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Use of Photogrammetry for Non-Disturbance Underwater Survey: An Analysis of In Situ Stone Anchors

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Abstract:	Stone anchors comprise a significant portion of observable underwater cultural heritage in the Mediterranean and provide evidence for trade networks as early as the Bronze Age. Full documentation of these anchors, however, often requires removal from their underwater environment, especially to acquire mass. We offer a methodology for using photogrammetry to record stone anchors still in situ and calculate their approximate mass. We compare measurements derived using measuring tapes with those derived using two different software programs for photogrammetric analysis, PhotoModeler Scanner (Eos Systems, Inc.) and PhotoScan Pro (Agisoft). First, we analyze stone anchors that previously have been removed from the underwater environment to establish a reference methodology. Next, we implement this methodology in an underwater survey off the southern coastline of Cyprus. Linear measurements for both programs correlate closely with those attained via measuring tape. The resulting volumes of anchors in situ and on land are slightly greater using the photogrammetric methodology than the reference volumes obtained using a water displacement methodology. Overall, as an analytical tool, this methodology generates detailed surface information in minimal time underwater and preserves data for future analysis without necessitating the removal of the anchor from its underwater environment.
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Data Availability. The excavated anchors studied in this article belong to the collection of material recorded in the *Tsaroukkas*, Mycenaeans and Trade Project (catalogue numbers: TSBS003, TSBS005, TSBS009, TSBS011, TSBS014, TSBS018, MT418, MVASP187) will be housed at the Larnaka District Museum, Plateia Kalograion, Larnaka, Cyprus. Inquiries into access can be made by contacting the director of the project, Dr. Sturt Manning, 120 Goldwin Smith Hall, Cornell University, Ithaca NY 14853. The three-dimensional models of the anchors created and analyzed in this study are stored at the Curtin University's Research Data repository, managed by Curtin's Office of Research and Development, Curtin University, Kent Street, Bentley, Perth, Western Australia 6102. Access can be arranged by contacting Dr. Andrew Hutchison via email (A.Hutchison@curtin.edu.au).

Anclas de piedra forman una parte importante del patrimonio cultural subacuático observable en el Mediterráneo y proporcionan evidencia de las redes comerciales ya en la Edad del Bronce. La documentación completa de estas anclas, sin embargo, a menudo requiere la eliminación de su entorno bajo el agua, sobre todo para adquirir masa. Ofrecemos una metodología para el uso de la fotogrametría para grabar anclas de piedra todavía in situ y calcular su masa aproximada. Comparamos las mediciones obtenidas usando cintas de medición con los que se derivan utilizando dos programas de software diferentes para el análisis fotogramétrico, PhotoModeler escáner (Eos Systems, Inc.) y PhotoScan Pro (Agisoft). En primer lugar, se analizan las anclas de piedra que han sido previamente retirados del medio ambiente bajo el agua para establecer una metodología de referencia. A continuación, ponemos en práctica esta metodología en una encuesta bajo el agua frente a la costa sur de Chipre. Mediciones lineales para ambos programas se correlacionan estrechamente con los obtenidos a través de una cinta de medir. Los volúmenes resultantes de anclajes in situ y en la tierra son ligeramente mayor utilizando la metodología fotogramétrico que los volúmenes de referencia obtenidos utilizando una metodología de desplazamiento de agua. En general, como una herramienta analítica, esta metodología genera información detallada superficie en un tiempo mínimo bajo el agua y conserva los datos para el análisis futuro sin necesidad de la eliminación del anclaje de su entorno bajo el agua.

In this paper, we present the results from an experimental application of three-dimensional (3D) imaging practices in an underwater survey conducted along the southern Cypriot coastline off two known archaeological sites: the Late Bronze Age (LBA) and Iron Age site of Maroni-*Yialos* and the LBA site of Maroni-*Tsaroukkas* (Figure 1). While many previous applications have focused on using photogrammetry to digitally record large sites, this project focuses on recording singular anchors through photogrammetry in order to accurately document survey finds without removing them from their underwater context and to create 3D digital models for further analysis. In particular, we use these models to calculate the volume and mass of *in situ* anchors, which can aid the creation of anchor typologies and facilitate detailed comparisons. More generally, this process can be applied to analyze other *in situ* stone remains, either underwater or on land.

Stone anchors comprise a significant portion of the observable underwater cultural heritage in the Mediterranean and provide evidence for maritime practices and trade networks as early as the Bronze Age (Frost 1963, 1970; McCaslin 1980; Wachsmann 1998). Through the analysis of these anchors, scholars have worked to create chronological and geographical typologies, noting the importance of size, weight, and shape as well as the number and placement of holes in the stone (Tóth 2002). However, due to their irregular shapes, it is difficult to quickly and accurately record measurements and surfaces of stone anchors. Full documentation of anchors often requires their removal from the underwater environment, especially to acquire mass, yet this process can be problematic due to the logistics of lifting a large, heavy object as well as the required resources and facilities for its removal and storage.

In order to analyze anchors without removing them from their context, we create 3D digital models of the anchors by using two different software programs for photogrammetric analysis, PhotoModeler Scanner (Eos Systems, Inc.) and PhotoScan Pro (Agisoft). We compare measurements and volumes attained via traditional measuring techniques, such as the use of measuring tapes and water displacement, with those calculated from the 3D digital model. Finally, after deriving densities, we use these digitally calculated volumes to estimate mass. This approach yields results comparable to using traditional measuring tapes and scaled photographs, and will ultimately benefit typological characterization for archaeological analyses and cultural resource management purposes.

Review of Recent Advances in Underwater Photogrammetry

Recent advances in technology have made photogrammetry an easy and effective means of creating 3D records of archaeological sites and objects, thereby digitally preserving cultural heritage (De Reu et al. 2013; Kersten and Lindstaedt 2012). Photogrammetry has been used extensively not only for recording terrestrial sites (Olson et al. 2013; Verhoeven 2011), but also for recording underwater features, sites, and objects. Stemming from the use of photomosaics underwater to rapidly and accurately map targets, 3D digital point cloud models record objects and features with precision (Ballard et al. 2001; Green and Gainsford 2003; Green et al. 2002; Sedlazeck et al. 2010). While the underwater environment imposes some constraints on the accuracy of photogrammetric measurements due to refraction and limited visibility (Telem and Filin 2010), these methodologies have proven effective in underwater conditions with poor visibility, limited bottom time for divers due to depth and decompression constraints, or deep water surveys in which cameras have been attached to remotely operated vehicles (Demesticha et al. 2014; Foley et al. 2009; Kwasnitschka et al. 2013; McCarthy and Benjamin 2014). Photogrammetry has the benefit of being suitable for both large-scale sites, in which an entire shipwreck is recorded over multi-year campaigns (Demesticha et al. 2014; Skarlatos et al. 2012), as well as small surveys in which a pair of divers can extensively document a large area (McCarthy and Benjamin 2014) or individual objects, including anchors (McCarthy 2012).

Moreover, digital data can provide new ways of analyzing and comparing sites and objects, especially when fully integrated in multi-referential databases that link together geo-referenced objects with other data. This digital preservation not only facilitates the visualization of objects and sites (Sedlazeck et al. 2010), but also enhances the types of analyses that can be conducted. For instance, volumetric analysis has precedence in other areas of archaeological study, such as the calculation of volume for ceramic containers in order to ascertain standardization (Zapassky et al. 2009). Digital models are also created in nautical studies in order to assess how a ship would have sailed, to derive hull lines, and to approximate cargo capacities (Kocabaş 2012; Martorelli et al. 2014). In this paper, we add to this list of analyses with a methodology for obtaining 3D models of *in situ* stone anchors that enables the calculation of approximate volumes and estimation of weight values. These results will yield a more comprehensive archeological analysis of anchor typologies that can improve our understanding of their use and establish a baseline for comparing data.

Methodology

During an underwater survey from 1993-1996 conducted by the Maroni *Tsaroukkas* Seabed Project, anchors were identified in an area off Maroni-*Tsaroukkas*, Cyprus, in direct association with LBA ceramics, which provided a possible date for this anchorage (Manning et al. 2002). However, winter storms in this area can deposit or scour the sandy substrate, thus burying or uncovering anchors and making it difficult to evaluate the total extent of this anchorage. Therefore, in 2014, the area from Maroni-*Limni* to *Tsaroukkas* was reassessed as part of the Cyprus Ancient Shoreline Project (Figure 1), which concentrated on extending views of coastal and maritime interaction in LBA Cyprus (Andreou and Sewell 2015). As part of this survey, in order to develop a methodology for analyzing anchors without disturbing their context, we used traditional measuring techniques and rendered 3D digital images of stone anchors in two different photogrammetric programs, PhotoScan Pro (Agisoft) version 1.0.4 and PhotoModeler Scanner (Eos Systems, Inc.) version 6.4. These methods were first tested on anchors that had been excavated and raised in 1996 and implemented on *in situ* anchors surveyed in 2014.

Anchors on land were photographed using a Lumix DMC-TZ5 digital camera (9.0 megapixel, wide-angle Leica zoom lens). Underwater images were collected using a Sony NEX5 digital camera (16.1 megapixel, 16 mm lens) in an Acquapazza housing with a dome port. For each anchor, the image set included the whole width of the anchor and represented a closed loop set of images, in which the last image overlapped with the first. For the PhotoModeler software, both cameras were calibrated using the same single sheet calibration method as outlined in the PhotoModeler instruction manual. The cameras were not calibrated for PhotoScan since, as other studies have shown, the images would have a very low susceptibility to error in lens geometry due to the closed loop sets, the use of scale bars, and the visibility of the entire anchor in the photograph (Luhmann et al. 2013:332; Remondino et al. 2014).

Since both Agisoft PhotoScan (De Reu et al. 2013; McCarthy and Benjamin 2014; Olson et al. 2013) and PhotoModeler Scanner (Barazzetti et al. 2011; Pollefeys et al. 2003; Tejerina Antón et al. 2012) are frequently used in archaeological applications and published elsewhere, we focus in this paper on the procedures we adapted to the underwater environment. To aid in linking the photographs, we printed computer generated ringed automatically detected (RAD) targets from the PhotoModeler Scanner software, which were laminated in strips of four to facilitate their use underwater. Once placed around the anchor, the targets were secured with weights to eliminate movement. Each target is unique so that the software matches the same points in each photograph and links the different angles. Since the distance between each target on the strip was known and because the targets were fixed in place, these targets also provide a known measurement for scaling and orienting the object. Depending on an object's size, up to six laminated strips of targets were placed around each object.

Photographing Anchors On Land and In Situ *Underwater*

Eight stone anchors were recorded on land and had been in dry storage since their prior excavation in the early 1990s. Six of these anchors (labeled as TSBS) had been removed from the underwater environment off the LBA site of Maroni-*Tsaroukkas* in 1996 (Manning et al. 2002:114). Additionally, two anchor-type stones came from terrestrial contexts, either excavated within the terrestrial remains at the same LBA site (labeled as MT418) or recovered during archaeological survey in the surrounding Maroni Valley (labeled as MVASP187) (Manning et al.

1994; Manning and Conwell 1992; Manning et al. 2002:114). Five of the anchors had single-holes and three of the anchors had three-holes.

Each dry anchor was placed on a green tarp, which served as a contrasting surface to minimize background noise, and the RAD targets were positioned around the anchor. Photographs were taken according to the procedures required by version 6.4 of PhotoModeler Scanner, which uses paired photographs to generate the 3D model (Figure 2). The same set of photographs was used in PhotoScan. A series of eight to ten pairs of photographs were taken around each anchor with the same focal length (set at 4.7 mm). An approximate 45 degree angle was maintained between the object and the camera; in addition, a set of photographs was taken directly overtop the anchor. Both sides of the anchor were photographed.

For these eight anchors that had been removed from their context, we acquired linear and volumetric measurements as well as mass. The linear measurements, which were taken via tape measure, can also be compared to those previously acquired when the anchors were *in situ*, either underwater or on land, during prior survey in the early 1990s. Volumes for each anchor were obtained using a displacement method: each anchor was lowered into a large container with a known quantity of water and the amount of water displaced was recorded with approximately ± 50 ml accuracy. Finally, each anchor was weighed using a DIGI DI-28 ± .05 kg scale from the Larnaca Carob Cooperative located in Zygi, Cyprus.

Nine anchors were recorded *in situ* underwater using the photogrammetric methodology: seven of these anchors had single-holes, and two had three-holes. Anchors were identified and mapped using a Garmin GPSMAP 78sc using WGS84 datum with an accuracy of ± 3 m. Prior to documentation, the targeted object was cleaned of marine organisms, such as seaweeds, that would obstruct photographic recording of clear edges. Additionally, divers removed the sandy substratum from around the anchors in order to expose the full profile. In cases where substantial hand-fanning was required to remove sand overburden or to expose depth profiles, divers returned sand to the area after recording to avoid instigating scouring.

These *in situ* anchors were imaged for photogrammetry and recorded using traditional measuring techniques. Working in pairs, divers recorded the linear measurements of stone anchors using a tape measure. A diver set out the RAD targets to prepare the anchor for imaging. To photograph the anchor, a diver would swim twice around each object, keeping an approximate three-meter distance to the anchor (Figure 3). Without adjusting focal length (set at 16 mm), the first circuit generated a series of images at an angle of approximately 20-30 degrees between the camera and object, followed by a second circuit taking photos at an angle of approximately 45 degrees. Swimming over the anchor, more photographs of the top of each anchor were collected to better capture the inside of any holes. Between twenty and forty pairs of photographs were taken to ensure adequate coverage, albeit not all of these photos were necessary to create the digital models. As the *in situ* anchors were not physically moved, only the exposed surfaces of these anchors were photographed.

Creating Three Dimensional Models

We followed the workflow outlined in the manuals for PhotoModeler Scanner and PhotoScan Pro to generate a dense point cloud of the anchor and a triangulated mesh model from the photographs (Figures 4 and 5). For PhotoScan, the entire photoset was used to create a point cloud model of the anchor in the surrounding environment; from this model, the anchor was isolated to generate a triangulated mesh. For PhotoModeler Scanner, image pairs were selected based upon their suitability and the anchor was isolated to create both the point cloud and mesh models. Because different techniques were implemented in PhotoModeler Scanner and PhotoScan to generate models, the total number of data points varied between programs (Tables 1 and 2). A scale was assigned based on the known distance between the RAD targets. Both programs include features that can be used to calculate linear and volumetric measurements of the models. Since only one side of the *in situ* anchors was photographed, the shape of the unseen underside was assumed to be flat, which obviously introduces a variable level of error depending on each artifact's unique shape, as discussed below.

Results

This study offers both qualitative and quantitative comparative data regarding the documentation of stone anchors *in situ* using photogrammetric and traditional measuring techniques. These resulting accuracies are connected to the environmental conditions impacting site-specific photographic acquisition as well as the specific parameters we implemented in the different software to achieve precision values. The use of the two software programs highlights the applicability of this methodology across different platforms, rather than a direct comparison of accuracies between the software. Even with our small sample size and these variations in conditions and parameters, the results indicate a close comparison between traditional and photogrammetric methods for recording anchors and highlight the benefits of creating a model for further analysis.

Comparison of Linear Measurements

While linear measurements given in this study were taken at multiple places along the anchor, only the principal measurements of length, width, and depth are presented here for ease of comparison (Figure 6). Since a tape measure is the traditional tool for acquiring measurements underwater, these measurements are used as references to which we compare those derived from the 3D models created in PhotoModeler Scanner and PhotoScan. For the anchors on land, there is a close correlation between measurements attained via tape measure and PhotoModeler (r = .99) as well as between tape measure and PhotoScan (r = .99). The average absolute difference from the reference measurements for PhotoModeler is 2.3 cm and for PhotoScan is 1.4 cm (Table 3). Measurements vary as much as 8 cm for PhotoModeler and 5 cm for PhotoScan on an anchor that is 44 cm in width. For the anchors *in situ*, there is also a close correlation between measurements attained via tape measure and PhotoModeler (r = .98) and PhotoScan (r = .99). The average absolute difference from the reference measurements for PhotoModeler is 3.3 cm and for PhotoScan is 3.6 cm (Table 4). Measurements of *in situ* anchors varied as much as 9 cm for PhotoModeler and 10 cm for PhotoScan on anchor 14, which is 78 cm in width according to the tape measure. While the absolute difference is greater for the anchors *in situ* than those on land, average absolute differences for the two programs were within 1 cm for experiments on land and underwater.

However, these results by no means reflect the accuracy of photogrammetry since a tape measure does not yield results without user error, especially when measurements are obtained underwater from irregular-shaped objects such as anchors. Recorded measurements are often made between different points and across a surface. Standard deviation for the three techniques conducted on the anchors on land is 1.6 cm and for the anchors *in situ* is 2.7 cm. Additionally, the anchors on land had been measured *in situ* when first excavated in the early 1990s and were re-measured using a tape for this study. Measurements differed on average by 1.6 cm (Table 5). Only seven out of the twenty-four measurements yielded the same result.

Comparison of Volumes

Volumes are approximated based on the surfaces generated in PhotoModeler Scanner and PhotoScan Pro. For the anchors documented on land, the volumes of the two sides differed on average by 8 percent of the overall volume for PhotoModeler Scanner and 10 percent for PhotoScan (Table 6). This difference in volume between the two sides is expected, since it reflects the variability in shape between the sides. Consequently, if volume is approximated from only one side of an anchor using the photogrammetric method, on average there likely will be as much as an 8-10 percent difference between the actual volume and our photogrammetrically estimated calculation.

Additionally, volumes of the anchors on land were also calculated via water displacement, which serves as a reference for the volumetric measurements from the 3D digital models. Volumes calculated from the digital models in PhotoScan and PhotoModeler are greater than those attained via the displacement method (Table 6). Moreover, the volumes derived from PhotoScan have a better correlation (*r* = .92) to the water displacement volumes than the correlation from PhotoModeler (*r* = .85). As discussed below, the variations between these two methods are impacted by environmental and user-related factors in image acquisition and processing, which is especially evident in the results of PhotoModeler Scanner that had a higher residual error in the projects due to the geometries associated with the pairs of photographs.

When the methodology was applied to the anchors *in situ*, volumes vary between the two programs by an average of 8 percent (Figure 7). Four of the *in situ* anchors (1, 2, 6, 14) have volumes with less than 5 percent of a difference between the two programs. Those anchors with the greatest variation (anchors 7 and 9) had single holes, had little marine growth, and were not imaged in poor visibility.

Derivation of Masses

We assessed approximations of mass by using the known weight of the dry anchors and the derived volumes to calculate the density of the stone. Due to their visual appearance, we determined that the stone anchors analysed in this paper were likely carved from limestone, which is a sedimentary rock composed principally of calcium carbonate or the double carbonate of calcium and magnesium. Previous research shows that the geological composition of limestone can be quite variable, even within the same quarry (Shaw 1995:286). However, a common density of limestone ranges from 2.1-2.5 g/cm^3 (Bell 2007; Cobb 2009; Oates 1998). As expected from the volume differences in PhotoModeler Scanner, the density is much lower than common limestone ranges (1.4-2.0 g/cm^3) but the average volume for the anchors recorded in PhotoScan yields a density ranging from 2.0-2.8 g/cm^3 (Table 6), which is close to the common range of the known density of limestone. When this average density is applied to the volumes of the anchors *in situ*, approximations of mass are determined to be within ± 8 percent of the actual mass based on variations in densities and volume approximations (Figure 8).

Discussion

In this study, photogrammetric methods using PhotoModeler Scanner and PhotoScan Pro were tested on two sets of anchors: one set of anchors previously removed from their archaeological context and one set of anchors still *in situ* underwater. These results illustrate one aspect of how a photogrammetric methodology can be implemented as an analytical tool in addition to its benefits for archaeological visualization.

Linear measurements taken from the 3D digital models for both programs were comparable to those taken using a measuring tape for both sets of anchors. However, there was more variation in measurements of the *in situ* anchors likely due to the underwater conditions that were not beneficial to producing optimally accurate results. Previous studies have noted the importance of photographing objects on a contrasting background in order to obtain the best results (Olson et al. 2013:250), but this condition is difficult to attain underwater, especially for stone anchors, since the stone is often similar in appearance to the sandy and rocky substrata. For instance, the two *in situ* anchors, 13 and 14, that had the greatest variation in linear measurements were photographed in poorer visibility and lower light than the others, perhaps influencing the ability to distinguish the anchor from the surrounding substrata. Additionally, any marine growth on the anchors camouflages and distorts the extent and shape of surfaces, making it necessary to remove this growth prior to documentation so as not to distort the final shape of the anchor. The most variations between the measurements derived from photogrammetry software and traditional recoding techniques were observed in volumetric calculations. Given the high level of accuracy for PhotoScan and PhotoModeler that have been shown elsewhere (Brutto and Meli 2012; Dall'Astra and Roncella 2014; Koutsoudis et al. 2014; Tejerina Antón et al. 2012), the quality of the volumetric calculations was influenced by the parameters of our two different workflows in each software and the anchors' difficult shapes, such as the holes and edges, which impacted the accuracy of measurement points. For instance, the PhotoScan workflow used all of the images available to render an initial model at the highest possible resolution, whereas the PhotoModeler workflow used selected images to render a model at a selected resolution. While the quality of the final 3D reconstruction does not have to be proportional to the number of data points (Remondino et al. 2014:161), surfaces that are rendered at a lower resolution can yield models with greater volumes as the mesh smoothes over these details, as shown in the PhotoModeler measurements. Additionally, size of the object may also influence the accuracy of measurements, as noted by a prior study in which greater errors in linear measurements were associated with smaller objects (McCarthy and Benjamin 2014). Further experiments with a greater sample size need to be conducted to determine whether these variations in volume are related to the size of the anchor or correlated to anchor typologies, especially the number of holes.

A photogrammetric methodology has several advantages over traditional recording techniques. Although there is variation in linear measurements between methodologies, 3D digital models provide an accurate way of judging the maximum edge for the anchor, essentially reporting absolute maximum planar measurements rather than surface measurements. Furthermore, when recording measurements underwater, divers must judge the limits to surface edges, which can be particularly problematic on objects such as anchors with irregular sides and sloping edges. Moreover, measurements attained via tape measure can also vary greatly, as shown by the different measurements of the same anchors conducted underwater and on land. Generating images for photogrammetry can also be acquired more quickly than the traditional methods of using a tape measure, scaled photographs, and a frame for drawing the shape of an object. Other advantages include the ability to accurately document an object without removing it from its underwater context and to conduct post fieldwork analyses on each anchor, resulting in a more thorough comparative analysis.

In order not to disturb an object from its context, this methodology assumes an approximation of the underside of the anchors, which can greatly impact the calculations of volume and mass. As shown by the results, the volumes between the two sides could differ as much as 10 percent of the overall volume. Given the effects of the underwater environment on photogrammetry, we would also expect an even greater difference in results for the *in situ* anchors. Since all of the anchors on land were photographed in a way to completely expose the edges, this reduced the amount that an anchor would need to be estimated when only one side was photographed. For the *in situ* anchors, while the edges were exposed, it was difficult to capture the full edge, which meant that more of the *in situ* anchor needed to be approximated. In order to obtain a precise volume, all sides of the anchor would have to be photographed to allow for seamless stitching of the photographs. However, in preliminary experiments, repositioning an anchor on the smallest edge, in a “standing technique”, provides one way to mitigate the amount of user error that may be introduced through approximating the underside of an anchor, albeit this method would completely remove the anchor from its *in situ* context. Further tests need to be conducted to determine the degree to which this technique will benefit increased accuracy for deriving mass. Additional work can also examine the accuracy of the photogrammetric workflow by using objects with known physical attributes (i.e., linear dimensions, volumetric measurements, and mass) to test these results underwater. This procedure would help quantify variations in photo acquisition and quality as well as assumptions about density and edge coverage.

Future work could also improve upon the scaling devices used in the photographs. In order to provide a scale for creating 3D digital models, the anchors were photographed in the same context as a measuring device, or in the case of this study, something with a known distance, such as the RAD targets from the PhotoModeler Scanner software. However, the laminated RAD targets used in this study were not rigid, so they bent when secured to the seafloor, thereby reducing the distance between the two points on the target that could be selected to scale the model. This effectively would render the objects as larger than they actually were. A solution to minimize this potential error would be to mount the printed targets on a rigid, dense plate that secures the targets in place.

In order to calculate an anchor’s mass, a photogrammetric and 3D imaging methodology also requires knowledge of an object’s composition. The object must either have a singular composition or have delineated components that can be identified and measured. All the anchors used in this study were of the same appearance and all assumed to be carved from limestone. As only direct physical measurement will enable an accurate mass or density calculation, we had to assume that the anchors on land were comparatively indicative of the range of densities of the anchors *in situ*. In doing so, we are able to approximate a mass for anchors *in situ* using the photogrammetrically derived volumes and the densities that have been calculated from the anchors with known masses. Thus, while recovery and direct measurement remains the simplest method of acquiring the mass, photogrammetry offers an effective option for determining anchor mass without the logistics and costs of recovery or the ongoing costs associated with collection management.

Conclusions and Future Study

For underwater research, advances in software for photogrammetry have expanded capabilities to quickly record and digitally preserve dimensions, surfaces, and contextual relationships. These new methodologies are particularly important for small research groups where funding and team size might be limited. While both measuring via tape and photogrammetry theoretically can be managed by one diver, depending on the size of the area or object, obtaining measurements by tape is significantly facilitated by two divers actively working together: one to write the measurements and one to manage the tape; in comparison, photogrammetry only requires one diver to be focused on obtaining measurements. Because of these components, this method has significant advantages for underwater surveys and on sites with limited bottom time.

Although the use of photogrammetry to document underwater cultural remains is complementary to traditional recording techniques, this technique provides a high-resolution documentation of the surface of anchors so that it can be the sole means for calculating measurements. Not only does photogrammetry potentially enable detailed surface and approximate volume information to be derived, it also offers more options for comparative analyses without necessitating the removal of a stone anchor from its *in situ* position; it generates a comprehensive record from which future analysis can be conducted. Leaving the object *in situ* preserves the contextual relationships for future study. In particular, these models can be reassessed to benefit typological classification of anchors, thereby aiding in reconstructing trade and transportation networks in the ancient Mediterranean. These data will also aid the creation of a digital database from which scholars can compare their findings and draw parallels and comparisons in size, shape, weight, and hole placement. Beyond survey, these weights and assessments play a role in understanding how anchors might have been deployed and how ships would have moored at anchorages like that off Maroni-*Tsaroukkas*.

This method has a significant value for cultural resource management and education. Due to their proximal location to coastlines, stone anchors have a history of being removed from the seafloor. Once anchors are imaged and geo-referenced, this technique provides a digital means to preserve what may be hidden by seasonal deposition or lost to looting. Because surfaces are accurately recorded, this ‘digital fingerprint’ could also be used to identify a particular object that had been removed from the marine environment. Thus, this record can be advantageous to underwater cultural heritage managers to aid their protection of sites and associated objects. Finally, the digital models can be incorporated into informative websites or reproduced for exhibits and educational purposes using 3D printing.

As described earlier, future work should focus on eliminating methodological assumptions and errors in this technique, but also testing the derivation of mass for other objects, particularly those that are heavy or those that cannot be moved, such as stone blocks used in architectural features. A similar methodology could estimate the mass of stones used to construct walls, and thus analyze building technologies by addressing questions of resource acquisition. These further lines of research will only add to establishing 3D digital models as an important and invaluable research tool for analysis and underwater cultural resource management.

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References Cited

Andreou, Georgia, and David Sewell

2015 Tochni-Lakkia Revealed: Reconsidering Settlement Patterns in the Vasilikos and Maroni Valleys, Cyprus. In *PoCA (Postgraduate Cypriot Archaeology) 2012*, edited by Hartmut Matthäus, Bärbel Morstadt, and Christian Vonhoff, pp. 198-219. Cambridge Scholars Publishing, Newcastle.

Ballard, Robert, Fredrik Hiebert, Dwight Coleman, Cheryl Ward, Jennifer Smith, Kathryn Willis, Brendan Foley, Katherine Croff, Candace Major, and Francesco Torre

2001 Deepwater Archaeology of the Black Sea: The 2000 Season at Sinop, Turkey. *American Journal of Archaeology* 105:607-623.

Barazzetti, Luigi, Luigia Binda, Marco Scaioni, and Paolo Taranto

2011 Photogrammetric Survey of Complex Geometries with Low-cost Software: Application to the ‘G1' Temple in Myson, Vietnam. *Journal of Cultural Heritage* 12:253-262.

Bell, Frederic

2007 *Basic Environmental and Engineering Geology*. Whittles Publishing Limited, Dunbeath.

Brutto, M., and P. Meli

2012 Computer Vision Tools for 3D Modelling in Archaeology. *International Journal of Heritage in the Digital Era* 1:1-6.

Cobb, Fiona

2009 *Structural Engineer's Pocket Book*. 2nd ed. Butterworth-Heinemann, London.

Dall'Asta, E., and R. Roncella.

2014 A Comparison of Semiglobal and Local Dense Matching Algorithms for Surface Reconstruction. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-5:187-194.

Demesticha, Stella, Dimitrios Skarlatos, and Andonis Neophytou

2014 The 4th-century B.C. Shipwreck at Mazotos, Cyprus: New Techniques and Methodologies in the 3D Mapping of Shipwreck Excavations. *Journal of Field Archaeology* 39:134-150.

De Reu, Jeroen, Gertjan Plets, Geert Verhoeven, Philippe De Smedt, Machteld Bats, Bart Cherretté, Wouter De Maeyer, Jasper Deconynck, Davy Herremans, Pieter Laloo, Marc Van Meirvenne, and Wim De Clercq

2013 Towards a Three-dimensional Cost-effective Registration of the Archaeological Heritage. *Journal of Archaeological Science* 40:1108-1121.

Foley, Brendan, Katerina Dellaporta, Dimitris Sakellariou, Brian Bingham, Richard Camilli, Ryan Eustice, and Dionysis Evagelistis

2009 The 2005 Chios Ancient Shipwreck Survey: New Methods for Underwater Archaeology. *Hesperia* 78:269-305.

Frost, Honor

1963 From rope to chain: On the development of anchors in the Mediterranean. *The Mariner's Mirror* 49: 1-20.

1970 Bronze Age Stone Anchors from the Eastern Mediterranean. *The Mariner’s Mirror* 56: 377-394.

Green, Jeremy, and Matthew Gainsford

2003 Evaluation of Underwater Surveying Techniques. *International Journal of Nautical Archaeology* 32:252-261.

Green, Jeremy, Sheila Matthews, and Tufan Turanli

2002 Underwater Archaeological Surveying using PhotoModeler, VirtualMapper: Different Applications for Different Problems. *International Journal of Nautical Archaeology* 31:283-292.

Kersten, Thomas, and Maren Lindstaedt

2012 Image-Based Low-cost Systems for Automatic 3D Recording and Modelling of Archaeological Finds and Objects. In *Progress in cultural heritage preservation 4th International Conference, EuroMed 2012: Limassol, Cyprus, October 29-November 3, 2012,* edited by Marinos Ioannides, Dieter Fritsch, Johanna Leissner, Rob Davies, Fabio Remondino, and Rossella Caffo, pp. 1-10. Springer-Verlag, Berlin.

Kocabaş, Ufuk (editor)

2012 *The 'old ships' of the 'new gate' = Yenikapı'nın eski gemileri*. 2nd ed. Ege Yayınları, İstanbul.

Koutsoudis, Anestis, Blaž Vidmar, George Ioannakis, Fotis Arnautoglou, George Pavlidis, and Christodoulos Chamzas.

2014 Multi-image 3D Reconstruction Data Evaluation. *Journal of Cultural Heritage* 15:73-79.

Kwasnitschka, Tom, Thor H. Hansteen, Colin W. Devey, and Steffen Kutterolf

2013 Doing Fieldwork on the Seafloor: Photogrammetric Techniques to Yield 3D Visual Models from ROV Video. *Computers & Geosciences* 52:218-226.

Luhmann, Thomas, Stuart Robson, Stephen Kyle, and Jan Boehm

2013 *Close-Range Photogrammetry and 3D Imaging*. 2nd ed. De Gruyter, Berlin.

McCarthy, John

2012 Undesignated Site Assessment: Sicar Rock, Dunbar, East Lothian. Unpublished fieldwork report for Wessex Archaeology on behalf of Historic Scotland. Electronic Document, http://orapweb.rcahms.gov.uk/wp/00/WP000743.pdf, accessed October 15, 2015.

McCarthy, John, and Jonathan Benjamin.

2014 Multi-image Photogrammetry for Underwater Archaeological Site Recording: An Accessible, Diver-Based Approach. *Journal of Maritime Archaeology* 9:95-114.

McCaslin, Dan

1980 *Stone Anchors in Antiquity: Coastal Settlements and Maritime Trade-routes in the Eastern Mediterranean ca. 1600-1050 B.C.* P. Åströms, Göteborg.

Manning, Sturt W., Diane L. Bolger, M.J. Ponting, Louise Steel, and A. Swinton

1994 Maroni Valley Archaeological Survey Project: Preliminary report on 1992-1993 Seasons. *Report of the Department of Antiquities, Cyprus* 1994:345-367.

Manning, Sturt W., and D.H. Conwell

1992 Maroni Valley Archaeological Survey Project: Preliminary Report on the 1990-1991 Field Seasons. *Report of the Department of Antiquities, Cyprus* 1992:271-283.

Manning, Sturt W., David Sewell, and Ellen Herscher

2002 Late Cypriot I A Maritime Trade in Action: Underwater Survey at Maroni Tsaroukkas and the Contemporary East Mediterranean Trading System. *The Annual of the British School at Athens* 97:97-162.

Martorelli, Massimo, Claudio Pensa, and Domenico Speranza

2014 Digital Photogrammetry for Documentation of Maritime Heritage. *Journal of Maritime Archaeology* 9:81-93.

Oates, Joseph A. H.

1998 *Lime and Limestone: Chemistry and Technology, Production and Uses*. Wiley-VCH, New York.

Olson, Brandon, Ryan A. Placchetti, Jamie Quartermaine, and Ann E. Killebrew

2013 The Tel Akko Total Archaeology Project (Akko, Israel): Assessing the Suitability of Multi-scale 3D Field Recording in Archaeology. *Journal of Field Archaeology* 38:244-262.

Pollefeys, Marc, Luc Van Gool, Maarten Vergauwen, Kurt Cornelis, Frank Verbiest, and Jan Tops

2003 3D Recording for Archaeological Fieldwork. *IEEE Computer Graphics and Applications* 23:20-27.

Remondino, Fabio, Maria Grazia Spera, Erica Nocerino, Fabio Menna, and Francesco Nex

2014 State of the Art in High Density Image Matching. *The Photogrammetric Record* 29: 144-166.

Sedlazeck, Anne, Kevin Köser, and Reinhard Koch

2010 Supporting Underwater Archaeology by 3D Reconstruction from Underwater Images. *Skyllis: Zeitschrift für Unterwasserarchäologie* 10:179-186.

Shaw, Joseph.

1995 Two Three-holed Stone Anchors from Kommos, Crete: Their Context, Type and Origin. *International Journal of Nautical Archaeology* 24:279-291.

Skarlatos, Dimitrios, Stella Demesticha, and Stavroula Kiparissi

2012 An ‘Open’ Method for 3D Modelling and Mapping in Underwater Archaeological Sites. *International Journal of Heritage in the Digital Era* 1:1-24.

Tejerina Antón, Daniel, Joaquín Bolufer i Marqués, Marco Aurelio Esquembre Bebia, and José Ramón Ortega Pérez

2012 Documentación 3D de pinturas rupestres con Photomodeler Scanner: los motivos esquemáticos de la Cueva del Barranc del Migdia (Xàbia, Alicante). *Virtual Archaeology Review* 3:64-7.

Telem, Gili, and Sagi Filin

2010 Photogrammetric Modeling of Underwater Environments. *ISPRS Journal of Photogrammetry and Remote Sensing* 65:433-444.

Tóth, János Attila

2002 Composite Stone Anchors in the Ancient Mediterranean. *Acta Archaeologica Academiae Scientiarum Hungaricae* 53:85-118.

Verhoeven, Geert

2011 Taking Computer Vision Aloft – Archaeological Three-dimensional Reconstructions from Aerial Photographs with PhotoScan. *Archaeological Prospection* 18:67-73.

Wachsmann, Shelley

1998 *Seagoing Ships and Seamanship in the Bronze Age Levant*. Texas A&M University Press, College Station, TX.

Zapassky, Elena, Israel Finkelstein, and Itzhak Beneson

2009 Computing Abilities in Antiquity: The Royal Judahite Storage Jars as a Case-study. *Journal of Archaeological Method and Theory* 16:51-67.

Figure and Table Captions

Figure 1. Map of the survey area off south-central Cyprus for anchors recorded *in situ* from Maroni-*Limni* to Maroni-*Tsaroukkas*. Red dots indicate the location of anchors that have been recorded *in situ*.

Figure 2. Photographs of anchor TSBS005 are shown. In general, anchors that had been previously removed from their archaeological context were photographed using a tarp to maximize contrast between the anchor and the background. Computer-generated RAD targets assisted the software in linking photographs.

Figure 3. A total of 48 photographs were taken for in situ anchor 5. While all of these images were used for PhotoScan, a selection of 14 photos, shown here, were used for PhotoModeler Scanner. Once partially cleaned of biological growth and the sides exposed, *in situ* anchors were photographed with RAD targets.

Figure 4. A comparison of triangulated mesh models for land anchor TSBS005: a) PhotoModeler Scanner (mesh with 65,191 triangles) and b) PhotoScan (mesh with 142,068 triangles).

Figure 5. A comparison of triangulated mesh models for *in situ* anchor 5: a) PhotoModeler Scanner (mesh with 85,288 triangles) and b) PhotoScan (mesh with 41,181 triangles).

Figure 6. Diagram of an anchor indicating measurements presented in this paper: maximum length, width at base, and depth near the main hole.

Figure 7. The volumes (cm^3) for anchors *in situ* varied between the two programs by an average of 8 percent.

Figure 8. Derived mass (kg) of anchors *in situ* calculated with average density of limestone (2.3 g/cm^3). Error bars represent the range in limestone densities (2.1-2.5 g/cm^3).

Table 1. Total number of data points generated for anchor models in PhotoModeler Scanner and PhotoScan for the anchors measured on land.

Table 2. Total number of data points generated for anchor models in PhotoModeler Scanner and PhotoScan for the anchors measure *in situ*.

Table 3. In comparing measurements for the anchors on land, photogrammetric measurements differed from the reference tape measurements by 2.3 cm on average for PhotoModeler Scanner and by 1.4 cm on average for PhotoScan.

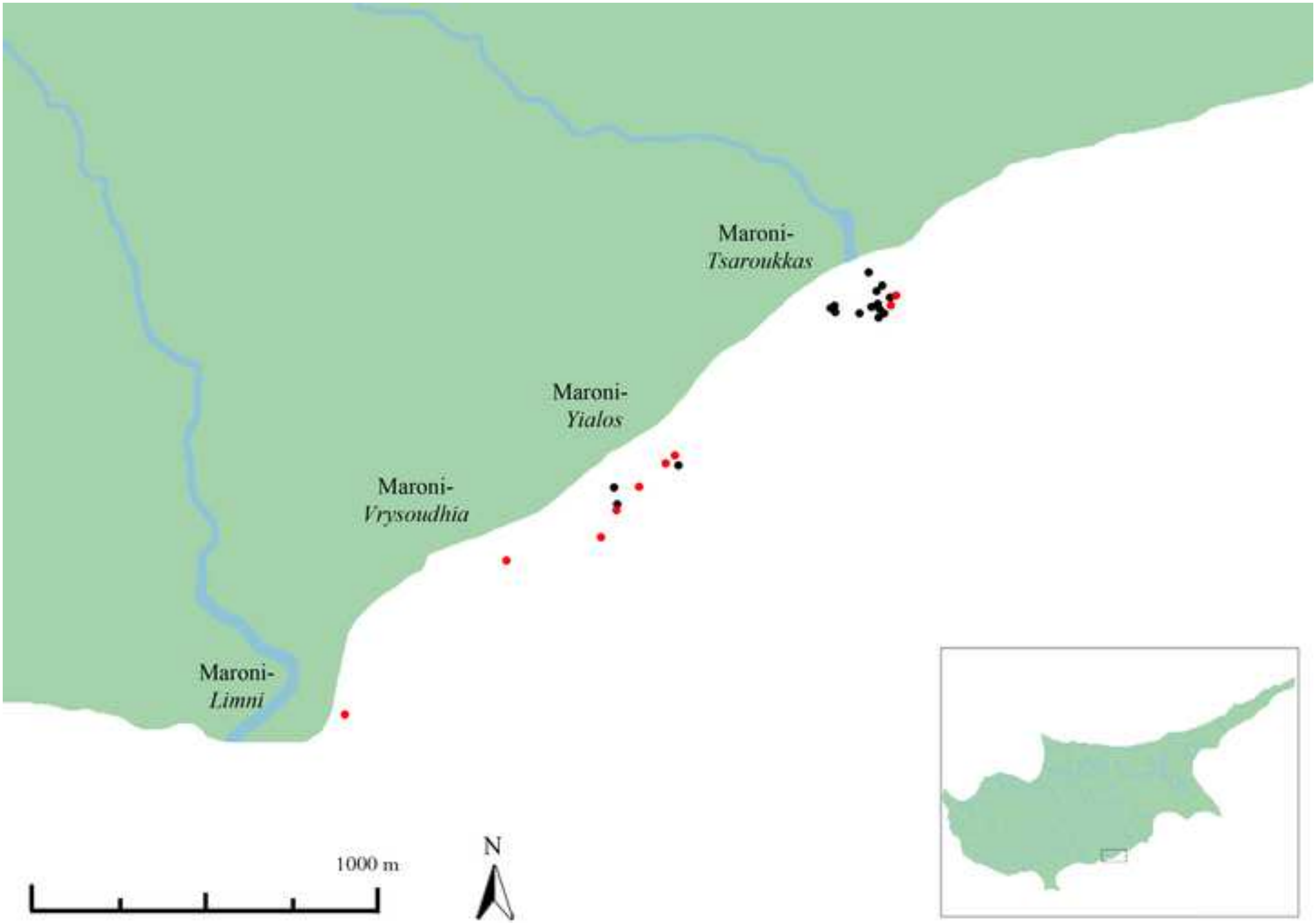
Table 4. In comparing measurements for anchors *in situ*, photogrammetric measurements differed from the reference tape measurements by 3.3 cm on average for PhotoModeler Scanner and by 3.6 cm on average for PhotoScan.

Table 5. Absolute difference for anchors on land between measurements attained when excavated in the early 1990s and re-measured for this study. Out of the twenty-four measurements taken, seventeen were different. On average, measurements differed by 1.6 cm.

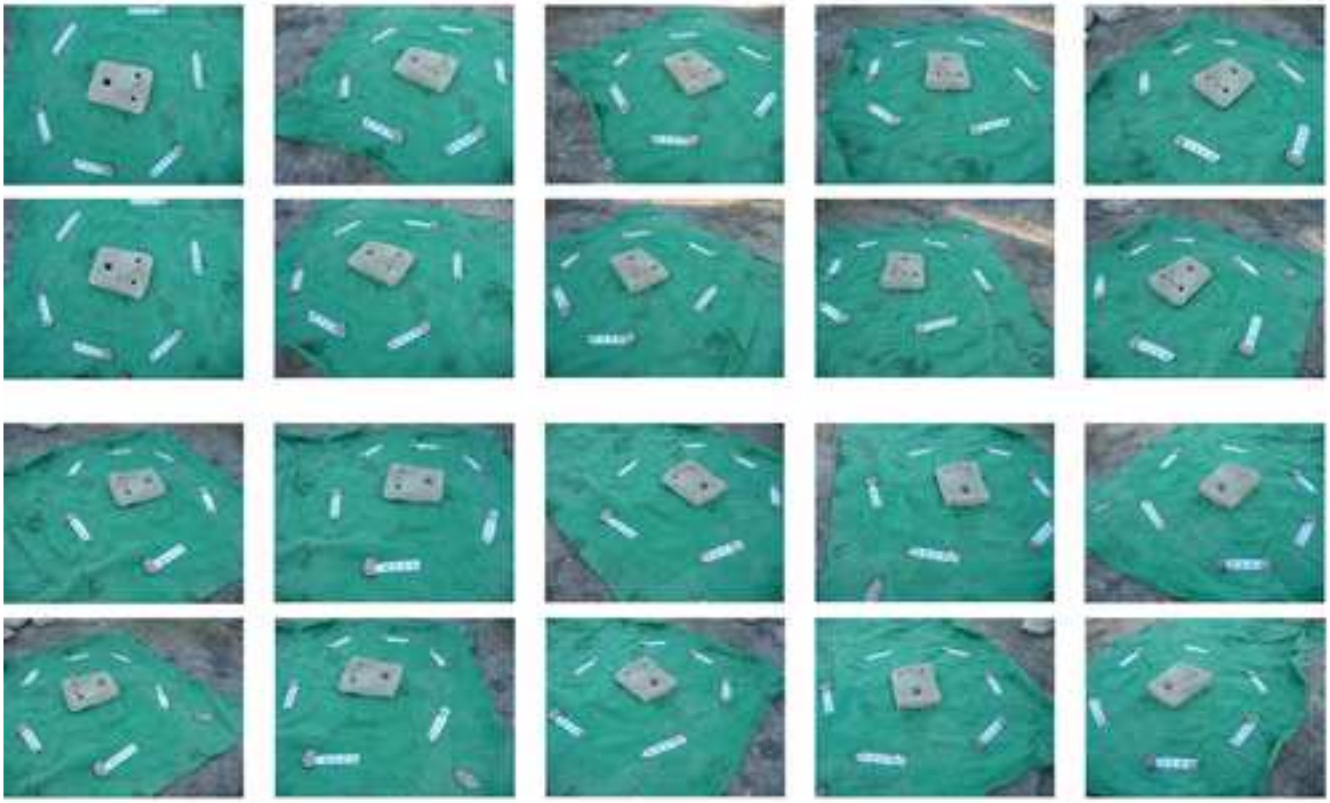
Table 6. Volumes (cm^3) for anchors on land with each side of the anchor imaged separately. Displacement (ml) measured with +/- 50 ml accuracy. NR = not recorded because the anchors were too large to be measured given the available equipment.

Table 7. The known mass and average volume used to calculate the density of each anchor on land. Volumes calculated in PhotoScan more closely match the known density of limestone (2.1-2.5 g/cm^3).

Figure 1 Click here to download Figure Fig 1_Anchors_MT_2014.jpg



TSBS 005 - Side 1



TSBS 005 - Side 2

Figure 3

Click here to download Figure Fig 3_Underwater Thumbnails.jpg

In Situ Anchor - 5

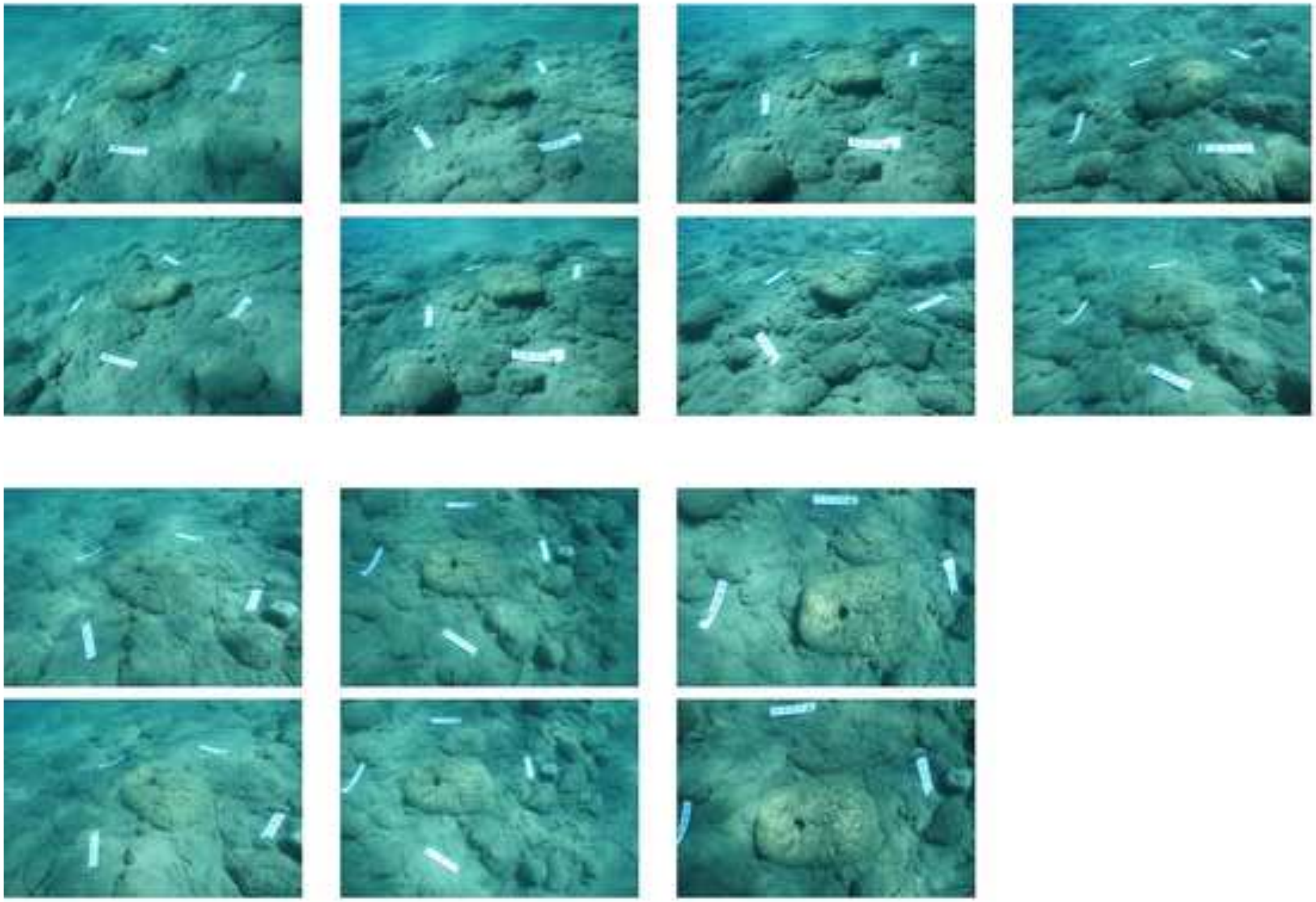


Figure 6

Click here to download Figure Fig 6_Anchor Outline.jpg

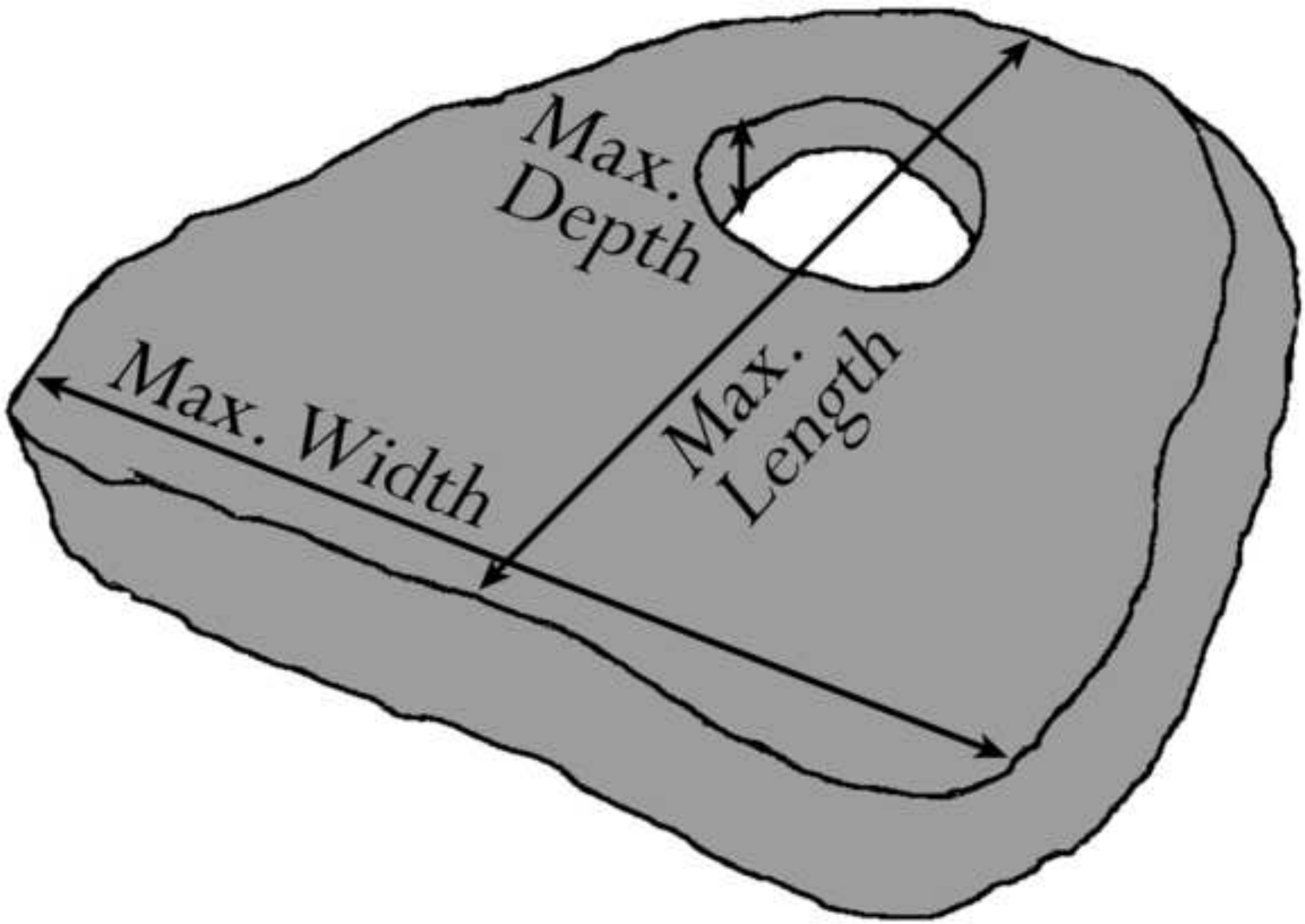


Figure 7

Click here to download Figure Fig 7_in situ volumes.jpg

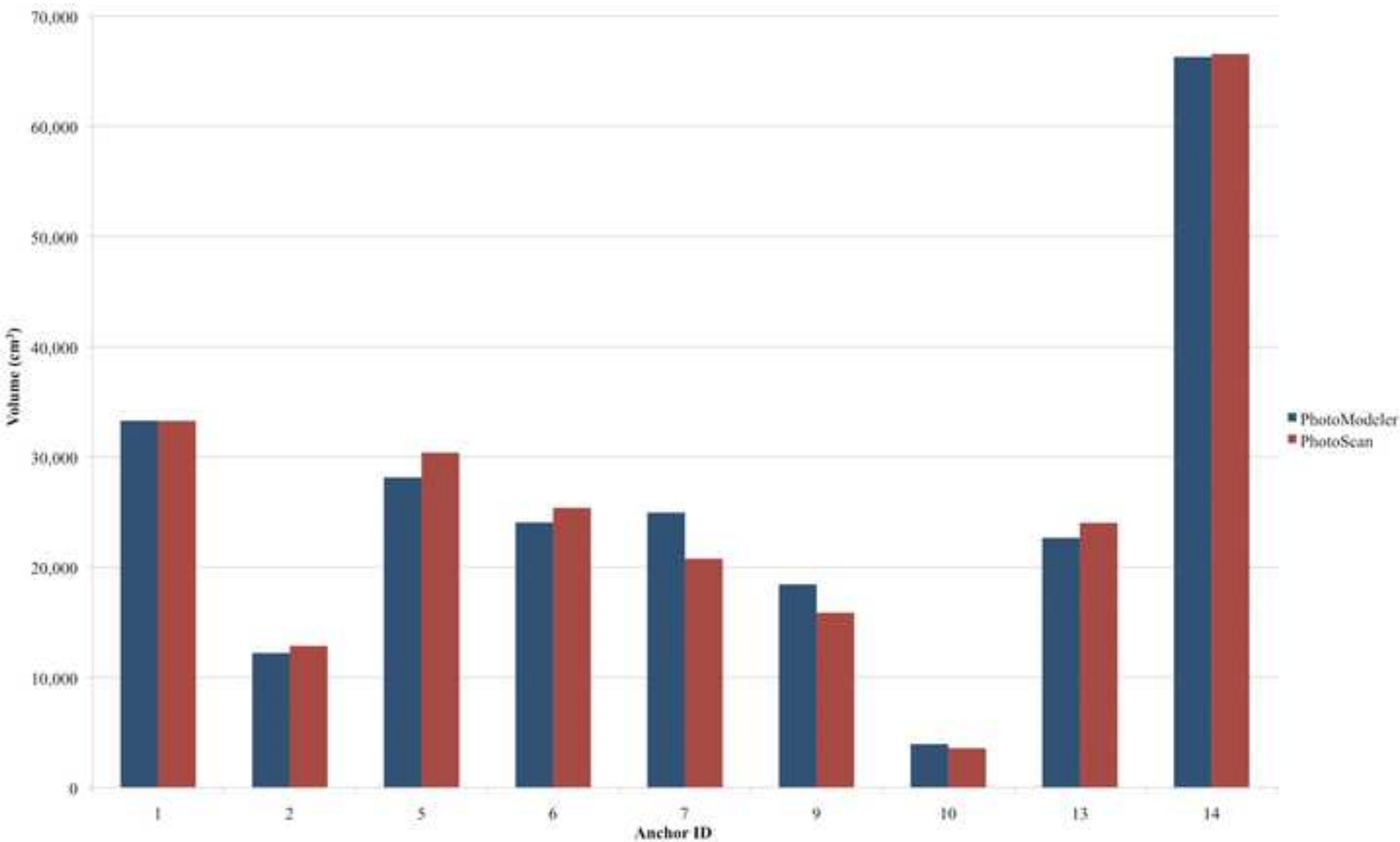
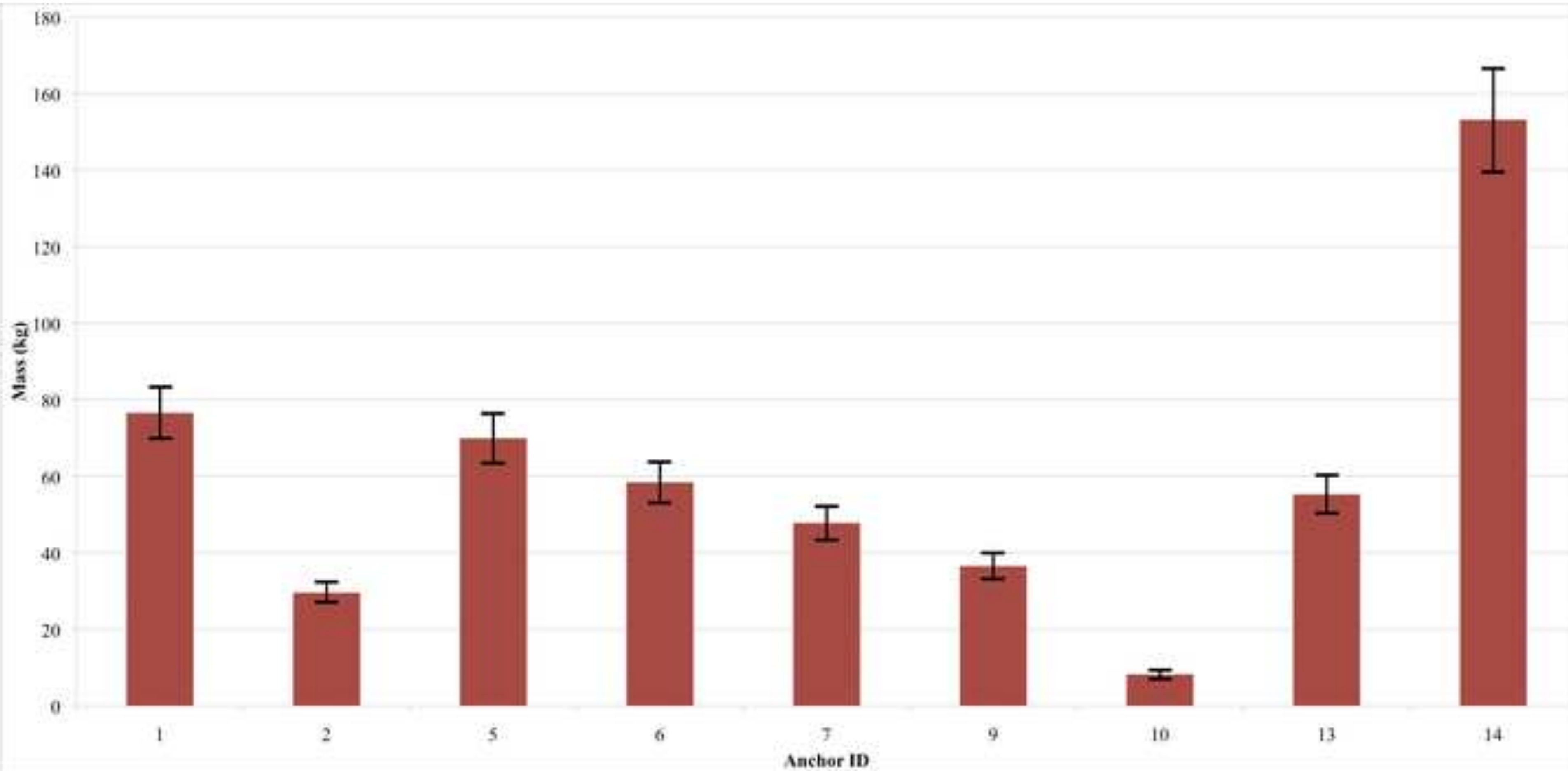
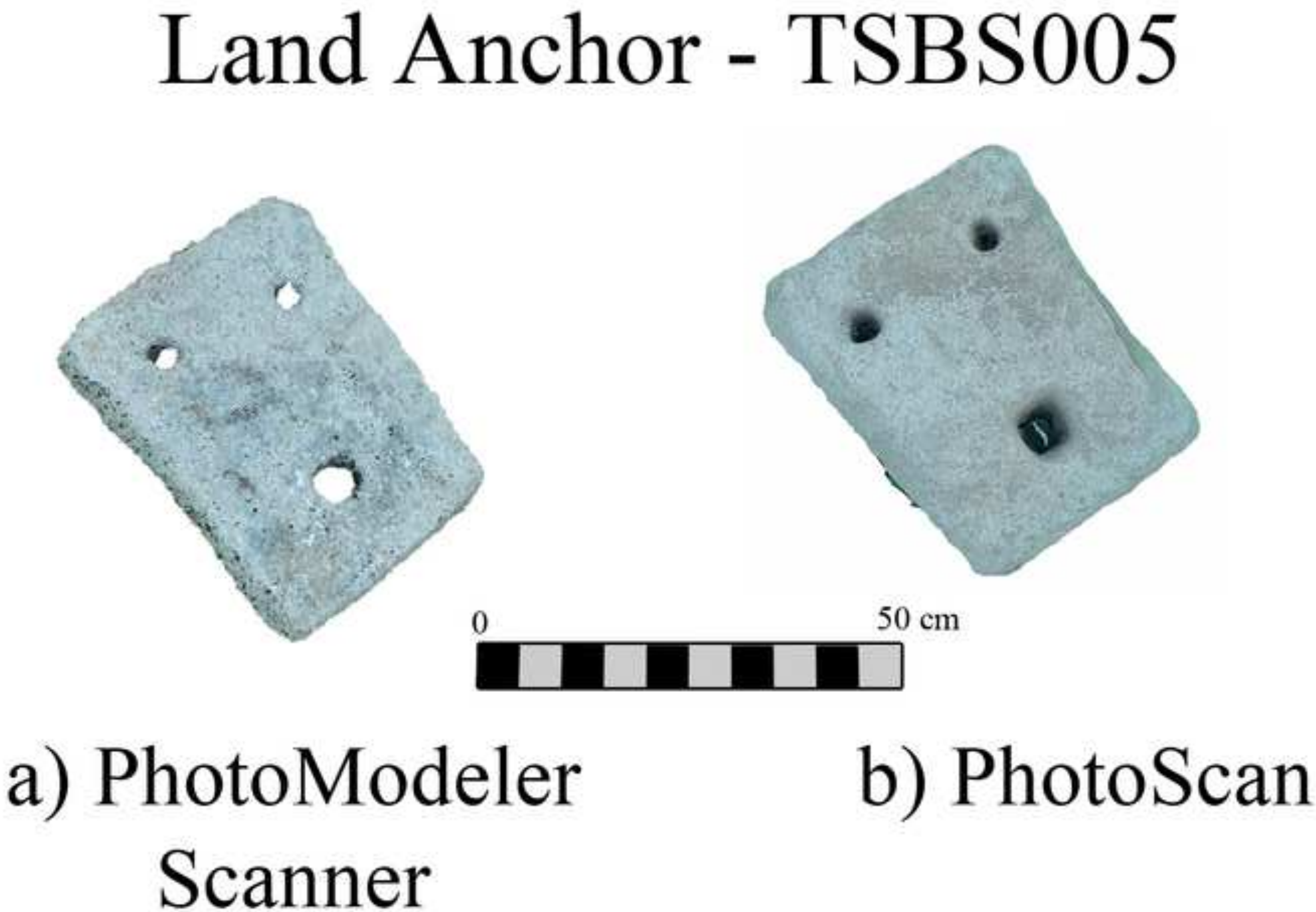


Figure 8

Click here to download Figure Fig 8_in situ mass.jpg




Land Anchor - TSBS005
0
50 cm
a) PhotoModeler
Scanner
b) PhotoScan

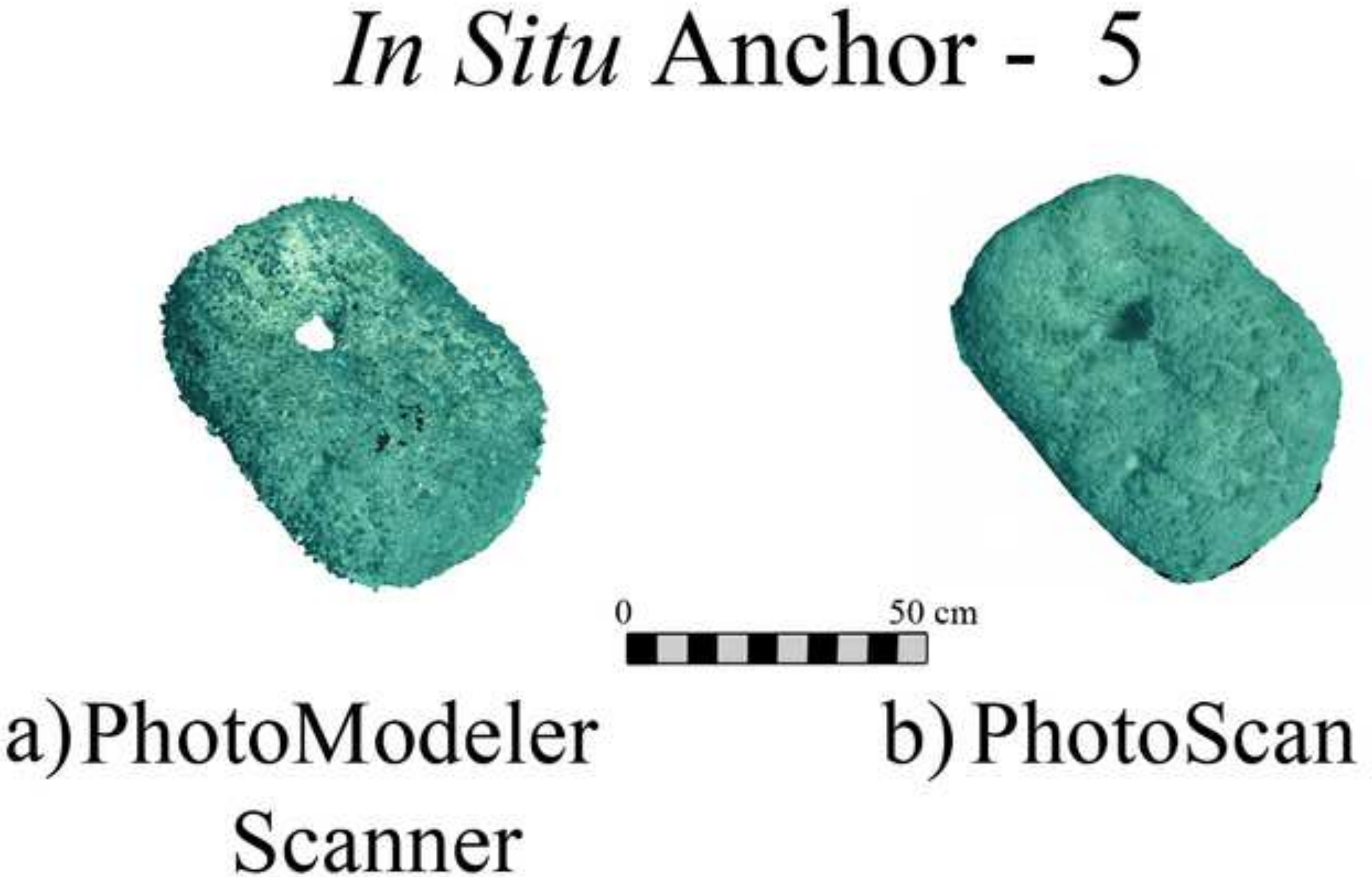

In Situ Anchor - 5
0
50 cm
a) PhotoModeler Scanner
b) PhotoScan

Table 1.

	No. of Holes	Side	Point Cloud		Triangulated Mesh		No. of Photos	
			Photo-Modeler	Photo-Scan	Photo-Modeler	Photo-Scan	Photo-Modeler	Photo-Scan
TSBS011	1	1	17,277	20,333,847	25,192	34,824	12	14
		2	11,949	21,305,372	20,117	31,478	12	15
MVASP187	1	1	28,858	21,283,509	43,505	20,168	12	14
		2	40,069	20,255,066	59,084	19,038	12	14
TSBS009	1	1	58,682	19,126,227	87,398	31,636	12	14
		2	21,317	21,892,418	35,607	35,784	12	14
TSBS018	1	1	60,394	23,021,202	93,850	60,744	16	19
		2	56,511	26,551,215	87,823	41,462	14	20
TSBS005	1	1	61,236	27,490,239	85,288	41,181	14	21
		2	41,067	24,605,155	59,284	23,372	16	18
TSBS003	3	1	47,354	26,854,344	85,776	83,800	16	20
		2	50,729	23,047,137	72,488	27,954	16	16
MT418	1	1	29,056	20,112,587	46,900	43,396	12	14
		2	26,379	20,319,807	45,934	36,606	14	14
TSBS014	3	1	28,869	17,077,993	56,281	78,278	16	16
		2	29,719	16,709,247	55,908	28,186	16	16

Table 2.

	No. of Holes	Point Cloud No.		Triangulated Mesh		No. of Photos	
		Photo-Modeler	Photo-Scan	Photo-Modeler	Photo-Scan	Photo-Modeler	Photo-Scan
1	1	21,157	35,523,866	34,234	90,052	14	38
2	1	33,512	45,815,309	63,606	41,262	16	61
5	1	35,037	37,687,341	65,191	142,068	14	48
6	1	96,640	52,986,694	178,360	155,974	14	82
7	1	13,461	28,811,957	25,228	135,112	14	27
9	1	54,973	24,381,978	106,307	192,730	16	68
10	1	28,666	3,494,881	50,384	6,240	18	54
13	3	8,500	29,244,047	16,767	100,040	10	52
14	3	3,463	32,339,105	6,080	216,332	18	54

Table 3.

	Length (cm)			Width at base (cm)			Depth at hole (cm)		
	Tape	Photo-Modeler	Photo-Scan	Tape	Photo-Modeler	Photo-Scan	Tape	Photo-Modeler	Photo-Scan
TSBS011	42	41	40	36	38	33	10	13	13
MVASP187	38	38	37	32	33	30	8	8	8
TSBS009	34	39	34	33	33	32	12	13	11
TSBS018	56	61	55	47	50	47	20	21	20
TSBS005	44	46	44	34	38	34	9	11	7
TSBS003	59	63	59	44	52	49	10	11	9
MT418	44	47	45	32	36	36	11	10	10
TSBS014	42	45	43	38	40	38	8	8	5

Table 4.

	Length (cm)			Width at base (cm)			Depth at hole (cm)		
	Tape	Photo-Modeler	Photo-Scan	Tape	Photo-Modeler	Photo-Scan	Tape	Photo-Modeler	Photo-Scan
1	64	59	57	61	60	59	22	26	22
2	47	49	49	39	36	38	8	7	13
5	72	70	68	46	52	44	14	12	9
6	56	54	49	48	46	38	10	15	7
7	50	47	51	44	45	39	16	13	13
9	40	42	39	32	31	30	15	18	15
10	30	24	30	30	24	24	7	7	8
13	68	64	66	45	50	46	10	14	19
14	97	95	91	78	68	69	20	26	22

Table 5.

	Difference in Length (cm)	Difference in Width (cm)	Difference in Depth (cm)
TSBS011	2	1	2
MVASP187	0	1	1
TSBS009	3	1	2
TSBS018	3	0	0
TSBS005	0	1	0
TSBS003	2	0	8
MT418	3	5	1
TSBS014	1	0	3

Table 6.

	Volume Side 1 (cm^3)		Volume Side 2 (cm^3)		Displacement Volume (ml)
	PhotoModeler	PhotoScan	PhotoModeler	PhotoScan	
TSBS011	14,494	12,617	15,851	12,756	10,730
MVASP187	9,402	7,539	8,411	7,320	6,800
TSBS009	14,599	10,564	13,143	9,851	9,700
TSBS018	48,051	45,217	57,940	46,512	NR
TSBS005	14,910	12,371	14,091	10,619	11,120
TSBS003	28,660	25,740	26,574	21,245	NR
MT418	15,186	12,626	15,879	10,515	11,420
TSBS014	12,689	6,664	12,641	7,688	6,920

Table 7.

	Mass (kg)	PhotoModeler		PhotoScan	
		Average Volume (cm^3)	Calculated Density (g/cm^3)	Average Volume (cm^3)	Calculated Density (g/cm^3)
TSBS011	31.65	15,172	2.0	7587.2	2.5
MVASP187	15.7	8,906	1.8	4454.1	2.1
TSBS009	21.85	13,871	1.6	6936.2	2.1
TSBS018	91.75	52,996	1.7	26498.6	2.0
TSBS005	26.35	14,500	1.8	12,371	2.1
TSBS003	51.65	27,617	1.9	25,740	2.0
MT418	29.2	15,533	1.9	12,626	2.3
TSBS014	18.35	12,665	1.4	6,664	2.8