Digital Applications in Archaeology and Cultural Heritage 31 (2023) e00293

Contents lists available at ScienceDirect

Digital Applications in Archaeology and Cultural Heritage

journal homepage: www.elsevier.com/locate/daach

Developing an interoperable cloud-based visualization workflow for 3D archaeological heritage data: The Palenque 3D Archaeological Atlas

Arianna Campiani [a,*], Scott McAvoy [b], Nicola Lercari [c], Rodrigo Liendo Stuardo [d], Gerardo Jiménez Delgado [d], Javier López Mejía [d], Dominique Rissolo [b], Falko Kuester [b]

[a] Sapienza University of Rome, Department of Ancient World Studies, Piazzale Aldo Moro 5, 00185, Rome, Italy
[b] University of California San Diego, California Institute for Telecommunications and Information Technology, 9500 Gilman Dr, La Jolla, San Diego, CA, 92093, United States
[c] LMU Munich, Institute for Digital Cultural Heritage Studies, Geschwister-Scholl-Platz 1, 80539, Munich, Germany
[d] National Autonomous University of Mexico, Anthropological Research Institute, Cto. Exterior s/n, Ciudad Universitaria, 04510, Coyoacán, Mexico City, Mexico

1. Introduction

Over the past two decades, there has been a continuous rise in the use of digital techniques to digitize museum collections and document monuments, archaeological sites, and cultural landscapes. This has led to the creation of high-quality multimodal giga-resolution 3D datasets. Archaeologists and heritage practitioners routinely utilize these large datasets of thousands of digital images, triangular meshes, point clouds, and derivative data to investigate the past and document its material culture in novel ways (De Reu et al., 2013; Fiorini et al., 2011; Forte and Campana, 2016; Galeazzi, 2018; 2016; Ioannides et al., 2017; Lercari et al., 2021; Scopigno, 2012). Various are the techniques employed to generate these 3D data, including but not limited to Image-based Modeling (IBM), also known as digital photogrammetry, Light Detection and Ranging (LiDAR), in its terrestrial or airborne configuration, and Global Navigation Satellite System (GNSS). Because of these techniques' enhanced precision, archaeologists have successfully integrated them into their documentation workflows and now widely employ them to produce archaeological drawings or conduct site surveying (De Reu et al., 2014; Dellepiane et al., 2013; Devereux et al., 2008; Djindjian, 2020; Guillem and Lercari, 2021; Hill et al., 2019; Kokalj et al., 2013; Lerma et al., 2010; Opitz, 2018; Remondino, 2011). However, processing 3D data to extract knowledge on a cultural object's or an archaeological structure's context, spatial features, utilization, and life cycle still requires sizeable resources concerning time, personnel, and hardware (Richards-Rissetto and Landau, 2019). Therefore, due to their resolution, scale, and complexity, 3D data may involve the risk of providing limited utility outside the specific software environments employed in the generation and post-processing. Higher dimensionality or complexity are often discarded in favor of down-sampled derivatives, which integrate better with established GIS and architectural pipelines or institutional documentation standards (Cignoni and Scopigno, 2008; Fresa et al., 2015; Richards-Rissetto and von Schwerin, 2017; Verhoeven, 2017). This is the case with 3D-native airborne LiDAR, also known as airborne laser scanning (ALS) datasets collected by research aircraft, which are often flattened and interpolated into 2D Digital Elevation Models (DEMs), for example to identify new archaeological sites or settlement patterns or detect objects and features in the archaeological landscape (Canuto et al., 2018; Canuto and Auld-Thomas, 2021; Chase and Chase, 2017; Evans et al., 2013; Inomata et al., 2018, 2021; Štular et al., 2012; Devereux et al., 2005; Risbøl et al., 2020; Masini et al., 2022). Another example of this trend is the decimation of triangular meshes of archaeological objects generated through IBM techniques. When archaeologists process these meshes for visualization and dissemination purposes in online 3D viewers, such as the widely-used Sketchfab, hundreds of millions of triangles, which make up to even 80–90% of the original geometric detail, are discarded through interpolation (Guidazzoli et al., 2017; Rahaman et al., 2019). As a result, archaeologists often decide not to share their raw 3D data captured in the field, for instance LiDAR scans, or high-resolution 3D models, such as the original meshes they obtain using IBM and related photo datasets. This choice is likely due to the complex computational dependencies associated with 3D data, which often leave them unusable by other scholars, let alone by non-academic stakeholders or the public.

This paper presents a pipeline to address the challenges of working with multi-resolution archaeological heritage 3D data and improve collaboration among archaeologists through cloud-based tools. The proposed workflow includes data capture, visualization, analysis, contextualization, recontextualization, and archiving (Fig. 1).

We contend that the proposed pipeline allows archaeologists to

* Corresponding author.
E-mail address: arianna.campiani@uniroma1.it (A. Campiani).

https://doi.org/10.1016/j.daach.2023.e00293
Received 25 July 2023; Received in revised form 25 August 2023; Accepted 22 September 2023
Available online 3 October 2023

leverage geomatics techniques to integrate and fuse different types of 3D data and collaborate remotely to identify in them meaningful correlations and patterns (Gattiglia, 2015; Stal et al., 2014). At the core of our workflow, there is the powerful open-source 3D visualization tool Potree Viewer (Potree) (Schütz, 2016). This Web viewer offers the enhanced capability to fuse, analyze, interpret, and share full-resolution archaeological 3D data in ways that foster exploration and make anomalies and correlations emerge "as a way to develop and to test new models for extra investigation, and to validate hypotheses" (Gattiglia, 2015, p. 4; see also; Galeazzi et al., 2016; Campiani, 2015; Liendo Stuardo, 2014; Matsushita et al., 2014). Potree is relatively user-friendly and easy to manage, and its interface gives users a good degree of interactivity. At the same time, its powerful WebGL-based rendering engine makes large datasets more intelligible and readable, therefore maximizing "human capacity to perceive, understand and reason about complex and dynamic data" (Llobera, 2011, p. 212).

The following sections of this paper describe how we utilized the proposed workflow to efficiently interlink, merge, present, contextualize, and recontextualize the 3D data we captured over several years at the ancient Maya city of Palenque, Mexico, to produce the Palenque 3D Archaeological Atlas (3D Atlas). This online geospatial collection enables synoptic visualization of 3D and geospatial data from large-scale excavation and digital archaeological surveys. We argue that our 3D Atlas allowed us to render our interpretations visible while enhancing our comprehension of the archaeological context through links and correlations. The discussion of our results in section 4 highlights the new knowledge and discoveries we made by using our 3D Atlas as a platform for collaborative interpretation and analysis.

2. Literature review

Our work situates within a broader effort to enhance archaeological research using new knowledge produced from bridging 3D data, remote collaboration, and data sharing. The potential of 3D spatial representation to convey interpretation and enhance collaborative research by sharing and discussing the collected 3D data has been long explored with different methods and techniques. Since the early 2000s, scholars in heritage-related fields have used workflows and platforms to manage, visualize, interact with, and analyze 3D data in various forms (Dell'Unto and Landeschi, 2022; Ioannides and Quak, 2014; Meyer et al., 2007; Pieraccini et al., 2001; Scopigno et al., 2011). These often involve analytical tools that can perform complex spatial analysis, search, queries, or collaborative tools that enable remote collaboration. Pioneering previous work includes, for example, VITA, a collaborative mixed reality system offering offsite visualization of an archaeological excavation (Benko et al., 2004), or the 3D Digging at Çatalhöyük project (Forte et al., 2012). This last effort aimed at virtually reconstructing the excavation data of a Neolithic house on a virtual reality desktop application or CAVE-like systems (Forte et al., 2012, 2013; Lercari et al., 2017; 2013). To enhance collaboration, the 3D-Digging Project developed TeleArch, a system for immersive real-time interaction among distributed users (Kurillo and Forte, 2012). Two major trends in managing 3D archaeological data have emerged in the last decade. The first builds on offline file-based desktop applications (Compton et al., 2017; Wheatley and Mark, 2022). The second focuses on online infrastructure capabilities (Jensen, 2018). Recent advancements in web technology, especially the advent of WebGL, have fostered the development of infrastructures for the visualization, interaction and manipulation of archaeological and cultural heritage 3D data (Galeazzi and Richards-Rissetto, 2018). For example, the MayaCityBuilder Project proposed new interpretations of archaeological contexts enhanced by 3D reality-based models of buildings linked with underlying spatial data (as LiDAR) and Virtual Reality (Richards-Rissetto, 2017a). The ADS 3D Viewer integrated the visualization of excavations 3D geometries with the related stratigraphic data stored in a repository (Galeazzi et al., 2016), while the Archaeo 3D viewer compiled 2D, 2.5D, and 3D excavation data into a semantically enhanced web-based platform (Jensen, 2018). Following this trend, the Interactive Reporting System (IRS) proposed a 3D web platform capable of managing the information collected during multi-year archaeological excavations and creating interactive reports connecting 3D visualizations with textual content (Derudas et al., 2021). More recently, the capability of importing 3D models into a GIS allowed archaeologists to incorporate, visualize and analyze the materials retrieved during fieldwork. The MayaArch3D project proposed QueryArch3D-WebGIS, a tool able to stream LiDAR data and 3D architectural models and foster spatial and visual research (Richards-Rissetto, 2017b; Richards-Rissetto and von Schwerin, 2017; von Schwerin et al., 2016; 2013). 3D GIS technology has also proven successful as a field tool thanks to a geodatabase capable of hosting complex 3D information (Dell'Unto et al., 2017). It has also performed well in managing the entire documentation of a cultural heritage site, or in post-excavation analysis (Campanaro et al., 2016; Dell'Unto et al., 2017; Landeschi, 2019; Landeschi et al., 2016). Lastly, the ATON open-source framework extends the potential of working with 3D cultural data in multiple mixed reality applications deployed through the web. The scalable and modular capability of ATON allows museums and cultural heritage professionals to easily present, inspect, and share cultural heritage data in a visually appealing and collaborative web environment that can be utilized on multiple devices directly via a web browser without the need to install the app (Fanini et al., 2021).

3. Materials and methods

3.1. Study area

The ancient Maya city of Palenque, Chiapas, Mexico, is located at the

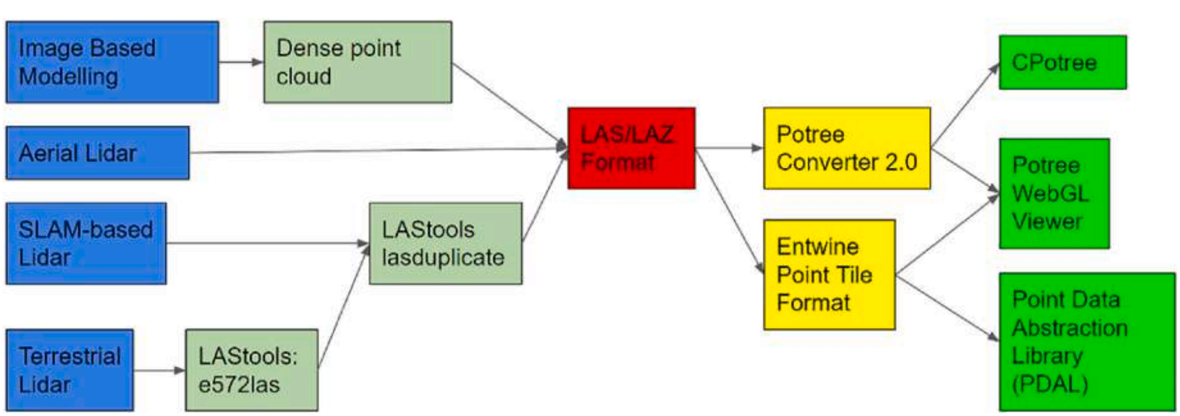


Fig. 1. Process pipelines for point clouds into Potree web viewer. Flowchart by author.

westernmost edge of the Maya Area (Fig. 2). Despite its peripheral location, Palenque became a powerful capital in the Classic Period (250–900 CE), with its apogee during the 8th century CE, when the city reached its maximum extension.

The city of Palenque was established in a strategic position on a 2.2 km^2 plateau between the mountains of the Sierra de Chiapas and the Tabasco plains, which extends toward the Gulf of Mexico. During the centuries, the ancient Maya modified the uneven morphology of Palenque's plateau through large-scale leveling and retainment works. Since the 6th century CE, the rulers ordered the erection of majestic public and religious buildings in the city center (de la Garza et al., 2012; Schele, 1986; Stuart and Stuart, 2008) (Fig. 3). These structures include outstanding examples of Classic Maya architecture, such as the Palace, and the temples of the Group of the Cross, which we digitally documented in 2018 (Lercari et al., 2019). Among Palenque's numerous mausoleums, we also recorded the Temple of the Inscriptions, which is widely recognized as one of the most iconic constructions of the entire Maya area (Greene Robertson, 1983; Miller, 1999). It was in 1952, that archaeologist Alberto Ruz retrieved inside this building the first intact tomb of a Maya ruler, the great K'inich Janaab Pakal, who erected the Temple of the Inscriptions in the 7th century as his funerary building (Bernal Romero, 2012; Ruz Lhuillier, 2013).

To preserve its tropical environment, in 1981, the Mexican government declared the site a National Park and enhanced its protection (Secretaría de Gobernación, 1981). Because of Palenque's unique characteristics in 1987, Palenque was inscribed in the UNESCO World Heritage List, further increasing its international reputation as an outstanding example of ancient Maya culture (UNESCO World Heritage Centre). Today, Palenque is visited by hundreds of thousands of visitors annually, which generally only explore about ten percent of the archaeological zone, focusing on the city center where most buildings are partially accessible (Fig. 4). However, Palenque spans a much larger area still hidden under a dense tropical forest. In the early 2000s, a team of archaeologists recorded approximately 1500 buildings using traditional survey methods (Barnhart, 2001a, 2001b), documenting structures of different sizes and dimensions mainly arranged around patios and small plazas. We believe that they were organized into neighborhoods headed by minor lords, who lived in a central compound comprising elegant two-story buildings, shrines, and a central plaza where people from the same neighborhood gathered (Campiani, 2017, Campiani, 2015; Liendo Stuardo, 2014, López Mejía, 2005; Marken and González Cruz 2007). This is the case of Group IV, an elite residential complex located northwest of the city center, whose buildings and central plaza we have excavated and documented employing digital methods since 2016 (Liendo Stuardo et al., 2017). The complex topography of Palenque, its majestic buildings, and intricate urban structure makes this archaeological site a unique case study to test the proposed workflow.

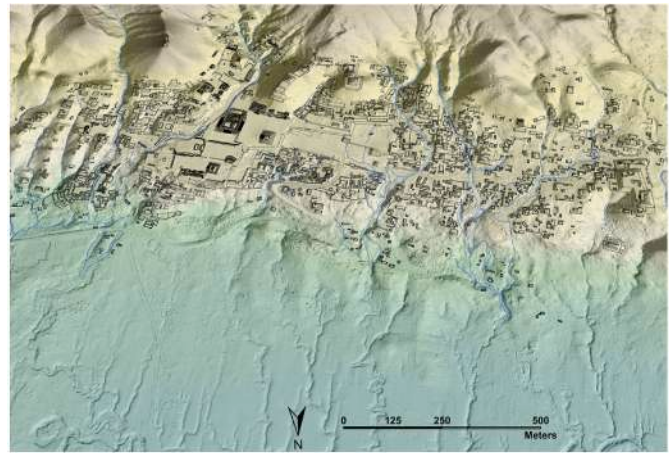


Fig. 3. The Digital Elevation Model of Palenque and its surveyed structures are seen from the north. Map by author, after Barnhart (2001a,b).

Fig. 2. Palenque's location in southern Mexico is seen in relation to other major Maya archaeological sites. Map by author, modified from ArcGIS Pro Basemap by National Geographic Society.

3.2. Palenque 3D data

Our multi-year research at Palenque produced a large and diverse dataset comprising geospatial and 3D data at multiple scales, from landscape-wide down to the individual building or excavation trench. We present below the data we successfully interlinked, merged, visualized, contextualized and recontextualized into the Palenque 3D Archaeological Atlas.

Fig. 4. Palenque's Palace building (foreground) and the Temple of the Inscriptions (top left) are seen in a photograph captured by a small UAV. Photograph by author.

3.2.1. Landscape-scale: aerial LiDAR

The ALS data included in our 3D Atlas is an accurate and extensive basemap that aligns all other 3D models. The dataset comprises 960 million points covering approximately 25 km^2 of terrain surrounding Palenque. Specialists from the National Center for Airborne Laser Mapping (NCALM) acquired it as part of a larger LiDAR observation campaign in Southern Mexico ("About the Center | NCALM," n.d.). NCALM used a three-wavelength Titan MW LiDAR unit, with a final horizontal accuracy of 15–20 cm and a vertical accuracy of 5–10 cm, following a custom-made workflow for LiDAR data acquisition in the Maya Area (Fernandez-Diaz et al., 2014, 2016; Golden et al., 2021). This ALS dataset was classified for noise, low, medium, and high vegetation, ground, and buildings. Our 3D Atlas allows users to toggle between classifications, enhancing visualization of both archaeological and natural features (Fig. 5).

3.2.2. Landscape-scale: LiDAR derivatives

While the bare ground resulting from the ALS dataset classification is easily segmented, points' sparse and inconsistent distribution makes it difficult to visualize features. For this reason, we also imported into our 3D Atlas DEM derivatives to connect the ground points into a continuous surface and highlight subtle detail. These derivative data have been manipulated with GIS platforms and plugins, such as ArcGIS Pro and QGIS, using the powerful plugins SAGA and WhiteBox. This way, we generated multiple visualizations emphasizing our study area's archaeological and natural features. More specifically, our GIS visualization pipeline used the Hillshade, Local Relief Model (LRM), and Red Relief Image Map (RRIM) techniques to produce several DEM derivates (Hesse, 2012; Kokalj et al., 2013; Kokalj and Somrak, 2019). We then converted these DEMs into 3D point clouds and applied their colored visualizations using the LAStools lascolor utility (Fig. 5). Because of the RRIM's capability to make various natural and anthropogenic features stand out, the RRIM-derived DEM projected in 2.5D constitutes the base layer of the Atlas (Fig. 6a) (Auld-Thomas, 2022; Chiba et al., 2008; Chiba and Hasi, 2016). As for comparison, the Hillshade and LRM visualizations highlight the subtle rises and indentations of potential archaeological mounds (Fig. 6b and c).

3.2.3. City-scale: aerial IBM

In 2018, we utilized a small unmanned aerial vehicle (UAV) to capture thousands of photographs of Palenque's civic-ceremonial core, including the areas and buildings mostly free from vegetation open to the public. We produced a high-resolution 3D model using a standard IBM workflow optimized for archaeological UAV-based applications (Aicardi et al., 2018; Fernández-Hernandez et al., 2015; Ferrari et al., 2015). More specifically, we utilized a DJI Inspire 1/RAW drone equipped with a Zenmuse X5 RGB camera, capable of capturing still images at 16 MP. We captured over four thousand photos of the mapped area using nadir camera angles perpendicular to the ground. We produced a colorized point cloud of over 418 million points, a DEM, and an orthophoto with a centimeter-level ground resolution (Lercari et al., 2019) (Fig. 7). Before the more recent acquisition of the ALS dataset discussed above, this UAV-based 3D dataset was the most detailed documentation of the site, as it captured the numerous asynchronous architectural phases currently exposed.

3.2.4. Building-scale: terrestrial LiDAR of the temple of the inscriptions

We included in our 3D Atlas an ultra-precise 3D documentation of the Temple of the Inscriptions. We scanned this building using proven terrestrial LiDAR (TLS) surveying and data processing workflows (Olsen, 2015; Olsen et al., 2010). We utilized a FARO Focus X120 shift phase range finder to scan the building on top of the temple's basement using a high-resolution setup to record the Temple's exterior walls, the sculpted figures of the temple balustrades and the stucco reliefs of the external wall piers. Using a lower-resolution setup, we also scanned the interior environments, including the limestone panels (Maudslay, 1887; Ruz

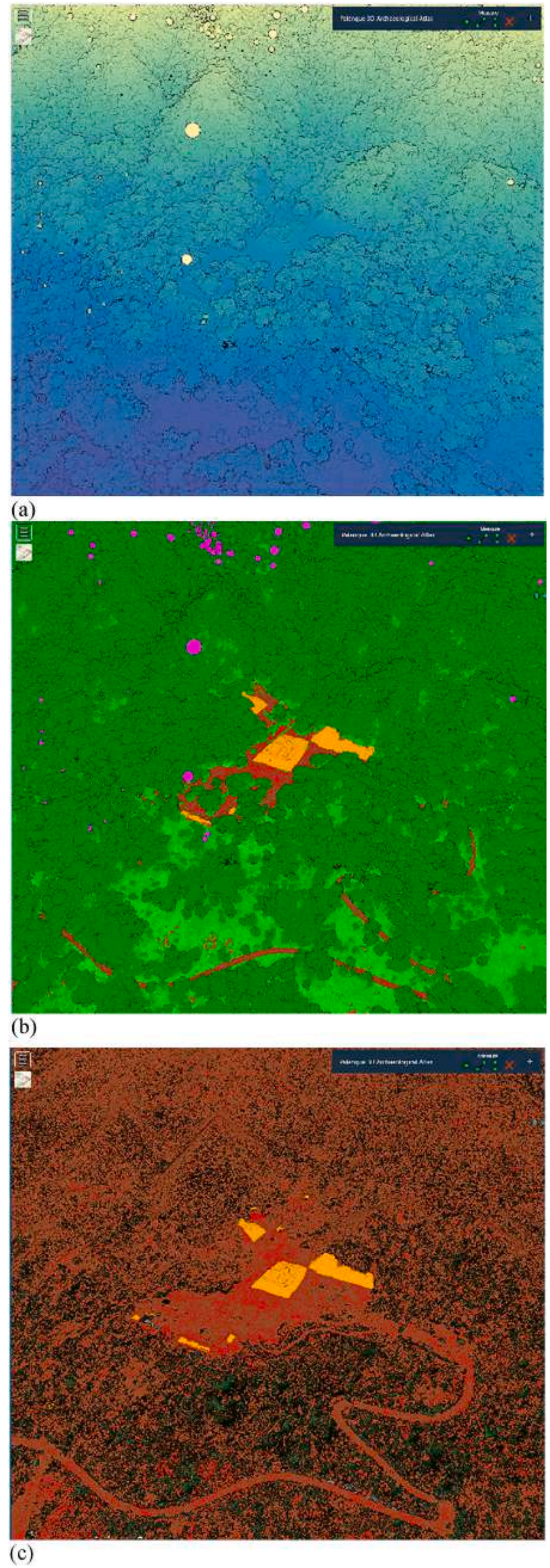


Fig. 5. Aerial LiDAR data (a) Colored by elevation height ramp; (b) Classification view, showing three levels of vegetation, buildings, noise, and ground; (c) Trees turned off to show ground points only. Potree visualizations by authors.

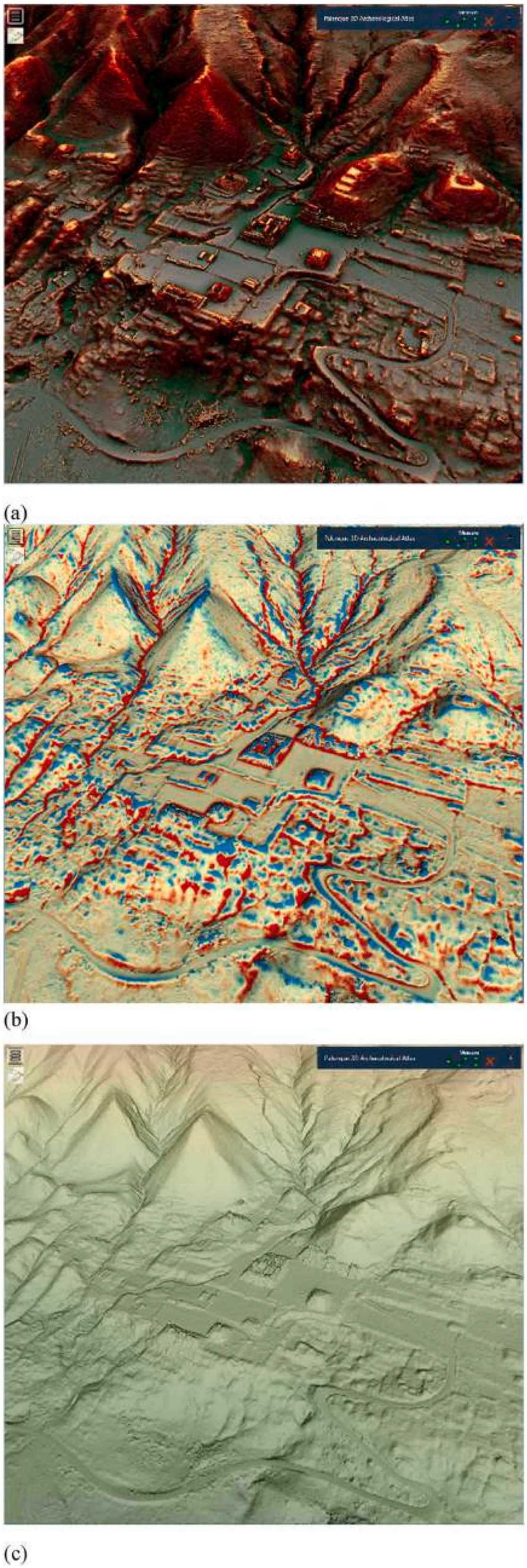


Fig. 6. ALS derivatives projected into the 3D Atlas (a) Red Relief Image (RRIM); (b) Local Relief Model (LRM); (c) Hillshade. GIS visualizations by authors. Potree visualizations by author. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

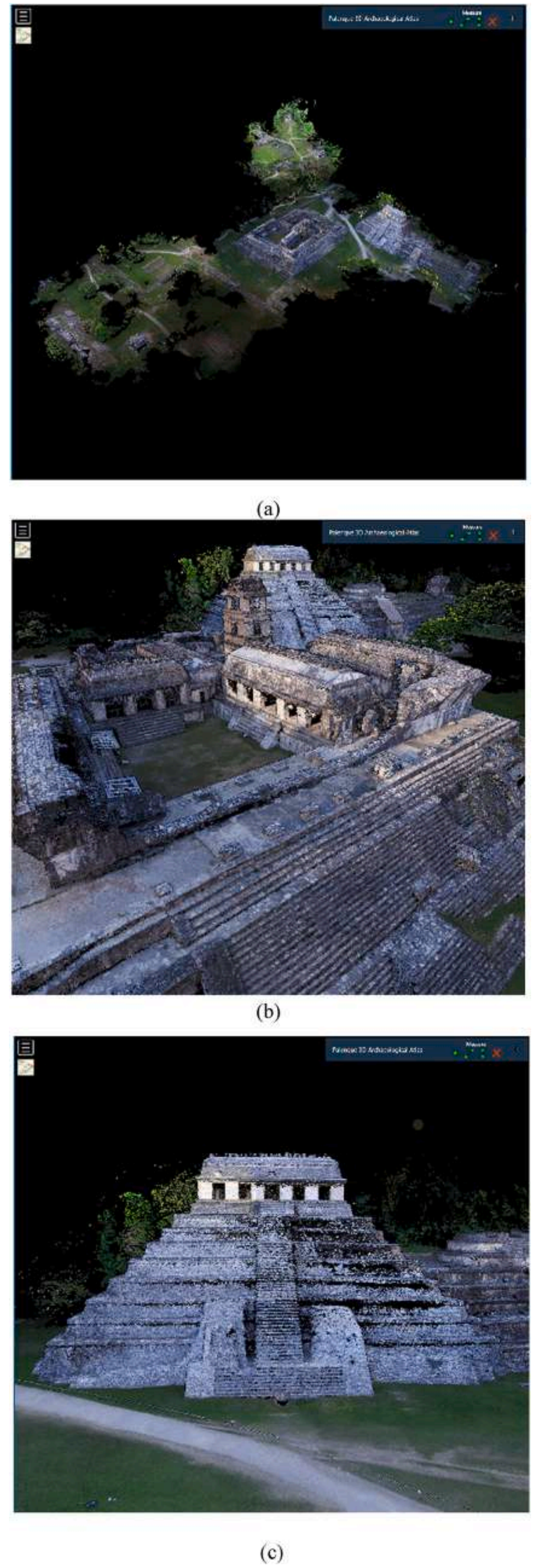


Fig. 7. Aerial IBM-derived point cloud 3D models of (a) Downtown Palenque, overview; (b) Detailing the Palace, and (c) the Temple of the Inscriptions. 3D models by authors. Potree visualizations by author.

Lhuillier, 2013), shafts, and the famous Pakal's funerary chamber with the ruler's sarcophagus(Campiani et al., 2022). Comprehensively, we recorded 38 laser scans that we post-processed in FARO Scene to produce a single point cloud of the above and below-ground structures featuring several hundred million measurements (Fig. 8).

3.2.5. Excavation-scale: terrestrial IBM of Group IV, excavation, burials, and artifacts

The 3D Atlas also includes the 3D documentation of our stratigraphic excavations of Group IV and 3D models of all the structures previously excavated and consolidated (Fig. 9a) (Liendo Stuardo et al., 2021). We produced this 3D record and derivative data using a standard IBM workflow customized for archaeological documentation (Galeazzi, 2016). Of note, we produced 3D models of the eastern shrine of Group IV plaza (building J7), which was built on top of an altar covering a stone crypt with a single male individual buried with jade ornaments and a vessel (Johnson, 2018). Furthermore, we digitally recorded the numerous burials excavated under the plaza level. Their documentation is particularly relevant as in the Maya Area it is uncommon to find such an abundance of interments all in one place (Fig. 9). Group IV plaza burials were generally composed by a stone crypt with slabs sealing the top. Our terrestrial IBM workflow was particularly suited to document these tombs as they are characterized by superimposed layers with more than one individual in a single crypt, often associated with artifacts such as spindle whorls or vessels (De Tomassi, 2021; Liendo Stuardo et al., 2017). Some of these restored objects have been digitized in the lab with IBM (Fig. 9e), and recontextualized in the Atlas.

3.2.6. Shapefiles: buildings and rivers

To complement the ALS, TLS, and IBM datasets available in our 3D Atlas with information verified on the ground by total station surveys, we utilized shapefiles derived from Edwin Barnhart's 2001 map of Palenque (Barnhart, 2001a; 2001b). This map represents 1478 individual structures as angled forms or "prisms" and the main rivers running through the site. As mentioned by Richards-Rissetto, converting GIS data into a 3D model could be problematic (Richards-Rissetto, 2013). Therefore, we modified the 2D shapefiles using ArcGIS Pro's "Feature to 3D by attribute" tool (Fig. 10a), which gives them depth by projecting the individual line segments over the surface of our aerial LiDAR-derived DEM (Fig. 10).

3.3. Data fusion techniques utilized in the 3D Atlas

Our multi-scalar corpus of data and formats had to be converted into point clouds following *ad hoc* pipelines to be compatible with the Potree Viewer, the multi-resolution platform at the core of our workflow. Potree is built on WebGL, the popular open-source web standard for online visualization (Aricò et al., 2023; Auer et al., 2014; Bezzi et al., 2018; Di Benedetto et al., 2014; Gaspari et al., 2023; Richards-Rissetto and von Schwerin, 2017; Schwartz et al., 2013).

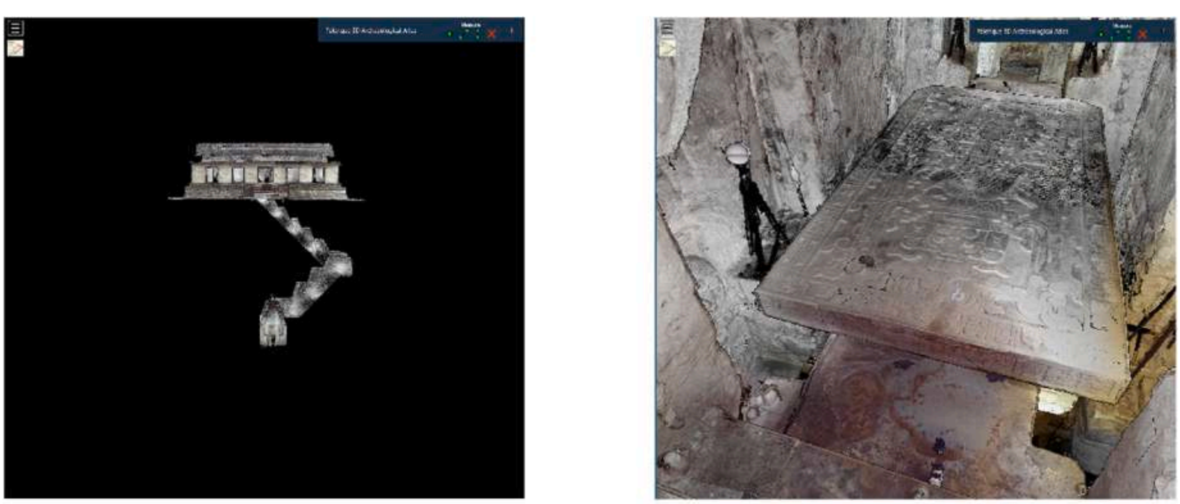
3.3.1. WebGL and Three.js

The 3D Atlas incorporates full-resolution 3D data from several sources, plugging them into a highly versatile open-source Web-based engine called Three.js. Three.js internally uses WebGL, a JavaScript API able to render "interactive 3D computer graphics in browsers without the use of plugins" (Richards-Rissetto and von Schwerin, 2017, p. 40). This Web implementation enables linking the data to external sources and embedding media. Besides, Three.js relies on a simple Apache-based server setup that allows users to build projects on a local machine and deploy them to a web environment when ready. Its versatility permits websites to be easily adapted to VR/XR-enabled contexts and throttled to optimize for devices of all types with differing graphical computing capabilities and internet speeds.

3.3.2. Potree Viewer and data structure

To solve the challenge of visualizing and collaboratively analyzing our 3D data, we leveraged the Potree viewer's multi-resolution capability. This system can visualize multiple point clouds consisting of billions of measurements and hundreds of gigabytes over the internet by scaling resolution to suit individual devices and network bandwidths, such as standard desktops, laptops, custom visualization walls, virtual reality headsets, and select Android tablets. Potree incorporates "octrees," or recursively nested cubes of finer and finer detail, trading network storage for local computing power (Schütz, 2016) (Fig. 11).

Therefore, we chose to use this viewer to create our 3D Atlas and leverage Potree's ability to load only visible points in real-time, enable custom annotation, contextualization, measurements, and colorization for all visualized datasets. We utilized Potree to also support visualization of LiDAR scalar values and different classifications, supporting all fields within the LAS specification and customized attributes. The 3D Atlas can also visualize our point cloud data as continuous surfaces with almost homogeneous point distributions, using the optimized "adaptive"



(a) (b)

Fig. 8. TLS Point clouds of (a) the Temple of the Inscriptions' upper temple and stairway and (b) Pakal's funerary chamber. 3D models by authors; Potree visualizations by author.

(e)

Fig. 9. IBM data from Group IV detailing (a) Contextual model of burial 10, placed within a larger model of the Group IV plaza; (b) Burial 10 layer 1, showing the first layer of capstones; (c) Burial 10 layer 2 showing second layer of capstones and revealing pottery offering; (d) Burial 10 layer 4 revealing another set of capstones covering human remains; e) The restored pot offering from Burial 10. 3D photogrammetric models of burial 10 (b,c,d,e) by M. De Tomassi, used with permission. Potree visualizations by author.

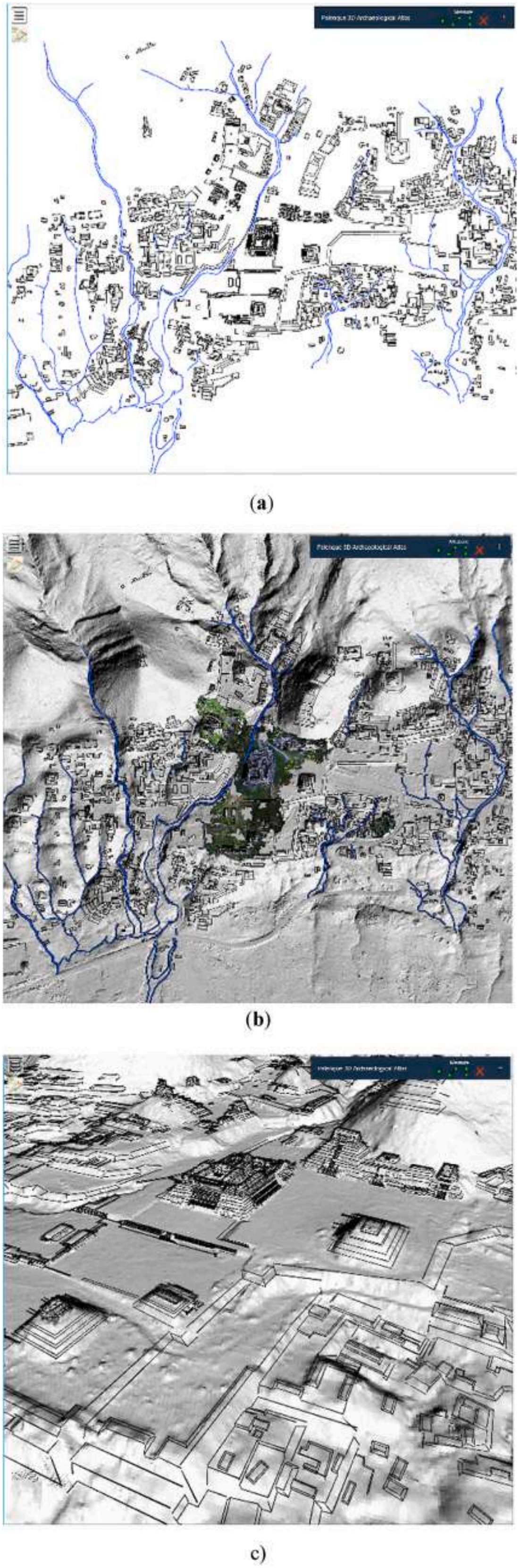


Fig. 10. Barnhart's buildings layout as (a) projected over the LiDAR surface; (b) and superimposed to the DEM derivatives visualization; (c) showing a good level of accuracy in data fusion. Images by author, modified after Barnhart (2001a,b).

point sizing feature in Potree.

3.3.3. *Point clouds and potree*

Though the Three.js WebGL engine natively supports dozens of 3D model formats, we converted our entire corpus of data into LAS and LAZ point clouds. We made this choice to take advantage of the highly efficient octree capability of the Potree viewer and utilize the standardized support for classifications (e.g., ground, trees, buildings, roads), custom scalar values (e.g., beyond intensity, scan angle) and map projections inherent to these file formats. ALS and aerial IBM workflows generally output LAS/LAZ point clouds that are directly compatible with Potree. Still, other terrestrial and SLAM-based LiDAR outputs must be processed for compatibility.

Potree viewer can display octree-sorted point cloud structures in three formats, Potree Converter 2 (© 2020 Markus Schütz), Entwine Point Tiles (EPT) and Potree Converter 1.6/1.7. While EPT and Potree Converter 1.6/1.7 offer some useful utility and compatibility beyond Potree Converter 2, the thousands, sometimes tens and hundreds of thousands, of tiny individual files they create can take days and weeks to process and transfer giga-resolution datasets. On the contrary, Potree Converter 2 offers an optimized pipeline to convert billions of unstructured points into a Potree viewer-compatible format. Potree Converter 2 turned out to be the best tool for octree conversion (Potree Converter 1.6/1.7 is used only for volumetric data), as it processes points into a compressed three-file bundle (Schütz, 2016). This program is only compatible with LAS/LAZ format point clouds and cannot handle duplicate points (sharing an XYZ coordinate) or structured data (evenly spaced volumetric grids). Despite these limitations, we feel that this utility's speed and capacity for giga-resolution data justify additional processing steps. Potree documentation lists the speed difference as 10 to 50 times faster than previous Potree Converter 1.7 on SSDs ("GitHub - potree/potree: WebGL point cloud viewer for large datasets," n.d.), and we have observed similar performance bonuses over EPT.

3.3.4. *Non-point data*

Though Three.js can load dozens of 3D formats in tandem with Potree structures, no other data format can currently scale to our needs (efficient streaming, no resolution and large file size limits, and combining all formats into a single context). Because large point clouds are relatively rare outside of survey and remote sensing applications, there is far less support for point cloud rendering and many rendering techniques are not currently compatible with point clouds. Nonetheless, it is possible to convert most types of visual data into point clouds (e.g., meshes, voxels/volumetric image stacks, polygons, images, DEMs …), benefitting from universal utility for all of Potree's standard point cloud metrology tools, which would otherwise have to be rebuilt for compatibility across all formats. In the proposed pipeline (Fig. 12), we have built processes to convert standard vector, raster, volume, and polygon formats into point clouds. The processes related to the conversion of non-point data are automatable but can be quite cumbersome to implement because they require specialized knowledge and familiarity with a wide array of toolsets. Specifically, the conversion to point clouds have been possible by employing several OA tools like Point Data Abstraction Library (PDAL) (PDAL Contributors, 2022), Cloud Compare (Girardeau-Montaut, 2019), ParaView (Ahrens et al., 2005), Geospatial Data Abstraction Library (GDAL) (GDAL/OGR Contributors, 2022) and Lastools (rapidlasso GmbH, 2023), the only one not open access.

In regards to the Palenque 3D Archaeological Atlas, every non-point dataset, has been converted into point clouds. The conversion into point clouds and the fusion with native point cloud dataset, as LAS, resulted in the project containing 9.5 billion points and 191 gigabytes of compressed point cloud data captured and processed by our collaborators, along with Barnhart's Palenque map data (2001b) (Table 1).

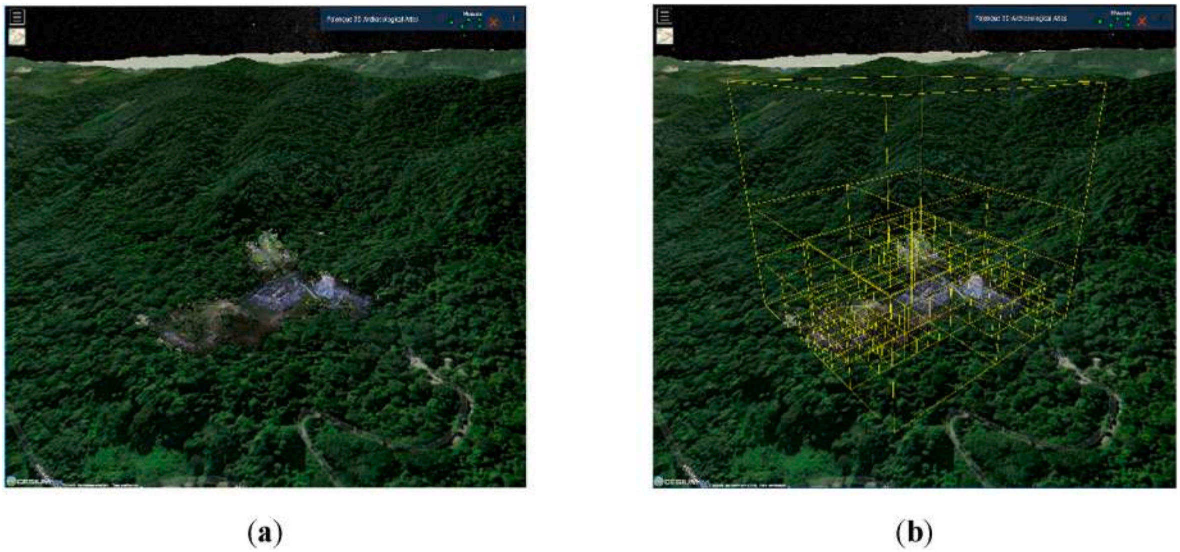


Fig. 11. Palenque drone photogrammetric model (a) superimposed to Cesium basemap; (b) Box visualization showing octree structure for current viewpoint. Potree visualizations by author.

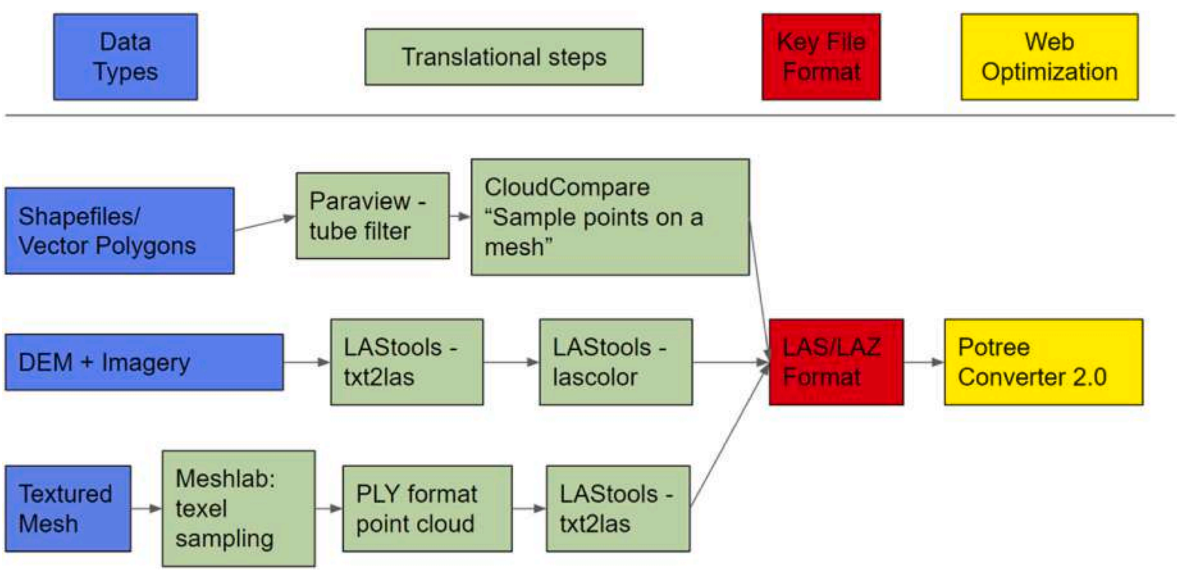


Fig. 12. Flowchart showing processing pipeline to create Potree viewer compatible point clouds from non-point data. (Blue) The Data types we converted into point clouds; (Green) the step and tools employed according to the different formats; (Red) the Key File Format obtained through the conversion to create, (Yellow) Potree viewer compatible point clouds. Image by author. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Table showing the datasets we converted and compressed with Potree and the number of points for each dataset we incorporated into the Palenque 3D Archaeological Atlas. Table by author.

Dataset	Models	Number of Points	Compressed Size (GB)
Aerial LiDAR	1	960,607,042	9.1
LiDAR derivatives	3	6,094,985,328	35
Aerial IBM	1	659,779,645	5
Terrestrial LiDAR	1	316,108,999	7.8
Terrestrial IBM	89	1,402,713,781	133
Shapefiles	2	106,308,302	0.6
Total	98	9,604,584,154	190.58

4. Results and discussion: the Palenque 3D archaeological Atlas

Investigations at the archaeological site of Palenque present many challenges due to the complex morphology of the landscape and the tropical jungle covering most of the Classic Maya city. While the forest reduces survey visibility and, thus, the perception of the context at a city-level, extensive excavations are limited to preserve Palenque Natural Park's unique environment. Archaeological inquiry can be conducted in several city sectors simultaneously and continue during multiple fieldwork seasons. This excavation strategy makes data correlation even more challenging. Moreover, in certain areas of the city, the archaeological stratigraphy is particularly complicated because, as it was common in pre-Hispanic Mesoamerica, the advent of a new ruler frequently entailed the renovation of existing constructions (Schele and Mathews, 1998; Sharer and Traxler, 2006). The ancient Maya often erected new buildings by incorporating old structures or built mausoleums with funerary chambers hidden within their basal platform, as in the Temple of the Inscriptions (Martin and Grube, 2008; Scherer, 2012).

The Palenque 3D archaeological Atlas represents a novel interactive way of overcoming these challenges, fostering cloud-based collaboration, visualization, analysis, contextualization, recontextualization and archiving. In fact, this online geospatial collection is capable of streaming large 3D and geospatial datasets obtained during different excavation seasons and digital archaeological surveys. Importantly, this 3D Atlas also improves the dissemination of our results by linking them to a Digital Object Identifier (DOI) (McAvoy, 2022). This unique and persistent identifier increases the capability of our visualizations to be retrieved, used, re-used, and cited by the archaeological community. Since providing full web access to our Palenque ALS dataset may compromise the confidentiality of the location of sensitive archaeological heritage and sites, complete usage of the 3D Atlas is, for now, restricted to project researchers. Nonetheless, an OA version of the Atlas is linked to the DOI. Even if it is limited to the archaeological area opens to the public and to Group IV, it grants full interactive visualization to Palenque downtown. Moreover, a video presented as additional material to this publication shows the full capability of the 3d Atlas. Following best practices in sustainable archaeological 3D data management and accessibility (Richards-Rissetto and von Schwerin, 2017, p. 22), we are also working on implementing different user access levels to the 3D Atlas. This enhanced capability will foster usage from the archaeological community, stakeholder institutions, site managers, and a wider public interested in exploring Palenque and its cultural landscape and examining our most recent interpretations of this iconic Maya site.

In this section, we evaluate the potential of our 3D Atlas for archaeological research, interpretation, and collaboration. We will demonstrate how the 3D Atlas can facilitate reflexive and interpretative practices from the landscape scale to the excavation scale. Its ability to integrate and interact with complex archaeological contexts online allows for volumetric and three-dimensional thinking, encouraging more comprehensive analyses and new interpretations.

4.1. The 3D Atlas' user interface and basemap capability

To increase focus on the presented datasets, we chose to keep the 3D Atlas' user interface to a minimum, using a simple interactive sidebar to enable users to navigate among the 3D layers (Fig. 13a). Data visualization in the 3D Atlas is complemented by a Cesium Ion 3D terrain global basemap with Bing-labeled aerial imagery overlaid, which provides users with additional geographic and contextual information. Utilizing the Cesium platform also allowed us to include in the Atlas a real-time star map, placing the sun and moon relative to the earth when the viewer is accessed (Fig. 13b). Of note, Julian dates and times can be set to ancient dates and animated to play at an accelerated pace, showing months and years of celestial movements in minutes. Even if this functionality is not intended as an alternative to archeoastronomy software, it can provide a preliminary interpretation tool within our 3D Atlas.

4.2. Landscape-scale results

Our team of researchers from four countries spent a considerable amount of time collaboratively analyzing the high-resolution LiDAR data visualizations included in the 3D Atlas. This enabled us to produce a new interpretation of Palenque's archaeological environment at the landscape scale. By streaming the 3D visualizations directly over the Web, we were able to work together to identify, quantify, and describe the various archaeological structures and architectural elements in Palenque. Our team believes that having this capability has given us unparalleled access and proximity to the intricate urban landscape of Palenque. The 3D Atlas has been particularly beneficial as it visualizes a continuous space from the regional to the archaeological context scale without any sudden breaks or gaps in data. Usually, archaeologists analyzing large regional datasets must examine them as separate parts due to technological limitations. However, the data continuum of the 3D Atlas allows for a different approach. This feature offered us a unique way to interact with the complete archaeological record of the city and its surroundings, allowing us to view Palenque's data as a single instance, providing an interactive and comprehensive overview at a glance. Moreover, Potree navigation tools enabled a more comprehensive spatial analysis, increasing our understanding of the natural and anthropogenic features captured in the LiDAR data. We used the 3D Atlas to navigate through the Palenque cityscape at the ground level without the obstacles posed by trees and ravines and maintain the data's scale and tridimensionality. Thanks to this capability, we could identify previously unknown paths and entryways to the city, "following" the possible informal routes toward the city center. In this way, we also assessed the existence of bridges and riverbank enlargements that allowed those movements, which we could not discover through pedestrian surveys of the site (Fig. 14).

Furthermore, we used the 3D Atlas for additional elevation analysis and classification. Any point cloud in our online collection can be

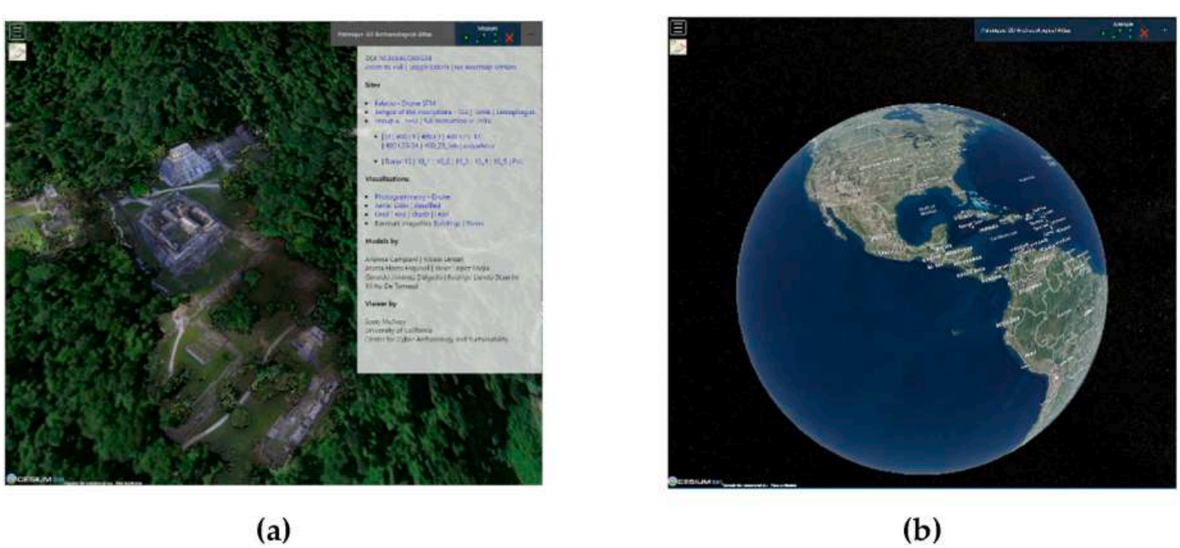


Fig. 13. a) Potree Html sidebar outlining contents and the added hypertext shortcuts to important features within the Palenque 3D Atlas; b) Cesium Ion Global Basemap locating Palenque within Mexico and displaying the real-time star map. Potree visualizations by author.

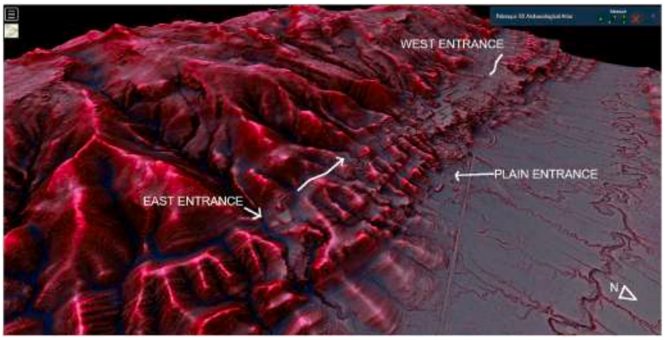


Fig. 14. 3D Atlas Fly control view, with highlighted entrances to the site. GIS visualization by authors. Potree visualization by authors.

colored using its Z (height) coordinate values, with nine standard selectable gradient schemes and an adjustable range slider to enhance the elevation characteristics of the dataset. This is a key capability that can be exploited for topographic visualization directly within the 3D Atlas, which we found more responsive and user-friendly than a 2D GIS platform when dealing with the massive datasets at our disposal (Fig. 15).

It has also to be noticed that the overlay of the Ion 3D terrain with the other features provides interesting insight into the location of buildings into the natural and anthropogenic environment (Fig. 16a and b). For instance, using our 3D Atlas it is also possible to assess deforestation in private terrains if compared with the Palenque Natural Park limits (Fig. 16c and d).

4.3. City-scale and building-scale results

At the city scale, using RRIM enhancement of spatial relationships within the ALS dataset, we gained a clearer understanding of how Palencanos have modified the natural environment over the centuries. This visualization technique also helped us to visually identify ancient buildings and features that are now concealed under the canopy. It also provided our team with an increased understanding of neighborhood size and spatial configuration. From our analysis of the ALS data in Potree, we were able to deduce that the investments made in modifying the environment were actually much greater than what we had initially determined through our GIS platform. This platform had been limited to a 2.5D visualization of the Palenque landscape that relied on interpolating survey points elevation and Mexico's National Institute of Statistic and Geography (INEGI) contour levels (every 4 mts) (Fig. 17) (Barnhart, 2001a; López Mejía, 2005).

We made an additional interesting discovery using the 3D Atlas related to the Escondido compound. This is a massive basal platform at the city's west entrance in a sector known as the Picota. The visualization of our ALS data using the RRIM technique gave us highly precise information about the construction of the sides of the basal platform. Additionally, it showed us how the Palencanos utilized the terrain's morphology by building a series of previously unknown smaller platforms to support additional structures towards the north. With the help of our 3D Atlas, we can now comprehend the correlation between the Escondido compound and the cliff that falls over 50 m onto a vast ledge (Barnhart, 2001a). This area is controlled by a new building (40 × 20 × 5 mt) (Fig. 18a), which is yet to be documented. Using the 3D Atlas, we could also identify new features related to the Escondido platform that involve significant infrastructural developments.

We also noticed an unexpected alteration to the natural shape of the hill between the Encantado and H groups, situated above the city center. It appears that the north and east sides of the hill were intentionally straightened to enhance the view of Temple H atop the mountain. This created an artificial plateau that mimics the base structure of the temple (Fig. 18b). We recognize that this new knowledge about the site's built environment was only possible through our collective interpretation and discussion of the ALS data through the 3D Atlas.

Concerning our results at a building scale, it's important to underline how we utilized the 3D Atlas to enhance our collaborative analysis of layered datasets, even when invisible walls or background features obstruct the view. A notable example is our analysis of Pakal's funerary chamber, hidden within the Temple of the Inscriptions' basal platform. To overcome visibility issues, our team utilized Potree's clipping box tool to place scalable and rotatable boxes in the scene. These boxes can highlight or exclude points inside or outside of the box. By choosing the "inside" option, we could allocate the entire viewer's global point budget to show finer detail within the clipped region, making it easier for us to assess the complex geometries of the funerary chamber (Fig. 19).

Additionally, we utilized the Eye Dome Lighting (EDL) tool to analyze better the often-eroded inscriptions and stucco reliefs of Palenque's iconic buildings. For example, the warriors modeled in stucco within Pakal's funerary chamber suffer from the extremely humid

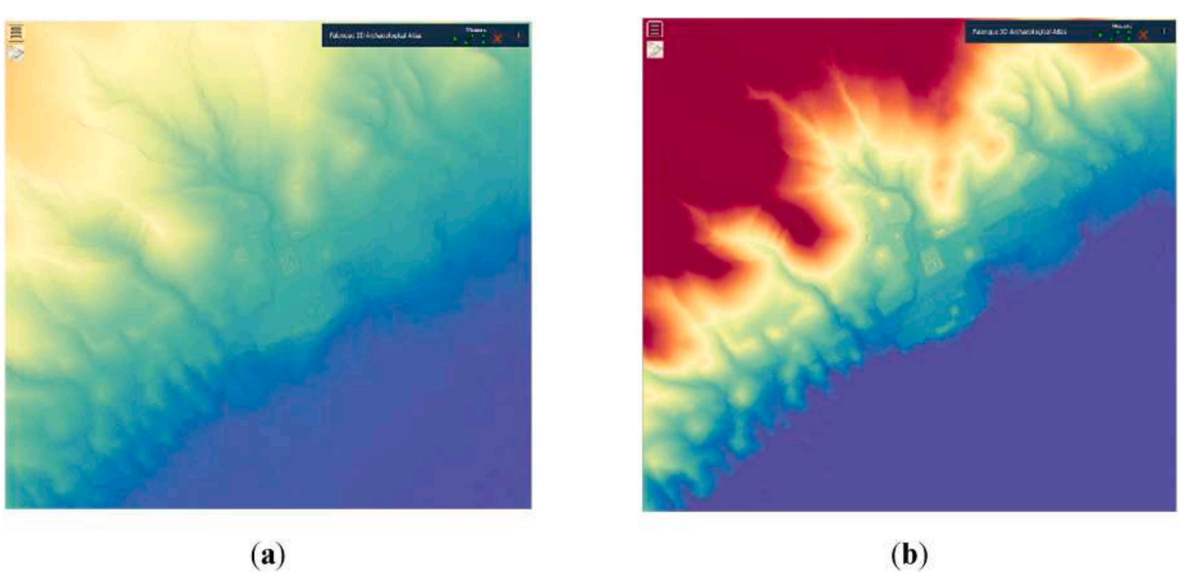
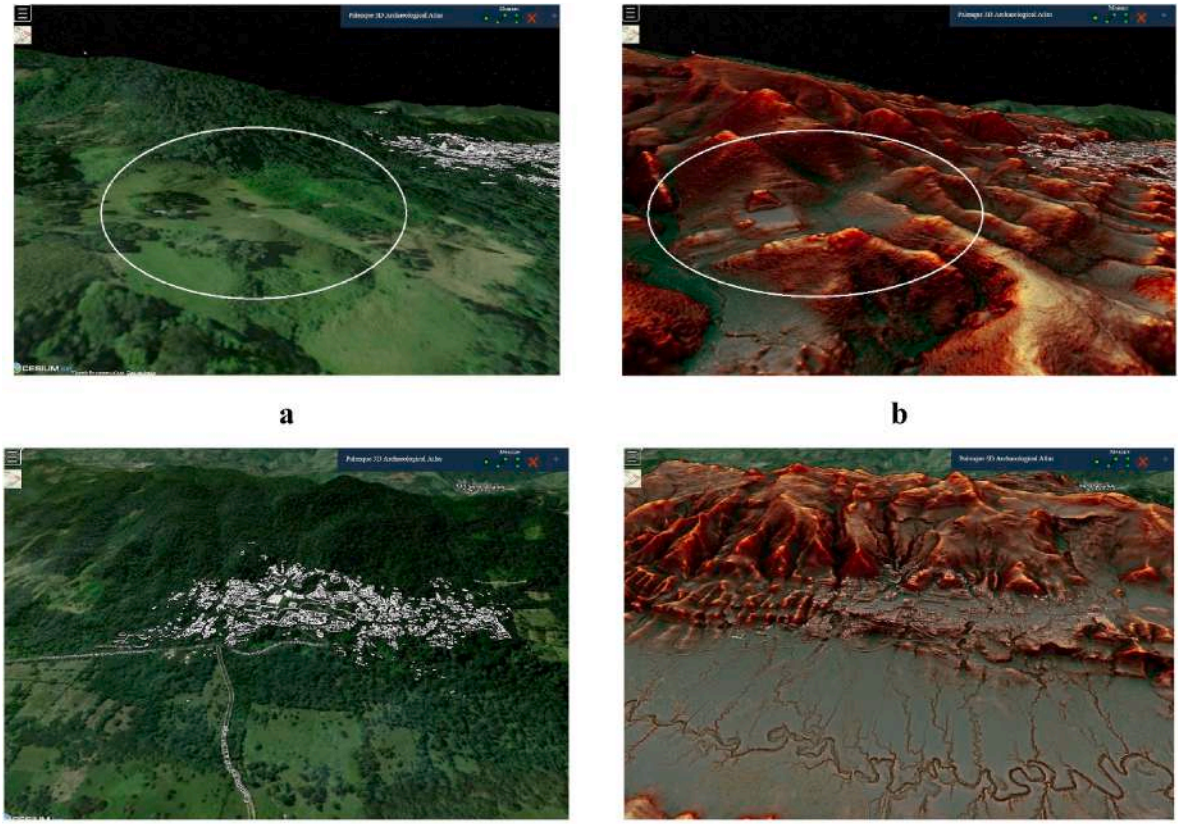
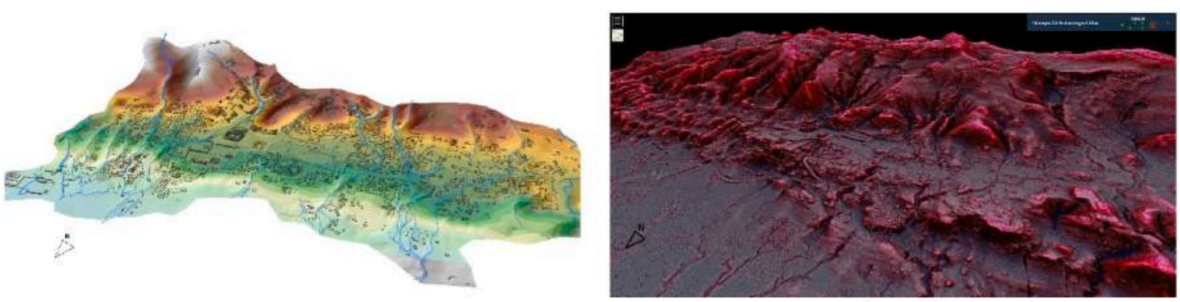


Fig. 15. Elevation classification is seen in Potree showing: (a) a zoomed-out view of Palenque DEM; (b) the capability of interactively narrowing the elevation range to highlight features in a particular area of interest. Potree visualizations by author.



a b c d

Fig. 16. a) Cesium Ion 3D terrain showing a newly discovered compound on private land and b) how it looks in the LiDAR data. c) Cesium Ion 3D terrain with superimposed Barnhart's map (2001a,b), and d) the Palenque environment without vegetation, enhanced thanks to RRIM visualization. Private land deforestation stands out against the tropical jungle of the Palenque park. Potree visualizations by authors.



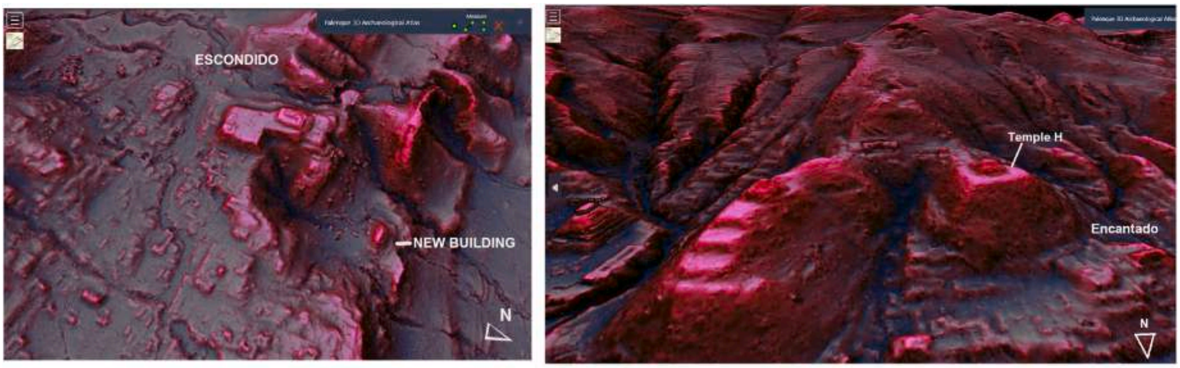
(a) (b)

Fig. 17. Palenque, as seen in (a) a zoomed-out ArcScene view, where DEM is obtained from interpolating survey points and INEGI contour level; and (b) Potree visualization of Palenque building on LAS. GIS and Potree visualization by authors.

environment causing severe calcareous concretion. These beautiful artworks can be appreciated in full detail in our 3D Atlas using the ELD tool compared to examining them in the poorly lit crypt (Fig. 20). Further, the EDL technique makes it possible to stream in real-time Palenque 3D high-resolution data and share them with epigraphers and conservation specialists who can evaluate their decay or observe almost invisible details directly from their computers anywhere in the world.

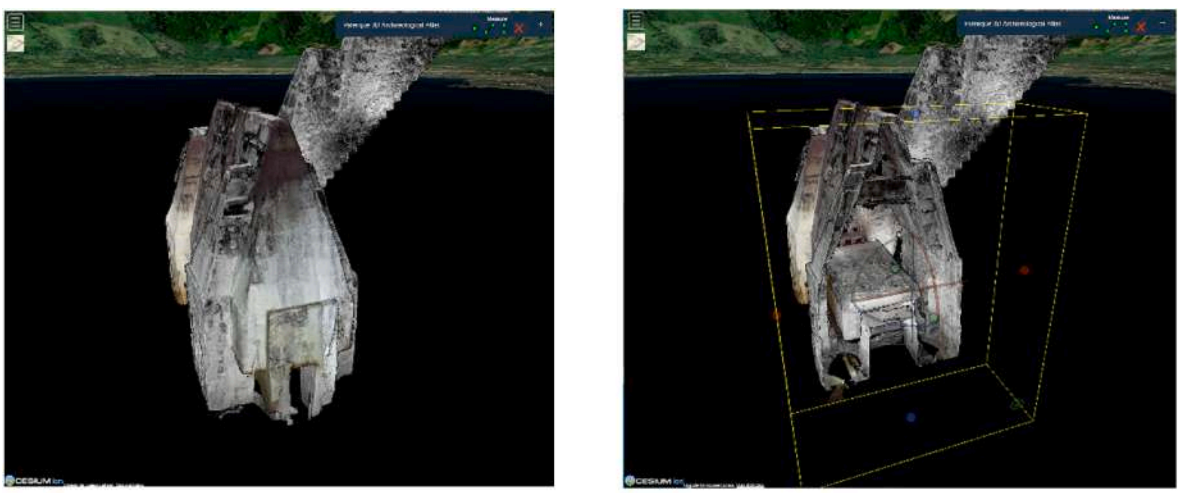
4.4. Excavation-scale results

At the excavation scale, we used the 3D Atlas and georeferencing in the data fusion process to stratigraphically connect burials from Group IV with the excavation layers, which we displayed simultaneously with the base DEM model. This capability allowed us to explore better the connection between overlaying datasets fostering an improved assessment of a particular context through Potree's vertical profile tool. This was particularly helpful in the analysis of building J7, the eastern shrine of Group IV we excavated in 2016. We used IBM to record the stratigraphic excavation layers of J7 and the older burial of a male individual whose crypt was dug into the bedrock of the hillside in the 6th century. During the following 100 years, an altar was built on top of the tomb, and several symbolic burning events accompanied the modification and final erection of Building J7 (Johnson, 2018; Liendo Stuardo et al.,



(a) (b)

Fig. 18. RRIM visualization of Palenque selected buildings and areas (a) The Escondido compound as seen from the north-east; (b) H temple as seen from the north. GIS visualization and Potree visualizations by authors. Image by Author.



(a) (b)

Fig. 19. Pakal's funerary chamber is seen "isolated" from its architectural context: (a) TLS data, viewed from the outside (b) Clipping box set to "outside," showing the sarcophagus and tomb interior. Potree visualizations by author.

2017). While J7 was excavated in 2016, investigations in the plaza were carried out also in 2017. This new campaign added further digital layers to an already complex stratigraphy. Leveraging the integration of all these terrestrial IBM data in the 3D Atlas, the profile tool helped our team relate the stratigraphy of J7 with the Group IV plaza (Fig. 21).

As for the important number of vessels and artifacts associated with burials in Group IV, our 3D Atlas allowed us to recontextualize these objects within the crypts they were found, therefore observing these important findings *in situ*. We used this technique to analyze the Burial 10 vessel described in section 3.2.4, which we scanned in the lab after it was restored. This recontextualization capability opens new opportunities to study objects and architectural decorations removed from their original context, when their excavation layers or archaeological contexts were also recorded in 3D.

4.5. Interoperability and mixed sources capability

As multiple layers in our 3D Atlas are aligned and integrated within a shared context, it should be noted that these layers can be loaded in additional external contexts. For example, suppose some researchers were only interested in topography. In that case, they could make their instance of Potree and stream in it only the aerial LiDAR layer, modifying the annotations and context to their preferred specifications without downloading or formatting the huge base files themselves.

This may also be an important feature for archaeologists who work with site managers and governmental agencies insisting on data sovereignty, as this feature enables the full use of the streamable layers while hosting them in the countries that authorize or sponsor their research. Finally, we can mix and match layers from different sources, for example, keeping protected artifact-level research data locally secure while streaming topographic and architectural contexts from various external repositories.

5. Conclusions

This article discussed the challenges of using digital documentation and observation methods in archaeology due to the fragmented nature of 3D data featuring multiple sources, scales, and formats. We highlighted how these characteristics may often limit the utility of 3D archaeological data outside the software environments employed in their creation. To address these issues, we presented a pipeline we developed using the online geospatial visualization tool Potree Viewer. Our workflow enables archaeologists to gather and fuse 3D data, interact with them in a novel way, visualize synchronic and diachronic

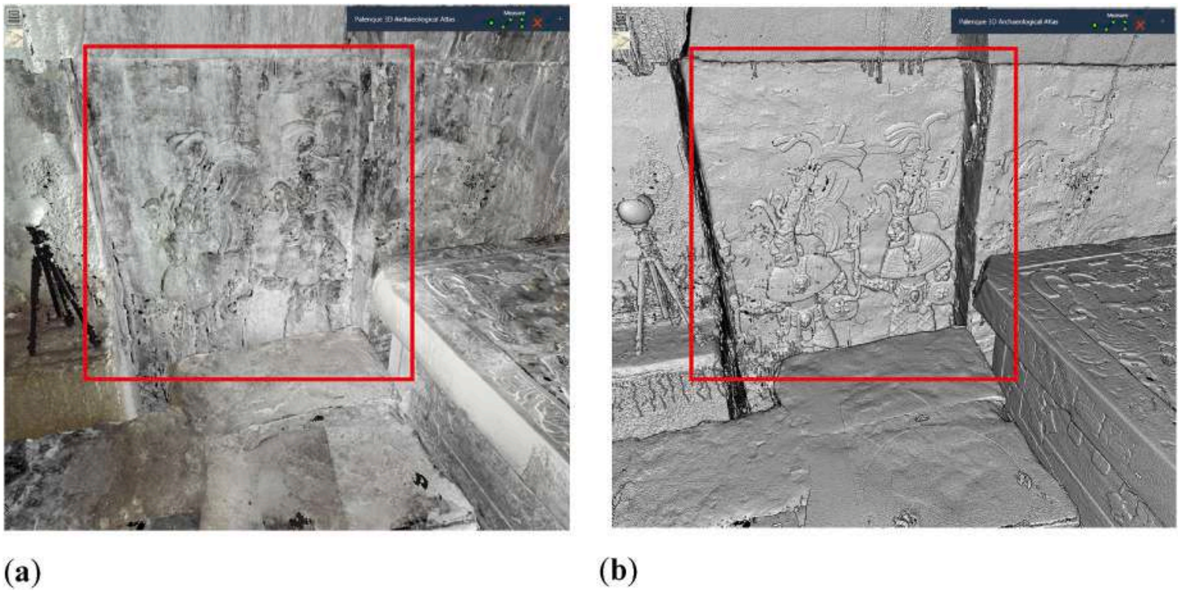


Fig. 20. View of TLS data showing wall stucco decoration in the Temple of the Inscriptions funerary chamber (red square). (a) Colored by laser intensity, compared to the (b) EDL shader enabled on the same point cloud, colored flat white. Potree visualizations by author. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

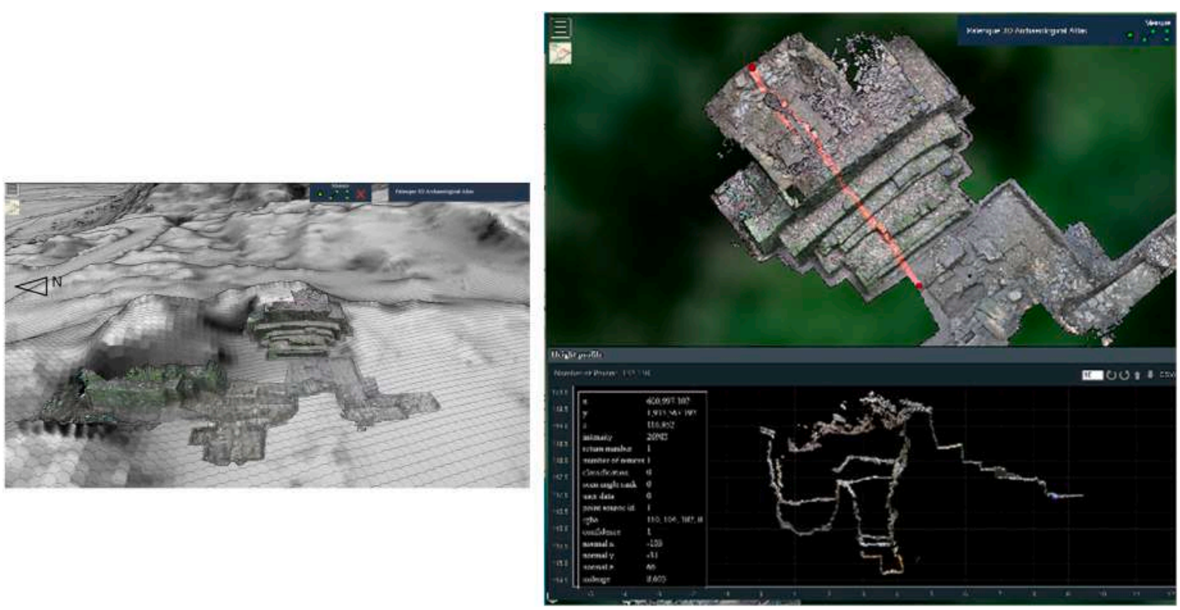


Fig. 21. Building J7 as seen in the Atlas, a) DEM Visible Sky visualization with superimposed 2016 IBM recording of Group IV excavations, with shrines J6 and J7. b) Potree profile tool showing a cross-section of shrine J7. The red line in the 3D denotes the area shown in the profile. The section highlights the complex stratigraphy of the building and the several IBM models superimposed in Potree. Potree visualizations by authors. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

information and recontextualize artifacts, beside allowing real-time interactive analysis and collaborative interpretation over the Internet. Furthermore, the ability of Potree to stream individual datasets in custom external web instances, consents external collaborators, students, and community stakeholders to re-purpose the research data in localized contexts.

This paper described how we utilized said workflow and Potree's capabilities to fuse a multi-scalar and multi-temporal archaeological dataset comprising LiDAR and TLS data, their derivative DEMs, aerial and terrestrial IBM data, and shapefiles data generated by pedestrian and total station surveying into the Palenque 3D Archaeological Atlas. Through this 3D Atlas, our team of researchers in four different countries could access the complex archaeological datasets we captured at Palenque over several fieldwork seasons and interact with them in real-time without abrupt breaks and gaps, which were limiting our analysis prior to using this technology. Therefore, we conclude the 3D Atlas served as a crucial instrument for our research collaboration, going beyond mere data visualization. The 3D Atlas allowed us to interpret archaeological findings collaboratively from various locations, in ways that were not previously possible for our team. In fact, dynamically visualizing and manipulating our geospatial and 3D data online, all while thinking volumetrically, opened the way for us to identify previously unknown correspondences and anomalies at the landscape, city, building, and feature scales. These capabilities make our 3D Atlas a suitable platform to generate new knowledge for our case study. Other archaeologists can also benefit from our research by adopting the proposed workflow and using the Potree Viewer to investigate other sites. For instance, the same workflow is being used for an archival integration project building on the 3D archaeological data collected at the Maya site of Chichen Itzá (McAvoy, 2023).

Finally, we believe that the web-based dissemination capabilities presented in our 3D Atlas represent a step forward in achieving data sustainability, which is increasingly important to specialists working with digitized or 'digital born' heritage data (Brin, 2021; Chase et al., 2020; Derudas et al., 2021; Guillem and Lercari, 2021; Richards-Rissetto and von Schwerin, 2017). However, we recognize that more effort is necessary to enhance the 3D Atlas with an improved user interface that would enable non-experts to interact with our data more easily. As discussed in Section 4, we also recognize the importance of strict data curation and management protocols to maintain the confidentiality of sensitive ancient Maya heritage and archaeological sites presented in the 3D Atlas. After the implementation of these enhanced capabilities, we will allow public access to the Palenque 3D Archaeological Atlas to promote further digital exploration of this iconic Maya site.

Author contributions

Conceptualization, A.C., S.M, N.L.; Data curation, S.M., A.C; Formal analysis, S.M., A.C., N.L.; Funding acquisition, A.C., N.L., R.L.S; Investigation, S.M., A.C.; Methodology, S.M.; Project administration, S.M., R. L.S., D.R., F.K., A.C.; Resources, S.M., A.C., R.L.S., D.R., F.K.; Software, S. M.; Supervision, S.M., D.R., A.C.; Validation, S.M; Visualization: S.M., G. J.D., J.L.M., A.C.; Roles/Writing - original draft, A.C., S.M., N.L.; and Writing - review & editing, N.L, A.C., S.M., D.R. All authors have read and agreed to the published version of the manuscript.

Funding

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie [Grant Agreement No 839602]; the Hellman Family Fellows Award, the University of California Merced Hellman Fellows Award [2017], the Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT-UNAM) [Project Nr. I N404820]; and Conacyt [Project Nr. CF-2019/682138].

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly Premium in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgement

The data presented in this research were collected with the permission of the Instituto Nacional de Antropología e Historia (INAH, Mexico). We are especially grateful to the National Center for Airborne Laser Mapping (NCALM) for acquiring and processing the utilized ALS dataset. We thank Mirko De Tomassi for providing the 3D models of the artifacts retrieved in Group IV burials.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.daach.2023.e00293.

References

Ahrens, J., Geveci, B., Law, C., 2005. In: Hansen, C.D., Johnson, C.R. (Eds.), ParaView: an end-user tool for large-data visualization, Visualization Handbook. Butterworth-Heinemann, Burlington, pp. 717–731. https://doi.org/10.1016/B978-012387582-2/50038-1.

Aicardi, I., Chiabrando, F., Maria Lingua, A., Noardo, F., 2018. Recent trends in cultural heritage 3D survey: the photogrammetric computer vision approach. J. Cult. Herit. 32, 257–266. https://doi.org/10.1016/j.culher.2017.11.006.

Aricò, M., La Guardia, M., Lo Brutto, M., 2023. Web exploration of cultural heritage with limited accessibility: first experimentation for hypogeum archaeological sites. Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci. 111–117. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-111-2023. XLVIII-M-2–2023.

Auer, M., Agugiaro, G., Billen, N., Loos, L., Zipf, A., 2014. Web-based visualization and query of semantically segmented multiresolution 3D models in the field of cultural heritage. In: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Presented at the ISPRS Technical Commission V Symposium, vol. II-5. Copernicus GmbH, Riva del Garda, Italy, pp. 33–39. https://doi.org/10.5194/isprsannals-II-5-33-2014, 23–25 June 2014.

Auld-Thomas, L., 2022. A Recipe for Simple Red Relief. Ancient Maya Settlement. URL. https://ancientmayasettlement.com/2022/02/12/a-recipe-for-simple-red-relief/ (accessed 4.21.22).

Liendo Stuardo, R., Campiani, A., Lercari, N., Chávez Herrerías, A., Vilchis Silva, R., Varela Scherrer, C., Trabanino, F., Maestri, N., Johnson, L.M., Ciudad Ruiz, A., Adánez Pavón, J., Iglesias Ponce de León, Ma.J., García Barrios, A., de Rojas, A., Núñez Enríquez, L.F., Bellomo, C., Suzuki, S., 2021. Informe de las temporadas 2017-2018 en el Grupo IV de Palenque (Informe de Excavación). Ciudad de México. 2021.

Lercari, N., Campiani, A., Liendo Stuardo, R., 2019. Intra-site Digital Documentation of the Ancient Maya city of Palenque, Mexico, in: 2018 3rd Digital Heritage International Congress (DigitalHERITAGE) Held Jointly with 2018 24th International Conference on Virtual Systems & Multimedia (VSMM 2018). Presented at the 2018 3rd Digital Heritage International Congress (DigitalHERITAGE) held jointly with 2018 24th International Conference on Virtual Systems & Multimedia (VSMM 2018) 26-30 Oct. 2018, IEEE, San Francisco, CA, pp. 459–467. https://doi.org/10.1109/DigitalHeritage.2018.8810003.

Liendo Stuardo, R., Campiani, A., Johnson, L.M., Maestri, N., Vilchis Silva, R., Chávez, A., Vázquez López, V.A., Kupprat, F.A., 2017. Primer Informe Parcial de Excavaciones, Grupo IV, Palenque, Chiapas. Temporada 2016. Instituto Nacional de Antropología e Historia, Mexico.

Campiani, A., Liendo Stuardo, R., Lercari, N., 2022. The Mausoleum Architectural Project: Reinterpreting Palenque's Temple of The Inscriptions through 3d Data-Driven Architectural Analysis. Ancient Mesoamerica 33 (2), 278–293. https://doi.org/10.1017/S0956536120000498.

Campiani, A., 2015. Arquitectura de la Arqueología: Análisis de la estructura urbana de Chinikihá y Palenque entre los siglos VIII IX. Universidad Nacional Autónoma de, México, Mexico City. https://doi.org/10.22201/dgpyfe.9786070268731e.2015.

Campiani, A., 2017. Una proposta di lettura integrale della città Maya antica: la morfologia urbana di Chinikihá e Palenque (Chiapas, Messico) nel periodo Classico. Restauro Archeologico, 114–127. https://doi.org/10.13128/RA-20530.

Liendo Stuardo, R., 2014. Una revisión arqueológica de la historia de Palenque durante los siglos VIII y IX (fases Murciélagos-Balunté). Cuicuilco 60, 67–82.

López Mejía, J., 2005. Los grupos arquitectónicos de Palenque. Una propuesta de clasificación. Bachelor's thesis, Escuela Nacional de Antropología e Historia, Mexico.

Barnhart, E.L., 2001a. The Palenque Mapping Project, 1998 - 2000 Final Report (No. 99101). FAMSI.

Barnhart, E.L., 2001b. The Palenque Mapping Project: Settlemente and Urbanism at an Ancient Maya City. University of Texas, Austin. PhD Dissertation.

Benko, H., Ishak, E.W., Feiner, S., 2004. Collaborative mixed reality visualization of an archaeological excavation. In: Third IEEE and ACM International Symposium on Mixed and Augmented Reality. Presented at the Third IEEE and ACM International Symposium on Mixed and Augmented Reality, pp. 132–140. https://doi.org/10.1109/ISMAR.2004.23.

Bernal Romero, G., 2012. Historia dinástica de palenque: la era de K'inich janahb' pakal (615-683 D.C.). Rev. Digit. Univ. 13, 1–16.

Bezzi, L., Bezzi, A., Boscaro, C., Feistmantl, K., Gietl, R., Naponiello, G., Ottati, F., de Guzman, M., 2018. Commercial archaeology and 3D web technologies. J. Field Archaeol. 43, S45–S59. https://doi.org/10.1080/00934690.2018.1505410.

Brin, D., 2021. In: Lercari, N., Wendrich, W., Porter, B., Burton, M., Levy, T.E. (Eds.), Data as at-risk cultural heritage: the dig data publication initiative, Preserving Cultural History in the Digital Age. Sending Out an S.O.S. Equinox Publishing, Sheffield, pp. 161–175.

Campanaro, D.M., Landeschi, G., Dell'Unto, N., Leander Touati, A.-M., 2016. 3D GIS for cultural heritage restoration: a 'white box' workflow. J. Cult. Herit. 18, 321–332. https://doi.org/10.1016/j.culher.2015.09.006.

Canuto, M.A., Auld-Thomas, L., 2021. Taking the high ground: a model for lowland Maya settlement patterns. J. Anthropol. Archaeol. 64, 101349 https://doi.org/10.1016/j.jaa.2021.101349.

Canuto, M.A., Estrada-Belli, F., Garrison, T.G., Houston, S.D., Acuña, M.J., Kováč, M., Marken, D., Nondédéo, P., Auld-Thomas, L., Castanet, C., Chatelain, D., Chiriboga, C.

R., Drápela, T., Lieskovský, T., Tokovinine, A., Velasquez, A., Fernández-Díaz, J.C., Shrestha, R., 2018. Ancient lowland Maya complexity as revealed by airborne laser scanning of northern Guatemala. Science 361. https://doi.org/10.1126/science.aau0137 eaau0137.

Chase, D.Z., Chase, A.F., 2017. Caracol, Belize, and changing perceptions of ancient Maya society. J. Archaeol. Res. 25, 185–249. https://doi.org/10.1007/s10814-016-9101-z.

Chase, A., Chase, D.Z., Chase, A.F., 2020. Ethics, new colonialism, and lidar data: a decade of lidar in Maya archaeology. J. Comput. Appl. Archaeol. 3, 51–62.

Chiba, T., Hasi, B., 2016. Ground surface visualization using Red Relief Image Map for a variety of map scales. In: Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLI-B2, pp. 393–397. https://doi.org/10.5194/isprsarchives-XLI-B2-393-2016.

Chiba, T., Kaneta, S., Susuki, Y., 2008. Red relief image map: new visualization method for three dimensional data. Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci. XXXVII, 1071–1076.

Cignoni, P., Scopigno, R., 2008. Sampled 3D models for CH applications: a viable and enabling new medium or just a technological exercise? J. Comput. Cult. Herit. 1 (2), 1–2. https://doi.org/10.1145/1367080.1367082, 23.

Compton, M.E., Martin, K., Hunt, R., 2017. Where do we go from here? Innovative technologies and heritage engagement with the MakerBus. Digit. Appl. Archaeolo. Cult. Herit. 6, 49–53. https://doi.org/10.1016/j.daach.2017.04.002.

PDAL Contributors, 2022. PDAL Point Data Abstraction Library, version 2.5.5.

de la Garza, M., Bernal Romero, G., Cuevas García, M., 2012. Palenque-Lakamhá, Fideicomiso Historia de las Américas. Serie: Ciudades. Fondo de Cultura Económica-El Colegio de México, Ciudad de México.

De Reu, J., Plets, G., Verhoeven, G., De Smedt, P., Bats, M., Cherretté, B., De Maeyer, W., Deconynck, J., Herremans, D., Laloo, P., Van Meirvenne, M., De Clercq, W., 2013. Towards a three-dimensional cost-effective registration of the archaeological heritage. J. Archaeol. Sci. 40, 1108–1121. https://doi.org/10.1016/j.jas.2012.08.040.

De Reu, J., De Smedt, P., Herremans, D., Van Meirvenne, M., Laloo, P., De Clercq, W., 2014. On introducing an image-based 3D reconstruction method in archaeological excavation practice. J. Archaeol. Sci. 41, 251–262. https://doi.org/10.1016/j.jas.2013.08.020.

De Tomassi, M., 2021. To grasp the bundle: the funerary usage of bone needles in Late Classic Palenque. Mexicon 43, 135–142.

Dellepiane, M., Dell'Unto, N., Callieri, M., Lindgren, S., Scopigno, R., 2013. Archeological excavation monitoring using dense stereo matching techniques. J. Cult. Herit. 14, 201–210. https://doi.org/10.1016/j.culher.2012.01.011.

Dell'Unto, N., Landeschi, G., 2022. Archaeological 3D GIS. Routledge, Oxon, London and New York.

Dell'Unto, N., Landeschi, G., Apel, J., Poggi, G., 2017. 4D recording at the trowel's edge: using three-dimensional simulation platforms to support field interpretation. J. Archaeol. Sci.: Report 12, 632–645. https://doi.org/10.1016/j.jasrep.2017.03.011.

Derudas, P., Dell'Unto, N., Callieri, M., Apel, J., 2021. Sharing archaeological knowledge: the interactive reporting system. J. Field Archaeol. 46, 303–315. https://doi.org/10.1080/00934690.2021.1911132.

Devereux, B.J., Amable, G.S., Crow, P., Cliff, A.D., 2005. The potential of airborne lidar for detection of archaeological features under woodland canopies. Antiquity 79, 648–660. https://doi.org/10.1017/S0003598X00114589.

Devereux, B.J., Amable, G.S., Crow, P., 2008. Visualisation of LiDAR terrain models for archaeological feature detection. Antiquity 82, 470–479. https://doi.org/10.1017/S0003598X00096952.

Di Benedetto, M., Ponchio, F., Malomo, L., Callieri, M., Dellepiane, M., Cignoni, P., Scopigno, R., 2014. In: Ioannides, M., Quak, E. (Eds.), Web and mobile visualization for cultural heritage, 3D Research Challenges in Cultural Heritage: A Roadmap in Digital Heritage Preservation, Lecture Notes in Computer Science. Springer, Berlin, Heidelberg, pp. 18–35. https://doi.org/10.1007/978-3-662-44630-0_2.

Djindjian, F., 2020. Big data and archaeology. Has Mag. 1, 208–217.

Evans, D.H., Fletcher, R.J., Pottier, C., Chevance, J.-B., Soutif, D., Tan, B.S., Im, S., Ea, D., Tin, T., Kim, S., Cromarty, C., De Greef, S., Hanus, K., Bâty, P., Kuszinger, R., Shimoda, I., Boornazian, G., 2013. Uncovering archaeological landscapes at Angkor using lidar. Proc. Natl. Acad. Sci. USA 110, 12595–12600. https://doi.org/10.1073/pnas.1306539110.

Fanini, B., Ferdani, D., Demetrescu, E., Berto, S., d'Annibale, E., 2021. ATON: an open-source framework for creating immersive, collaborative and liquid web-apps for cultural heritage. Appl. Sci. 11, 11062 https://doi.org/10.3390/app112211062.

Fernandez-Diaz, J.C., Carter, W.E., Shrestha, R.L., Glennie, C.L., 2014. Now you see it… now you don't: understanding airborne mapping LiDAR collection and data product generation for archaeological research in Mesoamerica. Rem. Sens. 6, 9951–10001. https://doi.org/10.3390/rs6109951.

Fernandez-Diaz, J.C., Carter, W.E., Glennie, C., Shrestha, R.L., Pan, Z., Ekhtari, N., Singhania, A., Hauser, D., Sartori, M., 2016. Capability assessment and performance metrics for the titan multispectral mapping lidar. Rem. Sens. 8, 936. https://doi.org/10.3390/rs8110936.

Fernández-Hernandez, J., González-Aguilera, D., Rodríguez-Gonzálvez, P., Mancera-Taboada, J., 2015. Image-based modelling from unmanned aerial vehicle (UAV) photogrammetry: an effective, low-cost tool for archaeological applications. Archaeometry 57, 128–145. https://doi.org/10.1111/arcm.12078.

Ferrari, V., Guacci, P., Merico, A., 2015. The use of drones in aerial archaeology. Archeologia Aerea Studi di aerotopografia archeologica 9, 66–68.

Fiorini, A., Urcia, A., Archetti, V., 2011. In: Dellepiane, M., Nicolucci, N., Pena Serna, S., Rushmeier, H., Van Gool, L. (Eds.), The digital 3D survey as standard documentation of the archaeological stratigraphy, The 12th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST. The Eurographics Association, p. 8.

Forte, M., Campana, S.R.L. (Eds.), 2016. Digital Methods and Remote Sensing in Archaeology: Archaeology in the Age of Sensing. Quantitative Methods in the Humanities and Social Sciences. Springer International Publishing.

Forte, M., Dell'Unto, N., Issavi, J., Onsurez, L., Lercari, N., 2012. 3D archaeology at Çatalhöyük. Int. J. Herit. Digit. Era 1, 351–378. https://doi.org/10.1260/2047-4970.1.3.351.

Forte, M., Dell'Unto, N., Haddow, S., Lercari, N., 2013. 3D documentation at Çatalhöyük: new perspectives for digital archaeology. In: Digital Heritage 2013 - from Space2Place.

Fresa, A., Justrell, B., Prandoni, C., 2015. Digital curation and quality standards for memory institutions: PREFORMA research project. Arch. Sci. 15, 191–216. https://doi.org/10.1007/s10502-015-9242-8.

Galeazzi, F., 2016. Towards the definition of best 3D practices in archaeology: assessing 3D documentation techniques for intra-site data recording. J. Cult. Herit. 17, 159–169. https://doi.org/10.1016/j.culher.2015.07.005.

Galeazzi, F., 2018. 3-D virtual replicas and simulations of the Past:"Real" or "fake" representations? Curr. Anthropol. 59 (3) , 268–286. https://doi.org/10.1086/697489.

Galeazzi, F., Richards-Rissetto, H., 2018. Editorial introduction: web-based archaeology and collaborative research. J. Field Archaeol. 43, S1–S8. https://doi.org/10.1080/00934690.2018.1512701.

Galeazzi, F., Callieri, M., Dellepiane, M., Charno, M., Richards, J., Scopigno, R., 2016. Web-based visualization for 3D data in archaeology: the ADS 3D viewer. J. Archaeol. Sci.: Report 9, 1–11. https://doi.org/10.1016/j.jasrep.2016.06.045.

Gaspari, F., Ioli, F., Barbieri, F., Rivieri, C., Dondi, M., Pinto, L., 2023. Rediscovering cultural heritage sites by interactive 3d exploration: a practical review of open-source WebGL tools. The international archives of the photogrammetry. In: Remote Sensing and Spatial Information Sciences, pp. 661–668. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-661-2023. XLVIII-M-2–2023.

Gattiglia, G., 2015. Think big about data: archaeology and the big data challenge. Archäol. Inf., Fokus: Open Access & Open Data 38, 1–12.

GDAL/OGR contributors, 2022. GDAL/OGR Geospatial Data Abstraction Software Library, version 3.6.0.

Girardeau-Montaut, D., 2019. CloudCompare, version 2.12.4.

GitHub - potree/potree: WebGL point cloud viewer for large datasets [WWW Document], n.d. URL. https://github.com/potree/potree (accessed 10.23.22).

Golden, C., Scherer, A.K., Schroder, W., Murtha, T., Morell-Hart, S., Fernandez Diaz, J.C., Jiménez Álvarez, S. del P., Alcover Firpi, O., Agostini, M., Bazarsky, A., Clark, M., Kollias, G.V., Matsumoto, M., Roche Recinos, A., Schnell, J., Whitlock, B., 2021. Airborne lidar survey, density-based clustering, and ancient Maya settlement in the upper usumacinta river region of Mexico and Guatemala. Rem. Sens. 13, 4109. https://doi.org/10.3390/rs13204109.

Greene Robertson, M., 1983. The Temple of the Inscriptions, the Sculpture of Palenque. Princeton University Press, Princeton, NJ.

Guidazzoli, A., Liguori, M.C., Chiavarini, B., Verri, L., Imboden, S., De Luca, D., Delli Ponti, F., 2017. From 3D Web to VR historical scenarios: a cross-media digital heritage application for audience development. In: 2017 23rd International Conference on Virtual System & Multimedia (VSMM). Presented at the 2017 23rd International Conference on Virtual System & Multimedia (VSMM), pp. 1–8. https://doi.org/10.1109/VSMM.2017.8346273.

Guillem, A., Lercari, N., 2021. In: Lercari, N., Wendrich, W., Porter, B., Burton, M., Levy, T.E. (Eds.), Global heritage, knowledge provenance and digital preservation: defining a critical approach, Preserving Cultural History in the Digital Age. Sending Out an S.O.S.. Equinox Publishing, Sheffield, pp. 27–41.

Hesse, R., 2012. In: Kluiving, S.J., Guttmann-Bond, E. (Eds.), Using LIDAR-derived Local Relief Models (LRM) as a new tool for archaeological prospection, Landscape Archaeology between Art and Science. Amsterdam University Press, Amsterdam, pp. 369–378. https://doi.org/10.1515/9789048516070-027.

Hill, A.C., Limp, F., Casana, J., Laugier, E.J., Williamson, M., 2019. A New Era in Spatial Data Recording: Low-Cost GNSS. https://doi.org/10.1017/aap.2018.50 [WWW Document]. Cambridge Core.

Inomata, T., Triadan, D., Pinzon, F., Burham, M., Luis Ranchos, J., Aoyama, K., Haraguchi, T., 2018. Archaeological application of airborne LiDAR to examine social changes in the Ceibal region of the Maya lowlands. PLoS One 13, e0191619. https://doi.org/10.1371/journal.pone.0191619.

Inomata, T., Fernandez-Diaz, J.C., Triadan, D., García Mollinedo, M., Pinzón, F., García Hernández, M., Flores, A., Sharpe, A., Beach, T., Hodgins, G.W.L., Durón Díaz, J.J., Guerra Luna, A., Guerrero Chávez, L., Hernández Jiménez, M. de L., Moreno Díaz, M., 2021. Origins and spread of formal ceremonial complexes in the Olmec and Maya regions revealed by airborne lidar. Nat. Human Behav. 5, 1487–1501. https://doi.org/10.1038/s41562-021-01218-1.

Ioannides, M., Quak, E. (Eds.), 2014. 3D Research Challenges in Cultural Heritage: A Roadmap in Digital Heritage Preservation, Lecture Notes in Computer Science. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-44630-0.

Ioannides, M., Martins, J., Žarnić, R., Lim, V. (Eds.), 2017. Advances in Digital Cultural Heritage, Lecture Notes in Computer Science. Springer, Cham, Switzerland.

Jensen, P., 2018. Semantically enhanced 3D: a web-based platform for spatial integration of excavation documentation at alken enge, Denmark. J. Field Archaeol. 43, S31–S44. https://doi.org/10.1080/00934690.2018.1510299.

Johnson, L.M., 2018. Tracing the Ritual 'Event' at the Classic Maya City of Palenque, Mexico. University of California, Berkeley, Berkeley, CA. Ph.D. Dissertation.

Kokalj, Ž., Somrak, M., 2019. Why not a single image? Combining visualizations to facilitate fieldwork and on-screen mapping. Rem. Sens. 11, 747. https://doi.org/10.3390/rs11070747.

Kokalj, Ž., Zakšek, K., Krištof, O., 2013. In: Opitz, R.S., Cowley, D. (Eds.), Visualizations of lidar derived relief models, Interpreting Archaeological Topography: Airborne Laser Scanning, 3D Data and Ground Observation, Occasional Publication of the Aerial Archaeology Research Group. Oxbow Books, Oxford, UK ; Oakville, CT, pp. 100–114.
Kurillo, G., Forte, M., 2012. Telearch—integrated visual simulation environment for collaborative virtual archaeology. Mediterr. Archaeol. Archaeometry 12, 11–20.
Landeschi, G., 2019. Rethinking GIS, three-dimensionality and space perception in archaeology. World Archaeol. 51, 17–32. https://doi.org/10.1080/00438243.2018.1463171.
Landeschi, G., Dell'Unto, N., Lundqvist, K., Ferdani, D., Campanaro, D.M., Leander Touati, A.-M., 2016. 3D-GIS as a platform for visual analysis: investigating a Pompeian house. J. Archaeol. Sci. 65, 103–113. https://doi.org/10.1016/j.jas.2015.11.002.
Lercari, N., Forte, M., Zielinski, D., Kopper, R., Lai, R., 2013. Çatalhöyük at DiVE. Virtual reconstruction and immersive visualization of a Neolithic building. In: Proceedings of the 2013 Digital Heritage International Congress.
Lerma, J.L., Navarro, S., Cabrelles, M., Villaverde, V., 2010. Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Parpalló as a case study. J. Archaeol. Sci. 37, 499–507. https://doi.org/10.1016/j.jas.2009.10.011.
Llobera, M., 2011. Archaeological visualization: towards an archaeological information science (AISc). J. Archaeol. Method Theory 18, 193–223.
Marken, D.B., González Cruz, A., 2007. e. In: Marken, D.B. (Ed.), Elite residential compounds at late classic Palenqu, Palenque: Recent Investigations at the Classic Maya Center. Altamira Press, New York, pp. 135–160.
Martin, S., Grube, N., 2008. Chronicle of the Maya Kings and Queens: Deciphering the Dynasties of the Ancient Maya, second ed.
Masini, N., Abate, N., Gizzi, F.T., Vitale, V., Minervino Amodio, A., Sileo, M., Biscione, M., Lasaponara, R., Bentivenga, M., Cavalcante, F., 2022. UAV LiDAR based approach for the detection and interpretation of archaeological micro topography under canopy—the rediscovery of perticara (basilicata, Italy). Rem. Sens. 14, 6074. https://doi.org/10.3390/rs14236074.
Matsushita, R., Suita, H., Yasumuro, Y., 2014. In: Ioannides, M., Magnenat-Thalmann, N., Fink, E., Žarnić, R., Yen, A.-Y., Quak, E. (Eds.), Digital archive system with 3D web portal interface, Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection, Lecture Notes in Computer Science. Springer International Publishing, Cham, pp. 564–571. https://doi.org/10.1007/978-3-319-13695-0_56.
Maudslay, A.P., 1887. Biologia Centrali-Americana, or, Contributions to the Knowledge of the Fauna and Flora of Mexico and Central America, Archaeology. R. H. Porter and Dulau & Co., Londres.
McAvoy, S., 2022. Palenque 3D Archaeological Atlas. https://doi.org/10.34946/D6KS34.
McAvoy, S., 2023. Chichen Itza 3D Archaeological Atlas. https://doi.org/10.34946/D6B88P.
Meyer, É., Grussenmeyer, P., Perrin, J.-P., Durand, A., Drap, P., 2007. A web information system for the management and the dissemination of Cultural Heritage data. J. Cult. Herit. 8, 396–411. https://doi.org/10.1016/j.culher.2007.07.003.
Miller, M.E., 1999. Maya Art and Architecture. Thames & Hudson, New York.
NCALM [WWW Document], n.d. URL. https://ncalm.cive.uh.edu/home/about-center (accessed 10.23.22).
Olsen, M.J., 2015. In situ change analysis and monitoring through terrestrial laser scanning. J. Comput. Civ. Eng. 29, 04014040 https://doi.org/10.1061/(ASCE)CP.1943-5487.0000328.
Olsen, M.J., Kuester, F., Chang, B.J., Hutchinson, T.C., 2010. Terrestrial laser scanning-based structural damage assessment. J. Comput. Civ. Eng. 24, 264–272. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000028.
Opitz, R., 2018. Publishing archaeological excavations at the digital turn. J. Field Archaeol. 43, S68–S82. https://doi.org/10.1080/00934690.2018.1505409.
Pieraccini, M., Guidi, G., Atzeni, C., 2001. 3D digitizing of cultural heritage. J. Cult. Herit. 2, 63–70. https://doi.org/10.1016/S1296-2074(01)01108-6.
Rahaman, H., Champion, E., Bekele, M., 2019. From photo to 3D to mixed reality: a complete workflow for cultural heritage visualisation and experience. Digit. Appl. Archaeol. Cult. Herit. 13, e00102 https://doi.org/10.1016/j.daach.2019.e00102.
rapidlasso GmbH, 2023. LAStools - Efficient LiDAR Processing Software (version 220107).
Remondino, F., 2011. Heritage recording and 3D modeling with photogrammetry and 3D scanning. Rem. Sens. 3, 1104–1138.
Richards-Rissetto, H., 2013. From mounds to maps to models: visualizing ancient architecture across landscapes. In: 2013 Digital Heritage International Congress (DigitalHeritage). Presented at the 2013 Digital Heritage International Congress (DigitalHeritage). IEEE, Marseille, France, pp. 519–522. https://doi.org/10.1109/DigitalHeritage.2013.6744820.
Richards-Rissetto, H., 2017a. What can GIS + 3D mean for landscape archaeology? J. Archaeol. Sci. 84, 10–21. https://doi.org/10.1016/j.jas.2017.05.005. Archaeological GIS Today: Persistent Challenges, Pushing Old Boundaries, and Exploring New Horizons.
Richards-Rissetto, H., 2017b. An iterative 3D GIS analysis of the role of visibility in ancient Maya landscapes: a case study from Copan, Honduras. Digit. Scholarsh. Hum. 32, 195–212. https://doi.org/10.1093/llc/fqx014.
Richards-Rissetto, H., Landau, K., 2019. Digitally-mediated practices of geospatial archaeological data: transformation, integration, & interpretation. J. Comput. Appl. Archaeol. 2, 120–135. https://doi.org/10.5334/jcaa.30.
Richards-Rissetto, H., von Schwerin, J., 2017. A catch 22 of 3D data sustainability: lessons in 3D archaeological data management & accessibility. In: Digital Applications in Archaeology and Cultural Heritage, The Past now showing in 3D: Case Studies in 3D Archaeology, vol. 6, pp. 38–48. https://doi.org/10.1016/j.daach.2017.04.005.
Risbøl, O., Langhammer, D., Schlosser Mauritsen, E., Seitsonen, O., 2020. Employment, utilization, and development of airborne laser scanning in fenno-scandinavian archaeology—a review. Rem. Sens. 12, 1411. https://doi.org/10.3390/rs12091411.
Ruz Lhuillier, A., 2013. El Templo de las inscripciones: Palenque, second ed. Fondo de Cultura Económica, México.
Schele, L., 1986. In: Benson, E.P. (Ed.), Architectural development and political history at Palenque, City-States of the Maya: Art and Architecture: A Conference, Jay I. Kislak Collection (Library of Congress). Rocky Mountain Institute for Pre-Columbian Studies, Denver, pp. 110–137.
Schele, L., Mathews, P., 1998. The Code of Kings: the Language of Seven Sacred Maya Temples and Tombs. Scribner, New York.
Scherer, A., 2012. The classic Maya sarcophagus: veneration and renewal at Palenque and tonina. Res. 61–62, 242–261. https://doi.org/10.1086/RESvn1ms23647833.
Schütz, M., 2016. Potree: Rendering Large Point Clouds in Web Browsers. Institute of Computer Graphics and Algorithms, Vienna University of Technology, Vienna. Master's Thesis.
Schwartz, C., Ruiters, R., Weinmann, M., Klein, R., 2013. WebGL-based streaming and presentation of objects with bidirectional texture functions. J. Comput. Cult. Herit. 6 (11), 1–11. https://doi.org/10.1145/2499931.2499932, 21.
Scopigno, R., 2012. Sampled 3D models for Cultural Heritage: which uses beyond visualization? Virt. Archaeol. Rev. 3, 109. https://doi.org/10.4995/var.2012.4537.
Scopigno, R., Callieri, M., Cignoni, P., Corsini, M., Dellepiane, M., Ponchio, F., Ranzuglia, G., 2011. 3D models for cultural heritage: beyond plain visualization. Computer 44, 48–55. https://doi.org/10.1109/MC.2011.196.
Secretaría de Gobernación, 1981. Decreto por el que se declara Parque Nacional con el nombre de Palenque, el área con superficie de 1,771-95-01.22 Has., en el Estado de Chiapas y se expropia en favor del Gobierno Federal una superficie de 1,381-11-79.87 Has. In: DOF - Diario Oficial de la Federación [WWW Document]. URL. https://www.dof.gob.mx/nota_detalle.php?codigo=4680859&fecha=24/08/1981#gsc.tab=0 (accessed 10.11.22).
Sharer, R., Traxler, L., 2006. The Ancient Maya, sixth ed. Stanford University Press, Stanford,CA.
Stal, C., Van Liefferinge, K., De Reu, J., Docter, R., Dierkens, G., De Maeyer, P., Mortier, S., Nuttens, T., Pieters, T., van den Eijnde, F., van de Put, W., De Wulf, A., 2014. Integrating geomatics in archaeological research at the site of Thorikos (Greece). J. Archaeol. Sci. 45, 112–125. https://doi.org/10.1016/j.jas.2014.02.018.
Stuart, D., Stuart, G., 2008. Palenque: Eternal City of the Maya. Thames & Hudson.
Štular, B., Kokalj, Ž., Oštir, K., Nuninger, L., 2012. Visualization of lidar-derived relief models for detection of archaeological features. J. Archaeol. Sci. 39, 3354–3360. https://doi.org/10.1016/j.jas.2012.05.029.
UNESCO World Heritage Centre [WWW Document], n.d. Pre-Hispanic City and National Park of Palenque - URL https://whc.unesco.org/en/list/411/(accessed 10.11.22).
Verhoeven, G.J., 2017. Mesh is more—using all geometric dimensions for the archaeological analysis and interpretative mapping of 3D surfaces. J. Archaeol. Method Theor 24, 999–1033. https://doi.org/10.1007/s10816-016-9305-z.
von Schwerin, J., Richards-Rissetto, H., Remondino, F., Agugiaro, G., Girardi, G., 2013. The MayaArch3D project: a 3D WebGIS for analyzing ancient architecture and landscapes. Lit. Ling. Comput. 28, 736–753. https://doi.org/10.1093/llc/fqt059.
von Schwerin, J., Richards-Rissetto, H., Remondino, F., Spera, M.G., Auer, M., Billen, N., Loos, L., Stelson, L., Reindel, M., 2016. Airborne LiDAR acquisition, post-processing and accuracy-checking for a 3D WebGIS of copan, Honduras. J. Archaeol. Sci.: Report 5, 85–104. https://doi.org/10.1016/j.jasrep.2015.11.005.
Wheatley, D., Mark, Gillings, 2022. Spatial Technology and Archaeology: the Archaeological Applications of GIS. Taylor & Francis, London.