Hiding in Plain Sight: The Discovery of a New Monumental Structure at Petra, Jordan, Using WorldView-1 and WorldView-2 Satellite Imagery

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This article describes the discovery and mapping of a large, previously unknown monumental structure at Petra, Jordan, using Google Earth, WorldView-1 and WorldView-2, and drones. Petra represents one of the most well-known and surveyed archaeological parks in the world; yet significant structures within range of its central city remain to be discovered. This article discusses the significance of the new discovery in relationship to Petra and its cultural landscape as well as the potential of WorldView-1, -2, and -3 satellite sensors for other archaeological projects in similar geographic areas.

Keywords: Petra; Jordan; remote sensing; monumental platform; survey

Petra, Jordan, has one of the richest histories of archaeological exploration in the world as a World Heritage site, visited yearly by half a million tourists. Archaeologists have documented thousands of carved and constructed monuments within the ancient city center as well in the wadis and mountains that surround it—many of which are cataloged in standard publications (e.g., Brünnow and von Domaszewski 1904; Dalman 1908; 1912; Bachmann et al. 1921; Nehmé 2012; Wadeson 2010; 2013; and Wenning 1987; 2001; 2012). The landscapes of important hinterland sectors directly associated with Petra have also been surveyed, including the regions around Jabal Harun to the south (Kouki and Lavento 2013) and the areas between the city and Beidha to the north (Alcock and Tuttle 2012; Alcock and Knodell 2012).

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Modifications to the landscape of the Petra city center and other nearby sectors do not appear to have been as systematically surveyed as the investigated regions of the southern and northern hinterlands (or the work remains unpublished). Even after two centuries of fieldwork in Petra and its environs, new discoveries and identifications of monumental structures continue to be made both within and around the urban center.[1]

Tourism, tourism infrastructure, general topography, geology, and changes to the landscape of Petra over time all represent challenges unique to conducting surveys, but these are challenges that new technologies can address. Ongoing work at Petra focuses on major conservation efforts and delicately balancing the needs of tourism with protecting the central city area; and precisely because of its length of excavation and survey history, Petra is an outstanding site to test new survey technologies. Petra's archaeological teams have used aerial photographs in their survey work (Myers and Myers 1995: 284–85, figs. 5–7; Levy et al. 2013) and ground-based remote sensing (Tullis and Worthington 1998; Bedal 2003; Urban, Alcock, and Tuttle 2012; Urban et al. 2013; 2014), both of which have allowed archaeologists to locate features

[1] See, e.g., the International Umm al-Biyara Project (IUBP) and the North East Petra Project (NEPP). To view the online field reports, go to: www.auac.ch.

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otherwise difficult or impossible to see. Via a collaborative project supported by the BBC and DigitalGlobe in 2011, we decided to test Google Earth, WorldView-1 (WV-1), and WorldView-2 (WV-2) satellite imagery in the survey of the central city of Petra and its environs, accompanied by ground survey to assess the satellite results.[2] We have discovered multiple previously unknown features, including a monumental structure just 900 m southwest of Petra's city center. We propose that well-known and well-surveyed archaeological sites across the globe could benefit from reassessment, beginning with Google Earth and then using the WV-1 and WV-2 satellite sensors, and suggest possible technical approaches for these data. Potential new discoveries at sites, once ground-truthed and confirmed, can be mapped in far more detail using unmanned aerial vehicles (UAVs, or drones), which can aid in their interpretation. In addition, the new discovery of the structure assists with our overall understanding of monumental architecture and landscape use at Petra, and suggests that additional potential major structures may be found there.

The Potential of High-Resolution Satellite Sensors for Archaeology

New satellite sensors and remote sensing technologies are transforming our understanding of ancient landscapes and archaeological sites across the globe. Most importantly, they are allowing archaeologists to ask better questions about past human–environment interactions and to see landscapes and sites as integrated rather than separate. Perhaps, then, archaeologists should not think in terms of either archaeological sites or landscapes but of "sitescapes." Given the increasing number of academic papers, dissertations, and academic posts requiring expertise in GIS and remote sensing, it seems that remote sensing has finally become a part of the standard archaeological tool kit (Parcak 2009; Wiseman and El-Baz 2007). Yet it is surprising how few archaeologists regularly employ satellite data or how many papers at academic conferences still focus on coarse-resolution NASA satellite data sets. While useful for countrywide or regional survey, Landsat and ASTER satellite data sets (resolution: 15–90 m) simply cannot see architectural features. Within the field of Near Eastern archaeology, more professionals are using satellite remote sensing, although the approach is not yet common (Altaweel 2005; Beck et al. 2007; Casana and Cothren 2008; Hritz 2010; 2014).

When choosing remote sensing tools for landscape mapping, site assessment, or feature location, archaeologists need to think about their landscapes, the available sensors, date (i.e., seasonality), weather, and data cost. The aerial sensor with the greatest potential for high-resolution topographic mapping is LiDAR (Light Detection and Ranging) (Harmon et al. 2006). Ongoing LiDAR project work in Central America has the major potential to map hundreds of currently unknown or little-known ancient Mayan sites, as evidenced by the discovery of over 1,200 previously unknown structures at the site of Caracol, Belize. One wonders what potential LiDAR might have at other sites like Copán, Guatemala (which Parcak visited in December 2008), with numerous unexcavated structures evident in the rainforest surrounding the site. Archaeological zones not as well mapped, such as Cambodia, also have hundreds of sites currently hidden by dense rainforest canopy and could yield other major cities similar to the one discovered by Damian Evans et al. (2013). The major barriers to success with LiDAR are cost, which is nearly \$1,000 per km^2, and potential military restrictions, which most archaeologists working in the Middle East-North Africa region may encounter. In the future, space-based LiDAR may provide similar tools for archaeologists at a fraction of the cost, or smaller LiDAR systems could be flown on UAVs, similar to the looting map work done in Jordan in the Follow the Pots project (Salopek 2014).[3]

High-resolution sensors provide a balance among cost, availability, and usefulness in feature detection and mapping, although their use is limited in rainforest regions, where they can detect potential sites based only on vegetation changes (Saturno et al. 2007). Landsat, ASTER, and other sensors are still useful for environmental assessment or broad-scale mapping, and most are free. Archaeologists can begin their work using Google Earth Pro (GEP), which archaeologists have used to identify sites (Thomas et al. 2008) as well as to map looting (Contreras and Brodie 2010). GEP is now free and allows teams to download high-resolution imagery, which can be georeferenced. Imagery cannot be manipulated like raw satellite data and is visual only. Projects will need to assess their data needs: obtaining countrywide high-resolution data is simply not affordable.

Archaeologists need to be strategic about data acquisition. High-resolution data from Geoeye, Quickbird, WV-1, and WV-2 costs between \$8 and \$24 per km^2 (minimum order of 25 km^2). DigitalGlobe even has a foundation, which considers requests for satellite data.[4] Newly tasked satellite data are much more expensive,

[2] Parcak analyzed the satellite data; Parcak and Tuttle conducted background research; Tuttle undertook the ground-truthing in Jordan; Parcak and Tuttle designed the study; and both discussed the results and contributed to this article.

[3] For more information about this project, go to: http://followthepotsproject.org/.

[4] For more information about this important program, go to http://www.digitalglobefoundation.org/.

costing thousands of dollars, and the timing is not guaranteed; yet most sites have current archived data. Satellite data requires expertise in processing. Opening up a high-resolution image and doing basic processing in Photoshop can be helpful but uses only a fraction of the satellite data, especially regarding data fusion, feature classification, and imagery enhancement (Lillesand, Kiefer, and Chipman 2008).

DigitalGlobe provided WV-1 and WV-2 imagery for this project, taken on June 29, 2010. WV-1 is panchromatic (black and white) with a 0.5 m pixel resolution, while WV-2 has eight data bands (specific ranges of data within the electromagnetic spectrum) with a 1.85 m multispectral pixel resolution. Each range within the light spectrum, measured in nanometers (nm), is useful for detecting specific features types, such as red, red edge, and near infrared for vegetation health differences. The bands of WV-2 data are coastal (400–450 nm), blue (450–510 nm), green (510–580 nm), yellow (585–625 nm), red (630–690 nm), red edge (705–745 nm), near infrared 1 (770–895 nm), and near infrared 2 (860–900 nm) (see DigitalGlobe 2010). For this analysis, seasonality did not make a difference. The imagery came subdivided into 12 quadrants measuring approximately 7.5 × 7.5 km each, with a total image size of 20 km east–west × 26.5 km north–south. We used ERDAS ER Mapper as the program for imagery analysis.

Analysis

A simple question drove our research design: To what extent did the Nabataeans alter the landscapes in and around Petra (Ortloff 2005; Alcock and Knodell 2012; Kouki and Lavento 2013; Urban et al. 2013) in ways that previous survey and excavation might have missed (Barker et al. 1999; Beckers et al. 2013; Mattingly et al. 2007)? We assumed that a large, well-surveyed site like Petra could have features in its central city region and environs that remained hidden or overlooked due to location, topography, geology, and angle of placement.[5] That said, at Petra, the geology and lack of vegetation indicators for buried architecture were such that neither seasonality nor timing played a major role in our choice of imagery.

We reviewed previous excavation and survey data as well as maps of known features to obtain the range of features we might encounter, including roads, shrines, cairns, walls, forts, caravanserai, monumental structures, and housing (especially in the peripheral zones). We pan-sharpened the WV-1 and WV-2 data for each quadrant, which merged the 0.5 m black-and-white visual data with the multispectral data, giving 0.5 m multispectral data. Within ER Mapper, there are tools that allow us to pan-sharpen data easily. Bands 8, 7, and 6 made the data more sharp than other combinations of bands, due to the geological features being enhanced (DigitalGlobe 2010). We assessed general site topography in GEP. In Google Earth, four images of Petra appear: a SPOT image (December 2004), two Quickbird images (one from January 2006, the other from June 2010, which was of poor quality and was not in the same data set as used in this project), and a CNES/Astrium image (from May 2013, which was not available while we conducted this study). During the examination of GEP data, some initial features of interest appeared, marked for further assessment with the WV-2 imagery (**Fig. 1**).

We then applied a high-pass 11 × 11 filter to each pan-sharpened WV-2 data set, which allowed for local feature sharpening. High-pass filtering is a fairly common remote sensing tool and is particularly useful for archaeological remote sensing analysis. High-pass filters weight local features more strongly (Lillesand, Kiefer, and Chipman 2008). If a site has a partially buried wall that is difficult to see, a high-pass filter will make the wall "pop" out more because its pixels will be made darker than the surrounding soils. We attempted different high-pass filter combinations with imagery enhancement for each band (including Gaussian equalization, histogram equalization, default linear transform, and autoclip transform, all of which can be found under the algorithm box in ER Mapper). Dry areas with stone structures can be more challenging for imagery analysis, since most structures tend to be constructed from local materials. When a possible feature appeared, we changed the sun angle on the data to see varying alignments of the structure, to test if it might be natural rather than manmade. A number of features became apparent, which Tuttle initially examined. Once we confirmed that each feature could be manmade, we adjusted the contrast to make the features stand out even more. We also applied edge detection (a standard high-pass filtering technique) to differentiate between pixel values. We note that for the safety of the previously unknown features discovered, and to protect them against looting, we have obscured their exact locations intentionally on the satellite imagery maps in this article, although we provide a general location in **Figure 1**.

Four initial clusters of potential features appeared 2 km south-southwest of the city center, none of which appeared in the GEP images. The first feature, measuring 15 × 20 m, oriented northeast by southwest, appeared to have double chambers with 1.75 m thick walls. The second appeared as a series of 1 m thick walls, some connected, but not forming a distinct structure. The third structure appeared ambiguous but worth ground-truthing, as a

[5] For comparative examples of new discoveries in the city, see the IUBP and NEPP projects cited above. For the northern hinterlands, see Bikai, Kanellopoulos, and Sanders 2008; Sinibaldi and Tuttle 2011; and Vella et al. 2012.

Fig. 1. The central city area of Petra in the context of the region. (Courtesy of Google Earth)

series of potential chambers measured 4 × 4 m. The final structure within this grouping appeared to be a platform, measuring 19 × 21 m (**Fig. 2**).

Another feature became apparent north of this cluster. One straight edge and one corner appeared in the 2006 GEP imagery, with additional faint eastern and southern lines in the 2013 GEP imagery, leading to additional analysis with the pan-sharpened WV-1 and WV-2 data. Within GEP, the western straight edge aligned perfectly with a series of additional straight edges running down a cliff edge, leading Parcak to believe that the feature could be natural. The feature discovered in the processed data appeared roughly 1 km south-southwest of the city center, measuring 53 × 82 m. The southeast, northwest, and northeast corners all appeared clear, with multiple walls and internal features appearing slightly less clear (**Fig. 3**).

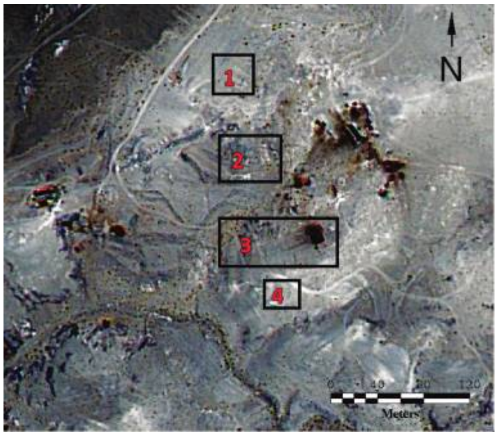

Fig. 2. Pan-sharpened WV-1 and WV-2 imagery of four features (in Parcak Areas 1–4) with high-pass filters and Gaussian equalization applied. (Courtesy of DigitalGlobe)

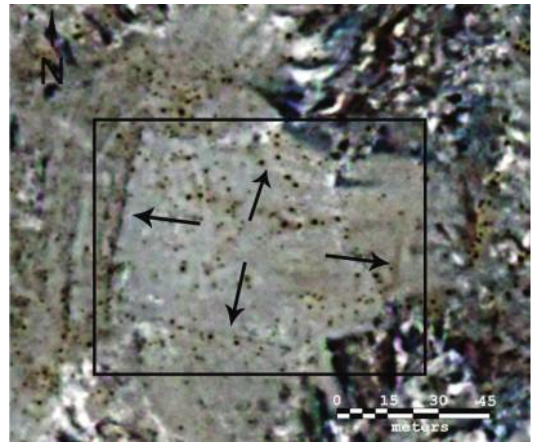

Fig. 3. Pan-sharpened WV-1 and WV-2 imagery of platform area, with high-pass filters and Gaussian equalization applied. The platform is located within the rectangle. Arrows point to the four sides of the platform. (Courtesy of DigitalGlobe)

Ground-Truthing and Results

A crucial part of remote sensing includes ground investigation, and we deemed these features worthy of field checking. Tuttle led four ground-truthing trips to investigate the features identified by Parcak's analysis of the satellite data. He and his team used maps created from the satellite data containing details about the GPS coordinates of the central point and four corners of each potential feature. They navigated to these areas using GPS units. To determine accuracy, the team checked the GPS points of each feature against the coordinates given, as well as additional landscape features apparent in the satellite imagery. The first site investigated is located on the southwestern edge of the city center. It appeared in the data as a north–south-aligned rectilinear feature on the south slope of the Al-Katute Hill. The feature was not a structure but the remains of an old excavation trench. However, the discovery of the feature bears historical significance: research showed it to be the location of the first scientific excavations at Petra, undertaken in 1929 by George Horsfield and Agnes Conway Horsfield (Horsfield and Conway 1930; Horsfield and Horsfield 1939; 1942), the exact location of which was never published on any maps.

The four initial clusters (Parcak 1–4) investigated are located in a sector south of the city center where the landscape appears to have received relatively little attention in published and unpublished work. The sector is bound on the north by the Wadi Farasa at the southern foot of ez-Zantur, to the west by the modern track to Jabal Harun, to the east by Jabal al-Madhbah and Jabal an-Nmayr, and to the south by the "South Ridge" that overlooks the Wadi ath-Thughrah necropolis with its famous "Snake Monument" tomb. The landscape of the sector is predominantly highland, consisting of a ridge-like formation that extends from a peak at its northern terminus overlooking the Wadi Farasa and extending southward to the northern face of the "South Ridge" base. The first cluster of identified sites discussed here is located at the southern edge of our search area, on or near the base of the southwestern slope of the "South Ridge." The landscape to the south of this sector is predominantly used for agriculture and animal husbandry. The target area itself is heavily disturbed by modern activity, with a permanent Bedouin tent encampment and traces of a second itinerant camp as well.

The first target area (Parcak 1) represented a recently tilled section where the soil contained many pottery sherds and a few white limestone tesserae but no architecture. Parcak 3–4 contained numerous traces of water management and agricultural installations: terrace walls, barrage dams, and hewn reservoirs; this was expected, as clear evidence exists that past inhabitants used the slopes of the "South Ridge" for agricultural purposes (see **Fig. 4,** far right, for obvious terrace lines on the northeastern slope). The region of Parcak 2 yielded the best architectural results. A long north–south alignment of walls and collapsed chambers from a building complex was identified (**Fig. 5**, labeled CAT 2); no obvious function could be determined from this preliminary visit, and the pottery scatters included materials from the first century B.C.E. through to at least the third century C.E. A more distinct structure was also identified nearby (CAT 1). This was an approximately 14 × 14 m elegant building built on a small platform with its entrance on the east side; it contained columns (**Fig. 6**), pilasters, a flagstone floor, and

Fig. 4. Overview of the monumental platform, looking southeast. Jabal an-Nmayr is is indicated by the left-facing arrow, and the slope of "South Ridge" with agricultural terracing by the down-facing arrow. (Photo by G. al Faqeer)

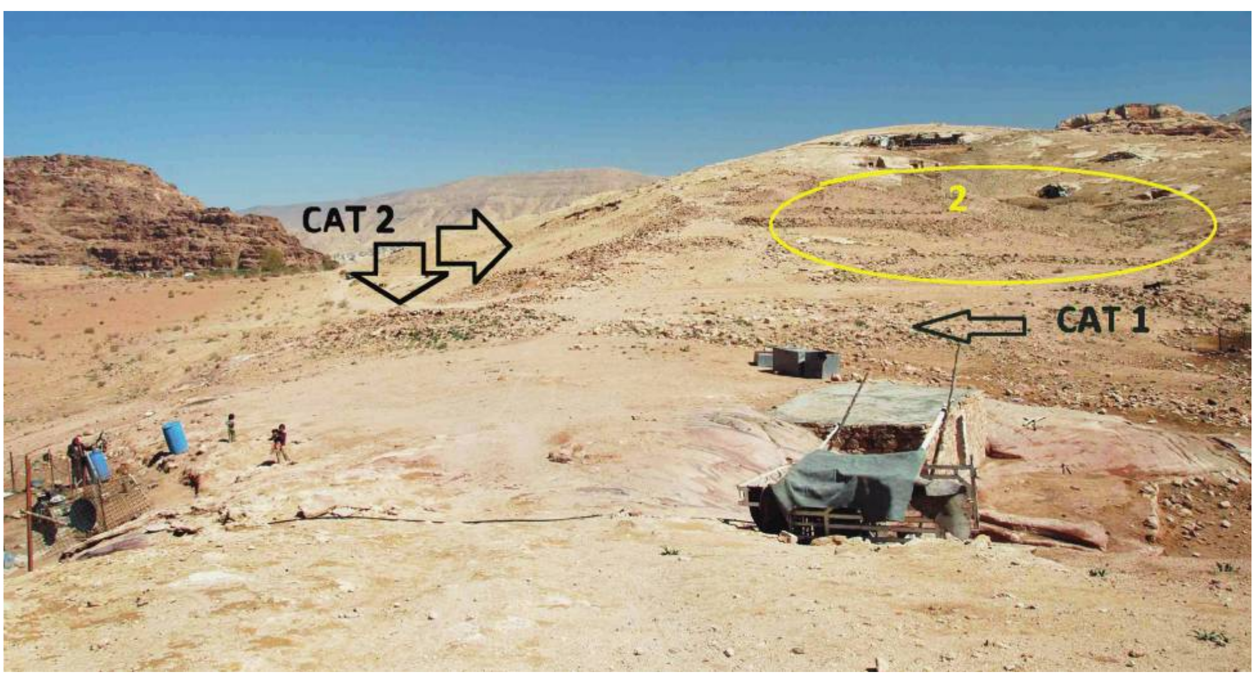

Fig. 5. View to the north of Parcak 2 target area (yellow oval) showing structures CAT 1 and CAT 2. (Photo by C. A. Tuttle)

Fig. 6. Extant sandstone column drum inside structure CAT 1. (Photo by C. A. Tuttle)

an external cistern with its cover stone in situ. It is poorly preserved and provided no clear evidence of function or chronology.

Very little information could be gleaned from the site visits alone. The modern use of the area has irrevocably disturbed much of the extant architecture and the surface scatters. The predominance of the agricultural and hydrologic systems does confirm some expectations about ancient land use in the area and suggests the possibility that the remnant structures may be somehow related to this use. The sector could benefit from a more systematic pedestrian survey and some test excavations, as this would place the structures in a more detailed context.

The main feature identified in this study lies farther to the north, back toward the city center, on a flat plateau along the north–south ridge-like formation almost directly opposite the opening into the Wadi an-Nmayr. We made three documentation visits to the site that included collecting architectural measurements and GPS points, a non-collection pedestrian survey of construction elements and artifact scatters, and a UAV flight to obtain aerial photographs (**Figs. 7, 8**). We note that satellite imagery along with associated UAV flights for archaeological mapping is only possible in areas where military restrictions do not exist.

The feature is a large rectangular platform (ca. 56 m north–south × 49 m east–west) (**Fig. 9**) that was constructed by leveling the natural plateau on the ridge-like formation. It is supported on its west side by several tiers of substantial terrace walls, which may have been necessary to augment the available bedrock. A smaller platform (ca. 46 m north–south × 44.5 m east–west) was constructed on the first (**Fig. 10**) and was originally paved with flagstones, a section of which was exposed by erosion in the southwest corner (**Fig. 11**); this pavement lies at approximately 956 m above sea level (± 3 m). The east side of the smaller platform was originally fronted by a row of columns made from sandstone drums, several of which had been partially revealed by illegal excavations. This row of columns crowned a monumental stairway that spanned the entire width of the smaller platform, of which several treads were found farther down the slope. A second set of 10 m wide steps gave access to the smaller platform from the south, near the southwestern corner (see **Fig. 9** for layout).

There is one prominent structure on the interior platform that is centered north–south but offset to the western side. It measures 8.5 × 8.5 m, and its entrance was centered on its east wall, the doorstep of which is still in situ (**Fig. 12**). Only a partial single course of wall stones is preserved above the foundation, and the state of the internal floor could not be determined without excavation. The structure's walls were composed of only a single row of stones, generally laid using a header-stretcher configuration, which suggests that the building was no more than one or two stories in height. The small building may have included at least one column at some point, as a remnant of a single drum was visible buried outside the west side (**Fig. 13**); this drum is smaller than those found in situ on the east side of the smaller platform.

Pedestrian surveys documented a range of very fragmented material culture remains. We located several weathered sandstone and limestone architectural elements that may derive from cornices and other moldings. We spotted quite a few small, square, plain limestone tesserae of the type usually associated in Petra with Late Roman/Byzantine-period constructions. The pottery scatter contained materials dated from the late Hellenistic through Late Roman/Byzantine periods (ca. second century B.C.E. through sixth century C.E.) and included Nabataean Painted Fine Wares (Dekorphases 1–4) and common wares, fragments of some imported wares (black-glazed, stamped wares, Terra Sigillata, and Eastern Sigillata), and several figurine fragments. We also noted sherds from handmade coarsewares that originated in the later medieval and early modern Islamic periods.

Significance of the Discovery

This monumental platform has no parallels at Petra or in its hinterlands at present. The unique platform design and location raise a number of intriguing questions regarding its function(s) over time throughout the life of the ancient city. The amount of effort to construct the site was massive, yet the focal building itself is quite small. The platform is located relatively close to the ancient city center but in a spot where easy access from the city center is not readily apparent. What seems to be a monumental "facade" (columns and stairway) faces the east rather than the city to the north and would not have been seen from the city center. This situation is not unusual for Petra, where many of its carved or constructed features are "hidden" from the city center due to their topographic locations throughout the surrounding mountains and valleys. However, there are directly visible relationships between this platform and the shrines known on Jabal al-Madhbah ("High Place of Sacrifice") and Jabal an-Nmayr to the east, with the structures on Umm al-Biyara to the northwest, and the ez-Zantur IV villa to the north.

These orientation relationships, architectural and construction styles, and pottery scatters all help to suggest that the platform was built when Petra was flourishing as the capital city of the Nabataean kingdom, possibly as early as the mid-second century B.C.E. It would appear highly likely that the platform and structures were initially

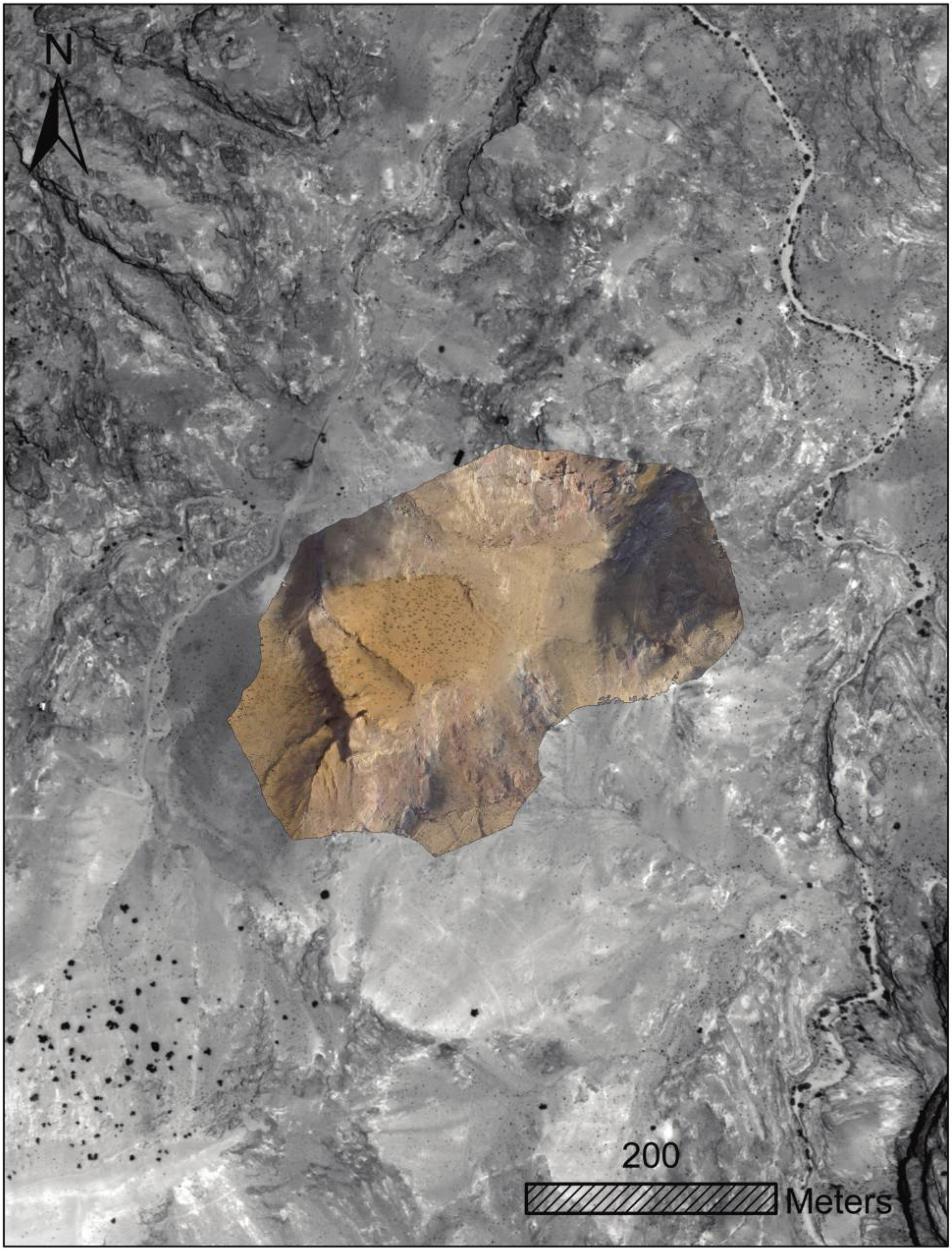

Fig. 7. Aerial image of "SM Platform." (UAV composite image created by I. LaBianca; S. Parcak overlaid the data on the WV-1 satellite imagery)

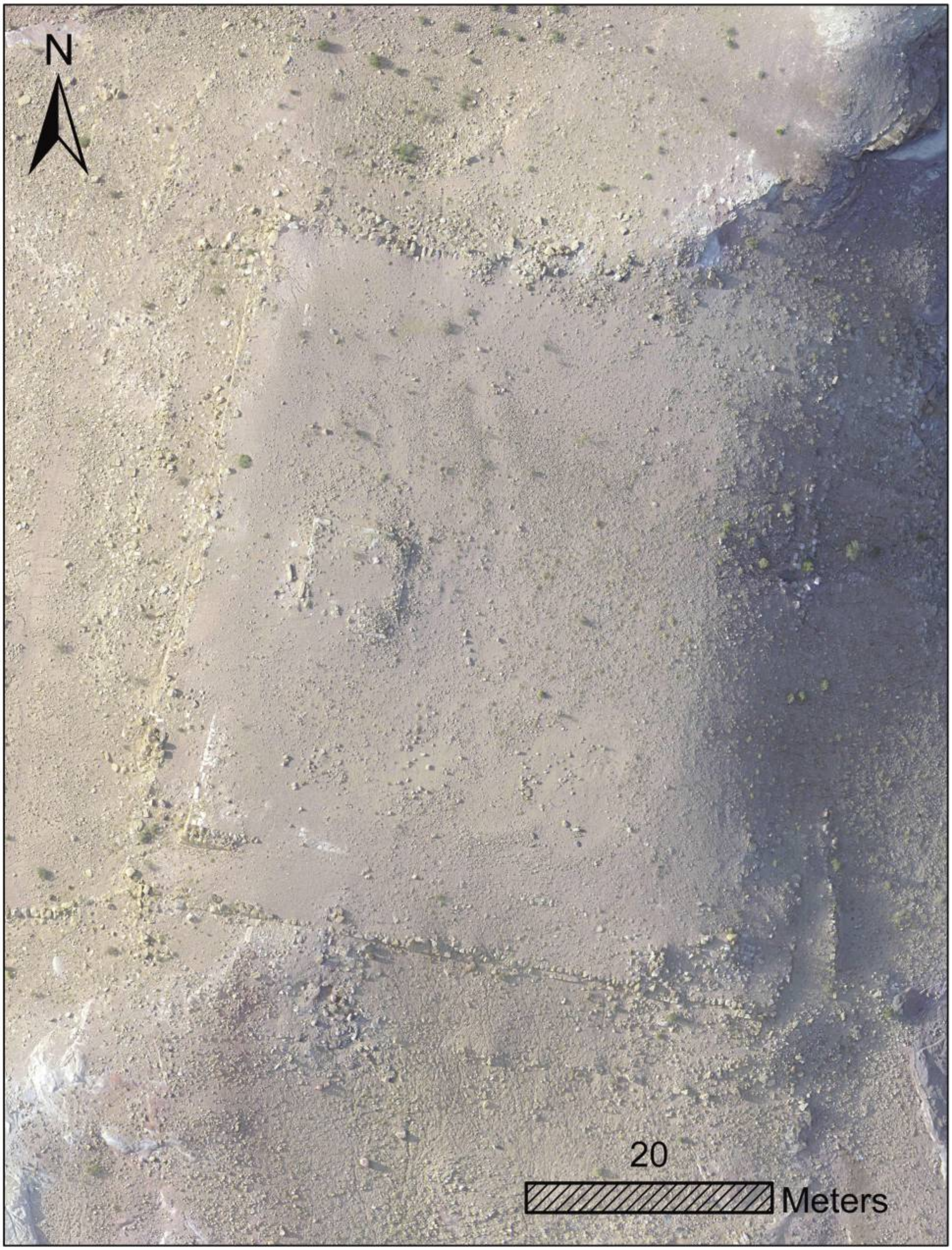

Fig. 8. Zoomed-in UAV image of platform. (Photo by I. LaBianca)

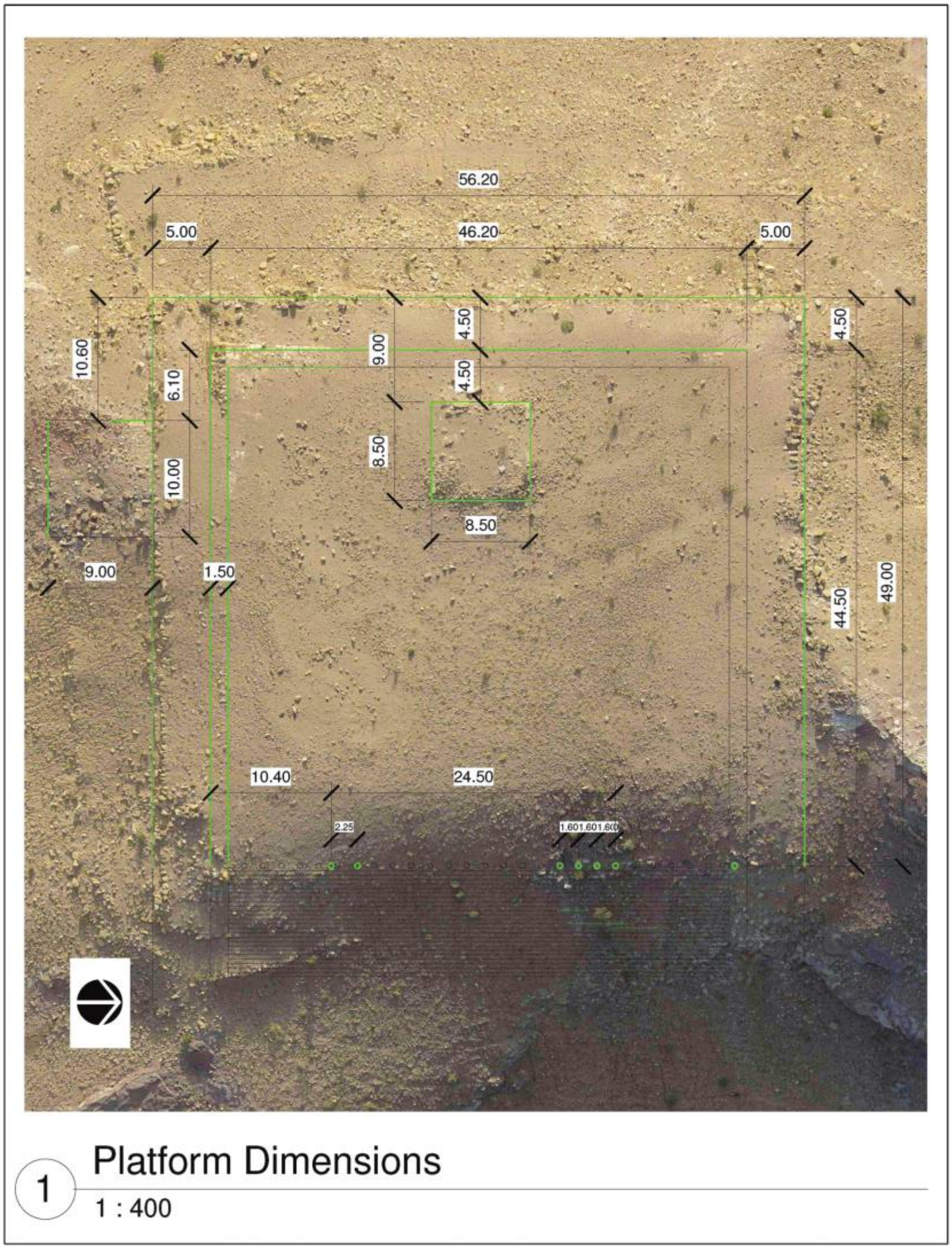

Fig. 9. Detail of monumental platform from UAV composite, with architectural details and measurements shown. (Photo by I. LaBianca; graphics by J. Blanzy)

constructed to serve ceremonial purposes. The east–west alignment of the small building may also have permitted its conversion to a Christian chapel during the Byzantine period. Based on comparisons with other similarly flat areas throughout the Petra region, the uses for the site during the later Islamic periods were likely more quotidian, perhaps as a threshing area or seasonal campsite.

Further investigation of this site would provide some valuable information for our understanding of Nabataean public ceremonial areas, a topic on which new research

Fig. 10. Tuttle standing at the southwest corner of the interior, smaller platform, looking north. (Photo by Q. Tweissi)

Fig. 11. Exposed flagstone pavers of the interior, smaller platform, looking north. (Photo by Q. Tweissi)

Fig. 12. Tuttle investigating the doorsill of the small building on the platform, looking southwest. (Photo by G. al Faqeer)

Fig. 13. Detail of the west side of the small building showing the single, buried column drum in the foreground. (Photo by Q. Tweissi)

is beginning to emerge (e.g., Bayda/Beidha, the Ad-Deir ["The Monastery"] plateau, and several smaller complexes ["Obodas Chapel" and "Aslah Triclinium"]). However, none of these other sites has direct parallels with this newly discovered platform south of the city center. The site would be ideal for both landscape survey and excavation work.

Although Petra is today "known" by many as the focus of both ongoing scientific research projects and as a tourist destination for hundreds of thousands annually, an argument can be made that the ancient city and its environs are still not all that well known in great detail, except, perhaps, to a handful of people. Most who visit this World Heritage site see but a tiny fraction of the total landscapes (or "sitescapes") in and around the city; most visitors experience only the city center and its immediate margins, about a 6 km^2 area, and do not realize that the Petra Archaeological Park, encompassing much (but not all) of the ancient city's direct impact zone, covers some 264 km^2. Given the complexities of the topography found in this extensive park, it is highly improbable that Petra has yet revealed all of its secrets.

This was the first project undertaken in the Petra Archaeological Park using the combined methodologies of satellite imagery analyses, UAV flights, and non-collection pedestrian survey. The results presented here clearly demonstrate both the effectiveness of and potential for combining these methods in the archaeological exploration of rugged, diverse, high desert terrains like the one in which Petra is situated. The use of new technologies, and of new project designs that employ them, have enormous potential for furthering our goals of understanding complex archaeological sites and their related, diachronic anthropogenic landscapes—even those like Petra that we think are already "well known." Subsequent to this project's efforts, similar combined methodologies have been employed to both discover and elucidate further "known" features, both within the city center environs[6] and in its hinterlands.[7] Other ongoing projects known to us that are exploring sites with established relationships to Petra have also subsequently benefited from similar research strategies, including the Udhruh Archaeological Project and the ʿAyn Gharandal Archaeological Project.[8]

Conclusions and Future Work

Future work at Petra will focus on a collaborative project to excavate the new monumental structure and study related findings. Could there be other "new" monumental structures awaiting discovery within close proximity to the central city? Based on the placement of this structure on a prominent hill overlooking the region and our examination of every other hillock within a 2 km radius of the central city, it is improbable but not impossible with the advent of new remote sensing technologies. Other large structures may have foundations that remain buried and will be difficult to locate without new sensors. Having a thermal infrared camera on the UAV may assist with the mapping of potentially buried walls and features that the satellites cannot see (Casana et al. 2014).

Given the discoveries at Petra, WV-1 and WV-2 satellite imagery analysis has much to offer other archaeological projects, especially at well-known sites with similar environmental conditions (Wilkinson 2003; Deroin, Téreygeol, and Heckes 2011), where new (and surprising) discoveries continue to make headlines. The near infrared and red-edge bands with WV-2 might be most useful for archaeologists working in regions with marked seasonal differences in weather and vegetation. With the mid-2014 lifting of imagery resolution restrictions by the National Geospatial-Intelligence Agency and the Department of Commerce in the United States, archaeologists now have access to 0.3 m satellite data. While the findings at Petra can be categorized as monumental and thus easier to locate from high-resolution satellite data, factors like the physical location of the previously unknown site and its construction materials hid it from surveyors for years. This situation can be re-created at many sites in arid regions. Just because a previous survey claims it visited an area does not mean that everything was found, especially prior to the use of satellite data. One can easily miss small bumps and ridges on the ground that may connect when seen in aerial imagery. This suggests that every archaeological site and its related hinterlands may benefit in some way from reinterpretation using satellite data.

It should be noted that satellite remote sensing can sometimes bias survey work. For example, small sites or pottery scatters cannot be seen on high-resolution satellite imagery. If archaeologists focus only on features discovered with satellite data, they might bias their results toward time periods and locales that feature either large architectural elements or easily visible past landscape alterations. Prehistoric sites, more ephemeral sites, and subtle past landscape changes can easily be missed. For this reason, satellite imagery should be used together with standard pedestrian survey, which by itself can often

[6] For the Ad-Deir Monument and Plateau Project, see https://pix4d.com/mapping-of-ad-deir-plateau-in-petra/.

[7] The Brown University Petra Archaeological Project in the Petra to Bayda/Beidha area is as-yet unpublished.

[8] The website for the Udhruh Archaeological Project is still under construction (http://www.opgravinginjordanie.nl/). For the ʿAyn Gharandal Archaeological Project, go to http://web.utk.edu/~religion/gharandal/index.php.

miss features due to their general state of preservation, location, and the inherent limitations that ground-based perspectives can impose on seeing and understanding interrelated details and relationships.

Not all sites can be examined with high-resolution satellite sensors, especially those beneath rainforest canopy, which must rely on LiDAR. While digital elevation models can be created from satellite data sets, point cloud data from LiDAR is far more accurate. LiDAR is too expensive at present to use regularly, and its use in some countries may be precluded by military restrictions. It is hoped that we can map Petra with LiDAR in the future to obtain a complete landscape elevation model. UAVs now have LiDAR capacity as well as hyperspectral cameras, and while the cost is presently prohibitive (these units range from $50,000 to $100,000), institutes may be able to find grant funding to purchase them.

A game-changing development for archaeology is the launch of the WV-3 sensor. With a 0.31 m panchromatic resolution, a 1.24 m multispectral resolution, a 3.6 m short-wave infrared resolution, and 29 bands of data (1 panchromatic band, 8 in the multispectral range, 8 in the short-wave infrared, and 12 bands in the CAVIS range, used to examine aerosols, ice, snow, and clouds), this sensor will allow archaeologists to map features invisible or only partially visible to current high-resolution sensors, especially in the short-wave infrared, which is useful for mapping geological signatures. Such data are now available to scholars but at a cost of $40 per km^2, which covers only the panchromatic and multispectral data.

What is the future of satellite remote sensing for archaeology? If current resolution trends continue, we may see 0.1 m high-resolution data within 10–15 years. There are few archaeological architectural features smaller than 0.1 m. Results will be restricted mainly to surface findings, unless there are unexpected advances in RADAR data, which at present works better in desert regions. Spectral resolutions will also likely improve, with high-resolution thermal data becoming available (currently, 90 m ASTER data), which will help to reveal features and sites that have heat signatures. With the improvement in spatial and spectral ranges, archaeologists will be able to detect not only specific features from space but also spectral signatures of specific time periods or zones on the surface of sites. For example, pottery or metal production areas can have high concentrations of slag, which affect the chemical signatures of surface soils when they are concentrated. Sites with well-known and excavated zones from specific time periods can be studied to determine if they have distinct spectral signatures. These findings can be extrapolated to other sites in the same region.

Archaeologists will always need to survey and excavate to confirm findings, but gaining a good sense of what time periods might be encountered will certainly help to set the scope of grant proposals and shape excavation season planning. Will we someday see a combination of space-based high-resolution LiDAR and hyperspectral cameras? Twenty-five years ago, we could not have imagined the data available today, so the next 25 years should continue to be exciting. Small satellites (termed CubeSats) such as Skybox also represent a brand new development for space science. With the global uptick in archaeological site looting, having access to daily high-resolution satellite data at little or no cost will benefit the work of numerous international heritage agencies, ministries of tourism/antiquities, and academics. Ultimately, satellites allow us to see, think, and visualize past landscapes differently. It appears that they are now a standard archaeological tool, and one that should be used with more frequency, as we take much for granted in terms of what is left to discover, even when monuments are hiding in plain sight.

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