. 2014; Opitz 2015; Roosevelt et al. 2015; Sapirstein 2015, 2016; Sapirstein and Murry 2017; Cucchiario et al. 2020; Jones and Church 2020].

SfM/IM photogrammetry (often shortened as SfM photogrammetry) stands at the center of a 3D revolution in archaeological research, holding the potential for near ubiquitous use within the discipline for a wide variety of purposes. But how do such methodologies integrate with, and augment, the current standard of scientific field archaeology? Will these techniques simply replace traditional methods or do they represent a qualitatively different kind of record? Since 2010, I have employed SfM-based methodologies in the course of an on-going small project of stratigraphic excavation in Pompeii - the Via Consolare Project (VCP). Since it is run from a State level university, it is largely without the resources of better-funded colleagues, a reality that is shared by numerous archaeological endeavors in a variety of academic and professional contexts. While the “low-cost” and open-source nature of SfM is one of its most frequently-cited benefits, it is notable that out of the numerous recent publications on the use of SfM in archaeology, only a handful have actually opted for open-source over commercial software processes. What impact do these “low-cost” techniques have on the operating practices of archaeological projects that must make use of open-source solutions and compromise in terms of equipment, time, and resources?

Adoption of SfM technologies on the VCP took place after its research was already well under way and when the revolution in image-based modelling was just beginning to be known to archaeologists. SfM was not adopted in order to push the boundaries of archaeological science, but rather to address pre-existing research needs that were driven by Pompeian research questions. While some researchers have pointedly set out to assess the capabilities of this new technology in focused case studies [De Reu et al. 2013, 2014; Green et al. 2014; Sapirstein 2015, 2016; Sapirstein and Murry 2017; Bianco et al. 2018], or even to explore the possibilities of replacing traditional methods of recording entirely [Olson et al. 2013; Roosevelt et al. 2015], my project has instead explored practical applications of this constantly-developing new technology in conditions that were rarely, if ever, ideal. This

included operating within a very restricted budget, employing equipment that had normally been acquired for different purposes, and exploring non-standard uses of this technology while focusing primarily on the main goals of the research.

Now, at the end of ten years, during which time the technology has seen an almost unimaginable rate of development, the release of an ever-changing and ever-expanding range of potential software options (both open-source and commercial), and with the widespread acceptance by projects all over the world, it is worth considering what the actual impact has been on day-to-day archaeological process, methodology, and results in a small, traditional project of field archaeology. The experiences of the VCP do not present a case study of ideal conditions or a formulation of best practices; rather they expose the realities of prolonged everyday use of SfM in a project with many other research priorities, working within the often-improvised solutions that, in my experience, are frequently encountered in fieldwork in Italy. Accordingly, this paper does not aim to contribute to the scientific assessment or detailed exposition of a technology which has, by now, already been well-explored; rather, it asks whether the lowest cost implementations of this "low cost" technology can still have an impact on the process of archaeological excavation.

2. THE VIA CONSOLARE PROJECT

I founded the Via Consolare Project in order to increase the unit of analysis of the ancient city of Pompeii, beyond that of an individual house or city block, to the scale of the city itself. The via Consolare, one of the earliest surviving roads through the city, provided the coordinating axis of the research. This thoroughfare connects a number of previously completed campaigns of archaeological research, including the University of Bradford's AAPP excavations [Jones and Robinson 2007; Anderson and Robinson 2018], excavations in the *Casa di Sallustio* [Laidlaw and Stella 2014], Arthur's exploration of the Forum [Arthur 1986], examination of Insulae 6 3 and 6 4 [Carocci et al. 1990], the study of the Casa di Marco Fabio Rufo [Grimaldi 2014; Aoyagi and Pappalardo 2015], and numerous investigations by *Progetto Regio VI* and beyond [Coarelli and Pesando 2006; Oriolo and Verzar-Bass 2010; Maratini and Zaccaria Ruggiu 2017; Giglio and Pesando 2017; Dessalles et al. 2015, 2016] and ongoing research by the Centre Jean Bérard, l'École française de Rome and le Centre Camille Jullian [Zanella 2017; Zanella et al. 2016; 2017]. I set out to augment these through architectural analysis and sub-surface exploration of two areas - the area of the Villa delle Colonne a mosaico and Insula VII 6, following a practice of stratigraphic excavation in targeted trenches, 100% screening of excavated ancient deposits for the recovery of artefacts, ecofactual floatation of soils, and the full study of the macro- and micro- botanical remains. Taken together with the results of the aforementioned projects, the intent was therefore to produce a 'slice' of stratigraphic understanding through the city, running from the area outside of the *Porta Ercolano* through to the core of the city and the forum. The precise urban history of this corridor will serve to shed light upon the development of the city as a whole, permitting comparisons between center and periphery, the reconsideration of the texture of the urban fabric, and encouraging city-wide explanations of the processes of urban development (Fig. 1).

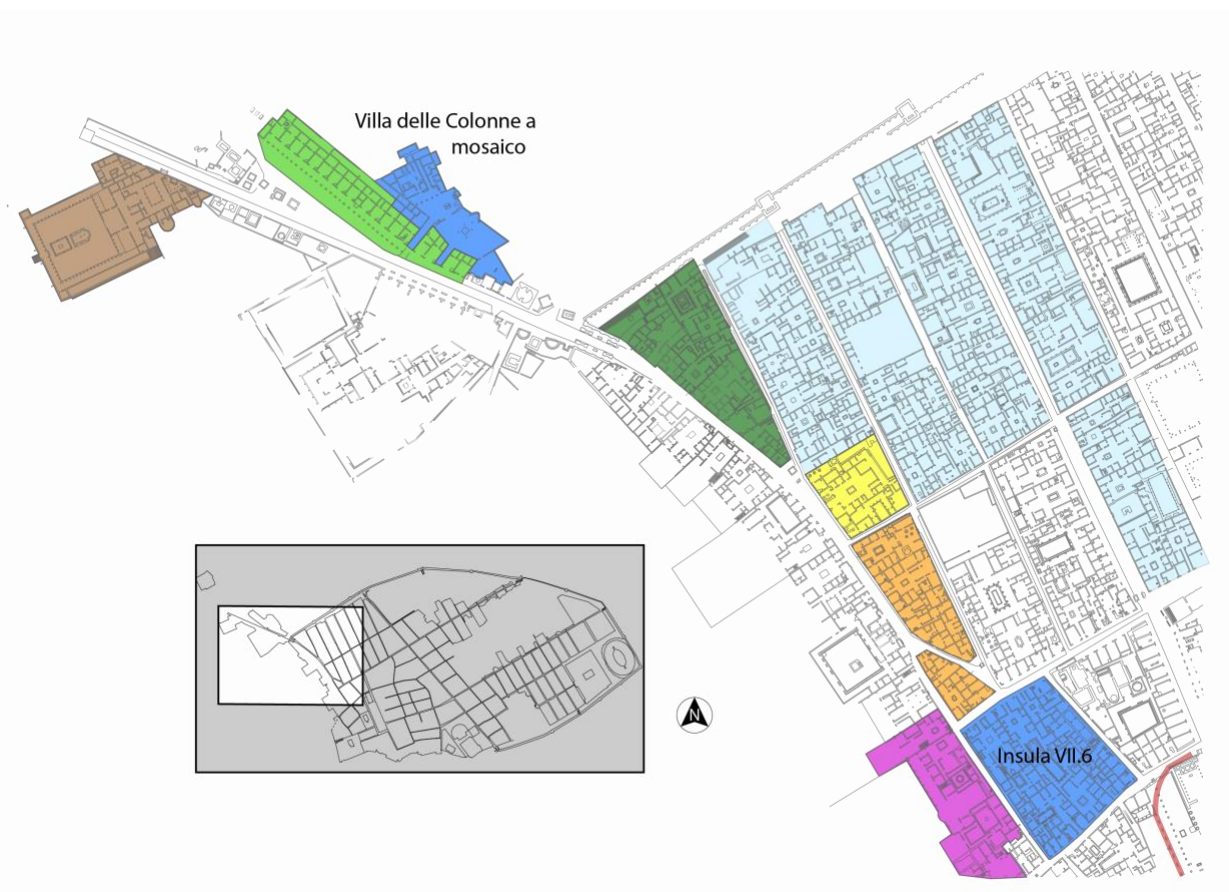


Figure 1. Via Consolare Project Research Areas marked in dark blue. Previous and on-going research: University of Bradford (green), Laidlaw and Stella (yellow), Carocci et al. (orange), Pappalardo and Grimaldi (pink), Arthur long trench (red), and Progetto Regio VI (light blue), Dessales et al. (brown), Zanella et al. (light green).

2.1 Area of the Villa delle Colonne a mosaico

The area of the Villa delle Colonne a mosaico consists of a large suburban villa on the north-eastern side of the via Consolare, which, as it extends beyond the walls of the city, is known as the via dei Sepolcri. The villa is situated behind a number of shops and tombs, which serve to seclude three large open areas that appear to have been largely unroofed in antiquity. The southern-most of these coordinated the space behind the tombs into a putative area for funerary ritual, while the main zone held the mosaic-covered columns that gave the villa its name, long ago removed to the Museo Archeologico Nazionale di Napoli (MANN) (Fig. 2a). To the north, a work-yard or cart-access corridor provided access to a number of upstairs spaces and to the villa itself via a monumental entrance. The elite and decorated rooms of the villa were situated in the upper stories, and hence generally do not survive. The service areas, however, which are located on the ground floor, are well preserved. The complex as a whole was built with, and over, an exterior row of 14 shops that served as the substructure so that the peristyle and rooms on the upper stories might enjoy a magnificent view of

the bay (Fig. 2b). Though partially damaged during Allied bombing in 1943 [García y García 2006], the villa presents a surprisingly urban fusion of domestic living, commercial space, and ritual activity that calls into question the degree to which it should be considered a ‘suburban’ space during Pompeii’s final years.

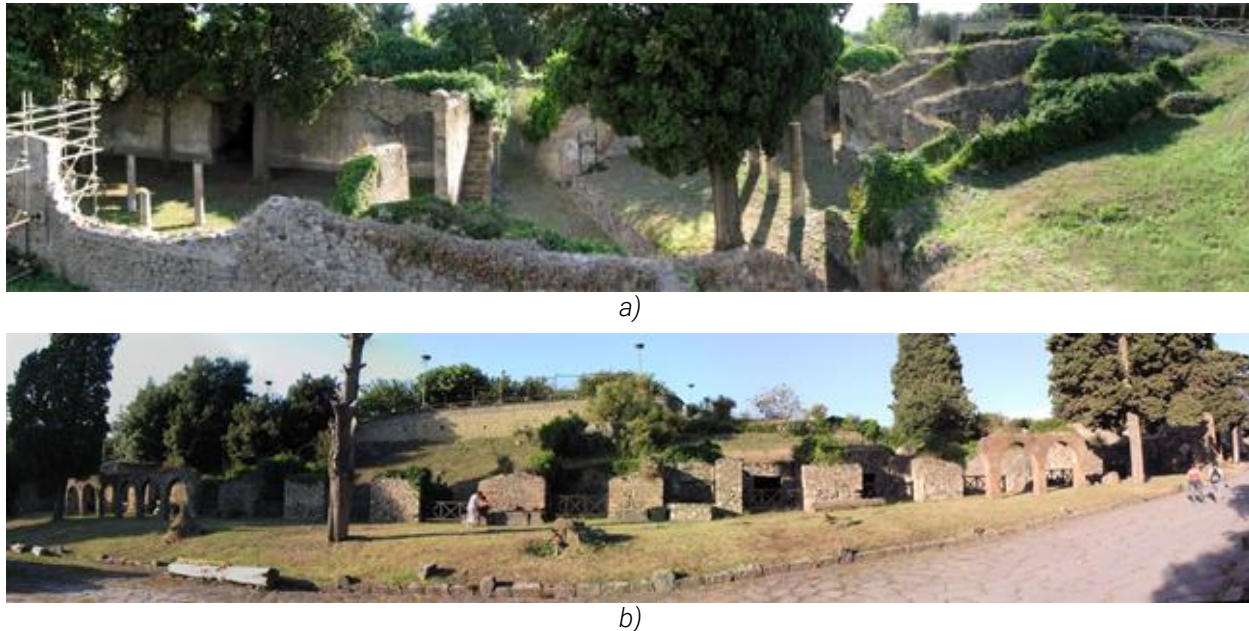


Figure 2. The Villa delle Colonne a mosaico: a) Open space with replaced columns on left, central core and traces of upper stories, right. Cart accessway is visible in centre; b) Row of 14 shops that supported the upper stories of the villa.

2.2 Insula VII 6

Insula VII 6 is situated immediately to the west of the Forum Baths and nearly adjacent to the forum itself. It consists of five houses interspersed with shops or bars that cluster mainly on its eastern side towards the forum and the baths (Fig. 3). A massive, three-part cistern, intended to store reserve water for the Forum Baths, came to occupy the eastern side of the block by roughly the late Augustan period, presenting important evidence for the interaction between municipal building projects and private property [Anderson 2015]. Primary excavation of the insula took place during a number of different campaigns beginning in 1758 and was finally completed in 1910. By 1943 however, it had been bombed so heavily that much of the area lies in ruins and today and has tended to disappear from most modern research. In fact, the circumstances of its widespread destruction shortly after its exposure means that many details of the 79 CE remain unrecorded.

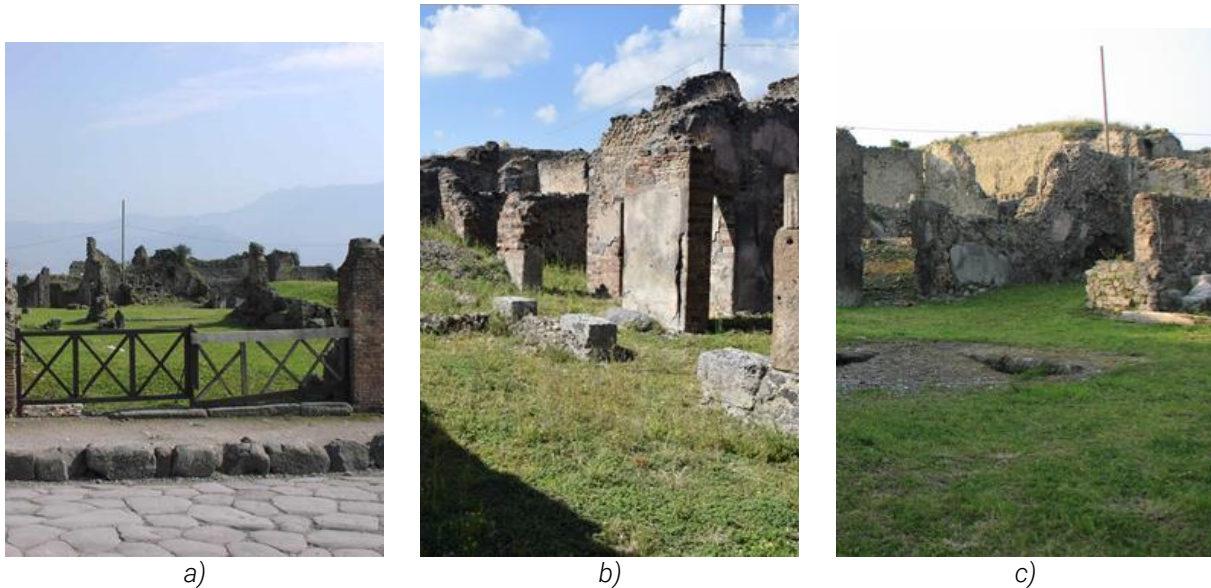


Figure 3. *Insula 7 6*: a) central property with peristyle; b) smaller house centred on peristyle; c) atrium of the largest house on the block.

3. FROM STITCHED ORTHOPHOTOGRAPHY TO 3D POINT CLOUDS

Given the absence of pre-existing, highly-accurate plans for the research areas, an early priority was the survey of these areas using a Leica TPS 805 Power total station. Over time, this produced a 3D wire-frame model of standing walls, preserving the outline of each face of every surviving element of architecture, including standing walls, visible flooring or foundations, windows, lintels, and other details (Fig. 4).

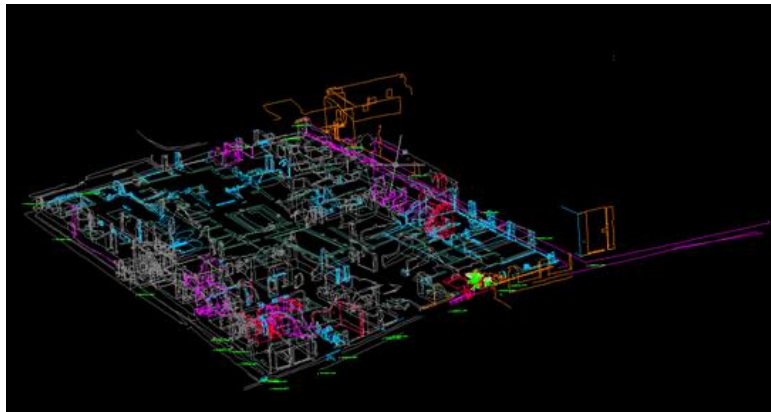


Figure 4. *Surveyed wire-frame dxf model of Insula 7 6*. Colors represent different seasons of survey work.

Contemporary with on-going geophysical analysis and survey, the stratigraphy of the walls was analyzed in order to identify and record any traces of earlier phases of construction, to find evidence for alteration or redecoration, and to reconstruct the overall building sequence. While the wireframe model captured the overall shape of each wall face, the sheer volume of architecture to be surveyed meant that the stratigraphic analysis of the walls had to be carried out independent of the total station survey. Previous experience in working on the publication of the University of Bradford's excavations in the Casa del Chirurgo had demonstrated that time-consuming hand-drawn records of wall stratigraphy not only tended to be inaccurate, but rarely ended up being especially useful in the process of final sequencing. In an effort to increase efficiency, and with an eye to the final illustrations that might be needed for future publication, focus therefore fell on the production of scaled, accurate, orthophotos of each wall surface, which would be used to produce detailed, digitalized records of the standing stratigraphy. The results of the in-field analysis of mortar composition, color, wall fabric, and stratigraphic sequence identified within entire systems of standing walls could then be appended to these records. This information was stored in traditional field notebooks supplemented by extensive wall sketches, afterwards to be transferred to a digital database.

In order to provide these orthophotos in the often highly-restricted architectural environment of Pompeii, efforts were first directed towards creating accurate stitched ortho-rectified photographs of wall surfaces using the freeware panorama software Hugin in a systematic field process [Anderson 2009]. While results were promising and could be matched against the surveyed wireframe (Fig. 5), this method could not cope with more complicated structural arrangements or three-dimensional features, and it quickly became apparent that a method that captured the full three-dimensional details of each wall surface would be required.

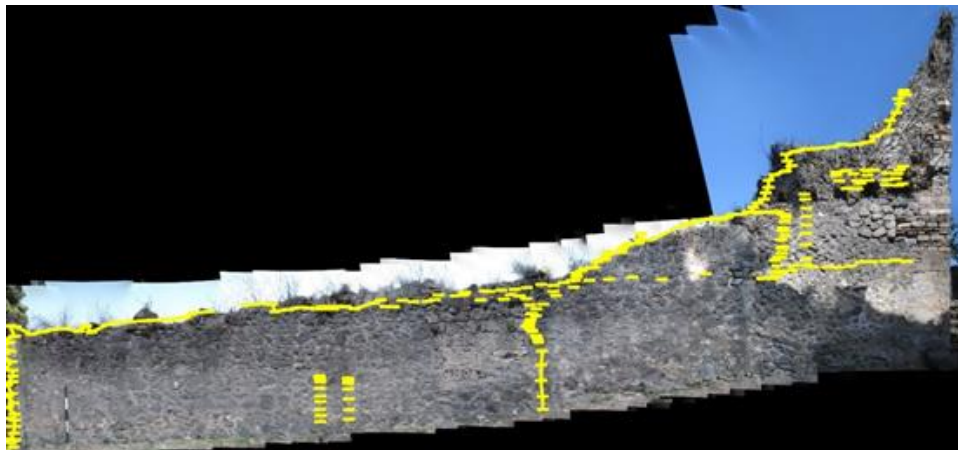


Figure 5. Hugin stitched rectified wall surface in the area of the Villa delle Colonne a mosaico, 2009. Surveyed outline marked in yellow.

Lacking sufficient resources for a terrestrial laser scanner, in 2008 I began to explore new computational photogrammetric techniques for 3D data acquisition that had recently begun to appear in digital archaeological circles [e.g. Ducke et al. 2011; Verhoeven 2011; Verhoeven et al. 2012a;

2012b], which held the promise of being low cost. Free options such as Automatic Reconstruction Conduit (ARC 3D) [VISICS 2011], Photosynth [Microsoft Corporation 2011], and early implementations of professional packages such as Eos Systems' Photomodeler Lite and Photomodeler Scanner [Eos Systems Inc. 2012] were also considered, but commercial products were abandoned when inquiries produced offers of academic licenses that were still well beyond the project budget. Following Ducke's personal suggestions in March 2009, and in preparation for the upcoming season of fieldwork, I ensured that the pipeline would run on the project laptop [for details of the process see Green et al. 2014]. Briefly described, this pipeline involved a multi-step process that began by identifying point matches between images produced first by scale-invariant feature transform matching (SIFT) [Lowe 2004] and later by VLFeat, fed into Linux-based Bundler [Snavely et al. 2006; 2008] which estimated camera positions and orientation. Results were then passed to Patch-based Multi-view Stereo Software (PMVS) [Furukawa and Ponce 2010], (Windows binaries produced by Pierre Moulon and Alexandre Leroy), in order to produce a dense 3D point cloud through Image Matching. Further steps included the use of Meshlab [Cignoni et al. 2008; Ranzuglia et al. 2012; 2013; Kazhdan and Hoppe 2013; Cignoni et al. 2009], to process resulting point clouds into useable triangulated and textured 3D meshes. Orientation, scale, or georeferencing had to be added manually via 3D transformation in CloudCompare and later through Meshlab itself.

In the field season of 2009, this open-source pipeline was put to work for recording wall surfaces within my areas of research, especially wall faces. Comprehensive sets of photos were acquired for many walls in the study area and organized in preparation for processing on the project laptop (first an AMD dual-core Turion 64 X2 (1.8GHz) with 2GB RAM and an Nvidia GeForce Go 6150, later an Intel Core i5 3230M with 16G RAM, and an Nvidia GeForce GTX 660M with 2GB onboard) in the field. Preliminary processing at a low resolution was possible, running overnight or for multiple days on large groups of images, but given that the project laptop was also necessary for other daily tasks (downloading points from the total station, organizing the digital photo record, preliminary work on AutoCAD models, primary record digitization, etc.), full-scale processing had to be postponed to the off-season on a desktop (Intel Core i7 920 / 2.66 GHz with 9 GB RAM and an NVIDIA GeForce GTX 260 with 896 MB onboard) or on the second, more powerful, field laptop just described. In 2013, the project substituted closed-source, but "free for academic use" VisualSFM [Wu et al. 2011; 2013] for Bundler, due to its streamlined pipeline and graphical user interface, which was easier for team members unfamiliar with command-line interfaces. The software handled the process of matching and bundle adjustment, and also employed Furukawa's Clustering Views for Multi-view Stereo CMVS (again with Windows binaries by Pierre Moulon), in order to break up large sets of photos into groups that could be dealt with individually by the computer system without excessive processing time.

While I had initially had some intention of publishing our early experiences with this technology, by this time, SfM had already taken archaeology by storm, witnessed by a growing number of conference presentations and publications and aided by an explosion of possible software packages, from open-source solutions, toolboxes for inclusion in Matlab, Python, or C++, and a variety of closed source, free and paid commercial solutions, including Autodesk's now defunct 123D Catch, Agisoft's Photoscan (now Metashape), among a number of others. Due to my previously unsuccessful efforts to find affordable licensing, and because the established method with VisualSFM suited current needs, I decided to maintain the open-source (or at least "free for academic use") pipeline. I was,

moreover, uncomfortable with the increasingly “black-box” nature of automatic commercial products that produced a final textured model without much user input. I imagined that the higher degree of base-level control that open-source or academic tools provide would permit greater control over the steps in the process, the ability to overcome image sets that produced poor initial results, and would provide a means of ensuring that the process itself was understood by the operators. It should be admitted, however, that none of these priorities was ever actually realized. I also believed that most projects would prefer open-source technologies in order to ensure transparency of process and longevity of results, but counter to my expectations, commercial solutions, particularly Agisoft's Photoscan, quickly became widely accepted as an archaeological standard [e.g., Verhoeven 2011; Verhoeven et al. 2012a; 2012b; De Reu et al. 2013, 2014; Sapirstein 2015, 2016; Sapirstein and Murray 2017; Olson et al. 2013; Roosevelt et al. 2015].

4. FROM PLANNED USES TO EXPERIMENTAL IMPLEMENTATIONS

From the outset, SfM produced results far beyond initial hopes, not only successfully fulfilling the primary intended purpose of recording the surfaces of standing walls and architectural features, but also promising 3D data capture abilities that had previously been out of the project's financial reach. While its intended use for recording surviving architecture remained its primary application, excavation itself rapidly began to encourage extensive experimentation for a variety of additional purposes that expanded the use of SfM on the project considerably.

4.1 Walls

The primary intended use of SfM for the Via Consolare Project was to record the wall faces within the research areas so that non-spatial data from wall analysis could be appended. For individual wall faces, and groups of walls, the SfM produced dense, and apparently detailed, point clouds of each face, roughly equivalent to those produced by other projects [Doneus et al. 2011; Verhoeven 2011; Verhoeven et al. 2012; De Reu et al. 2013; Green et al. 2014; Douglas et al. 2015; Willis et al. 2016] (Fig. 6). While areas of high contrast or features that had not been photographed from a sufficient number of encircling angles could sometimes produce sparse results (angles from below and above were particularly commonly under-photographed), the end result was sufficiently detailed to be able to distinguish different building phases for tracing, when combined with notes and sketches taken from observations in the field.

Though the initial intention had been to trace and label orthophotos produced from these point clouds in order to produce 2D sections marked with stratigraphic contexts, simultaneous work in producing 3D architectural models of the research areas quickly revealed the absurdity of using a three-dimensional dataset to replicate a two-dimensional recording practice. Accordingly, the process of tracing was moved into the 3D modelling package Blender 3D, so that tracing could occur directly onto the textured mesh. In a sense, this produced a more detailed wireframe model, but also marked the mesh surfaces for sub-division into elements that could be used to produce solid models of wall stratigraphic contexts.

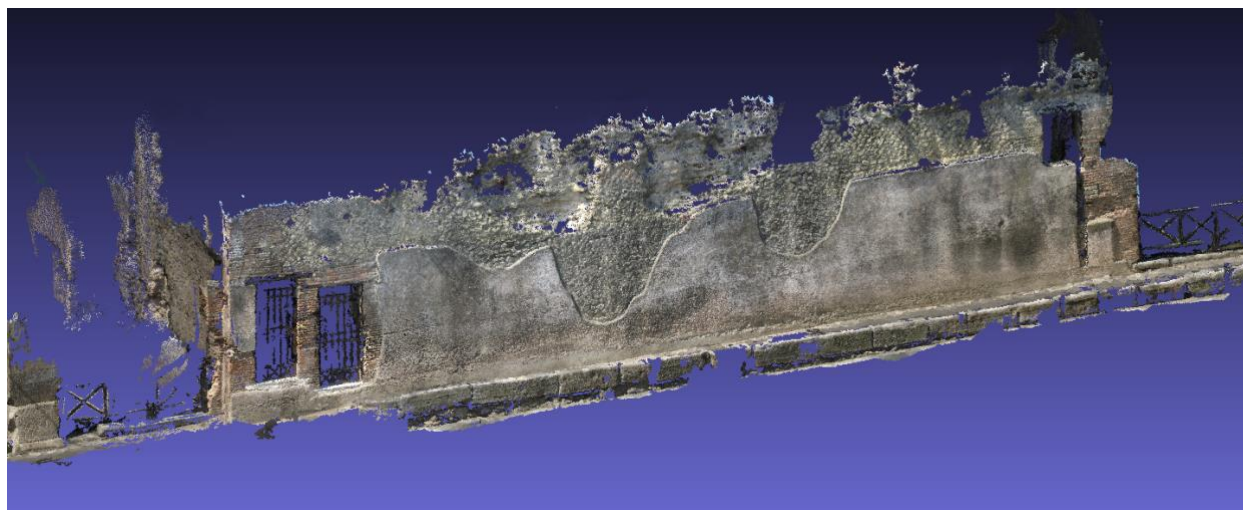


Figure 6. Point cloud of the "Great Cistern" on the eastern side of Insula VII 6, viewed in Meshlab.

4.2 Full Structures

As more wall surfaces were processed through the pipeline, it became clear that, with appropriate care, it was possible to connect groups of wall faces into single processing jobs that would produce point clouds representing whole systems of connected walls. This immediately presented the possibility of producing a 3D point clouds encompassing the full research area, which might be comparable to the results produced by traditional terrestrial time-of-flight scanners, such as that undertaken by Universidad Complutense Madrid in the nearby Casa della Diana [María Luzón and del Carmen Alonso 2017]. It was noted particularly that the SfM method was organic and flexible, permitting each set of photographs to capture precisely the area of interest, such that a wall could be photographed in a sequence that rotates around it from one face and then around to another, effectively producing a point cloud of both sides in a single step.

This aspect of SfM is best illustrated by the result from 426 images taken of the eastern side of the Via Consolare (Fig. 7). This experiment, which was undertaken to see if it was possible to provide a quick visual illustration of the archaeological section that is the primary goal of the Via Consolare Project itself, showcases one of the distinct strengths of SfM methodology – the flexibility in the process of data capture. The end result did not depend upon pre-existing surveyed elements, but was completed as a single combined process, which nevertheless captured relative orientation, topology, elevation, and texture for the full length of this street. It was also found that photos taken at different distances from the subject could be used to produce varying levels of resolution in the final point cloud. Particular details could therefore be photographed closely within the context of a larger wall, producing an area where the resulting point cloud is considerably denser in areas of interest, while economizing processing time on less important areas. (Fig. 8).

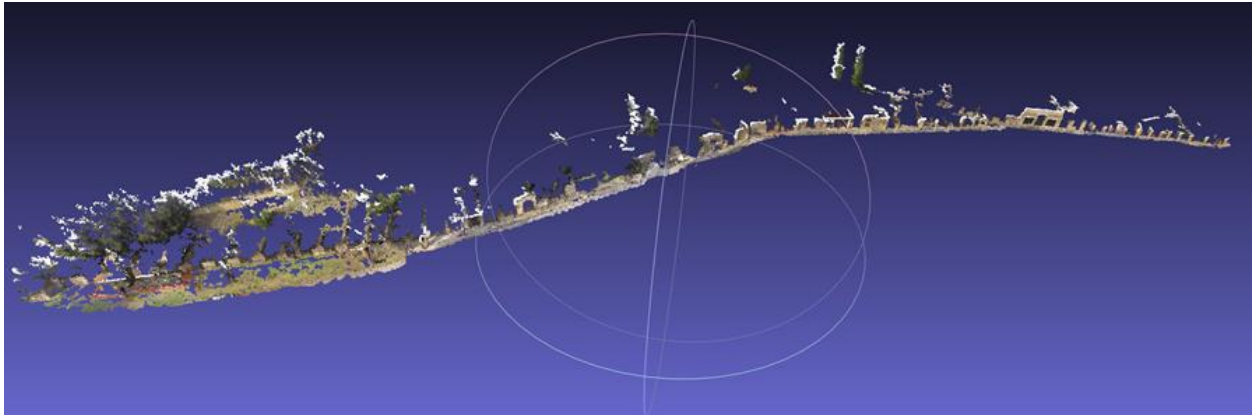


Figure 7. Raw point cloud of the northern part of the via Consolare and via dei Sepolcri. Viewed in Meshlab.

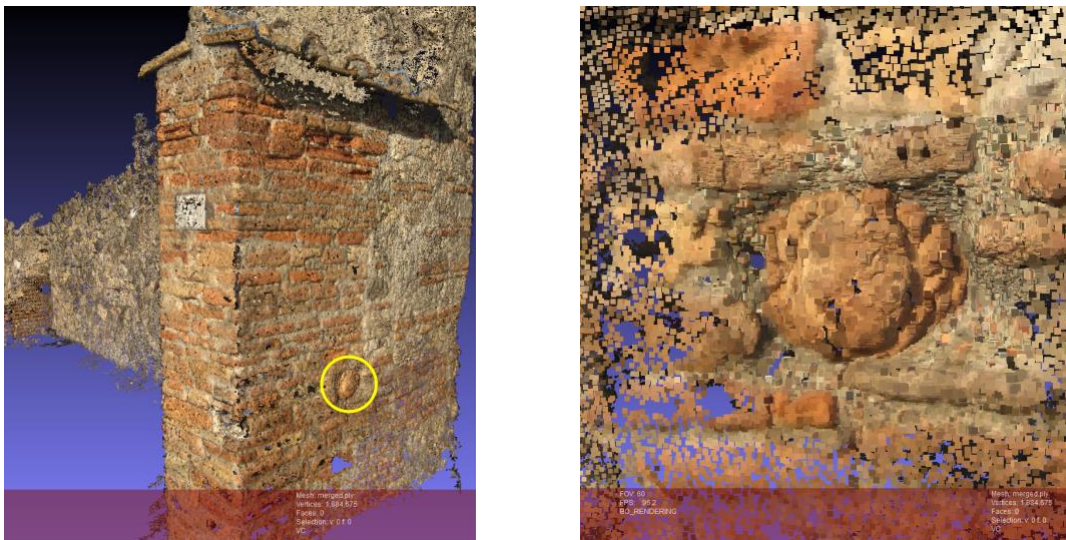


Figure 8. Wall in Insula VI 1, with detail of inset ceramic feature achieved through series of closer photographs within the larger overall SfM project. Viewed in Meshlab.

4.3 Geo-referencing and Registration

The goal of producing point clouds of full structures presented a number of new challenges, in no small part because it had not been the original goal of the work. The easiest way to combine multiple segments of architecture was simply to process all the files in a single large group, but such an approach was generally found to be too time-consuming to be practical on available computer systems (desktop detailed above), and moreover did not serve to place the results into a scaled and oriented coordinate system. In order to register the fourteen primary segments of walls in the Villa delle Colonne a mosaico, the previously surveyed wireframe model was used to provide the necessary control points from clearly identifiable features, which, since the photography of these

walls had been independent of the survey, proved to be a difficult process. The end result was some variation of scale between the point clouds that required considerable adjustment. Though automatic fine adjustment methods were attempted in both CloudCompare and MeshLab, these produced unsatisfactory results. Settling on exhaustive manual adjustment meant that while the end result was generally acceptable, it was far from infallible. As has been demonstrated, sufficient total station surveyed ground control points (GCPs) are a vital element in this process [Green et al. 2014], though the preferred coded-target method [Sapirstein and Murray 2017, 345] was not possible in the open-source pipeline.

However, despite these limitations and reservations, the end product still provides a useful near-scanned overview of the site suitable for presentations to the public, and has also proven to be detailed enough to support ongoing walls analysis during the off-season. While it was found that reexamination of evidence of surviving wall plaster and particulars of mortar composition was still best achieved using the traditional photographs (often the SfM photographic collections themselves), the ability to examine the villa from above, to explore the relationships abutting walls on both sides of a given wall at the same time, and to consider the meaning of overall alignments, were found to be particularly powerful analytical uses of the point cloud data.

An example of this involved the recombination of now disparate elements of the villa, in order to answer structural questions that could no longer be resolved from any analysis of the extant ruins at the site itself. The eponymous mosaic columns of the villa were removed to the MANN in 1838 [PAH II 5, 353; PAH II 5, 355; PAH III 1, 136-137] and were replaced with concrete substitutes that are neither the correct size nor in the original position. Using a second, scaled point cloud of these columns produced from photographs of the columns in the museum, it was possible to restore them digitally to their correct location.



Figure 9. Point cloud of mosaic columns relocated within the Villa delle Colonne a mosaico. Viewed in Meshlab.

It can be seen (Fig. 9) that the columns were aligned neatly with the nymphaeum fountain to the east, and with the doorway to the north, providing a window into the process of architectural design that would otherwise have been missing from analysis. Furthermore, their correct height, which matches the design of the mosaics on the nymphaeum and possibly aligns with other features on the surrounding walls, permits hypotheses regarding possible roofing arrangements in the area that can be tested via digital reconstruction.

4.4 Recording Stratigraphic Excavation

Given the apparent capabilities of the technology, it was natural to attempt to extend SfM to the recording of excavation, applied first to capturing the state of trenches at the end of the field season (Fig. 10). These experiments quickly led to the expansion of its use to recording every excavated context and feature, and by 2012, SfM photography had become simply another step in the normal pattern of excavation. Each time photography was planned to record an aspect of the trench, additional photographs were taken specifically for SfM processing. This ensured that the trench had already been cleaned of footprints and other extraneous materials. Moreover, since traditional photography in the trenches normally took place during the time of the most advantageous lighting, SfM photography could benefit similarly. The photographic routine entailed the comprehensive photography of the stratigraphic unit in multiple overlapping passes from at least two directions and at a variety of scales, including the positioning of scale bars on the trench extents and including trench baseline nails to serve as georeferenced points, matching the minima set by De Reu [2014, 252], but not the preferred quality of Sapirstein and Murray [2017: 343-346]. Photography was always terrestrial, since the project did not have access to a UAV.



Figure 10. End of season 3D of AA001 in 2009 (left) and AA005 in 2015 (right). Viewed in Meshlab.

While in practice, the primary and immediate use of these trench meshes tended simply to be to showcase each season's work in final reports, online, and at presentations, the ability to produce a 3D surface of each stratigraphic context immediately suggested a number of more scientific applications. One is the use of SfM to produce scaled orthophotos as a replacement for either traditional hand-drafted plans or total station surveys, against which, it compares quite favorably in terms of accuracy and efficiency, as has now been demonstrated by a wealth of case studies [Doneus et al. 2011; Olson et al. 2013; De Reu et al. 2014; Green et al. 2014; Douglas et al. 2015; Sapirstein 2016;

Willis et al. 2016; Jones and Church 2020]. While the 3D surfaces and orthophotos produced by the VCP found similar comparisons, it was also determined that SfM could not replace traditional methods entirely, as discussed below (cf. *infra*). SfM therefore did not end up replacing hand-drafted planning on this project. Instead, comprehensive 3D recording of the trench deposits was always planned to produce a 3D digital model of the whole excavation, with each stratigraphic unit separated as individual layers recorded in topographic detail, and coordinated not only with every other trench and the results from architectural analysis, but also connected to other data recovered from excavation, such as information on artefacts, ecofacts, and soil samples, in the form of a 3D GIS. Such a resource would represent a higher level of detail in archaeological documentation, and would be a step towards the creation of the sort of useful analytical tool that should be the next step for SfM [Newhard 2015]. Opitz [2015] has demonstrated the degree to which three-dimensional records can produce refined interpretations in post-excavation analysis, and the impact could only be expected to be greater as multiple trenches, especially those excavated over subsequent years and therefore never comparable contemporaneously, were combined into a unified 3D model of the excavations as a whole. Further advantages that have been suggested of a 3D trench model include accurate calculations of the volume of contexts [Olson and Placchetti 2015], the plotting of artefact densities, and the consideration of **the** spatial distributions of features, including their Z coordinate [Klinkenberg 2016; Leusen and Nobles 2018]. The precise location and orientation of any artefacts visible within recorded surfaces could also be recovered, and sections could be produced *post facto* from any angle across the trench.

Such a 3D GIS trench record has long been the end goal of a number of different projects [Barceló et al. 2003; Barceló and Vicente 2004; Merlo, S. 2004; Losier 2007; Katsianis 2008; Opitz and Nowlin 2012], all of whom have tackled this challenge with varying degrees of success. However, while easy to conceptualize, the actual implementation of such a goal is less straightforward. Though GIS has formed **a** central coordinating feature of archaeology since the 1980s and 1990s [Lock and Stancic 1995; Lock 2003; Wheatley and Gillings 2003; Conolly and Lake 2006], fully-functional 3D GIS software has been rather slower in development. Current GIS software does make it possible to integrate 3D results such as point clouds and textured meshes, but in practice, many of these uses remain effectively 2.5D surfaces rather than volumes, and many of the required 3D statistical analysis tools are not yet generally in place [Leusen and Nobles 2018]. Even ESRI's ArcScene, the typical destination for 3D meshes, was designed by ESRI primarily for visualizing the impact of building exteriors in an exterior urban environment [Van Leusen and Nobles 2018: 474]. Even though "multipatch" features clearly can be used to represent complicated 3D geometry in this way, and actual 3D GIS implementations are taking place [Polig 2017; Landeschi 2019], relatively elaborate methods are required to squeeze actual 3D functionality out of ArcGIS [Losier 2007; Katsianis 2008; Landeschi 2019]. In 2008, when efforts were directed towards using a 3D GIS to coordinate architectural analysis on the VCP, only GRASS GIS was capable of importing true 3D DXF wireframes, which in any case had to be created first in other 3D editing software. It was therefore decided for the time being to maintain a temporary 2.5D project GIS instead, while capturing data that would enable the production of a full 3D GIS as the software became more user-friendly. This directed the focus on this work towards the production of 3D solid meshes in 3D modelling software such as Blender 3D. Such elements could be imported thereafter as multipatch features, voxels, or some other form of 3D solid, to be connected to non-spatial database information within the GIS. The VCP has accordingly

focused not on implementations of trench data in 3D GIS per se, but rather the preparation of 3D elements that will be more efficiently implemented as time and resources permit.

The first steps towards producing a 3D GIS-ready trench model of complex 3D meshes was undertaken in the case study of a single trench that was excavated in 2015 (AA012). It was situated on the western side of the Villa delle Colonne a mosaico, in an area of a corridor that surrounded it on its ground floor, both separating it from nearby shops to the west, and serving to support the addition of extensive upper stories (Fig. 11). This trench produced evidence of eruptive lapilli and volcanic debris that had only been partially explored during primary excavations in the 19th and early 20th centuries. The removal of this material produced a wealth of finds deriving from the final-phase use of the villa and from the collapse of the upper stories during the eruption itself. During excavation, it was decided to employ the use of SfM to record the removal of the volcanic material at periodic stages, so that important information on the exact disposition of finds, their orientation, and condition, would be preserved. This context seemed like an appropriate test of the planned Blender 3D pipeline.



Figure 11. Location of AA012 in the area of the Villa delle Colonne a mosaico, Pompeii. Satellite imagery: Google Maps.

Each set of photographs was individually processed into an SfM point cloud, which was then meshed and textured. These meshes were then coordinated in Blender 3D, within the surveyed wireframe model of the villa and its trenches. Since modelling software generally does not accommodate geographical-scale coordinate systems, the whole trench was temporarily translated closer to the origin for this work and must be returned to the correct spatial context thereafter. As a preliminary step towards the full 3D meshes that will be needed in a 3D GIS, elements of the trench that were persistent between SfM meshes, such as the walls, the dolium, and unexcavated elements, were first cut into small fragments of 3D mesh and then recombined into 3D solids. Corresponding elements of

subsequent meshes were deleted, producing layers representing the top surface of each layer of the deposit. The next step will be to transform these layers into solid meshes of the excavated deposits.

Even as mesh surfaces, turning off visibility of each layer permits a step-by-step re-excavation of the eruptive deposits, beginning first with the top layer of disturbed volcanic lapilli and debris (Fig. 12a). After the removal of this material, the cleaner, less-disturbed lapilli became visible, surrounding an in situ dolium in use during the final phase of the villa. Seemingly for temporary storage, it was surrounded by several vessels to the northeast, including an amphora leaning against the southern wall (Fig. 12b). Continued excavation revealed a jug that had been used to recover contents from the dolium, which had remained inside during the eruption and had eventually settled to the bottom as the contents were lost. The amphorae and surrounding vessels, heavily damaged by the collapse of the vaulting in this area, were fractured into many in situ sherds (Fig. 12c). By continuing to turn layers on or off, the course of the excavation within the dolium, the removal of the vessel inside, and the exposure of underlying packed earth flooring of the pre-eruption phase of this part of the villa can be re-examined (Fig. 12d).

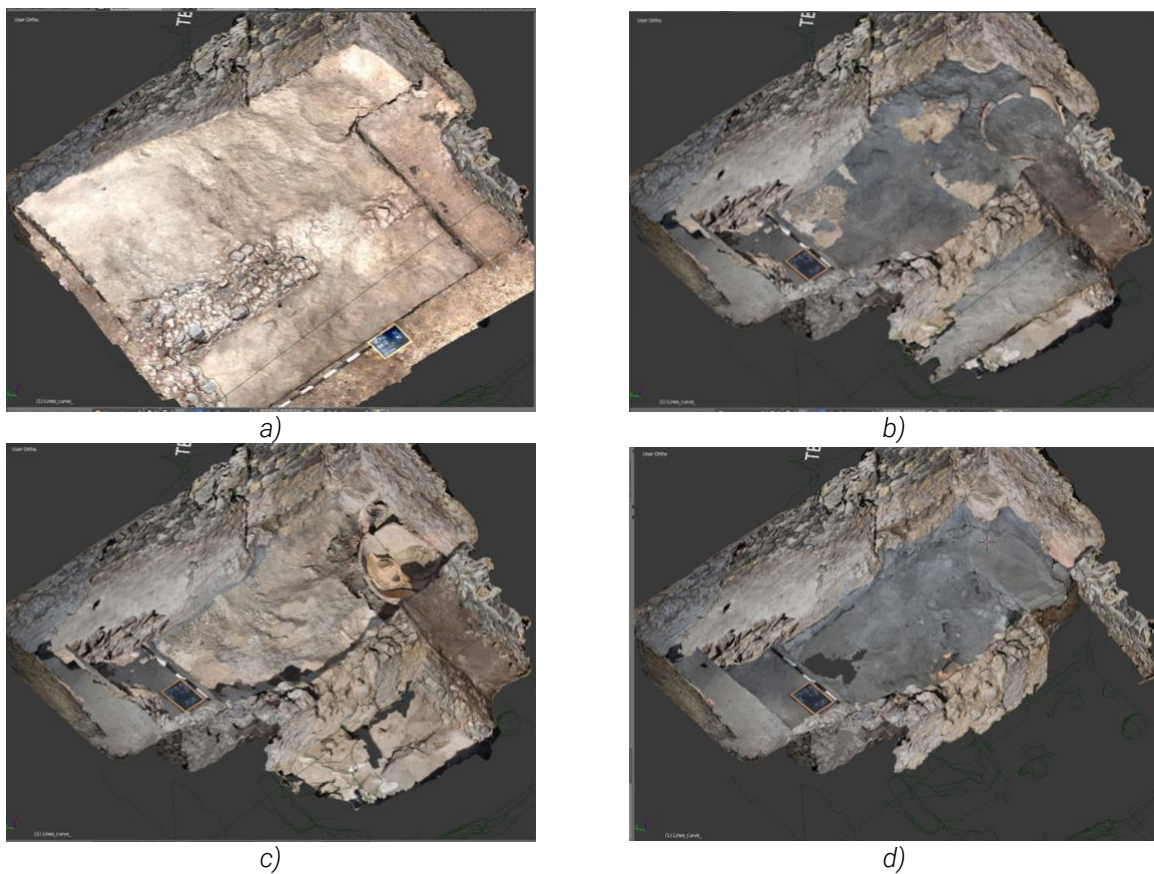


Figure 12. 3D model of trench AA012: a) top of disturbed lapilli, b) cleaner lapilli and beginnings of in situ vessel, c) lapilli having been cleared exposing vessels, d) underlying 79 CE level.

In examining the meshes that represent each removed element of volcanic layers, it can be seen that the orientation and position of individual artefacts recovered are well-documented, permitting the full understanding of their disposition and orientation within the context (Fig. 13). This is especially important given that the loose and fragile volcanic deposits can begin to change immediately after exposure, an aspect of excavation in Pompeii that seems to have served to limit the level of detail recorded by primary excavations, which generally chose to group finds by room or room zone. [Allison 2004: 31]. Ultimately, the major finds in this deposit could be separated into individual meshes, or replaced by more detailed meshes produced from the objects after excavation.

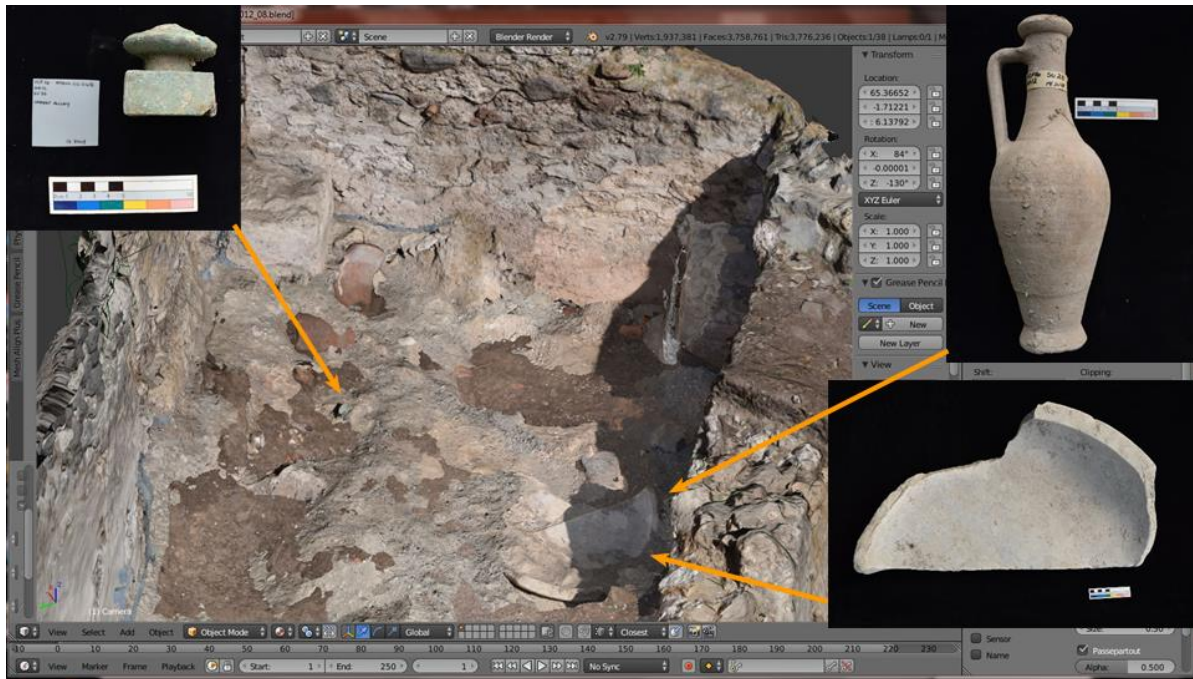


Figure 13. 3D model of AA012. Mesh surface reveals locations of bronze fitting, urceus, and marble labrum permitting reconstruction of positioning data and orientation in lapilli matrix.

5. THE PAST 10 YEARS OF SfM: CHANGES TO FIELD METHODOLOGY ON THE VCP

It is clear that SfM presents a valuable new tool to be added to the repertoire of techniques employed in excavation, and its widespread adoption by numerous researchers will undeniably alter the future standards of digital archaeological field practice as a whole. The past ten years of use of SfM for a number of planned and experimental purposes permits a number of observations to be made about how the use of this technology has actually served to change the field practices of the Via Consolare Project.

5.1 Changes in Recording Standing Architecture

The adoption of SfM by the project was driven primarily by a desire for precisely the three aspects of the technology that are the most discussed in archaeological scholarship: speed of recording, accuracy of result, and level of detail documented. The experiences of the Via Consolare Project confirm that even under less than ideal conditions and via an open-source pipeline, these three features hold the power to transform day-to-day practice. Certainly, in the recording of wall surfaces, SfM has been revolutionary. By removing the need to spend considerable time recording architectural evidence in the field, greater emphasis could be placed on analysis, understanding, and interpretation, speeding the overall process of study, and dramatically improving the quality of the end product. The bulk of the field study of the walls of two large areas of Pompeii, including the recording of their surface topology, was completed in just four seasons of field study, and the resulting record is at a much higher level of detail than would ever have been possible with traditional techniques.

5.2 Changes in Recording Excavation

Likewise, the expansion of the use of SfM for the recording of excavated contexts provides reliable and highly detailed records, even of highly complex surfaces such as pottery scatters and deep areas of the trench, both of which are difficult and time-consuming for traditional hand-drafted planning and total station survey alike. The additional step of SfM photography integrated seamlessly within the existing rhythm of photography, measured planning, and excavation without producing significant delay.

However, unlike some published case studies of SfM in excavation [Olson et al. 2013; Opitz 2015; Roosevelt et al. 2015], this new recording method did not ultimately replace either the process of traditional hand-drafted planning or the use of a total station to record excavated features on the VCP, but instead served to complement them. It was found that there were a number of important aspects of the recording process that simply could not be reproduced by SfM alone. Firstly, unless systems are in place both to ensure the regular production of 3D meshes or orthophotographs and to provide a means of trench-side accessibility (tablets, vel sim.) [Olson et al. 2013: 252-255], excavators will not be able to reference or annotate these records in the field [Opitz 2015]. While born-digital projects with interconnected data networks are currently trendy and obviously do possess some advantages in overall efficiency and data consistency, these must be weighed against in-field feasibility, reliability, and above all, cost. These factors restrict the numbers of projects for which such systems present a viable field solution, and undermine its value as a low-cost solution. However, the limitations of SfM-based recording also run deeper than such infrastructural requirements.

When well-executed, SfM is capable of recording the particulars of the trench, including photographic color, details of texture, elevation, and position in tremendous detail. But excavation plans and sections do not only document trench appearance. They are, more importantly, a record of an archaeologist's analytical process and interpretations. While many aspects of this thought process can, and should, be recorded in notes, sketches, and other records produced by the excavators, the precise reading of complicated stratigraphic interfaces **is** best observed and

documented in direct consultation with the actual archaeological record. This was noted even as SfM began to be introduced more widely to the field [De Reu et al. 2011: 1118]. In the work of the VCP, many soil-based contexts are distinguished primarily by the “feel” of the trowel in the soil, by its texture, and by its relationships with surrounding soils. Any effort to trace the outline of such a context from sketches or notes on a 3D model in the post-season would be no more than guesswork, no matter how detailed the model might be.

It is also true that key elements of an archaeologist’s thinking are stimulated and formalized by the process of planning itself [Opitz 2015, Rabinowitz 2015]. Having to put thoughts into a concrete and accurate form can highlight errors caused by overgeneralization and present further connections as details are explored analytically and mindfully. It is worrying that some who would adopt the SfM method wholesale do so precisely because it is seen to be “objective” and removes the “bias” of human investigators [De Reu et al. 2014: 26; Roosevelt et al. 2015: 325]. Leaving aside the question of whether photography, or its computer-processed end-products, could ever really be considered to be objective and free from human bias, it is worth considering whether such a goal would be desirable, even if it were possible. This view fails to account for a core aspect of archaeological recording. Scientific and accurate documentation is obviously important, but the investigator’s interpretation can also be a vital element of the record necessary for subsequent reinterpretation of the excavation results. To excavate without stimulating or documenting this intellectual level of the process would be tantamount to excavating with only photographs, notes, and sketches as the primary record. Naturally, there will be some situations in which contexts are mainly structural, or are so clearly distinguishable in the 3D models that such concerns may be less pressing. The nature of the archaeological record and the priorities of each project will need to determine best practice. Such was the case for the VCP’s own use of SfM to record walls, for instance. It is important however, that, in the rush to replace traditional methods with SfM, we do not also abandon vital elements of documentation and the archaeological cognitive process.

As a result of these observations, the VCP traditional hand-drawn and/or surveyed plans have continued to be used to record interpretations, to document the edges of excavated contexts, and some archaeological details. Orthorectified images of SfM-produced 3D meshes are employed to supply details, to provide any information that might accidentally have been overlooked, and to correct for human error in the process. Moreover, the combination of these line drawings with 3D surface capture, which may be achieved simply by snapping vectorized, two-dimensional hand-drawn plans onto mesh surfaces, provides an excellent synthesis that takes advantages of the strengths of SfM, while retaining the intellectually vital components of traditional methods (Fig. 14).

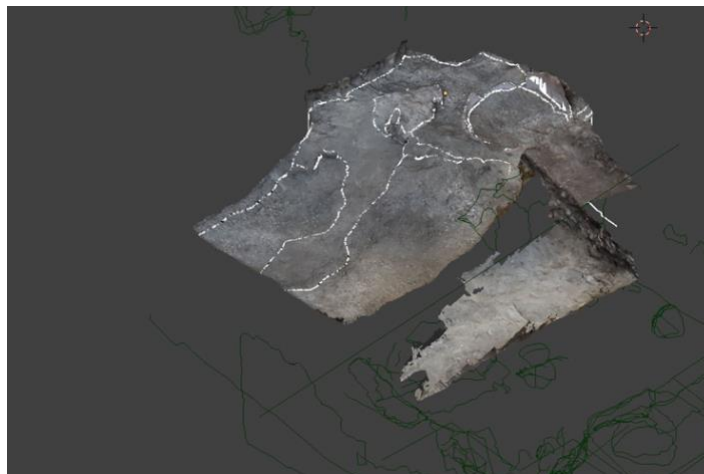


Figure 14. Traced line from hand-drawn plan projected onto 3d mesh surface within Blender 3D.

Using SfM to complement traditional recording still produces a considerable overall net increase in the speed of work undertaken, since excavators can focus exclusively on documenting key interpretative features of stratigraphic contexts, leaving the details and artistic flourishes to SfM. At the same time, the final product is both more accurate and more detailed. These advantages are most evident during periods when time constraints, such as the impending end of a season of excavation, might make traditional methods impossible. Image-based modelling can be used to ensure that details are not missed during these inevitably-rushed moments. Likewise, SfM has excelled in situations when traditional methods would have struggled to capture complex three-dimensional relationships, such as irregularly shaped sections on the inside of circular pit cuts.

5.3 Unplanned Implementations

SfM was also found to produce useful results in a number of unexpected and unplanned applications, including the use of datasets that had not specifically been designed for SfM modelling and for producing 3D models of features that were otherwise invisible or inaccessible. In 2012, the Via Consolare Project team was involved in the ancillary study of the architectural stratigraphy of Insula VI 1, including the Casa del Chirurgo, as a part of my work in helping the directors of that project to bring results to final publication [Anderson and Robinson 2018]. As a part of this work, the face of each wall was photographed from several angles so that they could be referenced away from the field, but without any plan for 3D reconstruction. Nevertheless, during the process of finalising the publication, it became apparent that key elements of the house were not present in the original team's excavation records, including plans of several well-preserved pavements on the northern side of the property and photomosaics for some northern walls intended for a photo-section of the house. In an effort to fill in the gaps, all of these photos were processed as a single job in SfM, in the hope that point clouds of these areas of the Casa del Chirurgo, however sparse, could be produced.

Results were similar to those produced by archival image processing attempted by De Reu et al. [2011: 1116]. Textured meshes were sufficiently detailed to be used to supplement records taken during the

primary excavations by the University of Bradford and to complete the publication, even in the absence of original records, and long after the field work had been completed. This was true even of the pavements, which had only been captured incidentally in the photographs of the walls. In one exceptional case, the orthorectified 3D mesh created from this point cloud made it possible to “rubber sheet” a legacy photograph from 1938 of flooring, which is now largely lost, onto those components that do survive. Simple rectification of this image using the room size would not have permitted the precise mapping of control points that was possible with the orthophotograph. The result was a digitally-created plan, that detailed elements of mosaic that no longer exist (Fig. 15). The adaptability and flexibility of SfM prevented a delay in publication that could have been considerable.

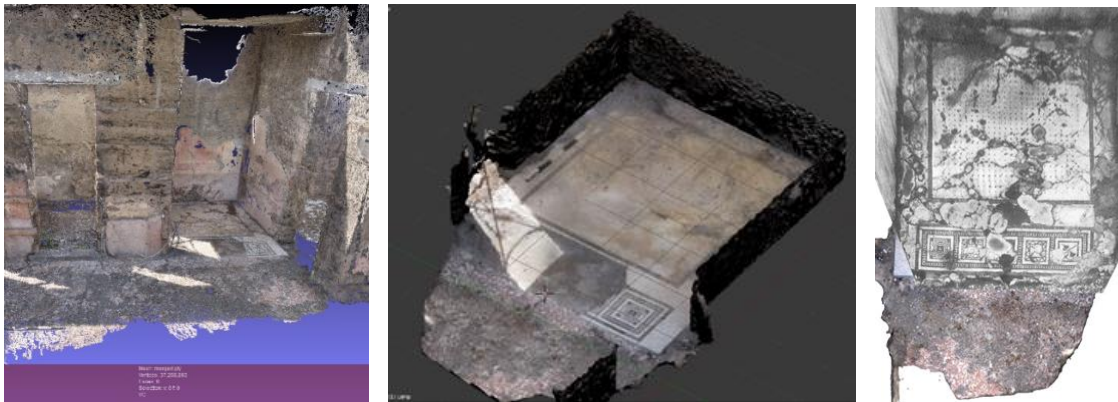


Figure 15. Point cloud of the Casa del Chirurgo (left). Mesh of current state of floor of ala 8A (center). Historical image (after Pernice 1938) of ala 8A projected onto mesh to restore missing details of mosaic (right). Viewed in Meshlab and Blender3D.

There have also been instances when the VCP has employed SfM simply a means of primary exploration, to examine features in ways that would otherwise have been impossible. For example, in 2013, a working point cloud was produced of the interior of root cavities recovered in Insula VII 6, prior to casting them in plaster (Fig. 16A). This was achieved by reaching into the voids with a small point-and-shoot camera (Canon IXUS 105), with flash activated, attempting to produce a full coverage of images. While the process ended up breaking the camera and the resulting point cloud is relatively sparse and noisy, it nevertheless documented the major features of the root cavity and its overall extent, serving to recommend the effort of physical casting. Similarly, a point cloud of a cistern, excavated to a depth of 2.5 meters, was also produced from photos taken from a camera on the end of a long rod, extended through a narrow 0.40 meter- wide opening that otherwise prevented access and would have thwarted all other recording or investigation methods (Fig. 16B). In 2018, another cistern was uncovered with an opening only 0.15 meters wide. Similar recording with SfM recovered information vital to the sequencing of this feature within the development of the area, even without the possibility of further physical investigation. Such uses were hardly planned implementations of the technology, but showcase the ability to leverage the flexibility of SfM into a tool for archaeological investigation.

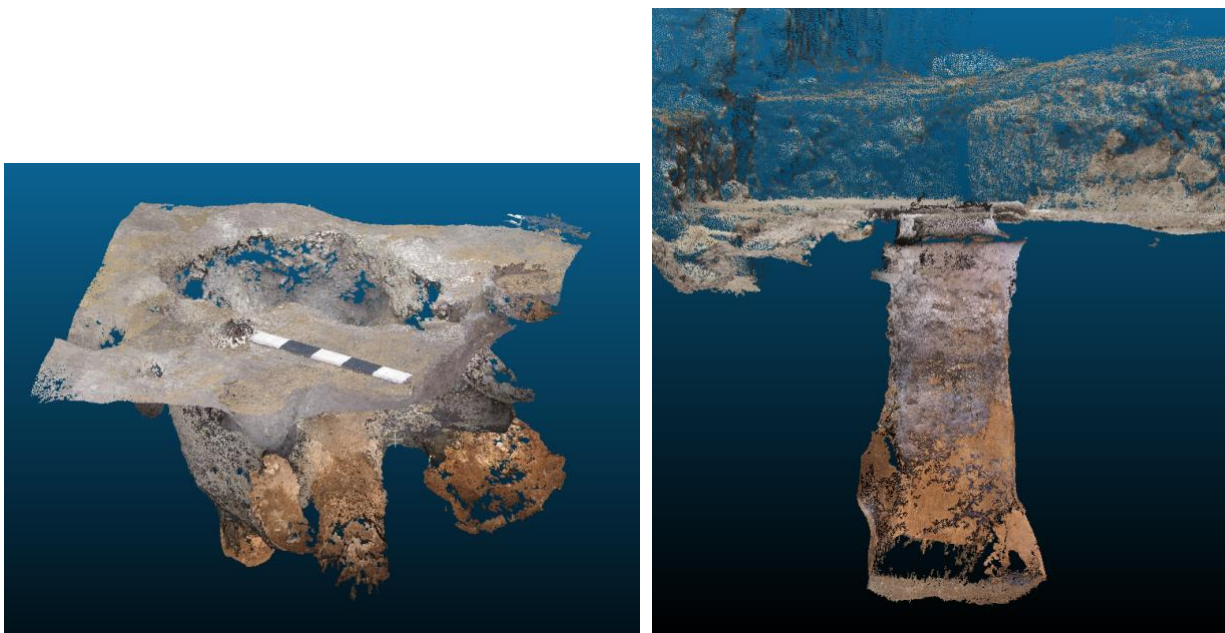


Figure 16. Point cloud of root cavity (left) and cistern (right) in AA008 during 2013. Viewed in CloudCompare.

6. THE NEXT 10 YEARS OF SfM: LESSONS LEARNED

While it is clear that SfM recording provides a number of clear advantages, a decade of SfM on the VCP has also highlighted a number of potential challenges and limitations, many of which are exacerbated by the use of a free and open-source pipeline, and the limitations of less-than-cutting edge hardware. Image-based modelling with SfM is clearly best implemented as the result of a carefully planned and thoughtfully executed process. The ad hoc and exploratory nature of its early adoption on the VCP, combined with the use of less-than-optimal equipment, led to results that were not always of equal quality to the best results produced by published case studies [Doneus et al. 2011; De Reu et al. 2014; Roosevelt et al. 2015; Sapirstein 2016]. This was due in part to the fact that SfM was only one of many priorities for fieldwork and limited funding and size meant that staff, hardware, and software could not be dedicated to this process exclusively. Furthermore, guides to practice [Sapirstein and Murray, 2017] that now exist were not available, and the limitations and capabilities of the technique had to be established through trial and error. It was also related to the financially motivated adoption of an open-source or “free for academic use” process, followed by my decision to remain committed to this pipeline, which also served to generate considerable challenges that might have otherwise been avoided. For instance, georeferencing, an element that is now clearly one of the most important factors determining the end-quality of SfM results and which is now an automated element of many commercial products such as Photoscan, proved to be a significant obstacle. While simple scaling would have been sufficient in the project’s initial intended use of SfM for orthophotos

of standing structures, its expansion to capture more and more complicated models meant that georeferencing steps had to be worked out contemporaneously with research, and within an evolving, and sometimes poorly documented, open-source pipeline that was initially quite limited. This not only tended to reduce the quality of the VCP point clouds, but to delay the final processing itself. At the same time, working with this technology during a period in which it has been developing at a particularly rapid pace, has also created its own difficulties, even within the short period of ten years. Point clouds and meshed surfaces produced early on are now considerably less resolute than those produced today. Some of these could likely be improved if processed through newer software, or replaced entirely with new sets of photos taken at higher resolutions. Others, such as excavation records, are naturally irreplaceable. In a desire to produce a standardized end product, there is a constant temptation to update or reprocess, but the final record will ultimately always be of variable quality. In the digital records of the VCP there are now hundreds of point clouds and models in different levels of quality and at various stages of completion, a fact that has not only hampered efforts to bring the end results together into a finalized product, but can also encourage an endless process of recreation.

6.1 “Time Saving” Is Really “Postponement”

There can be no doubt that incorporating SfM recording into field research at Pompeii produced a tremendous increase in efficiency in the field. However, it simultaneously increased the amount of time necessary for post-season processing dramatically, from the production of dense models from sets of images, to their subsequent meshing, georeferencing, and texturing, to their final combination and manipulation. The small scale of the VCP's operations meant that this work has had to be completed on the same computers that were being used for other academic work, including university instruction and academic publication. Even when dedicated systems could be employed, the open-source pipeline does not generally possess the batch-processing or automatic tools that can speed this work in commercial packages, meaning that the main cost in time may derive from necessary step-by-step human interaction and interventions in the process. Furthermore, while advancing technology does mean that computers with dedicated GPUs, high levels of RAM, and powerful processors are becoming cheaper in relative terms, the VCP was not always able to update to the cutting-edge and had to make do with once excellent, but now aging, hardware (see above desktop system). The end result is that the actual effect of SfM-based recording in the field was to transfer time costs from the field to the computer lab, and, given the amount of time spent after the fact, it is not entirely clear whether there has been a net savings in time. No doubt most researchers would quite happily maximize the use of expensive time in the field, at the cost of additional time spent in cheaper and perhaps easier environments at home. Over time however, this phenomenon can easily produce an extensive backlog of unprocessed data that might require years of post-processing to finalize, especially if provisions of time for post-processing **were** not included in the original plan of operations. Upon returning home at the completion of each field season to full-time university instruction, it has rarely been possible to devote as much time as was needed to see SfM datasets to their final conclusion. As a result, small yearly accumulations have gradually built up into a substantial amount of needed post-processing.

6.2 Challenges of Archival Storage and Metadata

Similarly, the storage requirements for such a large number of images **have** been found to be extensive. As an example, the work of the Via Consolare Project, having recorded every stratigraphic deposit and feature in excavation since 2012, as of 2020 had produced 139,101 image files requiring more than 1.5 TB of disk space, and this will only grow as more of these images are processed into 3D models. A standard series of photos captured for a single 'job' is roughly 160 images (or 2.18 GB) of storage. Processing these images into 3D point clouds and meshes adds a number of additional files (more than 800 in the case of a standard job), and a further 2.5 GB of storage. Certainly, having produced the dense point cloud or mesh, one could delete the intermediate steps, but at the cost of the time required to reproduce them, should they be required in the future. The decimation that is necessary to make most meshes workable entails so considerable a loss of data resolution that many researchers will wish to retain the original as well. In practice, numerous versions of these processing files tend to accumulate, especially if a given set of images requires refinement or must be processed multiple times to reach a satisfactory result. It can be difficult to know what to do with older versions, even those superseded by higher-resolution outputs, since the results are rarely entirely comparable. Simply organizing and keeping track of these data can be a considerable challenge, especially when processed in sporadic moments of limited free time. While personal storage of these data is relatively easy and cheap to acquire and therefore presents little difficulty, this is not so for plans for permanent archival storage or the provision of useful metadata. As has been highlighted by Rabinowitz [2015], for these datasets to be useful archives for the future, a minimum of information is required, which, given the vast number of elements involved, can easily become an overwhelming task. The raw input photos themselves can hold great potential in light of advancing technologies and possible future reprocessing [Rabinowitz 2015: 35; Olson et al. 2013: 248; Willis, et al. 2016: 30]. Numerous photos taken of Insula VII 6, for instance, were taken prior to the completion of extensive restoration works under the "Grande Progetto di Pompei," which served to fill in and occlude many details of wall stratigraphy in this area. Despite their lower resolution, such images therefore present a valuable historic resource documenting details that are no longer visible and can be used to create 3D models of conditions that cannot be reproduced. While such challenges of archival storage and metadata are in common with all of the products of archaeological excavation, from bags of potsherds to elements of primary written documentation, the volume components and outputs in SfM processing means that significant organizational and financial preparation is necessary to ensure appropriate future curation. It would be unreasonable to expect such data to be stored by the Directorate of the site of Pompeii, the archives of which reasonably can only accept a handful of still images each year. Alternative storage and curation strategies will need to be developed to deal with the 3D and 2D components of the SfM process by the projects that produce them to ensure that they are organized and accessible by future researchers as legacy data.

6.3 Recording Complacency and the Impact of Processing Delay

Finally, it should be noted that the impressive and powerful ability of SfM to record in great detail, with minimal effort, and at great speed, can also lead to complacency in the trench itself. Even when such methods are used only to augment and complement traditional recording, there can be a disturbing tendency to conclude that 3D data capture will be able to resolve any deficiencies of field

documentation. This problem is intensified by the delay that normally exists between photographic capture and 3D product. Except in cases where a project has particularly established systems and resources to ensure the timely delivery of 3D results [Olson et al. 2013: 252-255], SfM suffers from the same temporal division between documentation process and end-result that previously plagued film cameras and development, when it was possible to discover weeks later that excavation photography had been lost due to camera malfunction or poor choices in exposure by an area supervisor. In the same way, differences between the excavator's imagination of what the 3D point cloud will be, and the reality of the actual processed result, can lead to undesirable gaps in the archaeological record, which could easily be irrecoverable. While none of these difficulties serve to diminish the significant utility of SfM methodologies in field archaeology, they nevertheless present challenges that need to be overcome.

7. CONCLUSIONS

While the beneficial impacts of SfM are clearly felt most by projects that have sufficient resources for commercial software, cutting edge hardware, and dedicated archaeological staff, nevertheless, SfM technologies yet hold a wealth of diverse opportunities for all archaeological field projects, including those of small scale and limited means. Ease of setup and the ability to use even non-ideal or multi-functional equipment, means that it can augment, speed, and improve traditional recording methods. While 10 years of SfM use by the VCP has revealed a number of obstacles and limitations, it has also confirmed the robust utility of this technology. This is true even in imperfect conditions and utilizing an open-source or free for academic use pipeline, though some reduction in the quality of result and overall net efficiency must also be expected. It is also clear that, in its use for exploration and investigation, to fill in for missing data, or extract further details from legacy records, SfM may yet have even more to provide to field archaeology. Given this, it is surely right to echo others in urging every project of whatever scale to take SfM photographs of all excavations, for the future, if not for themselves [Willis et al. 2016: 30]. SfM provides a valuable tool that can be employed in all stages of archaeological field research from investigation, to recording, to publication, and its use in archaeological projects will surely soon become as universal as the trowel.

URLs for software employed/mentioned in this article:

Hugin - <http://hugin.sourceforge.net/>

VLFeat - <http://www.vlfeat.org/>

SIFT - <https://www.cs.ubc.ca/~lowe/keypoints/>

VISICS, 2011. ARC 3D Webservice. <http://homes.esat.kuleuven.be/wvisit3d/>

Agisoft's Photoscan - <https://www.agisoft.com/>

VisualSFM - <http://ccwu.me/vsfm/>

Clustering Views for Multi-view Stereo (CMVS) - <https://www.di.ens.fr/cmvs/>

Meshlab - <http://www.meshlab.net/>

CloudCompare - <https://www.danielgm.net/cc/>

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