PAQUIMÉ
CASAS GRANDES, MEXICO

Mapping the Ancient City of Paquimé:

Harnessing the Power of Pix4Dmapper and Unmanned Aerial Systems

PAQUIMÉ
Casas Grandes, Mexico

Mapping the Ancient City of Paquimé: Harnessing the Power of Pix4Dmapper and Unmanned Aerial Systems

by

Scott M. Ure
Research Archaeologist
Brigham Young University

and

Dr. Michael T. Searcy
Associate Professor of Anthropology
Brigham Young University

In collaboration with:

Instituto Nacional de Antropología e Historia

Pix4D SA

Department of Anthropology, Brigham Young University

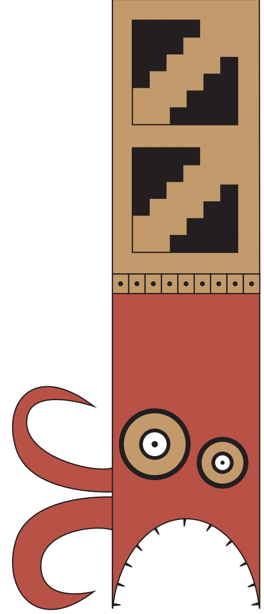
INAH

PIX4D simply powerful

THE DEPARTMENT OF ANTHROPOLOGY BRIGHAM YOUNG UNIVERSITY

PAQUIMÉ: A BRIEF HISTORY

Sometime in the thirteenth century A.D., the immense city of Paquimé arose in the Chihuahuan desert of northern Mexico (Figure 1). Charles Di Peso, best known as the primary excavator of Paquimé, estimates the city covered 88 acres or 36 hectares (1974:2:370). The native people who originally populated the Casas Grandes river valley lived in small farming hamlets, but an unknown cultural shift was the impetus for building a central polity where ceremonial mounds, multi-level apartment buildings, and Mesoamerican-style ball courts filled the city center by about A.D. 1300. These architectural features were constructed of massive adobe walls and stone masonry and represent a comprehensive organization of labor and people. Di Peso (1974:2:370) wrote that Paquimé was built by a "massive labor force, which, operating under the strict control of a few individuals, produced a telltale pattern of wall abutments, underground plaza drain systems, formalized plazas, public entries, subterranean ceremonial structures, and staggered outer wall designs."



The "feathered serpent" is an icon found on some polychrome painted pottery.

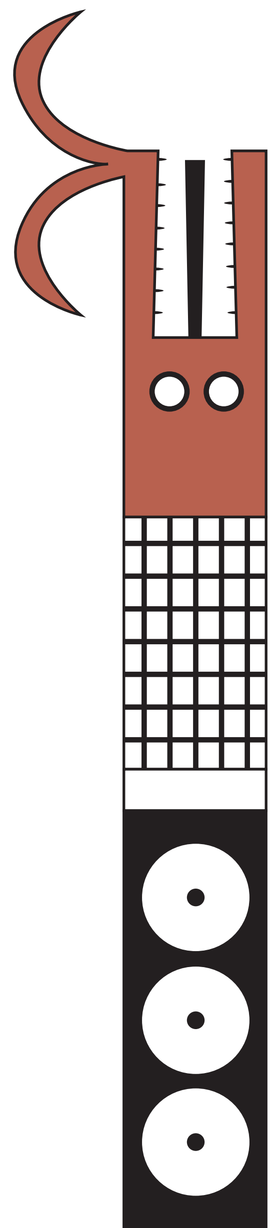


Figure 1. Map showing the location of Paquimé in northern Mexico.

In addition to large-scale architecture at Paquimé, artisans and tradesmen produced and warehoused goods from places near and far. Over four million pieces of marine shell were imported to the city from the Mexican west coast, as were finely-made copper bells. Pottery from the north was also stockpiled in rooms located in one of the ceremonial mounds. Evidence for aviculture (breeding birds, likely for their feathers) has also been discovered in the form of breeding pens and in hundreds of sacrificial macaw and turkey burials located throughout the city (Figures 2–4). Specific specialist took care of these magnificent birds and lived in the "House of the Macaws" (see Figure 20) (Di Peso 1974:2:599). Some individuals kept lilac-crowned parrots as pets which may have been venerated for their "talking" abilities (Di Peso 1974:2:599).

Figure 2. Scarlet macaw (*Ara macao*). These birds do not live naturally in the deserts of northern Mexico. They were likely first imported from further south in Mesoamerica (Somerville et al 2009). The macaws, along with other parrots, were eventually bred locally by over eight generations of breeders (Di Peso 1974:2:599). Photograph courtesy of Paul E. Minnis.

Figure 3. Macaw breeding pens found at Paquimé.

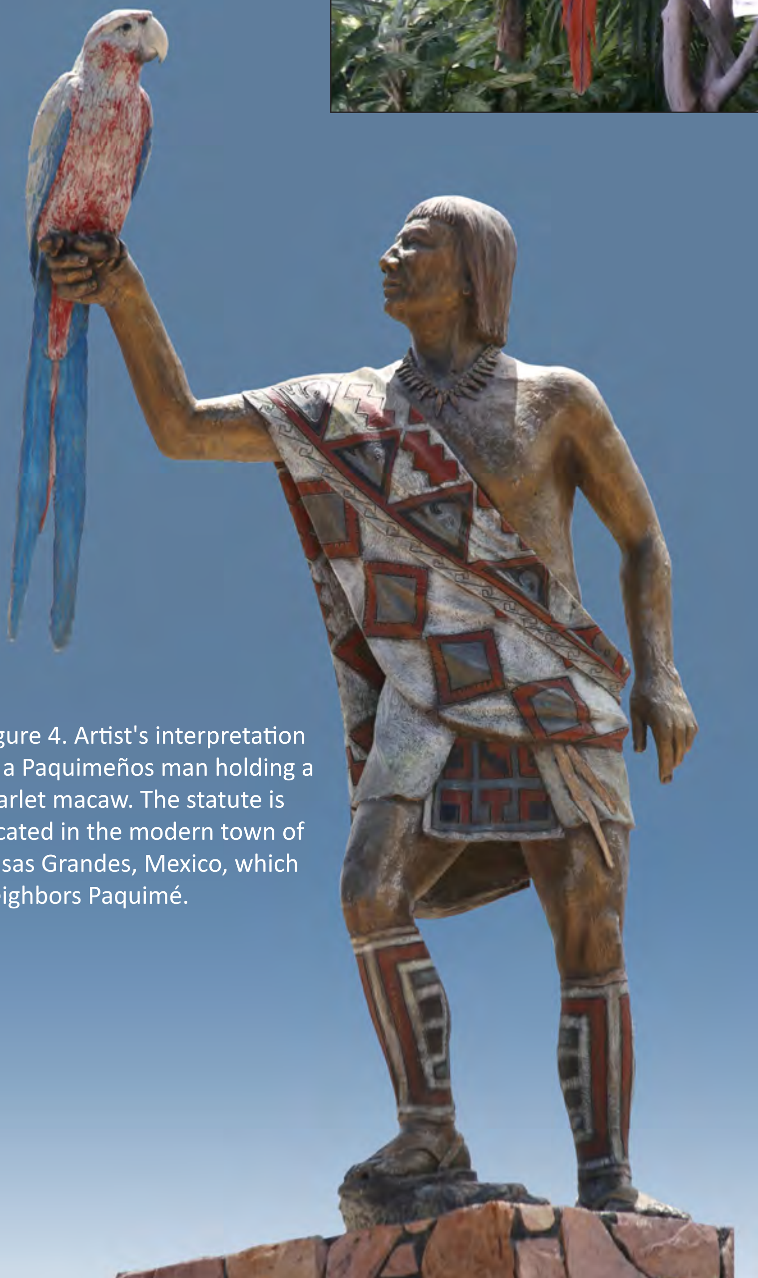


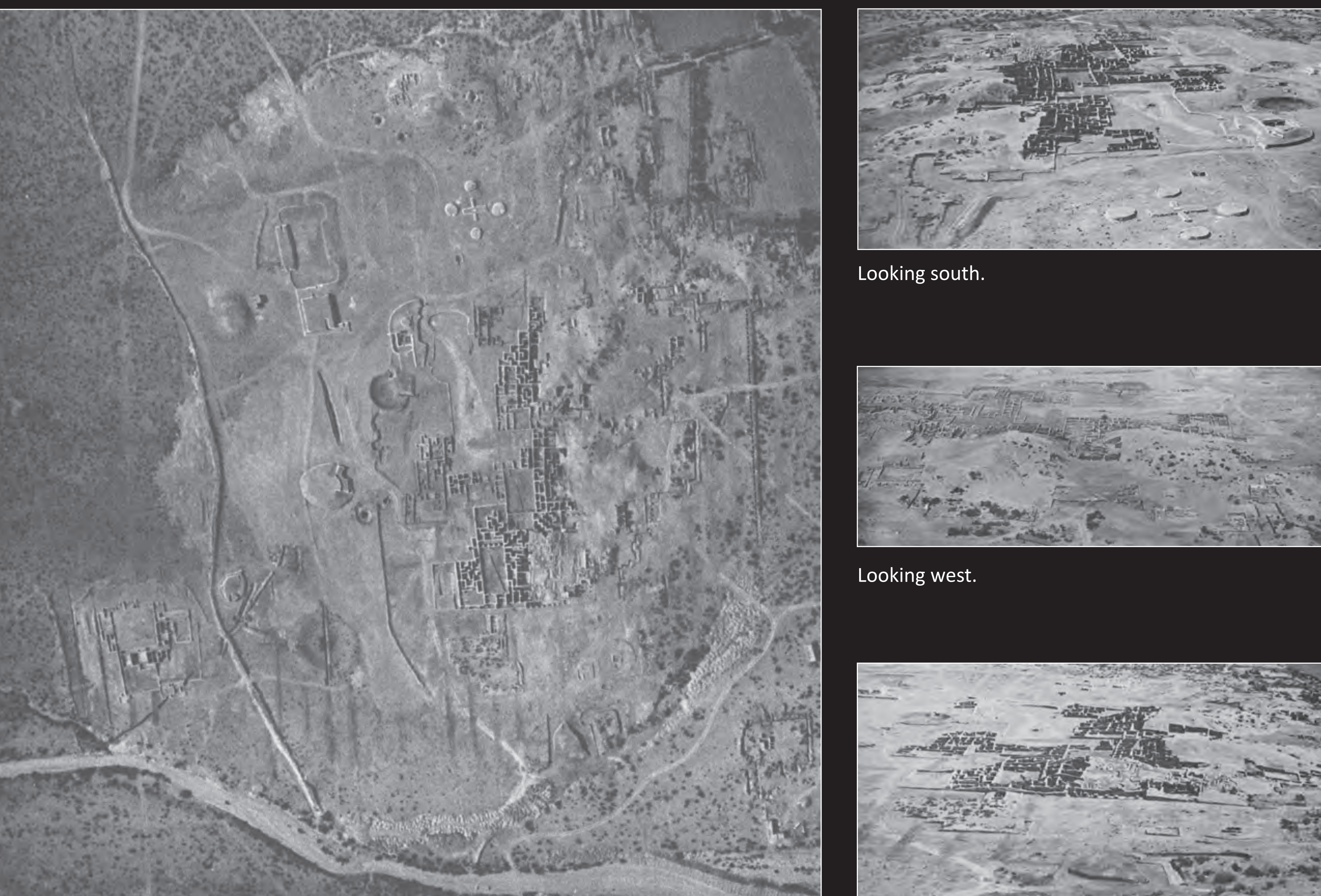
Figure 4. Artist's interpretation of a Paquimeños man holding a scarlet macaw. The statute is located in the modern town of Casas Grandes, Mexico, which neighbors Paquimé.

Paquimé was an impressive center of commerce, religion, and political power at one time (Figure 5). In fact, Mike Whalen and Paul Minnis (2003:315) consider Paquimé to be one of the largest, and most complex, ancient communities north of Mesoamerica. Sometime around the beginning of the fifteenth century (c.a. 1450 A.D.), however, the societal fibers of this great city began to unravel, and the site was eventually abandoned. For almost a century archaeologists have been working in northwestern Chihuahua, Mexico, to uncover evidence that could start to answer questions regarding long-distance trade, social and political organization, religious ethos, and scales of production at Paquimé.

Figure 5. The "Mound of the Cross" at Paquimé (foreground). The mound may be aligned to the solstices and equinoxes (Di Peso 1974:4:287). Drawing courtesy of The Amerind Foundation.

PAQUIMÉ: A BIRD'S EYE VIEW

Paquimé was among the largest, socially complex ancient communities in Northern Mexico and the American Southwest. In 1998 it was added to the UNESCO (1998:30) World Heritage list and described as bearing "eloquent and abundant testimony to an important element in the cultural evolution of North America, and in particular to prehispanic commercial and cultural links." Whalen and Minnis (2003:315) write, however, that "despite its fame . . . there have been few studies of the origin, structure, and decline of this primate center and of the region that surrounded it." There are likely numerous reasons why archaeologists have not focused on these research topics listed by Whalen and Minnis, but one of the reasons may simply be Paquimé's shear size and complexity. During his time at Paquimé, Di Peso acquired aerial imagery of the entire site from multiple angles and altitudes (Figure 6). We assume these images



Looking south.

Looking west.

Plan view.

Looking north.

Figure 6. Aerial photos of Paquimé taken during the 1960s (Di Peso 1974:2:291, 366–367). Photos courtesy of The Amerind Foundation.

helped him visualize the complexity and scale of the site. The aerial images he captured are extremely useful for seeing the city layout and its relationship to the surrounding terrain, water sources, and other natural resources. The image quality and detail provide a valuable historic view of Paquimé during Di Peso's excavations.

A UAV OVER PAQUIMÉ

Following Di Peso's tradition of recognizing the value of aerial imagery to better visualize the enormity of Paquimé, we conducted our own aerial reconnaissance in the summer of 2015 as part of the "Roots of Casas Grandes" project directed by Dr. Michael Searcy (Figure 7). Unlike Di Peso, we had the advantages of an unmanned aerial system (UAS) equipped with a GPS unit and a high-resolution digital camera, high-speed computers, and Pix4Dmapper, a powerful photogrammetry application made by Pix4D. Our goal was to capture high-detail, georeferenced, imagery of Paquimé in order to produce a series of new maps, models, and visualizations to update Di Peso's maps and images that are now nearly fifty years old.

The Flight: Methods and Materials

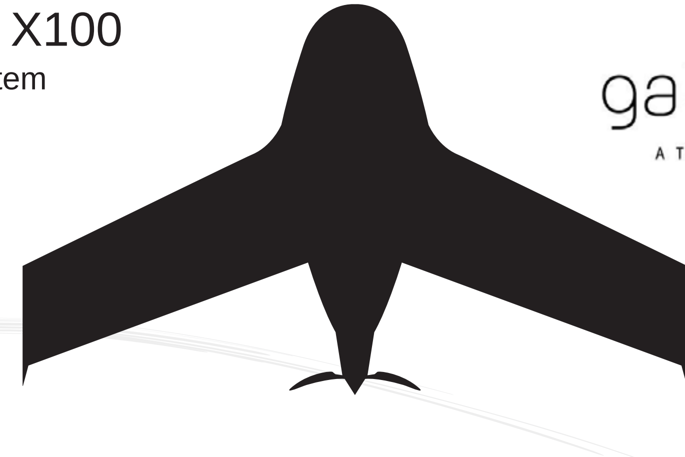
The first, and most important, step for flying our unmanned aerial vehicle (UAV) over Paquimé was to get approval from the Instituto Nacional de Antropología e Historia (INAH), and from Maurico Salgado Servín, Director of the Paquimé Cultural Center. We believe that asking for permission to fly at any location is critical for all unmanned aerial missions. This allows everyone to be involved in the preflight decision making, thus minimizing accidents and surprises during flight. Land owners can also provide valuable information about the surrounding area that may not be apparent to visiting UAS operators.

Figure 7. Take-off and landing location for the BYU 2015 X100 flight over Paquimé.

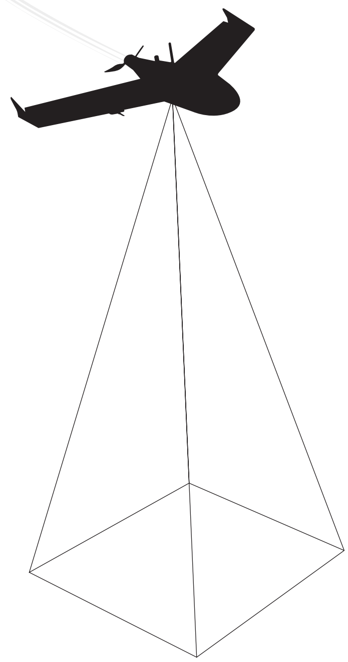
TRIMBLE GATEWING X100

Fixed-wing unmanned aerial system

Flight time: 40 mins.
Max. flight height: 750 m AGL
Min. flight height: 100 m AGL
Cruise speed: 80 km/hr
Max. take-off weight: 2.0 kg
Wingspan: 100 cm
Max. range: 5 km



gatewing
A TRIMBLE COMPANY



Ricoh GR IV
10 megapixel 1/1.7" CCD
6mm f/1.9 Lens
Hybrid Autofocus
3200 Max ISO

Figure 8. Trimble Gatewing X100 on the catapult in Mexico.

Once we were approved for flight, we examined the area to find a suitable landing and take-off location. This was done using Google Earth, as well as walking the area to identify a good location. We chose an area about 700 meters away from Paquimé to minimize the possibility of colliding with any part of the site during take-off or landing (see Figure 7). We then placed eight ground control targets and recorded their center points using a Trimble GeoXH GPS (SBAS enabled) with a Tornado antenna. These points were then post-processed using Trimble's GPS Pathfinder Office, resulting in 209 corrected positions with 50 percent in the 30–50 cm accuracy, 36 percent in the 15–30 cm accuracy, and remaining points falling in the 50 cm to 1 m range. Correction data was provided from the Safford, Arizona CORS (ITRF00 [1997] derived from IGS08 [NEW]).

Our flight over Paquimé was flown by a Trimble Gatewing X100 fixed-wing UAV which is launched via a catapult (Figure 8). Flight preparations were performed using Gatewing's Quickfield software, and in-flight monitoring was done using Micropilot's Horizon 3.4, which runs on a Trimble Tablet PC. The X100 is equipped with a GPS, autopilot (and associated sensors), 2.4 GHz data link, and a Ricoh

Figure 9. Flight path for the BYU 2015 X100 flight over Paquimé.

Figure 10. Kestrel 4500

GR IV 10 megapixel camera. The X100 is designed with multiple fail-safes whenever technical difficulties occur. Operators can also manually override the flight in various ways to minimize accidents.

The X100 flight over Paquimé covered 0.54 km^2 (133 acres or 53 hectares) in about 32 minutes, and flew 150 meters above the ground (Figure 9). The flight path had a forward and sideways overlap of 80 percent. The total distance flown measured 39 km (24.2 mi). Overall weather conditions, as well as wind speed and direction were monitored using a Kestrel 4500 weather meter (Figure 10).

Processing the Images using Pix4Dmapper

During the flight, the Ricoh camera captured 422 3648 x 2736 pixel photographs stored locally on an internal SD memory card. Each photo was taken with a 6.0 mm focal length, 1/250 shutter speed, f/4.0, and an ISO of 100. These photographs provided the raw data needed to produce a series of new maps, models, and visualizations using Pix4D's Pix4Dmapper software (Figure 11). These images were geotagged when taken, and eight ground control points provided additional geolocation information to create an accurate final georeferenced orthomosaic based on the NAD83 UTM Zone 13 North datum and coordinate system (Figure 12).

Figure 11. One of the individual photographs (cropped) taken from the X100 showing some of the walls of Paquimé.

Figure 12. Pix4Dmapper "Map View" showing initial camera positions and GCP locations.

Table 1. Internal Camera Parameters for a Ricoh GR IV Digital with 6mm lens (3648x2736) RGB. Sensor dimensions = 7.440 [mm] x 5.580 [mm]. EXIF ID = GRDIGITAL4_RICOHGRLENS_6.0_3648x2736.

	Focal Length	Principal Point X	Principal Point Y	R1	R2	R3	T1	T2
Initial Values	2945.236 [pixel] 6.007 [mm]	1824.003 [pixel] 3.720 [mm]	1368.002 [pixel] 2.790 [mm]	-0.065	0.062	-0.013	-0.000	-0.000
Optimized Values	2943.052 [pixel] 6.002 [mm]	1750.719 [pixel] 3.571 [mm]	1286.970 [pixel] 2.625 [mm]	-0.057	0.059	-0.013	-0.000	-0.001

Table 2. Ground Control Point Accuracy and mean Errors.

GCP Name	Accuracy XY/Z [m]	Error X [m]	Error Y [m]	Error Z [m]	Projection Error [pixel]	Verified/ Marked
"GCP1" (3D)	0.300/0.400	0.024	0.054	0.033	0.407	19/19
"GCP2" (3D)	0.300/0.500	0.070	-0.173	-0.071	0.418	18/18
"GCP3" (3D)	0.200/0.400	-0.052	0.064	-0.048	0.430	16/16
"GCP5" (3D)	0.300/0.500	0.063	-0.174	0.255	0.659	19/19
"GCP6" (3D)	0.300/0.400	-0.105	0.126	-0.049	0.504	17/17
"GCP7" (3D)	0.400/0.700	0.077	0.027	-0.148	0.631	18/18
"GCP8" (3D)	0.400/0.700	-0.015	0.024	0.120	0.412	16/16
"GCP9" (3D)	0.300/0.500	0.029	-0.002	-0.074	0.435	25/25
Mean [m]	—	0.011290	-0.006834	0.002264	—	—
Sigma [m]	—	0.060351	0.102630	0.121174	—	—
RMS Error [m]	—	0.061398	0.102857	0.121195	—	—

All 422 images were processed using Pix4Dmapper on a Dell Precision T7600 with 24 Intel(R) Xenon(R) E5-2630 0 @ 2.30 GHz cores, 64 GB of RAM, two NVIDIA Quadro 5000 graphics cards, and an NVIDIA Tesla C2075 GPU. Pix4Dmapper was able to calculate a 5.67799 average ground sampling distance (GSD) based on the 150 meter flight altitude. The quality check after initial processing returned a median of 24,761 key points per image, with all images enabled. The relative difference between initial camera parameters and optimized parameters was 0.07% which is well under the recommended 5% variation (Table 1). Pix4Dmapper calculated 14,608.6 matches per calibrated image and determined a mean RMS error of 0.094 m for the eight ground control points (Tables 2 and 3). The overall number of overlapping images was in the 5+ range for nearly the entire target area over Paquimé (Figure 13). This high degree of overlap significantly improved the quality of our results. In addition, 2D links between matching images were strong over the majority of the target area, aside from some weaker links designated by the lighter regions in the 2D Keypoint matches analysis (Figure 14). Based on the high accuracy and overlap, Pix4Dmapper was able to successfully compute corrected camera positions and generate automatic tie points between the photographs (Figure 15). This allowed us to produce accurate, georeferenced maps and models in a variety of formats. These include a georectified orthomosaic of the entire city of

Table 3. Absolute Geolocation Variance.

Min. Error [m]	Max. Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
—	-15.00	0.00	0.00	0.00
-15.00	-12.00	0.00	0.00	0.00
-12.00	-9.00	0.00	0.00	0.00
-9.00	-6.00	12.32	0.00	0.00
-6.00	-3.00	30.33	0.00	0.00
-3.00	0.00	6.64	45.97	53.79
0.00	3.00	5.92	54.03	45.97
3.00	6.00	36.49	0.00	0.24
6.00	9.00	8.29	0.00	0.00
9.00	12.00	0.00	0.00	0.00
12.00	15.00	0.00	0.00	0.00
15.00	—	0.00	0.00	0.00
Mean [m]	—	0.588902	2.475312	5.813387
Sigma [m]	—	4.869558	0.635736	0.938741
RMS Error [m]	—	4.905039	2.555647	5.888693

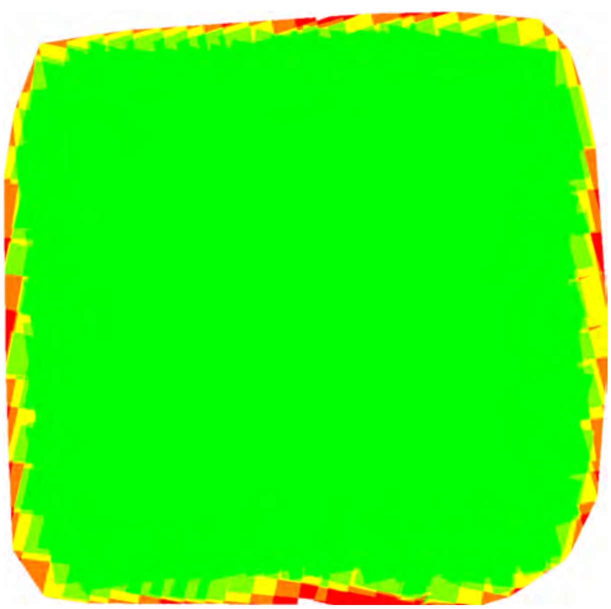


Figure 13. Visual depiction of the number of overlapping images computed for each pixel of the Paquimé orthomosaic. Green represents 5+ overlapping images.

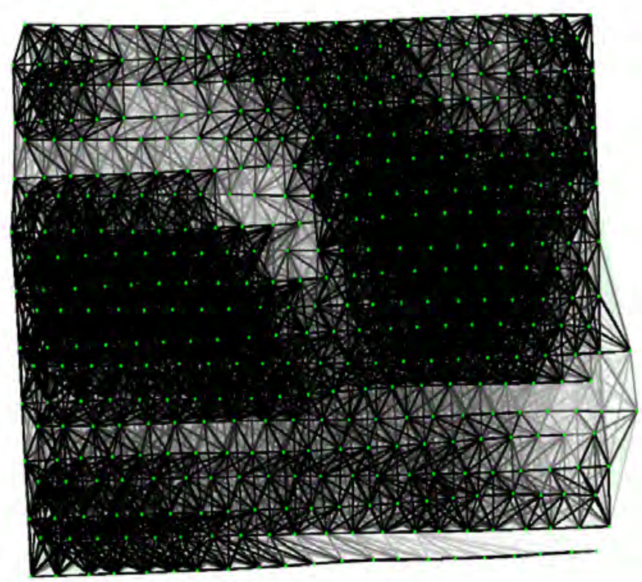


Figure 14. Plan view of the image computed positions with a link between matching images. Darker areas indicate strong links.

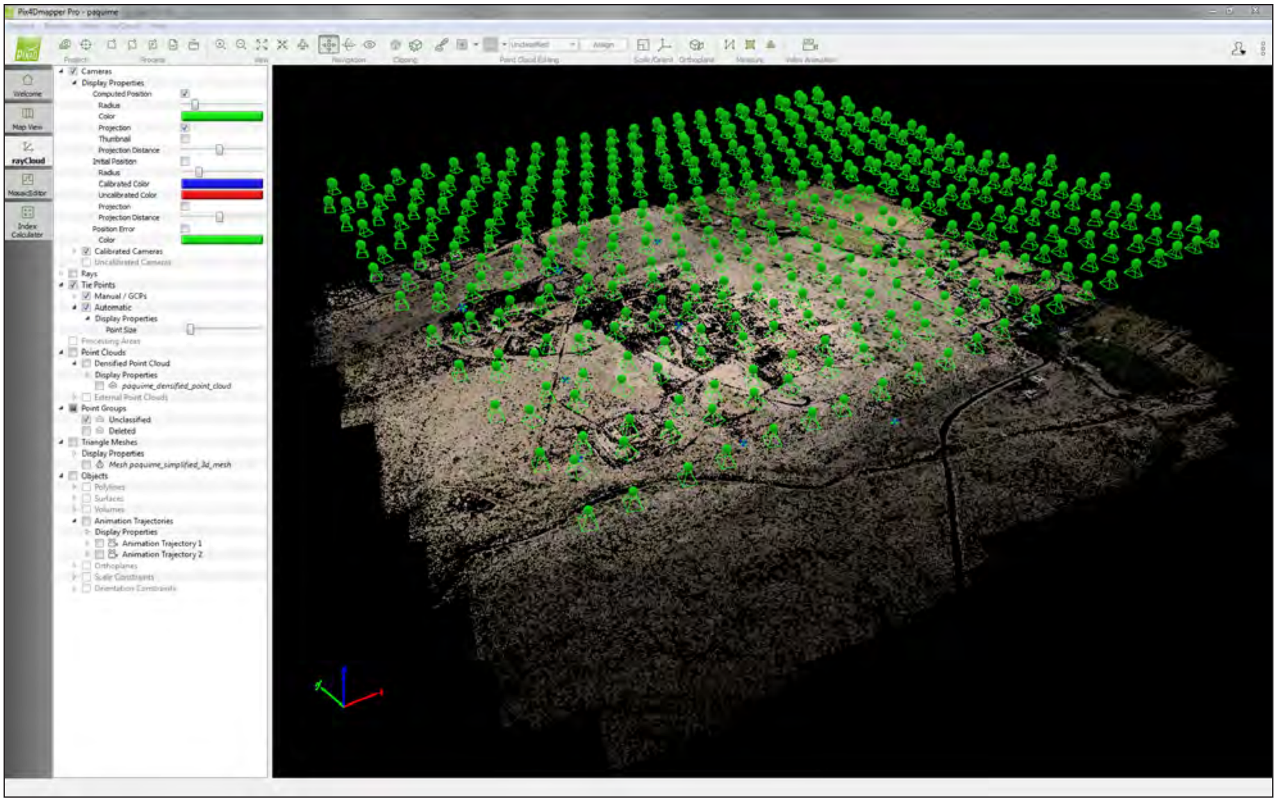


Figure 15. Pix4Dmapper showing computed camera positions, projections, and automatic tie points.

Paquimé, a digital surface model (DSM) used for slope surface analysis, and a georeferenced plan map of Paquimé with a 50 cm contour interval. In addition, with Pix4Dmapper, we were able to create 3D visualization animations from numerous angles and vantage points.

DISCUSSION AND CONCLUSIONS

Based on our experiences with the Paquimé flight, data processing, and subsequent image analysis, we will evaluate the overall Paquimé project in two ways. First, from an archaeological point-of-view, we discuss how these tools, compared to traditional techniques, helped us learn new information about the archaeological record at Paquimé. Second, from a technical perspective, we share our experiences using a UAV and Pix4Dmapper to map Paquimé. In short, we feel there are significant benefits to using Pix4Dmapper to process UAVs imagery to document archaeological sites.

New Tools with Powerful Results

Documenting Paquimé using a small UAV to collect aerial images, combined with the numerous tools provided by Pix4Dmapper, gave us the ability to efficiently and accurately map this ancient city at a high level of detail. In addition, with the help of Pix4Dmapper, we analyzed these aerial images using various methods that provide new insights that traditional methods simply cannot achieve without an exorbitant amount of time and funding.

For example, archaeologist typically map an archaeological site using either a total station run by two or three people, or alternatively, they pull a 100-meter long survey-grade measuring tape to take measurements (Figures 16 and 17). These methods were problematic at Paquimé, because portions of the city cannot be accessed due to their fragility, and using wheeled lift-vehicles to measure the taller buildings was not an option. This is where photogrammetry proved to be the ideal method to map Paquimé, and Pix4Dmapper made it very easy to process the photogrammetric images (Figure 18).

Pix4Dmapper's ability to take photogrammetric images and convert them into a 3D point cloud is perhaps its strongest feature. When combined with the rayCloud tool, and the ability to release the full computing power of a GPU, using the NVIDIA CUDA parallel computing platform, make Pix4Dmapper an incredible resource for anyone needing to processing photogrammetric images. With the point cloud Pix4Dmapper generated, we were able to produce an orthomosaic image compiled from all 422 separate photographs. This image, however, is not just a pretty picture. It is a spatially accurate, georeferenced,

Figure 16. An example of a total station used by BYU archaeologist to map tombs in the Petra Archaeological Park in Jordan. Note the data collector attached to the side.

Figure 17. BYU archaeology students holding a prism rod to map an excavation trench at the Hinckley Mounds site in Utah. This is a common mapping instrument used at many archaeological excavations world-wide. It typically requires one person running the total station by aiming the instrument at a prism attached to a pole (similar to what the student is holding in the photo). Once the instrument is focused and aimed correctly, the user can push a button to take a measurement. This data is either recorded on a hand-held device (see photo), or the X, Y, and Z coordinates are recorded by hand in a surveyor's notebook.

Figure 18. Georectified orthomosaic of Paquimé. The modern Paquimé Museum is located in the upper-left corner.

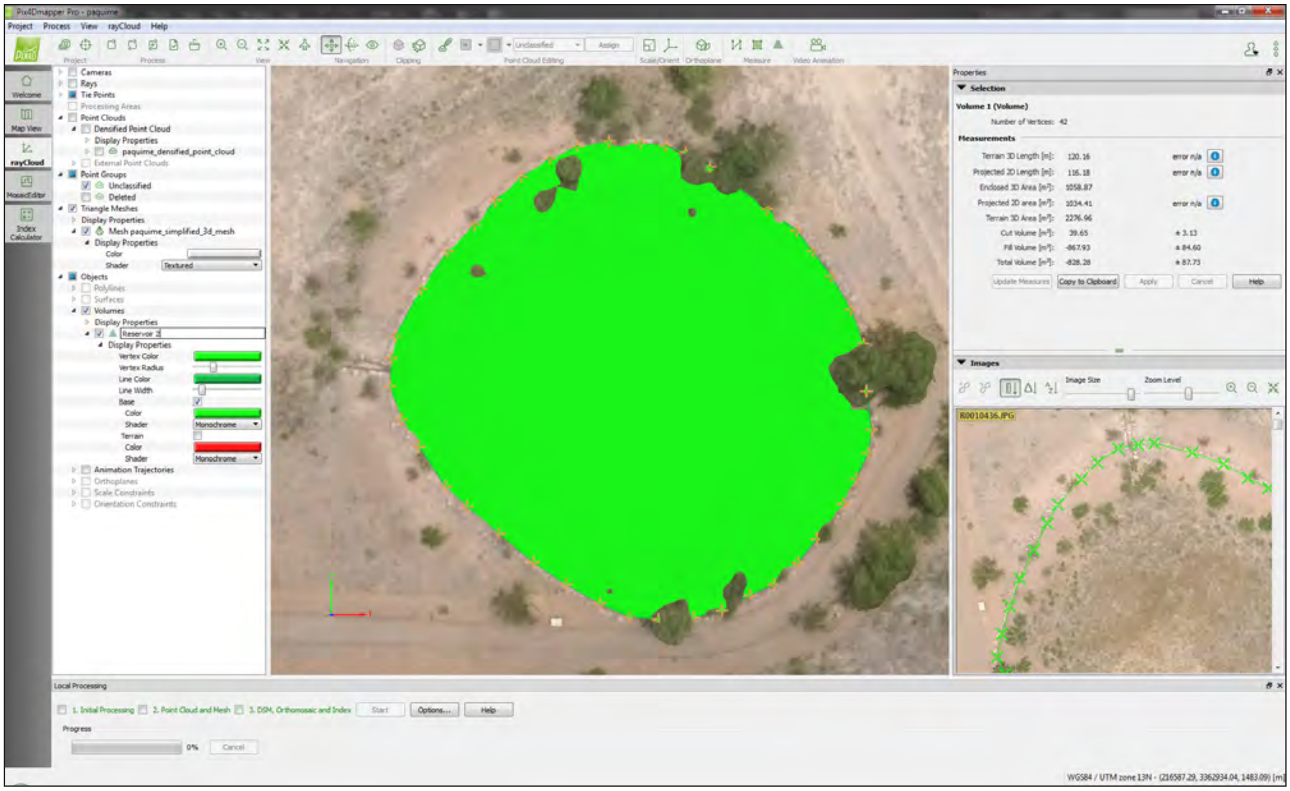


Figure 19. Volumetric measurement of Reservoir 2 at Paquimé

high-resolution, real-color image housing valuable spatial data ready for any number of analyses. The point cloud also provides the ability to calculate and measure in three dimensions. For example, we were able to measure the size of various buildings and architecture using the polyline, surface, and volume tools. This is especially useful, because we can now calculate the height, width, and volume of all the architecture at Paquimé without using a total station on site. For example, using the volume tool, we were able to calculate that "Reservoir 2" could hold approximately 828 m^3 (828,000 liters/218,734 gallons) of water when completely full (Figure 19). This is one example of the type of valuable calculations that Pix4Dmapper offers to help us learn new information about Paquimé. In this case these tools are helping us understand more about the number of people that may have lived in Paquimé based on what we know about human water consumption in hot and arid environments, compared to the capacity of Paquimé's reservoirs.

From the same point cloud we also generated 50 cm contour lines in shapefile format to provide elevation data for a topographic map drafted from the orthomosaic (Figure 20); a digital surface model (DSM) exported to ESRI's ArcMap for slope analysis (Figure 21) and hillshade modeling (Figure 22); and a 3D mesh for creating 3D models and animations (see Figure 24). The topographic map was drafted in Adobe Illustrator using Avenza's MAPublisher plugin. The orthomosaic and the DSM slope model provided the background to digitize all of the archaeological features, and the 50 cm contour shapefile was imported

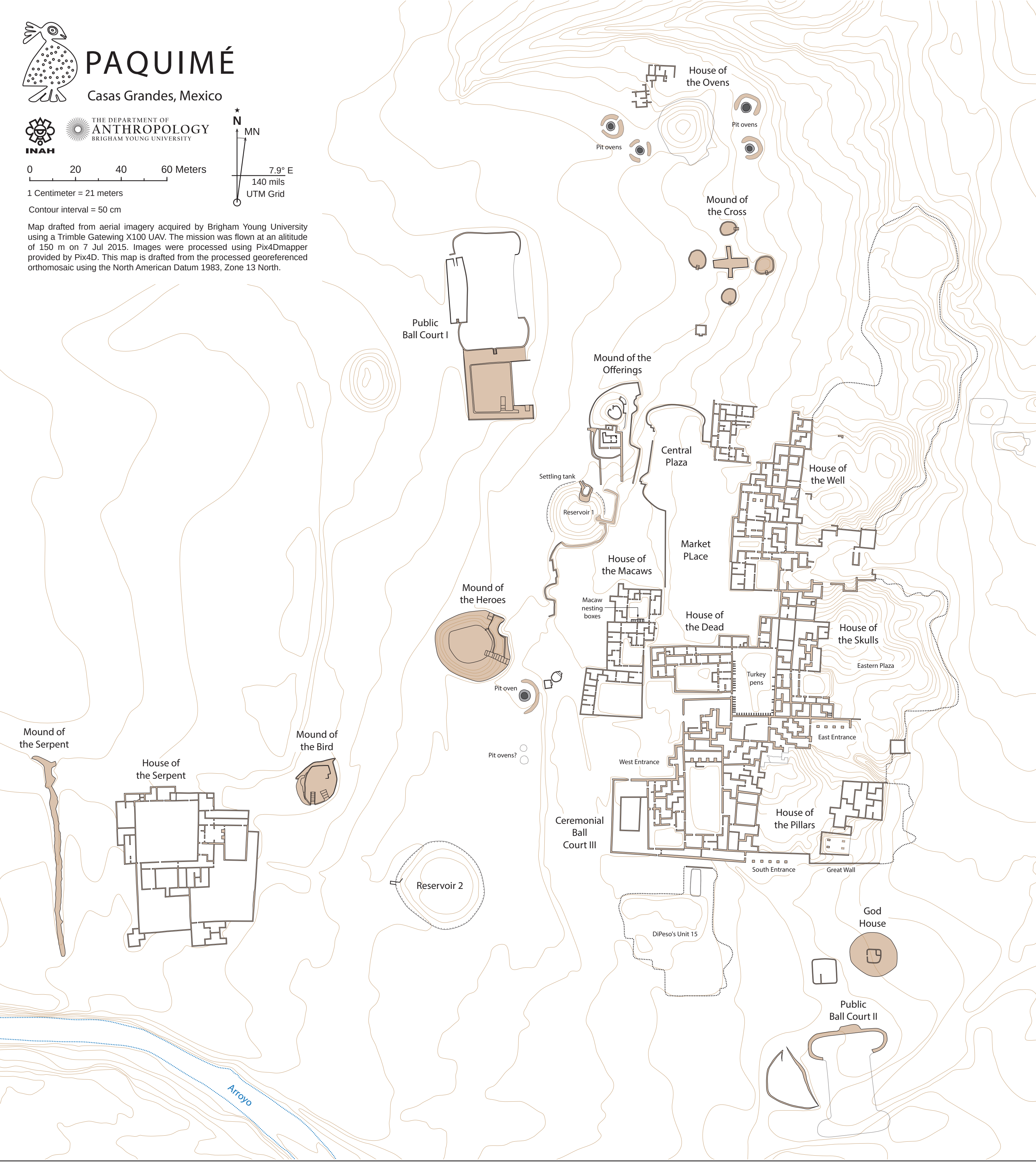


Figure 20. Georeferenced topographic map drafted from the orthomosaic and DSM slope analysis image. The 50 cm contours were generated in Pix4Dmapper and imported into Adobe Illustrator equipped with Avenza's MAPublisher GIS plugin.

into the Illustrator map using the same Avenza plugin, thus maintaining georeferencing for all digitized elements. As far as we are aware, this is the first comprehensive topographic map of Paquimé that includes all of the architectural features in a georeferenced format. This is a very valuable resource that provides precise spatial information for future conservation and exploration efforts.

The digital surface model was generated in Pix4Dmapper using the DSM and Orthomosaic tool under the processing options. It was run using "Noise Filtering" and "Surface Smoothing" with the type set at "Sharp". A raster DSM GeoTiff using "Inverse Distance Weighting" and "Merge Tiles" was also included in the final results. The DSM was imported into ESRI's ArcMap which has the ability to interpret DSM files. We then generated slope analysis and hillshade models to visualize the variation in terrain and architecture across Paquimé. Figure 21 and shows the slope analysis results where warmer colors represent angles nearing ninety degrees (vertical), and cooler colors are trending toward zero degrees (flat). The large pit ovens located near the "House of Ovens", on the north end of Paquimé, are especially visible due to their steep sides which display as red rings. Interestingly, two round circles (drawn as dashed lines in Figure 20) visible in the orthomosaic, located between the "Mound of the Heroes" and "Reservoir 2", were thought to be additional pit ovens; however, they barley appear in the slope analysis with only a 2.8–7.7º slope (see Figures 18, 20, and 21 for comparisons). Note that trees in the area look similar to the pit ovens, but they are typically smaller, more irregular-shaped bulls-eyes. We found that comparing the orthomosaic with the slope analysis was helpful for differentiating vegetation from actual architecture.

The results from the slope analysis also helped us identify several areas that are likely unexcavated portions of Paquimé. Mounds to the east of the "House of the Skulls" and northeast of the "House of the Well" are quite visible in the slope analysis results and in the hillshade model (Figures 20, 21 and 22). In addition, further east are two areas that look like they may be structural, based on their shape, size, and proximity to Paquimé proper. Moving south, to just below the "Ceremonial Ball Court II", Di Peso's "Unit 15" is very visible in the slope analysis model, and is another probable unexcavated area of Paquimé. Linear features, including aqueducts, and possible terrain alterations can be seen as well. It is unclear whether some of the linear elements are modern or ancient, but ground-truthing these will be much easier now that we have precise spatial locations.

Figure 22 shows the hillshade model which uses a gray-tone shaded relief to enhance variation in surface terrain. This is similar to the color gradient used in the slope analysis, but it represents a more natural looking surface. Similar to the slope analysis image, the same unexcavated areas, structures, and linear features are quite visible. Both hillshade and slope analysis models have proven useful for identifying these subtle changes in the terrain that are not evident in the orthomosaic alone. Figure 23 is a comparison of the orthomosaic to the slope analysis and the hillshade model. This area is called the "House of the Ovens" which is north of the "Mound of the Cross". Note how clear the mound is in the

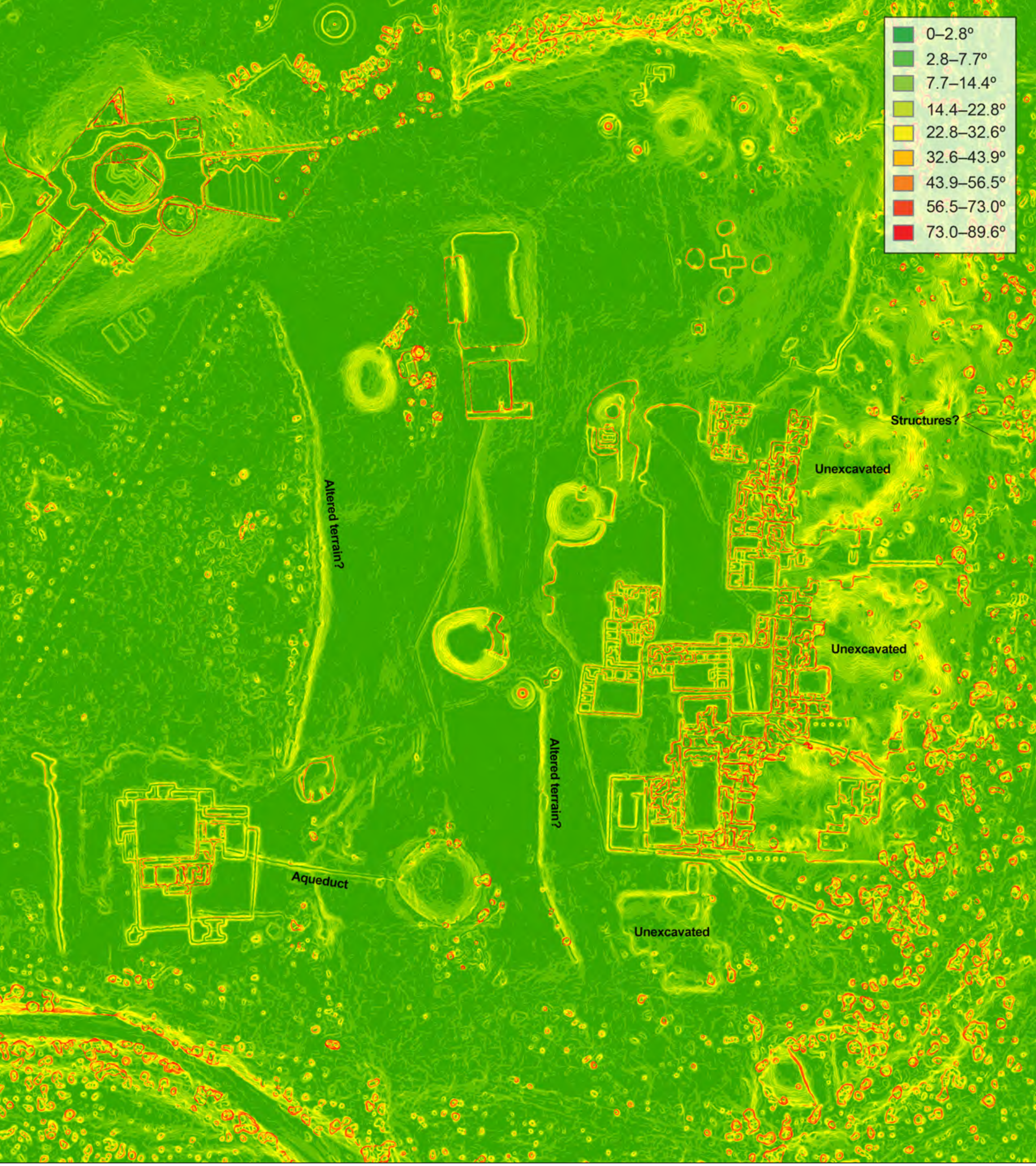


Figure 21. Paquimé slope analysis model generated in ESRI's ArcMap based on the DSM exported from Pix4Dmapper.

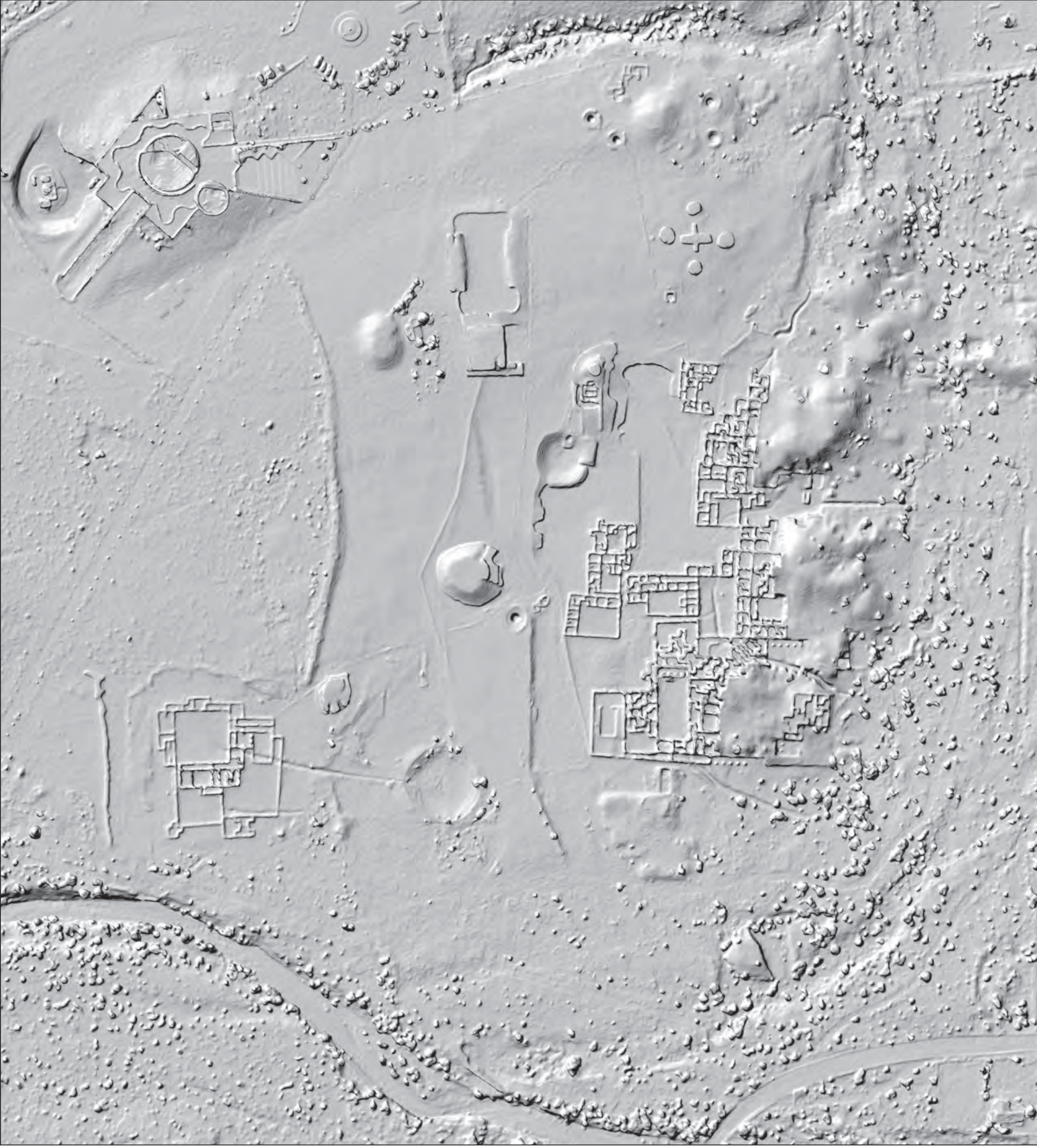


Figure 22. Paquimé hillshade model generated in ESRI's ArcMap based on the DSM exported from Pix4Dmapper.

bottom two images, compared to the orthomosaic. This short exercise shows the importance of using multiple methods to examine aerial images of archaeological sites, and likely other similar undertakings. Producing the slope analysis and hillshade model would not be possible without Pix4Dmapper's ability to export a DSM. This is an important feature that enhances Pix4Dmapper's effectiveness by providing outputs that easily integrate with other existing spatial analysis applications. For us, the ability to import the DSM into ArcMap helped us identify important architectural features at Paquimé that we may not have seen otherwise. Consequently, this new information will help us know what to explore further or leave intact to protect the remaining uncovered portions of the city.

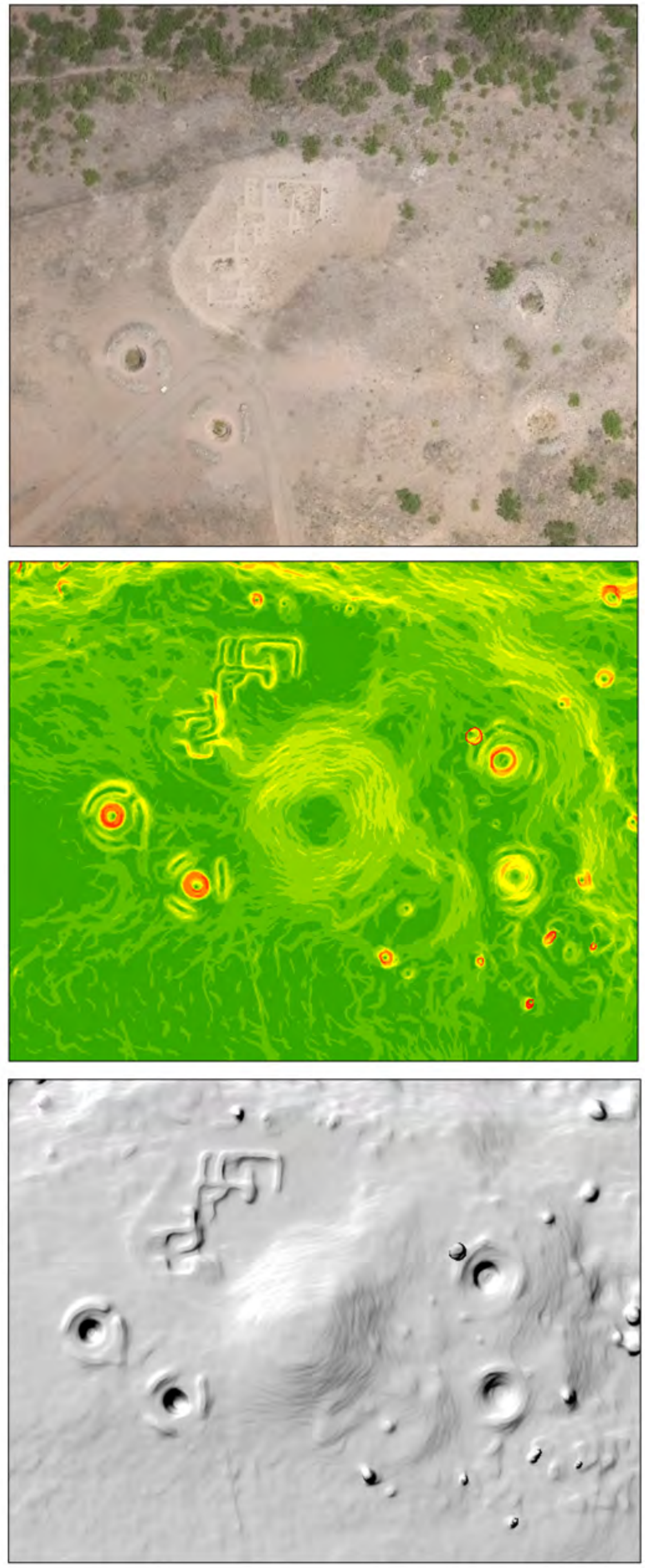


Figure 23. A comparison of the orthomosaic (top), with the DSM generated slope analysis and (center), and the hillshade model (bottom). Both the slope analysis and hillshade were generated using ESRI's ArcMap.

What We Learned

The versatility of a small UAV with the processing power of Pix4Dmapper is a powerful combination that made our Paquimé project successful. From take-off to landing, to data processing, everything went very smoothly. This was a direct result of proper training, preparation, communication, and support from both Pix4D and INAH. As mentioned previously, we worked closely with the INAH museum director and discussed our plans before doing anything (Figure 24). We made sure to include him in every aspect of the project, and he was extremely supportive, joining us during the entire flight.

We are convinced that we would not have been able to collect the amount, and quality, of data using traditional terrestrial surveying tools. In addition, we would not have been able to afford the time and money to map Paquimé by hiring a pilot or a survey company. This is one of the main benefits for using UAVs to document archaeological sites. They are an extremely cost-effective

Figure 23. Scott Ure prepares the X100 for take-off with Paquimé Museum director, Maurico Salgado Servín (wearing a white shirt), and his colleague (wearing a turquoise shirt). The Kestrel 4500 weather meter is in the foreground.

solution for mapping large, fragile, and inaccessible areas. In addition, multiple flights are quick and easy when using a UAV. This is one area, among many, where Pix4Dmapper shines. It provides users the ability to quickly examine the flight images using their rapid processing tools to identify missed areas while still in the field. If a specific area is missed during a previous flight, it is a simple matter of plugging in a fresh battery and flying that area again. Examining the results from the rapid processing tools in Pix4Dmapper allowed us to quickly determine that we had indeed captured all of the photographs we needed.

Pix4Dmapper: A Powerful Tool for Archaeologists

Our experiences capturing and processing photogrammetric data from Paquimé, as well as at other sites throughout the world, has shown that Pix4Dmapper offers archaeologists a suite of powerful tools to document any archaeological site. In our opinion, Pix4Dmapper's ability to generate accurate,

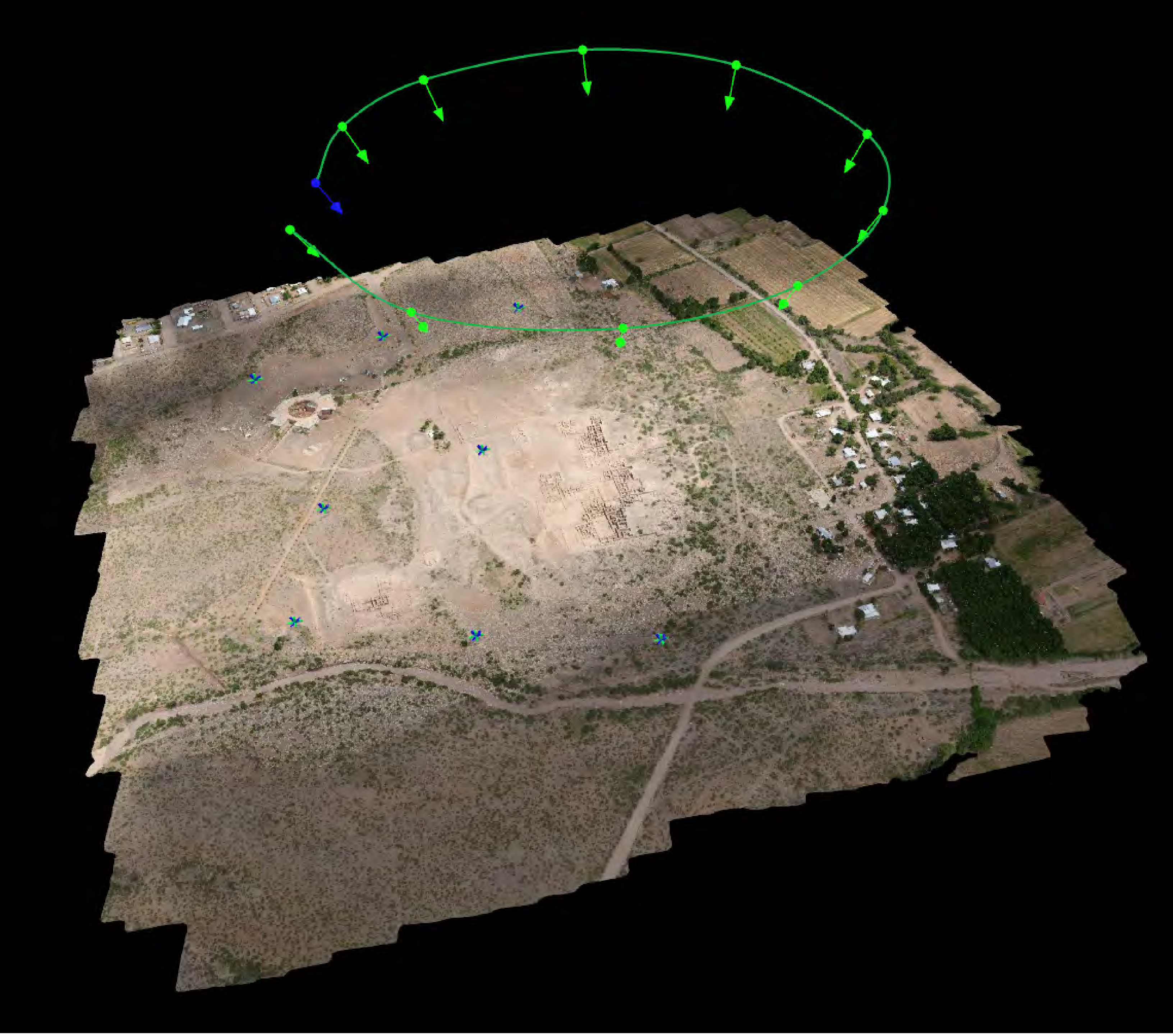


Figure 24. Pix4Dmapper trajectory used to show the camera path for an animation of the Paquimé photogrammetric model.

georeferenced point clouds, simply from photographs, makes it an essential tool for archaeologists. Pix4Dmapper can then produce orthomosaics, surface meshes, digital surface models, and animations (Figure 24) from both aerial and terrestrial photographs. This means that not only can you capture aerial images, but you can also produce 3D models of artifacts, rock art panels, caves and shelters, buildings, statues, and just about anything else using a camera and Pix4Dmapper. There are several similar software applications, but, in our opinion, none match Pix4Dmapper's complete solution: a combination of an intuitive and user-friendly interface with informative, accurate, and transformative results.

Figure 25. Baricora Polychrome pottery from Paquimé. On the left is a jar with the "feathered serpent" motive, and the on the right is a human effigy jar. Photographs courtesy of the Museum of Peoples and Cultures, Brigham Young University.

With Pix4Dmapper, archaeologist can capture, analyze, and visualize their data in cost-effective ways that were not previously possible. In addition, Pix4Dmapper provides new ways for sharing archaeological data with colleagues, clients, the public, and others interested in "virtually" analyzing, or visiting, a site or artifact in full, measurable 3D. This is an important capability, because archaeologists have an ethical imperative to share our findings. Archaeological sites belong to everyone, and Pix4Dmapper helps archaeologists share these wonderful ancient places in exquisite, colorful, and realistic detail.

ACKNOWLEDGMENTS

We would like to thank the Instituto Nacional de Antropología e Historia and Maurico Salgado Servín, Director of the Paquimé Cultural Center, for the privilege of working in Paquimé. This project would never have "made-it-off-the-ground" without their support. We would also like to acknowledge the good people of Casas Grandes who treated us as family and neighbors, and we specifically want to thank Julian Hernández and Lewis Tena for their hospitality and support during our visit to Paquimé.

We are certain that this project would never have happened without the support of Pix4D. Their generosity and technical support gave us the tools to capture Paquimé in all of its amazing, complex beauty. Lisa Chen has been a patient and knowledgeable resource, and Sonja Betschart believed in us when we were first getting into the world of UAVs and photogrammetry. Many thanks to both of them, as well as all of the other amazing people at Pix4D.

We are also extremely grateful for Rex and Ruth Maughan who provided financial support to acquire the X100 UAS. Their generosity has completely changed the archaeology program at Brigham Young University. Without their support, we would not have taken to the skies. Finally, we want to thank Dean Benjamin Ogles and Jim Crawley from the BYU College of Family, Home, and Social Sciences, and faculty and staff from the BYU Department of Anthropology for their continued support. They have all truly helped us make the world our campus.

REFERENCES

Di Peso, Charles C.
1974 Casas Grandes: The Medio Period, Vol. 2. In *Casas Grandes: A Fallen Trading Center of the Gran Chichimeca*, edited by Gloria J. Fenner. The Amerind Foundation, Inc. Dragoon Northland Press, Flagstaff, AZ.

UNESCO (United Nations Educational Scientific and Cultural Organization)
1998 Convention Concerning the Protection of the World Cultural and Natural Heritage. *Twenty-Second session of the World Heritage Committee*, Kyoto, Japan.

Whalen, Michael E. and Paul E. Minnis
2003 The Local and the Distant in the Origin of Casas Grandes, Chihuahua, Mexico. *American Antiquity* 68(2):314–332.