Mapping Ritual Landscapes Using Lidar

Cave Detection through Local Relief Modeling

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Archaeologists have long recognized the importance of landscape studies to help us understand how ancient people adapted to their environments and how in turn their activities shaped the history of the local landscape (Trigger 2006:247–250). It is difficult to lump landscape studies into a single framework or to define them with a single definition (Stoddart and Zubrow 1999), though the basic ontology typically involves the interaction between the physical environment and human presence (Ashmore 2007:255) similar to Yi-Fu Tuan's "space and place"(1977). Some define

ABSTRACT

Data collected from aerial lidar scanning provides new opportunities for archaeological survey. It is now possible, in a short period of time, to collect vast amounts of geographic data that would have taken years of pedestrian survey to acquire. This enhances and extends landscape studies by reducing time-frames and cost, encouraging analyses based on real-world data collection on a regional scale. This paper describes an approach for modeling the ritual landscape surrounding the ancient Maya center of Las Cuevas, Belize by analyzing the spatial aspects of ritual cave use. Using lidar-derived data, we describe a method for locating potential cave sites using Local Relief Models, which requires only a working knowledge of relief visualization techniques and no specialized skills in computer programming. Our method located the five known cave sites within our 222 km^2 lidar study area—including one with a fissure entrance. We plan to ground-truth potentialities to develop models of the ritual landscape that can be visualized and analyzed. By researching cave use on a regional scale and defining the relationships between caves and surface features, we advance cave studies by deepening our understanding of the ritual landscape and its articulation with ancient Maya socio/political dynamics.

Los datos recolectados por el reconocimiento aéreo lidar ofrece nuevas oportunidades para el estudio arqueológico. Ahora en un período corto es posible recopilar grandes cantidades de datos geográficos que antes tomaban años para adquirir en un reconocimiento peatonal, pero las imágenes digitales todavía requieren interpretación y verificación en el terreno. El nuevo método mejora y amplía el estudio del paisaje en que se reduce el tiempo y los costos del estudio. En esta manera fomenta el análisis basado en la recolección de datos del mundo actual en una escala regional. En este artículo enfocamos en diferente métodos de modelar el paisaje ritual que rodea el antiguo centro maya de Las Cuevas, Belice mediante el análisis de los aspectos espaciales de uso ritual de una cueva. Utilizando los datos de lidar, describimos un método para localizar posibles sitios de cuevas utilizando Shaded Relief Models que sólo requiere un conocimiento práctico de las técnicas de visualización, sin el conocimiento especializado en la programación de computadoras. Estamos a favor de un enfoque híbrido utilizando tanto automatizado y manual de evaluación, que ha demostrado ser eficaz en la búsqueda de las posibilidades más prometedoras. Nuestro método nos permitió a localizar todas las cuevas conocidas en el área de lidar de 222 km^2—incluso aquellas con entradas estrechas y horizontales. Con estos datos en mano tenemos la intención de desarrollar modelos de paisaje ritual y sus cambios en el tiempo que se pueden visualizar y analizar. La investigación del uso de las cuevas en una escala regional y la identificación de las relaciones entre las cuevas y los rasgos de la superficie, los estudios ayudaran nuestra comprensión del paisaje ritual y cómo coincide con las dinámicas sociopolíticas de los antiguos Mayas.

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landscape research by dichotomizing between studies of the natural physical environment and those that emphasize human/environment interactions (Knapp and Ashmore 1999), whereas others divide studies into those of landscape ecology related to human adaptation and those that investigate landscapes as meaningful spaces (Layton and Ucko 1999:2–3). Here we engage the latter by illustrating how aerial Light Detection and Ranging (lidar) data can be used to model ritual landscapes of the Classic-period Maya by investigating the distribution of ancient ritual cave sites over a region. We chose the term "ritual" landscape as opposed to "ceremonial" (Ashmore 2008:200) because of the nature of cave use. Wendy Ashmore defines ceremonial landscapes as "settings in which arrangements of specific features situate the cosmos on earth, and where ritualized movements to and among these features are means to evoke and reinforce understandings of cosmic order." This terminology well-describes ritual performance in caves, but the term "ceremonial" implies a much grander and public setting than many ancient Maya caves afford. As first suggested by James Brady (1989), many cave rites are done in secluded small spaces, suggesting that these are secretive or private performances, though of course others may afford much wider participation (Moyes 2012).

Our goal here is to demonstrate how lidar data may be used to facilitate such a landscape approach by helping to locate caves in densely forested tropical areas using Local Relief Models (LRMs). The problem with most studies of landscape and settlement in the Maya Lowlands is that acquiring these requisite data is time consuming and expensive. As A. Chase and his colleagues (2011) noted, in most surveys, only small parts of a kingdom's sustaining hinterland and associated secondary centers are actually investigated due to time, financial constraints, and the difficulty of moving through rough terrain with dense jungle growth. While aerial surveys and satellite imagery have been employed to detect large structures, these are not effective methods for locating smaller or obscure features that interest archaeologists, such as cave entrances. Accurate site detection is one of cave archaeology's greatest challenges, and typically researchers take a "gumshoe" approach in which local people escort archaeologists to known sites. By this time, most known caves are already looted, allocating much Mesoamerican cave archaeology to salvage work. For example, from 2011–2015, the Belize Cave Research Project (BCRP) was shown over 70 sites in northern, central, and western Belize, all of which exhibited signs of looting and disturbance. This problem is applicable not just to Mesoamerica, but to all regions containing archaeological cave sites. Because these sites often have excellent preservation and contain stratigraphic deposits of great antiquity, they are highly valued not just by archaeologists, but geologists, climatologists, and anyone studying the deep past (Collcutt 1979; Farrand 1985; Ford and Williams 1989:317; Sherwood and Goldberg 2001:145; Straus 1990:256**,** 1997 Woodward and Goldberg 2001:328). Yet they are constantly under threat. Locating caves using lidar-derived models will potentially mitigate this problem by presenting effective methods for survey and discovery.

Aerial lidar scanning provides archaeologists with a means to create detailed regional maps of anthropogenic and natural landscapes because it reveals high-resolution relief models of ground surfaces through forest canopy (Gallagher and Josephs 2008; Hofton et al. 2002; Weishampel, Blair, Dubayah, et al. 2000; Weishampel, Blair, Knox, et al. 2000). Lidar instruments that emit pulses of light are fitted to aircraft, so that large areas can be scanned in only a few days. Images are formed from arrays of reflected light pulses emitted from a laser at an angle. Vertical or sloped topography may be captured within limits when laser shots are at low-scan angles. Some light will bounce off of the canopy and vegetation, and some will rebound from the earth's surface so that physical models of the ground surface may be derived from those points. The returned data are then classified and displayed as 3D point clouds that can be further manipulated to create relief models of the earth's surface known as bare-earth models. Originally employed on a relatively small scale throughout portions of Europe (Sittler 2004), lidar-derived models are becoming one of archaeology's most important tools and have been described as "transformative" and the largest methodological advance since the invention of radiocarbon dating (Chase et al. 2012). Detailed relief maps have been generated for some of the largest and best known archaeological sites, including Stonehenge (Bewley et al. 2005) and Angkor Wat (Evans et al. 2013). These data contribute to both site management and research, and are typically used in settlement studies imperative to archaeological practice. Lidar-derived models allow archaeologists to make population estimates, understand the relationships between centers and hinterlands, reconstruct agricultural practices, and help to answer questions about political and social organization on local and regional scales (Chase, Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, Brown, et al. 2014).

Arlen and Diane Chase and their colleagues were some of the first to realize the potential of lidar for Mesoamerican archaeology. Working at the site of Caracol in western Belize, they acquired years of pedestrian survey data, so that when they obtained an aerial lidar scan in 2009, the site became an excellent test case for comparing ground survey results to lidar data. In a flurry of publications, they reported previously unknown anthropogenic and natural features across the landscape, such as structures, water holes, land modifications, causeways, agricultural terraces, and subterranean features such as caves, chultuns (underground storage chambers), and sinkholes, demonstrating the utility of the method (A. Chase etal. 2010, A. Chase et al. 2011; A. Chase et al. 2012; Chase, Chase, Awe,

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Weishampel, Iannone, Moyes, Yaeger, and Brown 2014; Chase, Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, Brown, et al. 2014; D. Chase 2011). Because the lidar in this area proved to be so effective, the Western Belize Lidar Consortium undertook a project to acquire more data for the region. As part of this initiative, in 2013, an additional 1,057 km^2 were flown in the Vaca Plateau and Belize Valley. The coverage included an area of 222 km^2 surrounding the site of Las Cuevas, a medium-sized center located in the Chiqubul Forest Reserve 14 km southeast of Caracol (Chase, Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, Brown, et al. 2014; Chase, Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, Brown, et al. 2014).

Las Cuevas was originally surveyed by Adrian Digby (1958) in 1957 and has been under investigation by the Las Cuevas Archaeological Reconnaissance (LCAR) since 2011. The Late Classic (A.D. 700–900) center is not extensive, but possesses a unique feature that sets it apart from others within the Maya Lowlands—a cave system that runs beneath the main plaza (Figure 1). Structures surround two plazas (A and B) situated around a large sinkhole 15 m in depth (Moyes 2013; Moyes et al. 2012, 2015). Entered through the sinkhole, the cave mouth sits directly below the base of one of the largest structures at the site, the eastern pyramid in Plaza A, which stands 17 m in height. A 335-m tunnel system underlies the plaza structures as well as an elite plazuela group located to the west. In the center of the massive entrance chamber of the cave is a natural spring set within a sink that fills during heavy rains. The spring is surrounded by plastered platforms, stairways, and terraces that ascend to the cave walls, creating an amphitheater-like space. This suggests that the chamber was used for well-organized ceremonies catering to large numbers of participants.

For years, Wendy Ashmore and her colleagues have argued that the Maya built environment reifies ideas of Maya cosmology and political order (Ashmore 1989; Ashmore and Sabloff 2002), and at Las Cuevas the site architecture incorporates salient features of the natural landscape, to create a space highly charged with theological import. To understand its significance, one must apprehend the concept of sacred geography at the heart of Maya cosmology—the mountain/cave/water complex that reifies the three-tiered cosmological model (Brady and Ashmore 1999:126). In their constructions, Maya often referred to and replicated the sacred landscape, constructing temples to represent sacred mountains and the rooms at their summits to represent caves (Schávelzon 1980; Vogt and Stuart 2005). Natural caves are one of the most revered cosmological features in the Maya landscape, particularly those that contain life-giving water. The presence of a cave can influence the choice of original settlement and can define geographic and spiritual boundaries (Farriss 1984:129, 148; García-Zambrano 1994; Moyes and Prufer 2013), so they may be referenced in the names of places or polities (Tokovinine 2013; Vogt and Stuart 2005**)**. They are considered to be entrances to the Maya underworld and the home of deities associated with fertility, rain, and the sacred earth (see Moyes 2012 for discussion), which explains why natural caves were and continue to be used exclusively as ritual spaces (Christenson 2008; Moyes and Brady 2012; Palka 2015; Prufer and Brady 2005). Archaeological research suggests that caves were central to rites associated with rainmaking, agricultural productivity, and fertility, as well as rites of passage and possibly ancestor worship (Brady 1989; Brady and Prufer 2005; Heyden 1975; McAnany 1995**:**159; Moyes and Brady 2012; Moyes et al. 2009; Prufer and Brady 2005; Thompson 1975; Stone 1995). As a path to power, ancient Maya rulers linked themselves to cosmological forces—ideologically or quite literally—by incorporating the natural landscape through cave ritual or creating artificial caves in their site constructions (Brady and Veni 1992; Moyes 2006; Moyes and Prufer 2013; Moyes et al. 2009).

Therefore, we can appreciate the cosmological symbolism inherent in the Las Cuevas site plan with its constructed temple mountain towering over the watery natural cave, forming a backdrop that sanctified the rites and ceremonies occurring within those precincts. Although constructing pyramids on top of caves is not entirely unique (See Moyes and Brady 2012:152 Table 10.2), Las Cuevas is set apart because it boasts the most extensive architectural elaborations of any cave site in the Maya Lowlands, demonstrating its importance in Late Classic Maya ritual life. Taking into account the natural landscape, site plan and construction, remote location, and non-local artifact assemblage (Kosakowsky 2014), it has been argued elsewhere (Moyes 2015; Moyes et al. 2015) that Las Cuevas is a Location of High Devotional Expression—a place of ideological significance where rites and ceremonies sustained the hopes and aspirations of pilgrims from far and wide (Renfrew 1985). As such, we might expect that the center was embedded within a greater ritual landscape, but how might we examine this issue? Here lidar data present us with a new opportunity to approach such a study that will enable us to analyze the distribution of ritual spaces or sacred places over a regional landscape.

Although cave research has grown over the past 40 years, there have been no surveys that have confidently provided 100-percent coverage of all caves surrounding a particular polity. This is a potentially monumental task when we consider that caves are often difficult to locate in forested areas and polity boundaries are fuzzy at best. Even regional cave studies tend to focus on caves that exhibit the most usage and rarely report on unused caves within the study area. Yet we would argue that to advance our understanding of cave use requires the study of all caves and cave-like spaces such as rockshelters, both large and small, used and unused, analyzing their distributions over the landscape as they relate to natural and anthropogenic features such as temples, settlements, water holes, or agricultural works. Aerial lidar scanning introduces the possibility that full coverage could be attained or closely approximated by allowing archaeologists to search remotely for these sites.

In this paper, our goal is to provide archaeologists with an effective method for locating potential cave sites using lidar in a way that is accessible and easy to understand. First, we describe the morphologies and types of features we expect to locate and then go on to propose useful techniques for identifying them using LRMs derived from commercial software. Finally, we test of our method by comparing known caves in our study area to those found on the lidar scan. Our method requires only a working knowledge of relief visualization techniques and no specialized skills in computer programming. While we agree that it is efficient to automate feature selection, we advocate a hybrid method of automation and manual evaluation that is effective in finding the most promising potentialities. These in turn create a framework for site discovery during ground-truthing that does not rely on local knowledge. Not only will the lidar-generated

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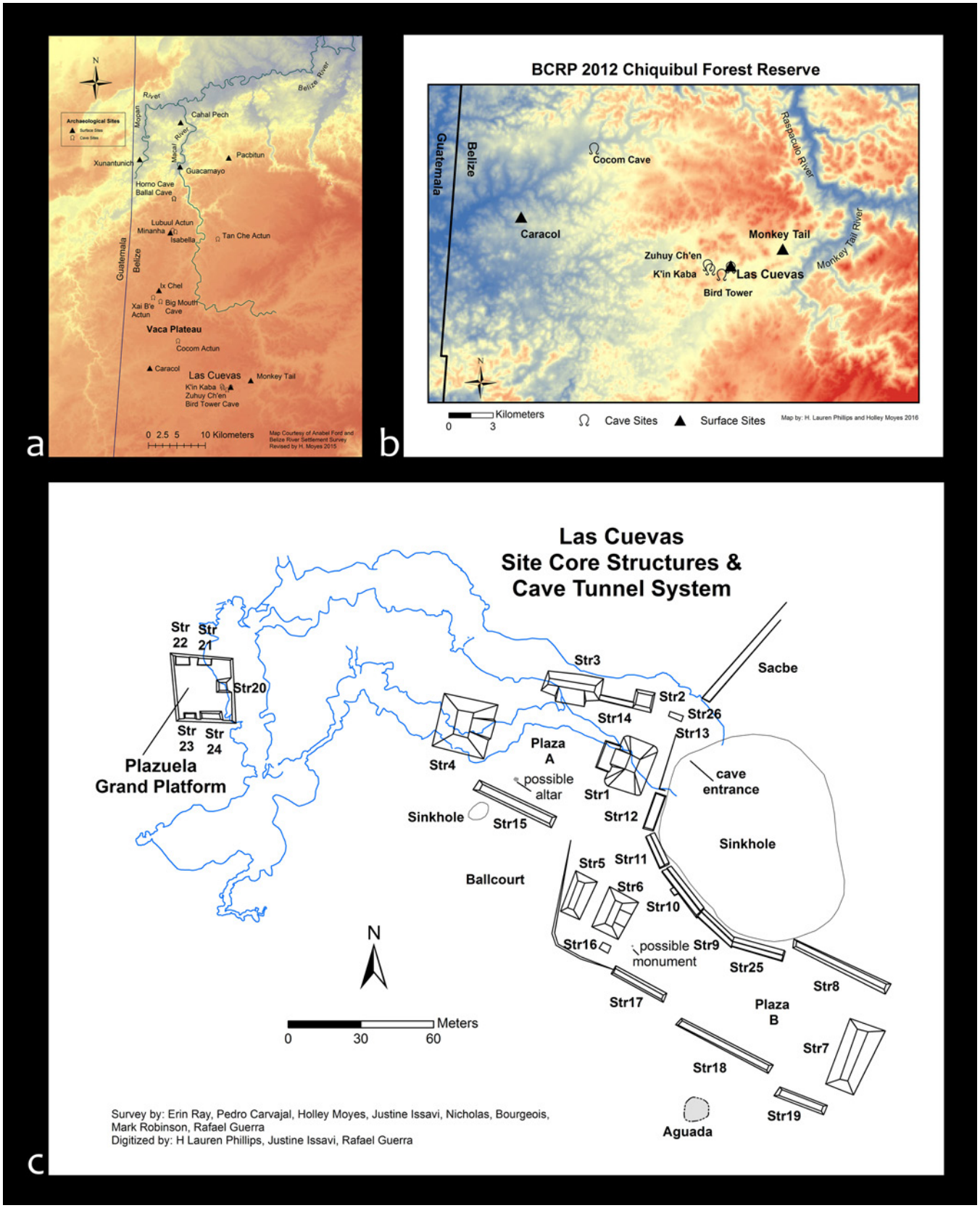


FIGURE 1. (a) Map of western Belize illustrating locations of sites mentioned in text; (b) location of Las Cuevas in the Chiquibul Forest Reserve and surrounding known caves; (c) plan view map of the Las Cuevas site illustrating cave running beneath Plaza A.

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data inform pedestrian surveys, but it will provide information about the natural and anthropogenic features of the landscape critical to our future analyses and will enable us to model a ritual landscape for the region. With these data, the project will be able to evaluate distributions of used or unused caves, appraise their dimensions and morphologies, explore relationships to surface features, and create chronologies to examine changes in use over time. By identifying patterns in cave use at this scale, we expect to better understand how ancient Maya ritual practice articulated with sociopolitical dynamics. The first step in the development of this research is to identify and describe what we are looking for.

WHAT IS A CAVE?

Definitions of caves are slippery and difficult to pin down because the word "cave" is considered a non-scientific term dependent on human interaction. In the *Encyclopedia of Caves*, geoscientist William White defines caves as "a natural opening in the Earth, large enough to admit a human being, and which some human beings choose to call a cave" (1988:60; see also Culver and White 2004:81). Similarly, in the *Encyclopedia of Cave and Karst Science*, John Gunn notes that the term "cave" is "commonly applied to natural openings, usually in rocks, that are large enough to permit entry by humans" (2003:vii). In both encyclopedias, the authors point out that caves cannot be defined by their geology alone, though there are morphological distinctions between caves and rockshelters. A rockshelter is usually defined as "a cave often at a cliff base, with more or less level floor extending only a short distance so that no part is beyond daylight" (Jennings 1997). Thus, rockshelters are caves but caves are not necessarily rockshelters.

Caves are ontologically "holes." Although holes are morphologically complex and come in many different forms, philosophers Alberto Casati and Achille Vazi (1994) describe three basic types: *superficial hollows* dependent on surfaces, *perforating tunnels* through which a string can pass, and *internal cavities* like holes in Swiss cheese that are dependent on three-dimensional objects having no contact with the outside environment or surface. In remotely sensed data, we hope to find superficial hollows or perforating tunnels that contact the surface, whereas internal cavities could be detected only by subsurface prospecting. So, in our lidar scan, ontologically we are not looking for holes, but rather we seek the interface of the hole with the earth's surface. So to be clear, we are not looking for "caves" per se, but cave mouths or rockshelter openings.

There are a wide variety of cave openings that may be positioned at different angles against the earth's surface with vertical or horizontal entrances at polar ends of the spectrum. There is no formal classification of cave entrance types, but here we distinguish between their sizes and morphology. When one can walk or crawl into a cave, we designate this as a horizontal entrance (Figure 2). Sizes can be classified as large (> 5 m in width and over 2 m in height), medium (1–5 m in width and 1–2 m in height), small (< 1 m in width and > 1 m in height), and fissures (< 1 m in height). Fissures necessitate crawling, small entrances accommodate one person, medium entrances may be used by fewer than 10 people, and large entrances accommodate 10 people or more. Special cases of this type might include entrances in sheer cliff faces that require climbing equipment to access or caves with water emerging from the entrance, and occasionally vertical drops accessed through horizontal entrances.

Vertical entrances necessitate down climbs or technical drops (Figure 3). These can be shafts with small manhole-like entrances (< 1 m in diameter) or may have larger openings. Based on their geologic formation processes, these entrances can technically be classified as sinkholes (or dolines), though in usage we tend to differentiate between the two. Sinkholes are characteristic features of karst landscapes that are closed depressions with internal drainage caused by downward gravitational movements (for example, collapse, suffusion, or sagging) of the cover rock, bedrock, or caprock. They come in a variety of forms (cylindrical, conical, bowl, or pan-shaped) and can be quite small or may measure hundreds of meters across and tens of meters in depth (Bensen and Yuhr 2016:16–25; Williams 2003). They may contain water or may be filled in with sediment. Cave tunnel systems can originate at the base of sinkholes and are often equated with them. Because sinkholes can be quite large, they can be more easily viewed using remote sensing techniques, but only about one-third of the 50 caves surveyed by the BCRP had sinkhole entrances. Not only this, but sinkholes can be quite deep and difficult to access. Typically, the Maya rarely entered caves with vertical drops over 30 m, and so for archaeologists the largest and deepest sinkholes are not necessarily desired targets.

FINDING CAVES USING REMOTE SENSING

Previous studies have attempted to detect caves remotely. For instance, Cameron Griffith (2000, 2001) employed LANDSAT imagery to locate cave openings based on thermal differentials between cooler air coming out of cave entrances and the warmer surrounding forest. The results were unsatisfactory because the thermal band of the LANDSAT image was simply too coarse to pick up subtle differences. However, an earlier study demonstrated that caves can be located by airborne infrared thermal detection, but only when a cave "breathes" based on changes in atmospheric pressure (Rinker 1975).

In archaeology, terrestrial lidar is used frequently to map the insides of caves, particularly sites containing artwork or sensitive remains (e.g., Rüther et al. 2009; Sadier et al. 2012), and both aerial and terrestrial lidar are used together to document and manage some high-profile world heritage sites (Novakovic´ et al. 2014). Yet few studies have attempted to remotely detect cave entrances using aerial lidar. Rather, there have been a number of successful studies that located sinkholes (Gutierrez et al. 2008; Kobal et al. 2015; Zhu et al. 2014). The process can be automated by employing filters, applying a hole-filling algorithm to estimate their shapes, and then, based on their morphological characteristics, employing a random forest classifier or decision tree to determine true sinkholes from false positives (Miao et al. 2013). This approach was taken by Weishampel and his colleagues (2011) in their study to locate caves near the site of Caracol by looking for sinkholes with steep depressions. They used the Topographic Position Index calculator to locate depressions over 10 m in depth. Of the 60 features located, many of descended over 50 m, with an average depth of 21.5 m.

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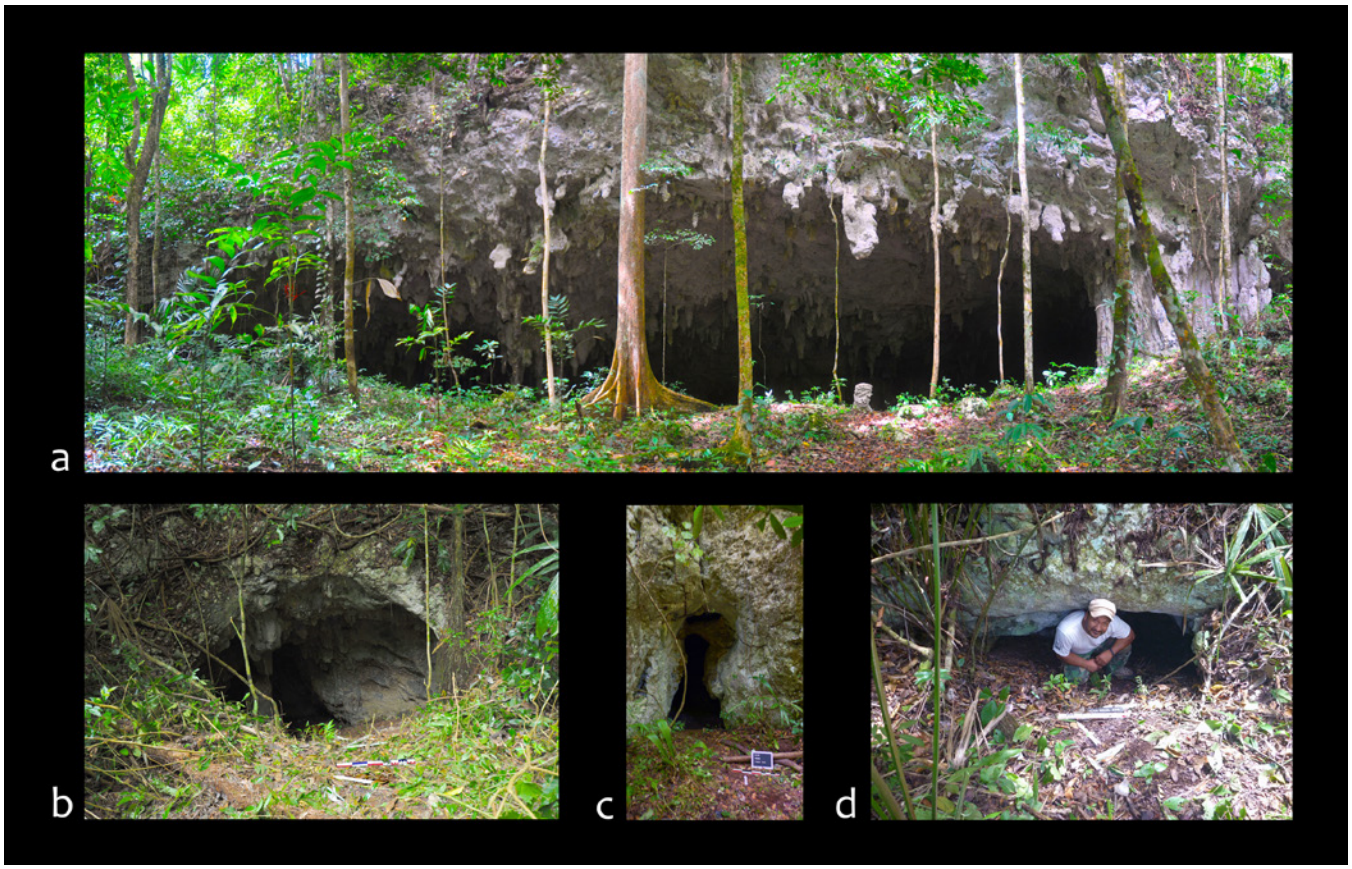


FIGURE 2. Photos of horizontal entrance types: (a) large horizontal entrance of Actun Isabella near the site of Minanha; (b) medium-sized entrance of Big Mouth Cave near the site of Ix Chel in the Vaca Plateau; (c) small entrance at Horno Cave near Las Ruinas; and (d) Gonzalo Pleitez poses in the fissure entrance at Ballal Actun also near Las Ruinas.

Of the nine known caves in the area (Feld 1994), the technique located only one. According to the authors, this was because the caves were too shallow or had horizontal entrances. The researchers reasoned that, because of the vertical direction of the lidar pulse, it would be unlikely to locate these sites. Further, because of the horizontal resolution of the DEM, they argued that caves with openings smaller than 1 m^2 were not likely to be detected (p.190). These horizontal sites were the caves with the most significant archaeological interest, so our challenge was to develop a method for finding not just vertical drops, but smaller horizontal cave entrances. It was with this in mind that we approached our project.

LIDAR-DERIVED LOCAL RELIEF MODELING

Lidar data for the west-central portion of Belize was acquired by the National Center for Airborne Laser Mapping (NCALM) in April and May of 2013 through a collaborative effort between multiple archaeological researchers (Chase, Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, Brown, et al. 2014). The campaign acquired data over 14 consecutive flights and covered approximately 1057 km^2 (105,700 ha) within the Vaca Plateau and along the Belize River Valley. NCALM used an Optech Gemini Airborne Laser Terrain Mapper (ALTM) mounted on a twin-engine Cessna 337 Skymaster aircraft, flying at 600 m above ground level with a ground speed of 60 m per second. Three hundred and twenty-five north-south survey flight lines were flown spaced approximately 137 m apart, which resulted in triple swath overlap. The laser was operated at a pulse rate of 125 kHz with a beam divergence of .8 mRad and a scan frequency of 55 Hz. The nominal scan angle was 18 degrees with an edge cutoff of 1 degree. The data acquisition resulted in an average density of 15 points per m^2 throughout the entire area of interest.

Lidar data obtained through laser pulses are stored in LASer (.LAS) format. This raw point-cloud data records an extensive amount of information and is useful in generating statistics on subjects such as canopy height and vegetative coverage. Yet the large number of returns makes the format cumbersome when attempting to model a bare-earth surface for a large region. In these instances, lidar-derived digital elevation models (DEMs) are often produced for landscape analysis purposes. At a spatial resolution of 1 m, these models are much more detailed than other satellite-derived DEMs, such as ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer). Once the lidar-derived DEM is created, other surface models and relief visualizations can be generated. Hillshading is perhaps the most commonly utilized relief visualization technique currently employed by archaeologists; however, the technique does have

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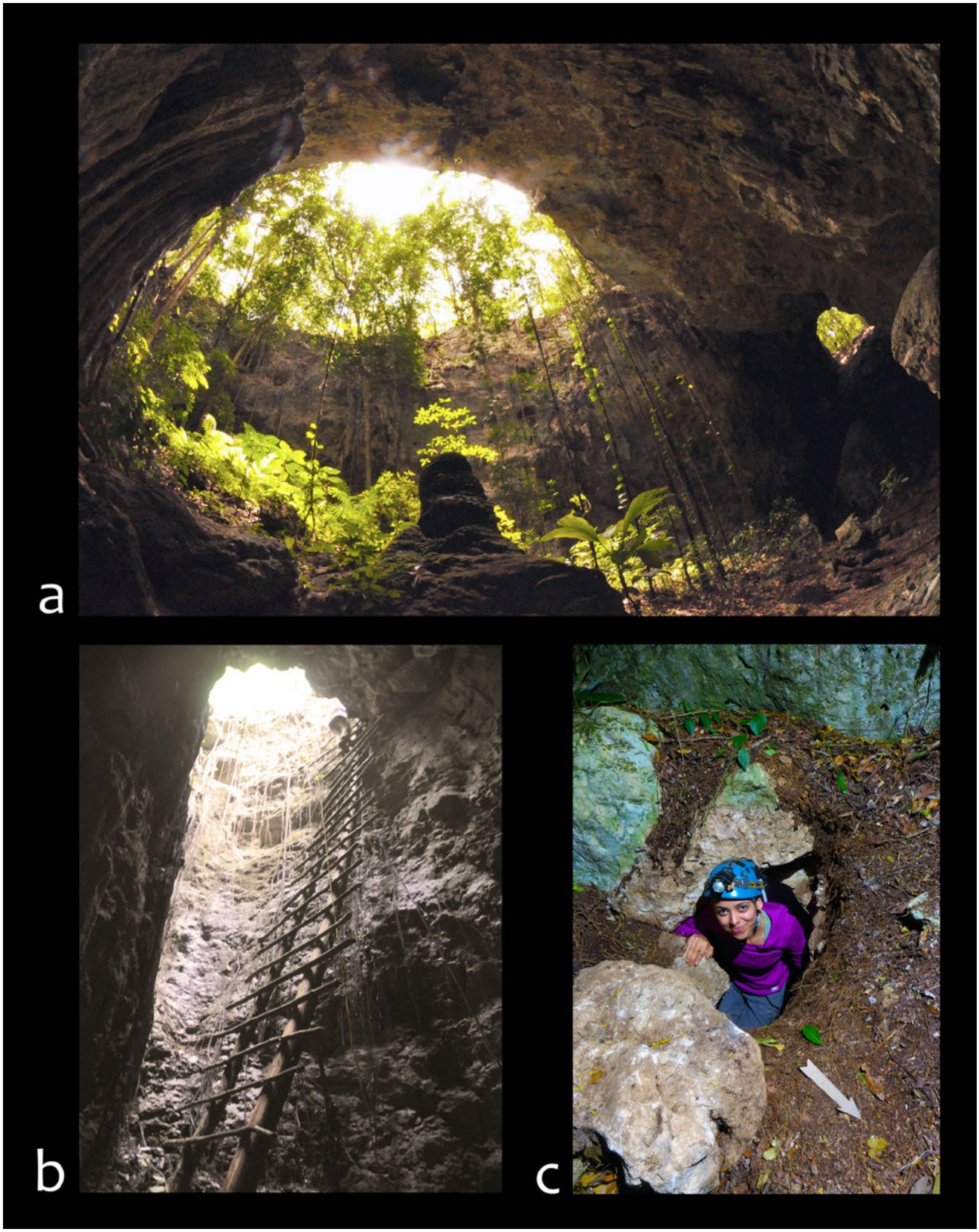


FIGURE 3. Photos of vertical entrance types: (a) large sinkhole entrance at the site of Tan Che in the Mountain Pine Ridge near Augustin Village; (b) large vertical shaft entrance at the site of Lubuul near Minanha; (c) Shayna Hernandez emerges from a small vertical shaft entrance at Actun Xaibe near the site of Ixchel in the Vaca Plateau.

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certain limitations when modeling anthropogenic features. The hillshade technique is suited best in moderately hilly topography and can fail to detect relief details on slopes steeper than 30 degrees (Zakšek et al. 2011). When determining hillshading from a single illumination source, large relief features can be obscured in shadow—i.e., southeast-facing slopes when the illumination source is projected from the northwest. Finally, hillshading does not classify the change in topography based on its immediate surroundings, but instead contains integer values based on shadow and illumination. The detection of small-scale elevation differences represents a crucial step in potentially automating the detection of archaeological features across a landscape.

Cave detection analysis was performed using ArcMap and LP360. Raster-based modeling was conducted within ArcMap, while LP360 was used to visualize ground point clouds in profile and 3D views. Other commercial software and freeware exist for the viewing, processing, and manipulation of lidar data. TerraSolid (Oy) and Surfer (Golden Software, LLC) are two of the main commercial software options available for advanced terrain modeling and visualization. Freeware programs capable of handling and processing lidar data include SAGA (SAGA Users Group Association), Quantum GIS (QGIS Development Team), and GRASS GIS (GRASS Development Team). FugroViewer (Fugro World Wide, Leidschendam, Netherlands) and CloudCompare (Daniel Girardeau-Montaut, Paris, France) are also free, open-source software programs designed to visualize point-cloud data in a manner similar to LP360.

A detailed LRM was created within a 222 km^2 area surrounding the monumental center of Las Cuevas, a region spanning both sides of the Monkey Tail Branch of the Macal River. Modeling analysis began with the creation of a 1 m horizontal-resolution lidar-derived digital elevation model (DEM) based on identified ground-return points. This process was performed by NCALM and processed through TerraScan (TerraSolid Oy) using an algorithm to build a triangulated surface model based on presumed ground points. The surface model added points based on a window size of 25 m, iteration angle of nine degrees, and iteration distance of 1.4 m. The iteration parameters restricted the inclusion of modern low structures, while retaining small and large scale landscape features. The bare earth DEM was constructed based on an average ground coverage of 2.8 points per m^2. Ground returns associated with the thickest vegetation and canopy across the complete area of interest averaged .3 points per m^2, while open or disturbed areas generated up to 9.4 points per m^2. The Las Cuevas area, which presently occupies an environment characterized by primary growth forest, allowed between one and three ground points per m^2, indicating a resolution capable of distinguishing small natural and archaeological features across the landscape.

The resulting bare-earth DEM was provided by NCALM, along with several other deliverables, including classified point-cloud data in LAS 1.2 format, a Digital Surface Model (DSM), and hillshade models based on ground and non-ground returns. The bare-earth DEM was segmented into smaller, more manageable tiles to avoid exceeding memory limits and processed through the LRM Toolbox (Novák 2014) in ArcMap 10.2 (ESRI, Inc., Redlands, CA). The LRM Toolbox is a custom geoprocessing toolbox available for download that integrates into the ArcGIS suite and provides relief visualizations based on common raster files. When viewed in Model Builder, the LRM Toolbox is comprised of eight tools linked together to create the final model. Other non-commercial software, such as the stand alone Relief Visualization Toolbox (Research Center of the Slovenian Academy of Science and Art, Ljubljana, Slovenia), is capable of generating local relief models, but the LRM Toolbox was chosen due to its ability to be manipulated and edited within Model Builder. The main goal of local relief modeling, as developed by Hesse (2010), involves rendering small-scale elevation differences within a DEM to better visualize the immediate variation within a landscape. Elevation data are manipulated during the process to highlight distinctive positive or negative fluctuations in local relief, making the technique applicable for the detection of both archaeological and cave features.

The first step of the LRM process involved smoothing the DEM through the application of a low pass filter based on a circular neighborhood radius of 25 m. This procedure is crucial for generalizing the larger landscape features while preserving minor variation in a given locale. The differences between the two elevation models were then subtracted to highlight the smaller natural and anthropogenic features across the landscape. Zerometer contours were generated from the difference model and break lines were established between positive (convex) and negative (concave) features. The distinction between concave and convex features within a surface visualization model avoids many of the potential optical illusions associated with viewing relief through hillshading (Hesse 2010). Physical elevations were calculated and extracted from the original DEM where cells intersected the break lines, resulting in a simplified elevation raster. This layer was then transformed into elevation points, a triangulated irregular network (TIN), and a digital terrain model (DTM), created from the simplified dataset. The final step involved the subtraction of the purged DTM from the original DEM, producing a LRM that focused on the immediate topographic variation across the entire region. The LRM Toolbox was edited to run each of the four tiles separately before combining the different DTMs through the Mosaic to New Raster tool prior to the creation of the ultimate relief model.

Once generated, the Las Cuevas LRM was projected over a stretched slope model derived from the original DEM and gridded in 500-m-x-500-m sections based on the tile network developed for the point cloud data. Each grid tile was given an alphanumeric designation which served as the base for a unique identification number connected to each of the potential cave entrances detected. Negative topographic features were identified within each section through analysis of index values and compared to the hillshade layer provided by NCALM. Potential cave entrances were identified through a combination of semi-automated LRM analysis within ArcMap and manual visualization of LAS data in LP360 (QCoherent Software, LLC). A work flow chart for LRM modeling is illustrated in Figure 4. All features detected through the LRM visualization were inspected in profile and 3D views of ground-classified point clouds in order to visualize the spatial nature of the entrances. Spatial measurements were gathered in LP360 regarding entrance width, maximum depth, and total number of ground returns below surface level. Features were classified according to cave morphology (vertically and horizontally accessed) and topographic setting.

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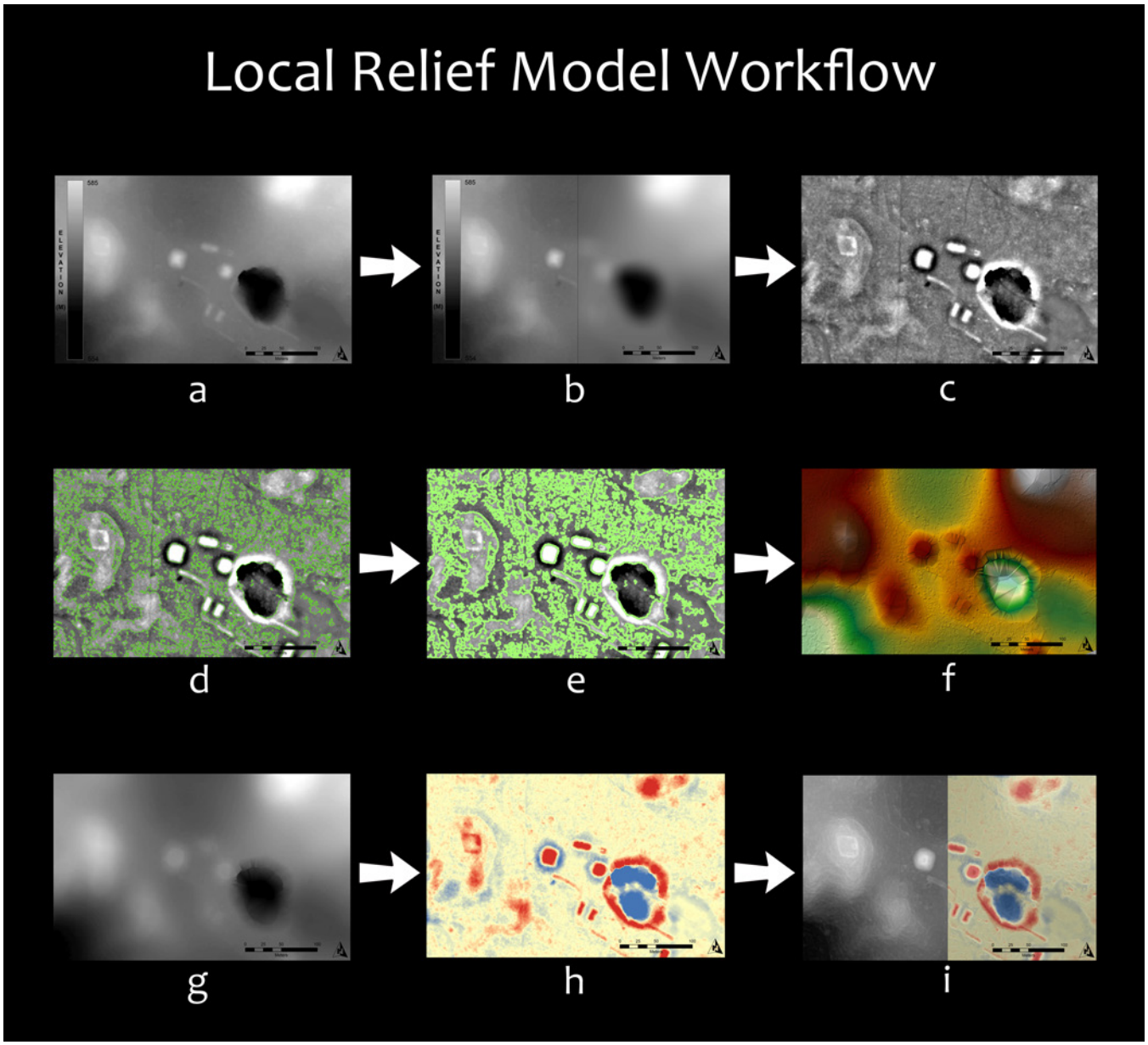


FIGURE 4. LRM Workflow Chart: (a) Original 1 m DEM of Las Cuevas; (b) split image of original DEM and smoothed DEM; (c) Difference of smoothed and original DEM; (d) creation of contour lines; (e) contours converted to elevation points; (f) TIN created from elevation points; (g) original DTM generated from TIN; (h) LRM created from subtraction of DTM from original DEM; (i) split image of original DEM and LRM.

Potential cave locations were then plotted across the landscape (Figure 5).

The Las Cuevas LRM aided in the identification of previously unknown potential cave features within the lidar scan. We found 377 potential cave openings documented across the 222 km^2 study area, including 63 within a 3 km buffer around the Las Cuevas site center. Approximately two-thirds of all recorded caves (66.6 percent) were classified as vertically accessed, sinkhole-like features; the remaining forms were categorized as horizontally accessed. Vertical caves produced opening dimensions of between .6–60 m and ranged in depth between 1.3–35.3 m. Horizontally accessed caves showed entrances of between 1–22.2 m in height. The number of ground returns below surface level was tallied only for features assigned to the vertical cave category; 76 of the 249 potential vertical caves (30.5 percent) produced only one negative ground return below the immediate surface, while 113 features (45.5 percent) possessed five or more return points below the neighboring landscape. Features identified by a single negative return point suggest two scenarios. Within the first, the negative return point has been incorrectly classified as a ground return or represents an error or artifact in the point cloud data set. Negative return artifacts have been identified within these data, but most are associated with the surface of water such as the Macal River and commonly exceed 100 m in depth. The vertical cave features in question have a

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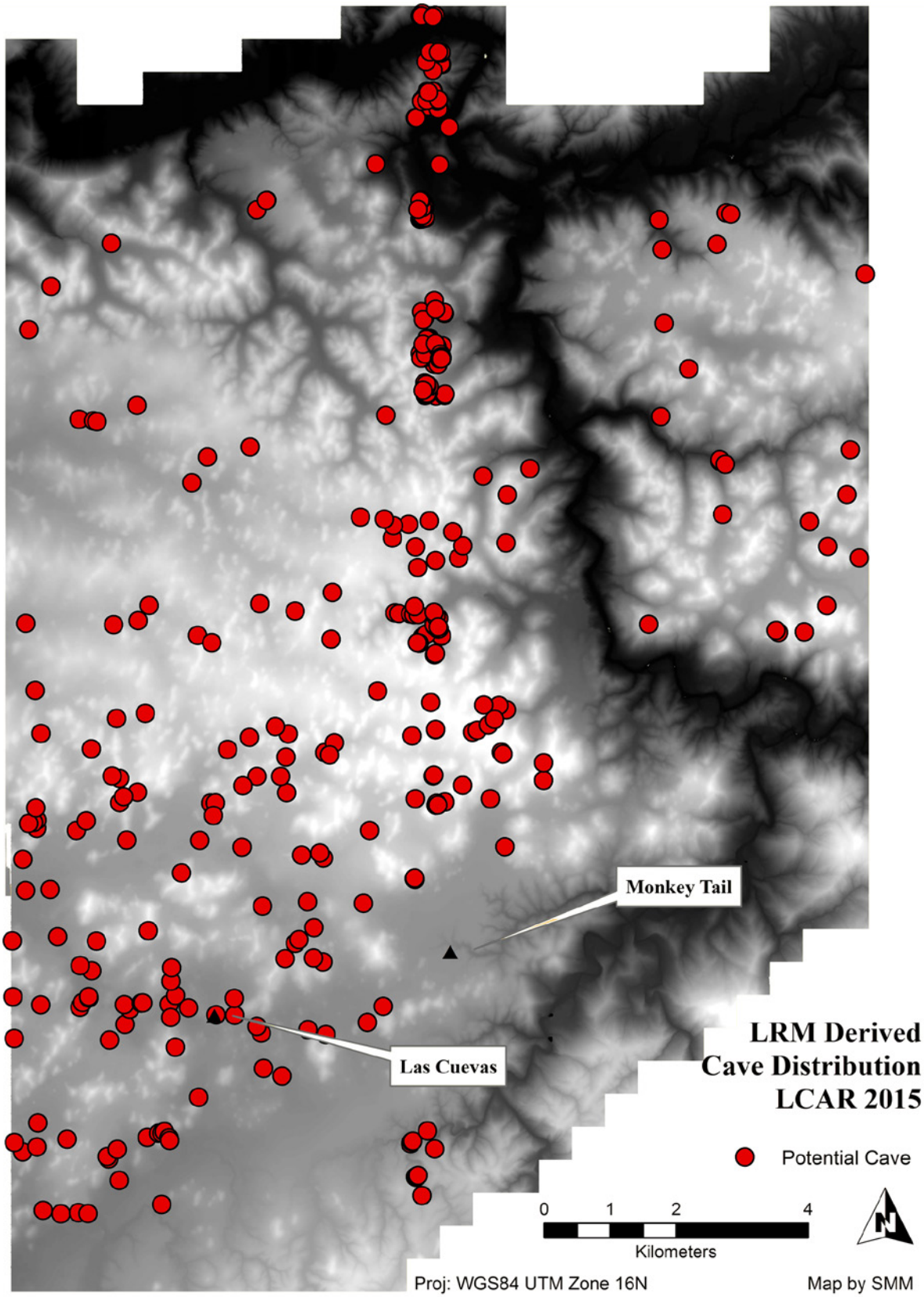


FIGURE 5. Potential cave locations identified through LRM modeling.

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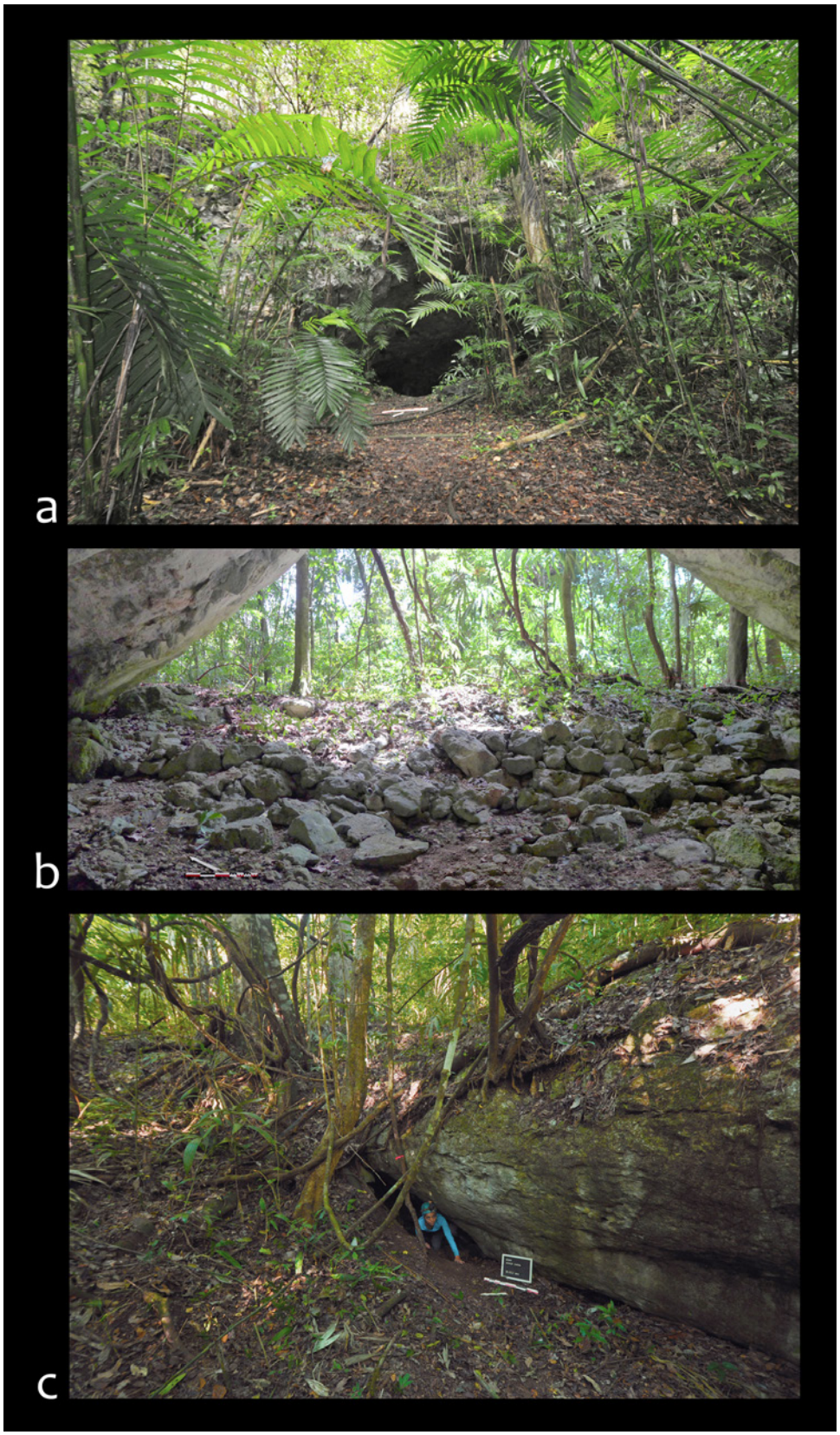


FIGURE 6. Photos of known three caves located within our lidar area: (a) entrance of the cave at Las Cuevas; (b) entrance of Actun K'in Kaba; (c) entrance of Zuhuy Ch'en (Shayna Hernandez pictured).

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mean depth of approximately 7 m, similar to the average depth of other sinkhole features with five or more returns; however, the maximum opening for single-return features are roughly half the size compared to the other group. The dimensional differences suggest that single return features may represent actual cave entrances with more restricted mouths, limiting the chance for multiple pulses to penetrate below the surface.

Horizontally accessed caves are more difficult to detect through LRM techniques and point cloud visualization. Features assigned to this category are commonly situated on hill slopes or at the bases of ridges and many times retain only one vertical face. Due to the constraints of aerial lidar, the point cloud data representing these features cannot differentiate between sheer cliff faces, rockshelters, or definitive cave entrances. Secondary topographic indicators associated with some features, such as stream outflows or sinks, increase the likelihood of subterranean entrances in the immediate vicinity. These particular associations, however, are rare within the sample, occurring in less than 5 percent of potential horizontally accessed caves.

RELATING POTENTIAL CAVE ENTRANCES TO KNOWN CAVE SITES

Although we have not yet systematically tested our results by ground-truthing, there are five known caves surrounding Las Cuevas that were visited by pedestrian survey. These included the cave at Las Cuevas, Bird Tower Cave, Zuhuy Ch'en (Untouched Cave), K'in Kaba (Birthday Cave), and Cocom Actun (Figure 6). We were able to locate each of these caves on our lidar, demonstrating the utility of our method. These five caves are situated in a variety of settings and represent a sample of the morphologically diverse cave entrances found throughout the greater area. Here we discuss three caves whose entrances differ significantly. First, the cave at Las Cuevas is the largest and most visible feature. The large horizontal entrance measuring 28 m across and 7.5m in height sits at the base of an 80 m wide sinkhole. A cross section of the point cloud reveals the anthropogenic and natural features together, with a scatter of returns extending several meters into the entrance chamber (Figure 7a). A bare-earth rendering clearly shows the relationship between the existing landscape and the built architecture above (Figure 7b). Local relief modeling indicated monumental architecture and other constructed features above the cave, in stark contrast to the cave entrance and sinkhole, especially when compared to a regular hillshade image (Figures 7c and 7d).

K'in K'aba resides at the southwestern edge of an amorphous, shallow depression ringed by moderate numbers of formal agricultural terraces, approximately 1.3 km from Las Cuevas. The horizontal entrance of the cave spans 20 m across and reaches a maximum height of 5 m. Detection of the cave based on local relief techniques was slightly less apparent than the cave at Las Cuevas, as the feature sits within a northwest trending ridge of exposed limestone faces and small rockshelters. The area encapsulating the K'in K'aba entrance was the only portion of the ridge to possess a major gap between ground returns when viewed in profile (Figure 8a). While such a gap does not necessarily indicate a cave opening, the data would suggest that the feature in question either represented a horizontally accessed cavern or large rockshelter, both of which are important areas of interest (Figure 8b). Both LRM and hillshade imaging reveal the nature of K'in K'aba and the rest of the Maya built environment dispersed across the immediate area (Figures 8c and 8d).

Zuhuy Ch'en (Untouched Cave) has the smallest entrance of the known sites. The cave is located 1.5 km west of the Las Cuevas site core, saddled between several large residential groups. Zuhuy Ch'en is unique within the sample because the entrance is a horizontal fissure with a ceiling height of less than 1 m (Figure 9a). Such fissures are sometimes difficult to detect even in the field (Figure 9b). Though the local relief model suggests a low cliff in the immediate vicinity, the technique does not differentiate between an actual cave entrance and a minor rockshelter at this spatial extent (Figures 9c and 9d). The cave entrance becomes apparent only when viewed in profile, where the vertical gap or void is visible even at these scales. Detection of such minor features is possible, but the low change between local topography requires a more thorough analysis utilizing both raster and point-cloud data.

Finally, the lidar revealed a new site that we feel relatively certain is a cave. Sombrero Cave represents a great example of the utility of lidar-derived techniques for the identification of cave features. The Sombrero complex consists of a massive, 60 m wide sinkhole with a maximum depth reaching approximately 30 m (Figure 10a). The main area resides on the western edge of a steep, north-south trending ridge flanked by terracing to the north and west (Figure 10b). Three secondary horizontally accessed entrances, measuring between 6 and 8 m, are scattered along the eastern slope of the hill (Figure 10c). At the ridge base, a creek sinks below the landform, delineating another opening (Figure 10d), which indicates that water is flowing into the cave's mouth.

Comparing our LRM results to known sites illustrates the utility of our method for locating not only sites located in sinkholes, but sites with horizontal entrances of all sizes including horizontal fissures such as Zuhuy Ch'en. This is compelling because these small entrances have the advantage of remaining well hidden, whereas large horizontal entrances attract looters wandering through the jungle. This increases our changes of discovering unlooted sites while ground-truthing these small crevices.

CONCLUSION

Locating potential caves using lidar-derived data changes the way that archaeologists locate these sites. In this paper, we described a user-friendly method for finding sinkholes, horizontal, and vertical caves using LRMs, and as a proof of concept demonstrated that our method has the capacity to locate the most difficult features to discern—horizontal fissures. While our pedestrian survey discovered only four new caves surrounding the Las Cuevas site core, we now have 66 possible cave features proximal to the site core and another 314 in the region. We plan to ground-truth as many of these sites as possible in our future surveys, so that we may better understand the structure of the sacred landscape.

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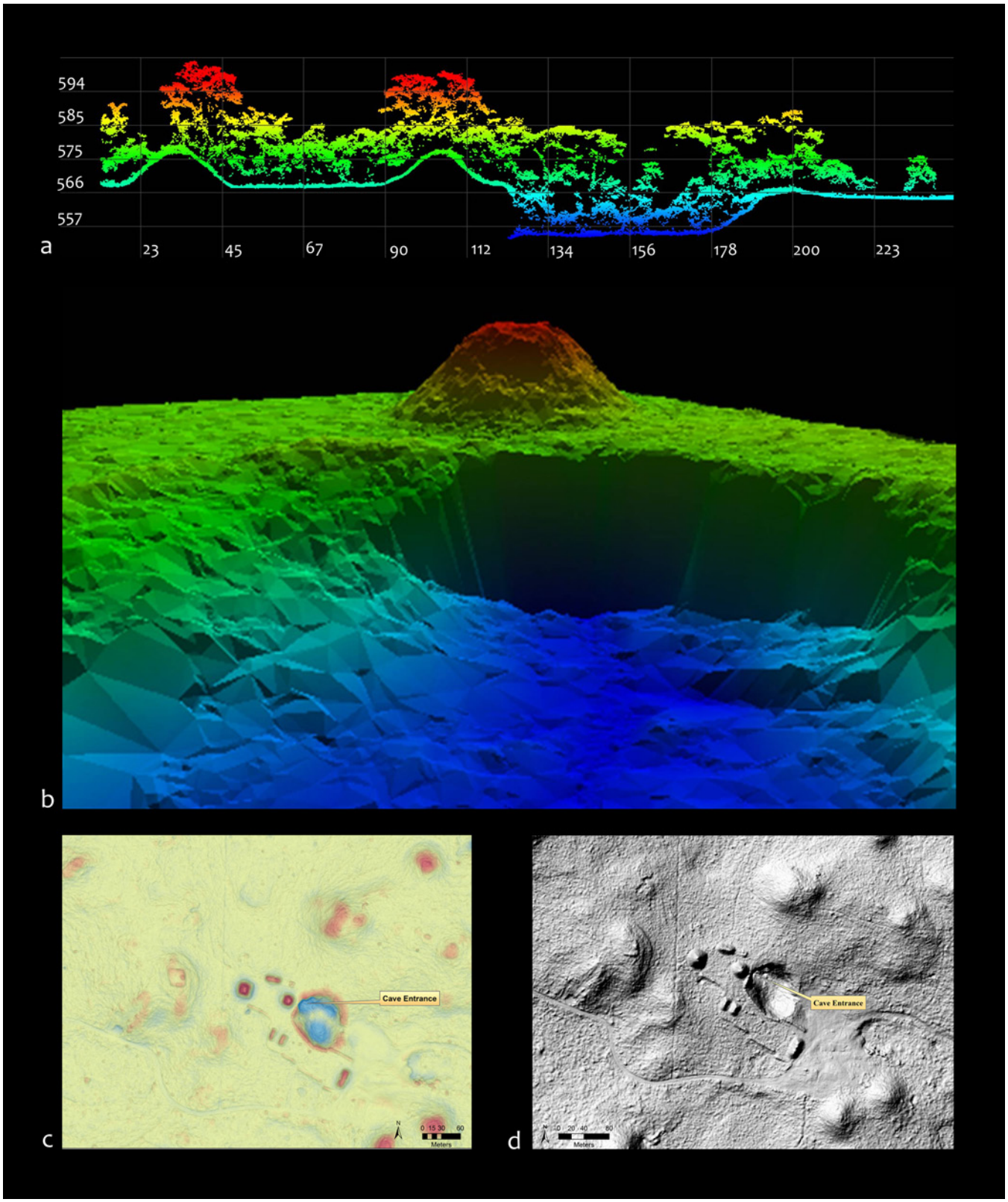


FIGURE 7. Models of the cave at Las Cuevas: (a) cross-section of the point cloud; (b) bare-earth rendering; (c) LRM; (d) hillshade image.

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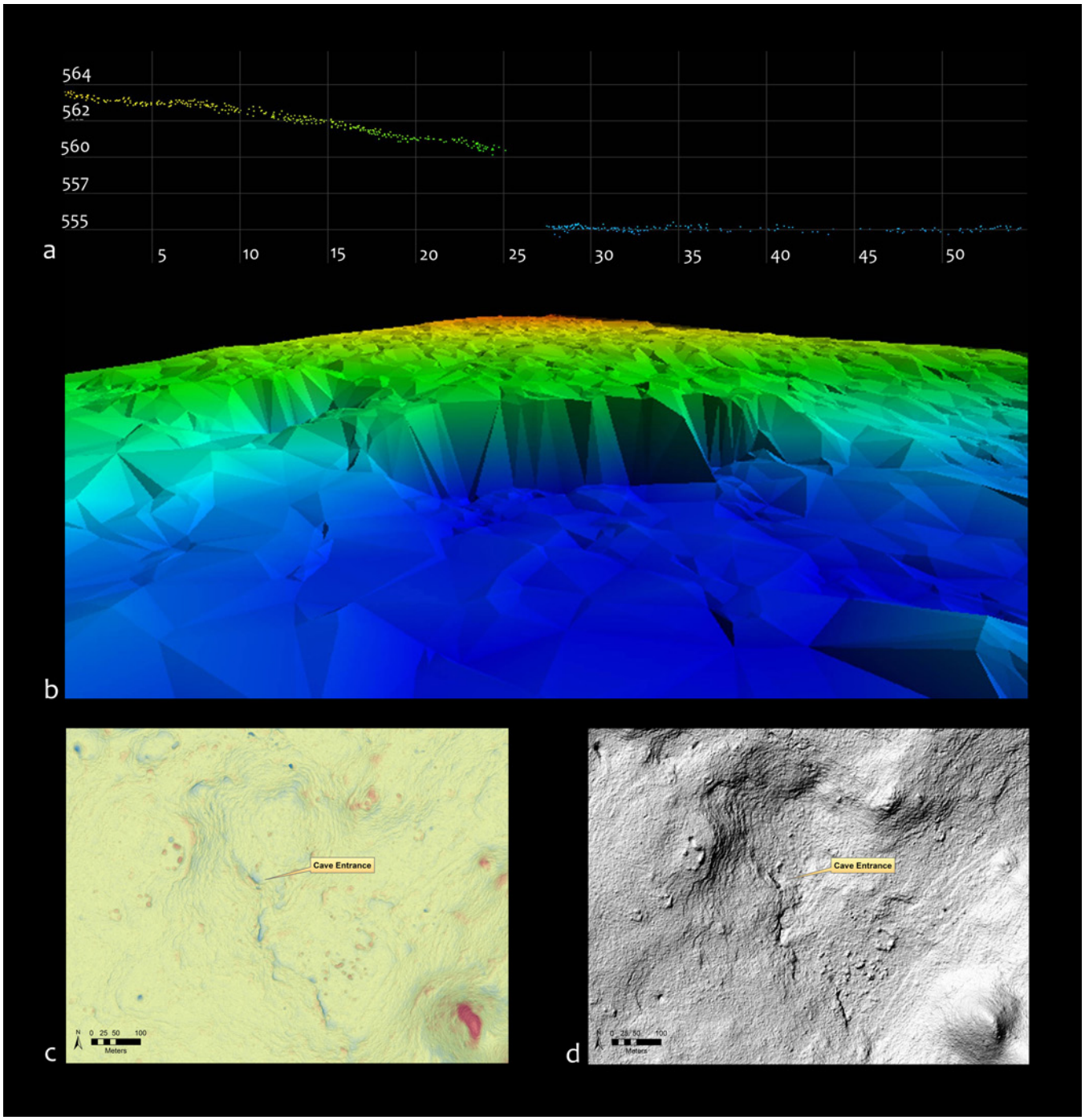


FIGURE 8. Models of K'in Kaba: (a) cross-section of the point cloud; (b) bare-earth rendering; (c) LRM; (d) hillshade image.

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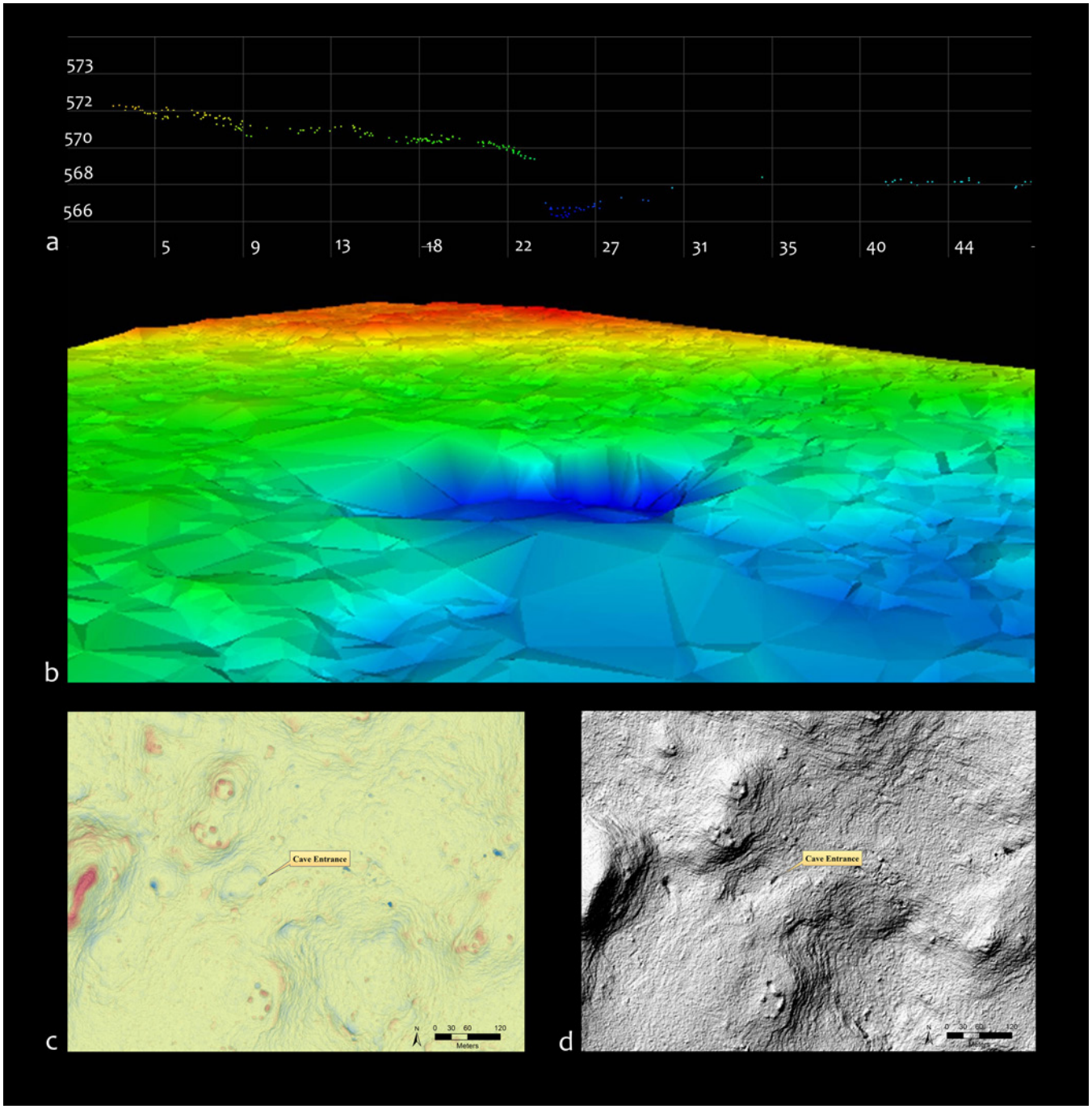


FIGURE 9. Models of Zuhuy Ch'en: (a) cross-section of the point cloud; (b) bare-earth rendering; (c) LRM; (d) hillshade image.

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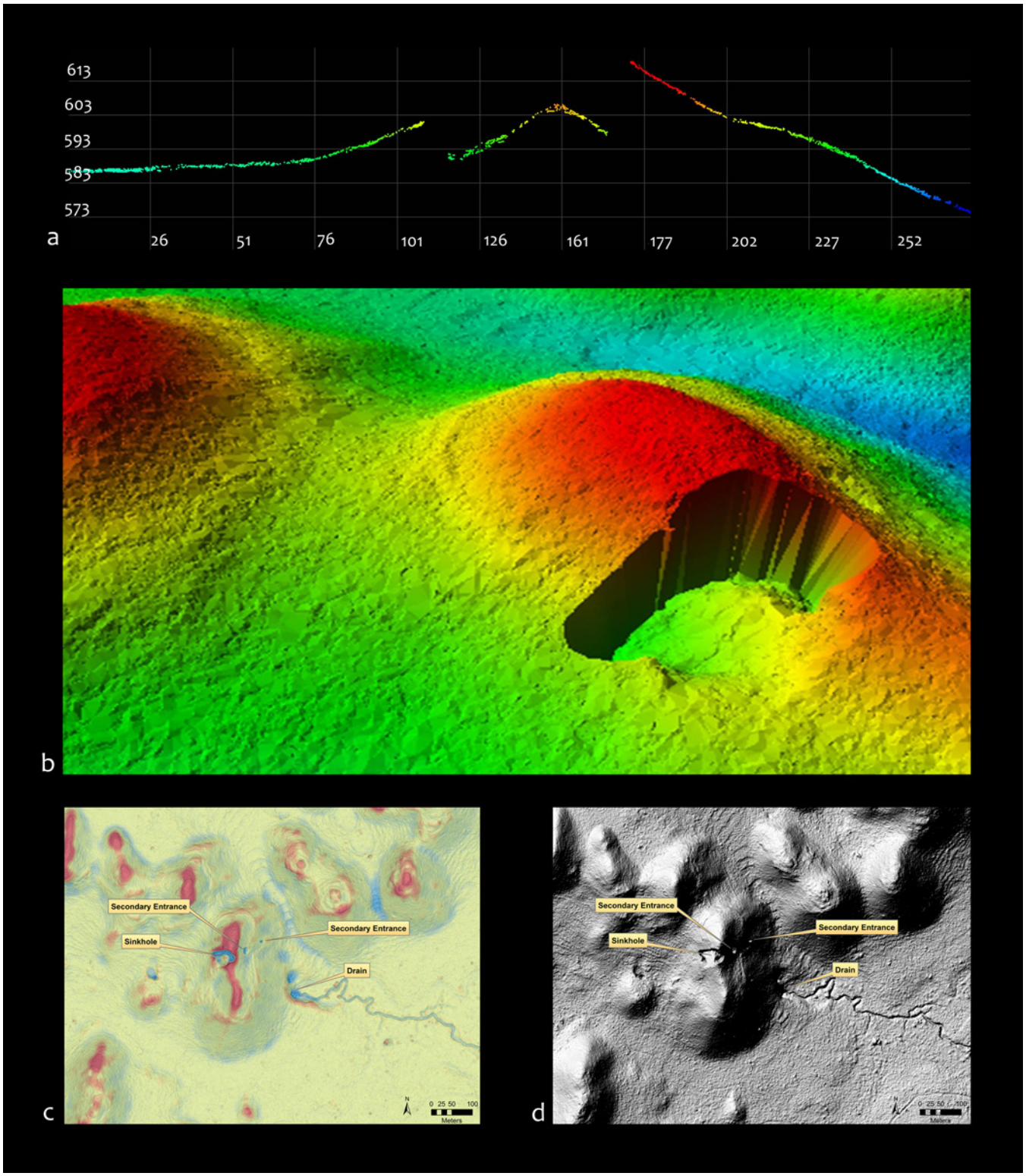


FIGURE 10. Models of Sombrero Cave: (a) cross-section of the point cloud; (b) bare-earth rendering; (c) LRM; (d) hillshade image.

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Lidar scans have the advantage of not only revealing potential caves, but illustrating the natural and environmental contexts in which they are embedded. These data are germane to a better understanding of ritual cave use and will allow us to study all cave distributions over the landscape, not just sites that were used. We will be able to seek patterning in the relationships between caves and natural or anthropogenic features, and we plan to analyze morphologies, temporalities, and the nature of ritual practices as evidenced by architectural elements and artifact assemblages. These large datasets make it possible for us to study the ritual landscape in a way that was unheard of only a few years ago, and we expect that future studies informed by lidar images will be the next major advance in cave studies and help to shed light on the social and political aspects of ancient Maya ritual practice.

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Data Availability Statement

In accord with the wishes of the Institute of Archaeology in the country of Belize, the lidar data reported in this paper are not available to the general public in order to protect the country's archaeological resources from further looting. However, the LAS digital files are on file with the Institute of Archaeology in Belize and may be provided to qualified professional researchers for valid teaching and learning purposes on a limited basis. The person to contact in Belize with regard to these files is: Dr. John Morris, Director, Institute of Archaeology, Archaeology Museum & Research Centre, Culvert Road, Belmopan City, Belize; phone: 501-822-2227; email: research@nichbelize.org. The collection of the lidar data for western Belize in 2013 was a collaborative effort by the archaeologists working in western Belize with the Institute of Archaeology and was not issued a formal permit.

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