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GROUND-BASED PHOTOGRAMMETRY AT AN AERIAL SCALE: PRELIMINARY RESULTS FROM THE 2022 SURVEY AT KHIRBAT AL-MUDYANA AL-'ALIYA, JORDAN

1. Introduction

Over the past fifteen years photogrammetry has increased steadily in popularity as a method of recording archaeological fieldwork (Magnani *et al.* 2020, 738-739). Indeed, many projects now use this technology almost exclusively for three-dimensional documentation (Doneus *et al.* 2011; De Reu *et al.* 2013; Olson *et al.* 2013; Fernández-Hernandez *et al.* 2015). Photogrammetry has also proven efficient at recording at-risk cultural heritage in 3D, as exemplified by the Institute for Digital Archaeology's reconstruction of the Palmyra Triumphal Arch (Million Image Database, https://digitalarchaeology.org.uk/projects/), and current efforts to record Ukraine's at-risk cultural heritage (Lauter 2022; Shydlovskyi *et al.* 2023). This ability to both efficiently document and digitally preserve cultural heritage has made photogrammetry a powerful, widely adopted tool for archaeologists and heritage professionals worldwide.

In part, the appeal of photogrammetry lies in its multi-scalar flexibility, what Magnani *et al.* (2020) have classified as 'object-based', 'ground-based', and 'aerial' scales of application. Of these applications, aerial photogrammetry has been most transformative in its ability to capture substantial archaeological structures, sites, and landscapes on a large-scale, in detail and over relatively short periods of time (e.g., Giuliano 2023; Da Villa *et al.* 2024). For example, an aerial survey of ISIS-inflicted damage at Nineveh captured an area of 825 ha in just five days (Campana *et al.* 2022, 443). However, aerial photogrammetry can also be one of the costlier applications of photogrammetry. It often requires access to expensive equipment, specialist drone pilots and logistically complex licenses and/or permits. Due to these, and other, limiting factors – including increasingly restrictive regulations regarding the use of Unmanned Aerial Vehicles (UAVs) in various countries – aerial photogrammetry is not always a viable option.

The goal of this paper is to present an operational protocol for 3D site recording at an aerial scale using ground-based photogrammetry methods. These methods are easily accessible, time- and cost-effective, and practicable in a wide range of field situations, particularly when access to UAVs is unfeasible. This protocol was deployed in a recent survey of the site of Khirbet al-Mudayna al-'Aliya, Jordan, where both restrictions on the importation and deployment of UAVs and perpetually high winds and strong updrafts,

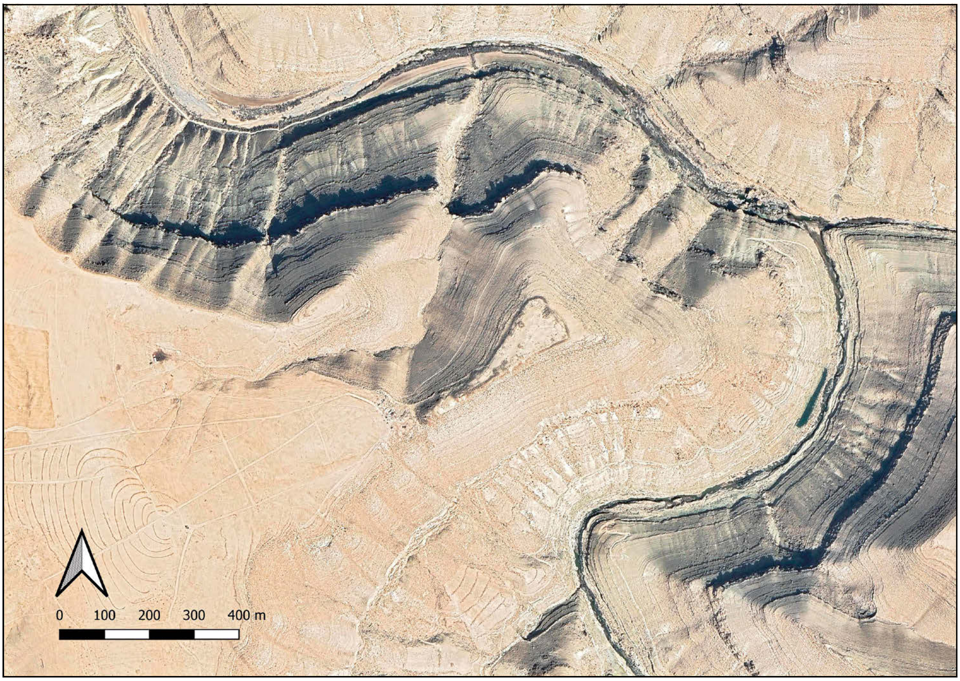

Fig. 1 – Satellite view of KMA (courtesy of Google Earth).

make the use of drone photography impractical. Through this protocol, we aim to provide a reliable alternative to aerial-scale documentation, expanding the scope for effective site recording in challenging circumstances.

2. Case study

Khirbet al-Mudayna al-ʻAliya (henceforth KMA) is a 2.3 ha Early Iron Age site in south-central Jordan. It is heavily fortified, with a substantial stone tower, dry moat, and a casemate wall with attached domestic buildings. A particularly striking feature of this site is the visibility and coherence of its architecture on the surface (Fig. 1), meaning that much of the site can be mapped with little or no excavation. The well-preserved nature of the site's architectural features allows for a thorough reconstruction of the site's original plan, construction methods and sequence, and variations in interior domestic buildings, providing insights into the social and political dynamics of the period. KMA is part of a cluster of similar sites located around the Wadi al-Mujib and its major tributaries. These 'Mudayna' sites (Routledge 2008) are usually situated on hillocks or promontories overlooking major

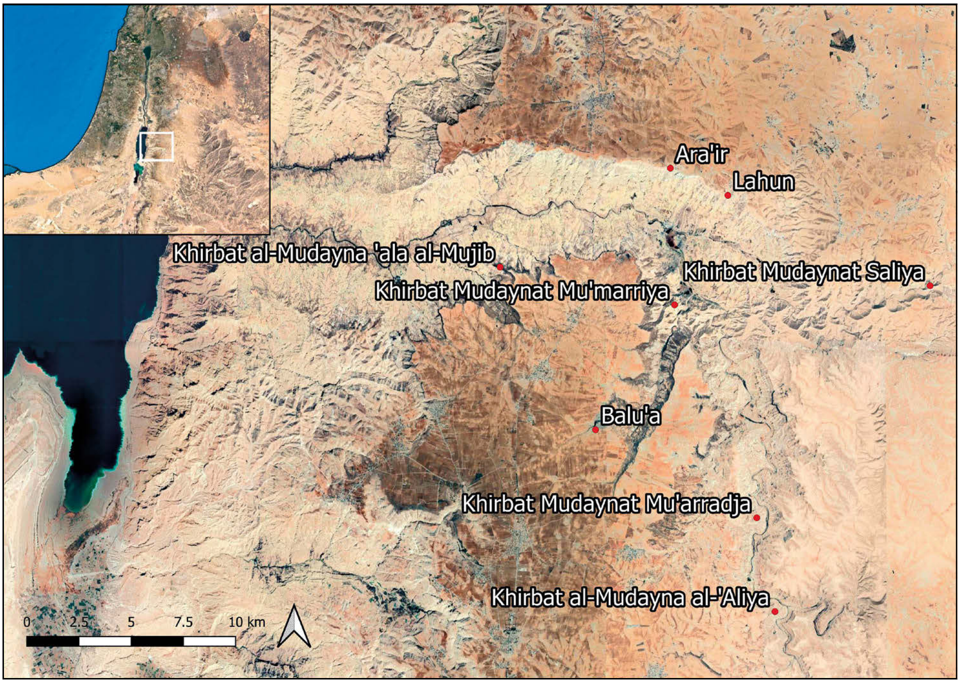

Fig. 2 – Map of ‘Mudayna’ sites around the Wadi al-Mujib and tributaries (courtesy of D.J.H. Halbertsma).

perennial waterways, with casemate fortification walls that follow the perimeter of the topographic feature on which the site is located. This strategic positioning leverages the steep slopes of the promontories to strengthen their defences. Access is usually limited to a single approach via a narrow spur or saddle linking the site to the plateau the promontory protrudes from. At least eight such sites have been identified thus far (Fig. 2), with recent studies illustrating that this phenomenon extends farther N to the Wadi Zarqa-Ma’in and possibly beyond (Routledge, Halbertsma in press; see also Danielson *et al.* 2024; Halbertsma 2025).

An extensive programme of radiocarbon dating has shown that KMA was constructed at some point in the 11th century cal BC and abandoned in the first half of the 10th century cal BC (Porter 2013, 129; Routledge *et al.* in prep.). Ceramic parallels suggest that the other ‘Mudayna’ sites were occupied in a similar time frame (Routledge 2008; Routledge *et al.* 2014). The dramatic locations, fortifications and limited use-life of these sites has generated several hypotheses regarding the socio-political dynamics behind their construction, that to varying degrees integrate the available

Fig. 3 – The Wadi an-Nukhayla, a perennial streambed situated below the site (courtesy of D.J.H. Halbertsma).

data. Many scholars have interpreted them as border fortresses protecting an early 'Moabite' polity in the northern Kerak plateau (e.g., Finkelstein, Lipschits 2011; Luria 2021; Ben-Yosef, Thomas 2023). 'Moabite', in this context, refers to the 9th century BC kingdom of Moab, with its capital city at Dibon (modern Dhiban), known primarily from the Mesha Stela and the Bible (e.g., Dearman 1989; Gass 2009; Porter 2023). The impetus for the formation of this earlier, 11th-10th century BC polity would have been the intensified copper-production in the Wadi Arabah. This copper, serving international markets, would have been traded northward to Syria across the Wadi al-Mujib, leading it through the area of the Wadi al-Mujib sites. This early Moabite 'territorial entity' (cf. Finkelstein, Lipschits 2011) would have formed around this northward copper trade, and would have had its capital at the archaeological site of Balu'a (Fig. 2). The heavily fortified Wadi al-Mujib sites, then, would have protected this capital and the borders of this polity. The underlying assumption here is that the co-occurrence of these sites and the size of their fortifications would require the organisational and logistical capability only a centrally organised, hierarchical society could have been responsible for (Halbertsma 2025).

However, excavations at KMA revealed that despite its fortifications there is little evidence to suggest an external social hierarchy, any significant involvement in trade, or a specialised military purpose. Rather, the site seems to have functioned as a relatively autonomous agro-pastoral village that made extensive use of resources from the adjacent Wadi an-Nukhayla (e.g., Porter *et al.* 2014; Halbertsma 2025; Fig. 3). This raises the question of how these sites were constructed, and for what purpose. If such fortifications require the presence of the administrative power of a kingdom, this ought to be quantifiable: e.g., the labour requirements for constructing KMA should significantly exceed the capacities of its inhabitants. However, if not, other social dynamics behind this sudden and substantial investment in labour can be considered (Halbertsma 2025; Halbertsma in prep.).

Accurately studying the construction of KMA's architecture requires obtaining precise measurements of both the building materials and the dimensions of its structures. This would allow reconstructing 'volumetric data' (see also Poggi *et al.* 2022), in this case the amount of building material used to construct KMA's architecture. This is a critical step in the quantification of labour costs (Abrams, McCurdy 2019, 4; Boswinkel 2021). Although estimates could be made from existing 2D site plans (e.g., Routledge 2000, fig. 4), direct field measurements would produce more accurate data (i.e., measuring the x, y, and z of standing architecture). This could be done during a targeted site visit, but ongoing research often raises new questions. Making repeated trips to the site over the course of several years was impractical. Therefore, capturing the entire site in 3D would allow future architectural studies to be conducted remotely, taking measurements of its architecture directly from the 3D model. Hence, a survey season at KMA was designed to gather the data needed for this quantitative assessment of the labour invested in site construct (see also Halbertsma 2022; Halbertsma *et al.* 2024). Additionally, agricultural activities have greatly increased in the immediate vicinity of the site, and recent bulldozing has significantly damaged some nearby archaeological features. As a result, creating a benchmark of the current state of preservation of the site became an important element of this project.

3. Methods

The 2022 fieldwork season was planned to take place in the month of May. We set out with a team of four people to capture the entire 2.3 ha site in 3D, using photogrammetry to generate a sufficiently accurate, georeferenced orthophoto of the site. This would not only allow us to refine the previously published 2D site plan (Routledge 2000, fig. 4), but also provide valuable data on various aspects of the site's construction techniques

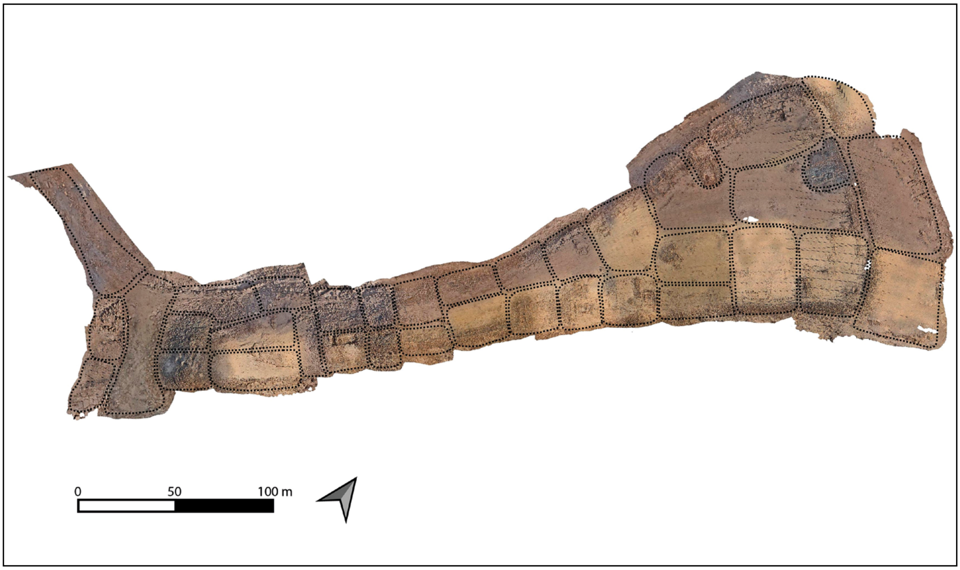

Fig. 4 – Plan of KMA with locations of the 37 individual zones (courtesy of D.J.H. Halbertsma).

and architectural features. In the context of these aims, the scale of KMA would warrant the use of drones, kites or balloons (e.g., Howland *et al.* 2014; Fernández-Hernandez *et al.* 2015; O'Driscoll 2018). However, local restrictions on the import and use of UAVs, adverse weather conditions at the site (both sudden and persistent strong winds) and the overall costs made these methods impractical. Consequently, although we aimed to achieve the results of aerial-scale photogrammetry, we were limited to ground-based methods and had to develop a methodology to circumvent these limitations.

Our plan was to divide the site into individual zones, which could be walked in transects while being documented photographically. These individual zones, once processed in 3D using photogrammetry software Agisoft Metashape Pro, could be stitched together to create a complete model of the site using computers dedicated to high-quality 3D imaging available in the Department of Archaeology, Classics and Egyptology at the University of Liverpool. We aimed to strike a balance between capturing zones large enough to limit the number of individual 3D models that we generated and small enough to produce file sizes that could be managed by the hardware available to us in the field. Based on advanced trials, which involved running trial models in areas of comparable topography (i.e., stone-built architectural elements spread over a wide area), we decided on 50×50 m as the maximum zone size. This maximum size was chosen primarily to optimise the processing stage for the available hardware (see below). Larger areas, requiring additional photographs, would take significantly longer in Agisoft Metashape's non-linear workflow. Furthermore, zone size could be reduced in specific cases based on the complexity of the architectural or geological features being documented, which would require a greater density of photographs.

To this end, the entire 2.3 ha site of KMA was subdivided into 37 separate zones (Fig. 4). Working with manageable zones allowed us to process each morning's photographs the same day, and thereby monitor the progress and quality of our work. In this manner, visible gaps, or insufficient detail for proper rendering, were noted and addressed on a daily basis. Accuracy was assessed by monitoring the built-in error function of Agisoft Metashape Pro, which we had aimed to keep below 5 cm for our purposes (see below). Being ground-based, maximizing the field of view of our photographs whilst maintaining portability and control, was a significant factor in limiting the number of photographs required to cover all features of the site. Advanced trials led us to choose 2.5 m camera poles as the best means of mounting our cameras, which were held at ca. 1 m off the ground resulting in the cameras being suspended at ca. 3.5 m. Photo poles and booms are quite commonly applied in archaeological projects where access to UAVs is limited, with various degrees of success (Verhoeven 2009; Pérez-García *et al.* 2018).

We used a Nikon D3300 DSLR and a Sony α6600 APS-C, with the former equipped with a 18-135mm lens, the latter with a 16-50mm lens. The lenses were fixed to the 18mm focal length for the Nikon, with the Sony at 16mm, with settings set to the 'auto' mode. These consumer-grade cameras and lenses, while perhaps not state-of-the-art, proved highly capable of sufficiently accurate 3D recording for our purposes during trials. Photographs were captured at an effective resolution of 6000×4000 pixels in both JPEG and RAW file format (the latter solely for posterity since Agisoft Metashape Pro does not process the RAW file format).

The cameras were provided with remote triggers to allow for remote photography. Mounted atop the camera poles, they were angled in such a way that the bottom of the camera frame was one meter from the bottom of the camera pole. This was measured with a measuring tape. This angle provided us with an elevated trapezoidal oblique view forward and outward, ensuring plenty of overlap between individual photographs and surface coverage. The higher level of detail in the foreground of the photographs would thus capture the site's architecture in sufficient detail, whereas the slightly more distant background would also ensure the overlap required for the photogrammetry software to construct the 3D models. This approach

Fig. 5 – Field-walker walking transect through KMA's dry-moat (courtesy of D.J.H. Halbertsma).

ensured sufficient photographic coverage, ensuring sufficient image overlap for accurate 3D model construction. This protocol proved highly effective once the photographs were processed as 3D models in Agisoft Metashape Pro (see below).

As good lighting conditions are crucial for successful photogrammetry models, we began by recording the site in the ca. 40 minutes of morning daylight available during this particular time of year, before the sun crests the horizon and begins producing shadows. However, these photographs often proved too dark for proper processing in the photogrammetry software. Hence, we shifted to photographing from sunrise until roughly 10.30am, when the light would become too harsh and the colours in the photographs too pale. Although this time of the day did produce significant shadows in the photographs, this did not prove an obstacle for accurately processing the 3D models (see below).

Our team was split into two groups, with two people field-walking with camera poles (Fig. 5) and two people surveying, planning the transects, and providing coordinate data to the transects. The walkers were directed in straight lines across the zones through the use of coloured flags, which were placed at intervals of 5 m along the edges of the zones by the surveying

Fig. 6 – Field-walker applying angled camera method (courtesy of D.J.H. Halbertsma).

team. Where the site contained steep slopes or standing architecture that complicated direct lines of sight across the transects, additional flags were placed intermittently to keep the walkers on a straight line.

To orient the survey within the site and parts of its surrounding landscape, we employed a topographical approach that considered both the site's architectural layout and natural terrain. Zones and transects were aligned in relation to visible architectural axes wherever feasible, but also adjusted to accommodate slopes, uneven surfaces, and existing topographic features that impacted line-of-sight. The entire survey was georeferenced using a Total Station to record the position of 106 strategically placed coded targets (see below), which were tied into a local grid and subsequently linked to national and global coordinate systems. This approach ensured that both orientation and georeferencing were contextually accurate and reproducible across the entire 2.3 ha site.

In principle, a single photograph was taken at intervals of 1.5 m along transects spaced 2.5 m apart, with alternating transects walked in the opposite direction to provide coverage from two faces and angles. This would amount to approximately 1 photograph per 4 m2 for a flat area. Two diagonal transects across each zone were also added to ensure sideways coverage of each area, while photographs on the edges of zones were always positioned to provide overlap with adjacent zones to aid in the subsequent stitching together of models. Where architectural features were particularly pronounced additional photographs would be taken at intervals while moving the camera pole in an arch from a 90°-180° angle (Fig. 6). Another strategy for capturing more detail in complex areas was to rotate the camera 360° from a stationary point while taking pictures at regular intervals. Additionally, the camera was occasionally removed from the pole to take supplemental handheld photographs (e.g., from a horizontal perspective), which was especially useful for capturing large standing architecture or narrow areas within buildings where manoeuvrability was limited. The added photographic coverage in areas with pronounced architectural detail enhanced the accuracy of the models, particularly for more complex structures like standing walls and pillars.

Each zone was provided with a series of visual georeferencing coded markers that were pre-generated by Agisoft Metashape Pro, as these have been shown to increase the accuracy of photogrammetry models (Sapirstein 2016, 140-141). While best practice is argued to require no less than three such coded markers visible in each photograph (Sapirstein, Murray 2017, 345), the sheer size of the site under investigation made this unfeasible. Sapirstein and Murray (2017) posit that an area of 25×55 m (0.125 ha) would require at least 300 coded targets. If applied at the 2.3 ha site of KMA this would result in some 3000 coded targets across the site, an amount exceeding practical considerations. Instead, markers were placed along the edges and at the corners of the individual zones, as well as at strategic positions within zones to aid the software in detecting sudden changes in elevation. These 106 markers were georeferenced by the survey team with a total station and provided with coordinates on the site's relative grid, which could later be georeferenced to national and global grids. Advanced trials conducted on standing architecture in the United Kingdom proved the efficiency, feasibility, and accuracy of this strategy, which was confirmed while in the field in Jordan. The overlap between the edges of zones would ensure that each individual zone would contain several markers in at least two adjacent zones. This system of overlapping markers was crucial in ensuring seamless integration of the models across zones, significantly benefiting the photogrammetry software in facilitating the eventual merging of the individual 3D models into a single comprehensive one.

4. Results

We managed to capture the entire site in only 7 days, working only a part of the morning to guarantee ideal lighting conditions. In total this

Fig. 7 – Orthorectified image of the entirety of the site of KMA (courtesy of D.J.H. Halbertsma).

represented 31 working hours in the field with a team of four people. This amounts to an average of 233 images per person, per hour. However, the site's more open areas were significantly easier to cover than the areas with more complicated architectural remains and topography. In total, we captured 28,919 JPEG photographs, amounting to 404 GB of data. This equates to roughly 1.26 photographs per m2.

To process the models during fieldwork we used a consumer-grade laptop with a dedicated graphics card (CPU – Intel i5-8300H @2.3Ghz; GPU – GTX1050 Ti 4GB; RAM – 16GB). Each day, after returning from the field, we processed the 3D models using Agisoft Metashape Pro (i.e., following the processing workflow from 'align photos' through to 'texture'), at the lowest resolution possible. This allowed us to gauge whether there were any noticeable gaps in coverage of the individual zones on a daily basis. Where such gaps occurred, we could return the next day and take additional photographs of these specific areas. The lowest resolution was chosen to ensure the timely processing of the approximately five to six zones we would capture in a day using this consumer-grade hardware, which could take several hours per 3D model.

The 3D models generated for the 37 individual zones are on average accurate down to 3 cm, entirely within the acceptable margin of error for the study's specific purposes. Each zone contained at least three or more georeferenced visual markers, and all zones had areas of overlap with at least two adjacent zones. This proved to be an effective method for merging the 3D models of individual zones into larger models with relative ease. This entails opening the fully processed 3D model of a given zone, using the 'append' function in Agisoft Metashape Pro to add an adjacent model, and then choosing the 'merge chunks' function. Then, choosing the option to merge by model and markers proved successful in creating a larger model without much loss of detail.

The final merged model is accurate down to 3.4 cm, with a mesh polygon count of 74,070,675 and a ground resolution (Ground Sampling Distance or GSD) of 0.884 mm/pix (retrieved with the Metashape 'Export Report' function). This GSD might seem excessive for our purposes, but is a direct result of not being able to use a drone which would generate more distance from the site, resulting in a lower GSD. Point Cloud Density (PCD) would differ significantly across the model, as archaeologically higher-density areas warranted additional photographs to capture the standing architecture, resulting in a higher PCD. Conversely, capturing archaeologically lower-density areas could be achieved using less photographs, resulting in a lower PCD. The PCD values from two different areas of the site, one high-density (the southern half of KMA's tower) and one low-density area (one of the areas within the site's open plaza), illustrate this well. The former had a PCD of 9.50 points/cm2, whereas the latter had a PCD of 1.54 points/cm2.

Although we used two different cameras under slightly different lighting conditions, this did not have a noticeable impact on the accuracy of the individual models, nor on the accuracy of the final merged model (Fig. 7). Furthermore, the presence of shadows cast by architecture in the models did not appear to significantly affect the processing stage nor the outcome of the models, apart from the presence of long shadows in certain areas. The only real challenges we encountered were in open areas, where the lack of distinguishing features meant that we failed to note several small gaps in our coverage while in the field. This highlights the importance of efficient planning and monitoring of the field-walking stage, ensuring no critical areas are missed during data collection. However, since our goal was to capture the standing architecture none of these gaps impacted the overall goals of the 2022 season, nor the labour cost studies it was designed for. As such, the 2022 field season generated a sufficiently accurate 3D model of the entire 2.3 ha site. The ability to take direct measurements from the 3D model facilitated further labour-cost studies (Halbertsma 2025; Halbertsma in prep.). Furthermore, it also generated a high-resolution site plan, in the form of a georeferenced orthophoto, making this a practical protocol for any archaeological project looking to quickly plan a large site without access to UAV's.

Beyond KMA, the protocol developed for this study has broad potential for future archaeological projects. Its low-cost and accessible nature makes it suitable for documenting a wide variety of archaeological sites, particularly when more expensive or specialized equipment is unavailable. Here, it must be noted that access to a Total Station, two consumer-grade DSLR cameras, a consumer-grade laptop, and professional photogrammetry software is not, on its own, necessarily low-cost or easily accessible. Yet, especially compared to access to the equipment and licenses involved with aerial photogrammetry, this combination of hardware and software is remarkably easier to access. Moreover, with the iterative improvement of handheld cameras and GPS devices, especially on smartphones, as well as the rapid development of open-source photogrammetry software, this protocol will likely prove increasingly accessible.

This is particularly relevant in an era where the availability of digital technology is reshaping the methodologies used in archaeological research, enabling small archaeological teams, researchers in resource-limited environments, and non-academic contributors to participate in the (digital) monitoring and preservation of global cultural heritage. Furthermore, the ability to track site preservation over time, such as through repeated photogrammetry surveys, creates opportunities for ongoing monitoring and conservation efforts. This protocol is particularly valuable for sites under

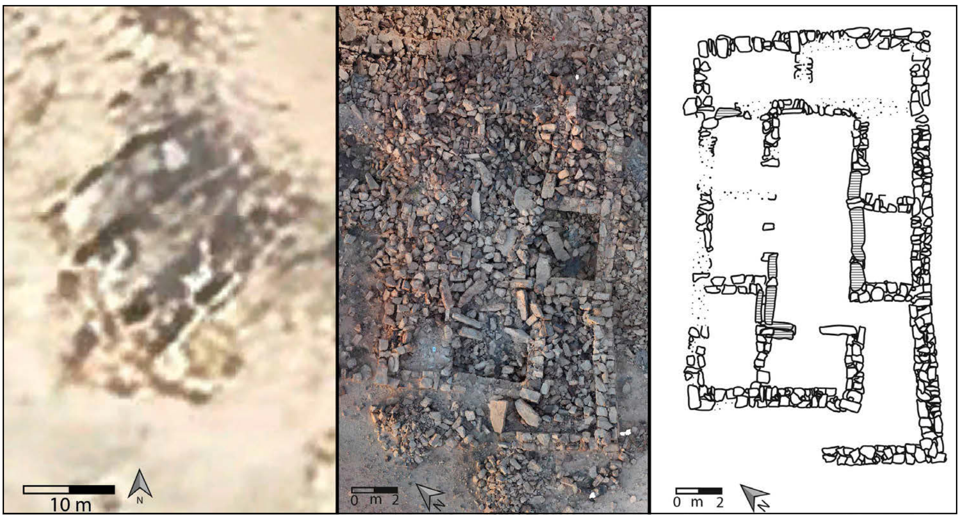

Fig. 8 – Comparative image demonstrating the level of detail of the 3D model. Left: close up of Building 100 from Google Earth; centre: close up of Building 100 from the 3D model; right: drawing of Building 100 (after Routledge 2000, fig. 10).

Fig. 9 – Oblique view of Building 500 looking S, demonstrating added information of recording in 3D: note the preserved stacked stones forming walls, upright pillars, and accurately captured stone rubble (courtesy of D.J.H. Halbertsma).

immediate threat from warfare, agricultural development, urban expansion, or climate change. The rapid generation of high-resolution 3D models can provide timely records of a site's condition before further degradation, allowing for better-targeted conservation strategies. Additionally, photogrammetry's capacity for 'time-slicing' site conditions – capturing changes in architecture or the surrounding environment over time – offers an invaluable resource for both heritage management and public engagement. Finally, due to its time-efficient nature, this approach could also be expanded to larger survey projects requiring the detailed documentation of multiple sites across a wide area.

5. Conclusions

The protocol described in this paper is an accessible alternative for archaeological projects looking to obtain aerial-scale photogrammetry results while limited to consumer-grade ground-based equipment. Its main advantages are that it is a low-cost, time-efficient, and logistically straight-forward way of documenting a substantial site with a high level of detail (Figs. 8-9). If you have access to a method of georeferencing (e.g., an accurate GPS system or a Total Station), photogrammetry software, a consumer-grade laptop or desktop computer capable of 3D processing, and entry-level DSLR or APS-C cameras and camera poles, this protocol is entirely viable.

As demonstrated by Campana *et al.* (2022), photogrammetry is a highly efficient tool for documenting heritage at risk, and allows us to preserve in 3D features, structures, sites, and even landscapes that can drastically and rapidly change due to agricultural practices, vandalism, climate change, and/or armed conflict. In the case of KMA, the comprehensive site model generated in 2022 constitutes a base-line record of the condition of the site with potential uses in site monitoring and site conservation that extend well-beyond our immediate academic goals. This sort of efficient, low-cost archiving, with the potential to 'time-slice' site conditions quickly and accurately, may well prove to be among the most transformative applications of photogrammetry within archaeology.

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ABSTRACT

This paper presents a cost- and time-effective, accessible, and practicable method of 3D site recording at an aerial scale using ground-based photogrammetry. The methodology was deployed in a recent survey of the site of Khirbet al-Mudayna al-'Aliya, Jordan. The authors used ground-based photogrammetry to capture this 2.3 ha site, generating a complete and accurate 3D model and georeferenced orthophoto of the site within several days. The paper demonstrates that ground-based photogrammetry can provide a valid alternative where aerial photogrammetry is impractical. Therefore, this method is useful for baseline recording of site conditions under varying circumstances, with potential uses in site monitoring and conservation.