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Three-Dimensional Characterization of Cave Networks Using Photogrammetry: Example from Longhorn Cavern, Central Texas

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ABSTRACT

Digital outcrop models are invaluable tools for quantitative analysis of geologic data that allow us to digitally inspect outcrops in three dimensions. This investigation focuses on reconstructing a modern cave system based on Longhorn Cavern in Burnet County, Texas, using photogrammetric methods to construct a digital outcrop model by capturing 6000 overlapping images of the cavern interior. Global positioning and survey data are integrated into the model to locate the subsurface cave geometry in geographical space. Using this data, we are able to inspect and analyze the cave system in a virtual environment.

INTRODUCTION

Digital outcrop models (DOM), a valuable tool in geologic modeling over the last decade, have allowed geologists to view outcrops in a virtual environment (Bellian et al., 2005). Lidar-generated DOMs have been an important tool for both interpreting geologic data and visualizing those interpretations, including previous work on 3D cave modeling (González-Aguilera et al., 2009; Lerma et al., 2010; Roncat et al., 2011).

Recent advancements in photogrammetry software and modern computer-processing speed have made DOM construction far more efficient at certain scales than lidar-based models. We are now able to deliver comparable 3D models at a fraction of the cost of a lidar survey, while maintaining a high degree of accuracy depending on the resolution of the dataset (Bemis et al., 2014). Digital photogrammetry has been used increasingly in recent years to image and model objects in 3D space. The ability to use a photogrammetry package and a georeferenced image-based dataset of overlapping images to recreate geologic features in 3D is an important advancement in geologic modeling (Bemis et al., 2014; Tavani et al., 2014; Vasuki et al., 2014). Photogrammetry-derived 3D models deliver data in a format similar to what one would expect from a lidar survey with comparable data such as color-rendered point clouds.

In this investigation, we duplicate the workflow of imaging outcrops in 3D (Zahm et al., 2016) and apply it to a new setting—a cave network (Longhorn Cavern in Burnet County, Texas; Fig. 1). We combine principles that are common to both outcrop modeling and traditional cave mapping and integrate them to produce a high-quality digital 3D representation of the cave system that can be analyzed on a desktop computer.

Here, we detail a methodology for the collection and creation of a 3D model that results in a georeferenced DOM of the Longhorn Cavern cave system (Fig. 2). This process consists of the collection and creation of a 3D model through use of images, ground positioning system (GPS), and survey data. Through processing and integration of data with photogrammetry software, we are able to generate a realistic digital model of the cavern's interior. The techniques implemented in this study generate a product that can be used to characterize a cave system and digitally measure aspects of the cave. The benefits of this photogrammetry method are savings in time and cost when compared to cave surveys accomplished using terrestrial lidar methods. Access to equipment such as lidar units and cameras, as well as potential rental fees for other instruments, is more expensive than the photogrammetry method. Certain stationary terrestrial lidar units, such as the Optech ILRIS, could also prove to be unsuitable because of the sheer amount of scans needed for modeling this cave system; long scan times are needed to achieve the point spacing comparable to photogrammetry-derived data. Lidar units capable of acquiring data in a 360° scene would prove to be more efficient in regards to time than a stationary lidar unit. Ultimately, the cost of purchasing or renting one of these units (~$20,000–30,000 to purchase or ~$600 per day to rent, based on estimates prior to survey) is comparatively much more expensive than collecting data with a Canon Digital Single-Lens Reflex (DSLR) 5D camera with appropriate lens (~$2000 to purchase).

The digital 3D model developed for Longhorn Cavern can be used for several tasks, including (1) modeling hydrology in

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Figure 1. Map with location of Longhorn Cavern, Burnet County, Texas.

cave systems, (2) developing objects for modeling paleokarst hydrocarbon reservoir development and flow, (3) aiding the management and conservation of cave systems, and (4) providing information to educate visitors.

STUDY AREA

The area of investigation is Longhorn Cavern, located in Burnet, Texas (Fig. 1; 30.684504N, 98.350292W). Longhorn Cavern is an active cave system in the Lower Ordovician Ellenburger Group near the edge of the Llano Uplift in Central Texas (Garner et al., 1993; Kastning, 1983). The development of the cave system is controlled by a Pennsylvanian-aged fracture system, which gives the cave system a rectilinear pattern.

METHODOLOGY

Photogrammetry offers high-resolution and accurate 3D modeling dependent on pixel resolution of the image and amount of overlap between images. Photogrammetry allows pairing of photographs taken of features from multiple perspectives to generate a 3D representation of said features. With the integration of GPS and survey data, we can create 3D models that are georeferenced into a geographic coordinate system that can be readily integrated with other geologic and/or geographical data. This integration allows the user to analyze data in a virtual 3D environment and measure geologic attributes with real-world spatial context to better understand the geometry and evolution of the cave system. The workflow consists of four major steps: (1) planning, (2) data acquisition, (3) data processing, and (4) interpretation and analysis.

Planning

Prior to acquisition of data, consideration was taken with regards to GPS, image quality, and the use of a photogrammetry package that can integrate source data to produce a model that is projected into a geographic coordinate system. The user can then extract information from the virtual cave model that has a strong relationship with actual physical attributes of the cave system.

One of the most critical parts of any modeling project is to define the equipment to use that will collect the data to construct the intended model. For this modeling project, a Canon 5D camera body functioned well in extreme low-light scenarios that exist in cave systems. Criteria for camera selection included high International Organization of Standardization sensitivity (ISO) and grain in the image, flexible shutter time to allow adequate light into the body to observe details and construct geometry of geologic bodies, and high resolution to quantify details in the cavern.

A Tokina 16–28 mm f/2.8 lens suitable for the Canon camera body was selected for its focal length and wide angle. It is important to have a lens that can capture images in narrow passageways. A wide-angle lens assures enough overlap between images to allow the photogrammetry software to assign matches and reconstruct the geometry of cave passages. Agisoft PhotoScan Professional software was selected for photogrammetry because of its ability to align images, construct dense point clouds, mesh, texturize mesh, and georegister models. With

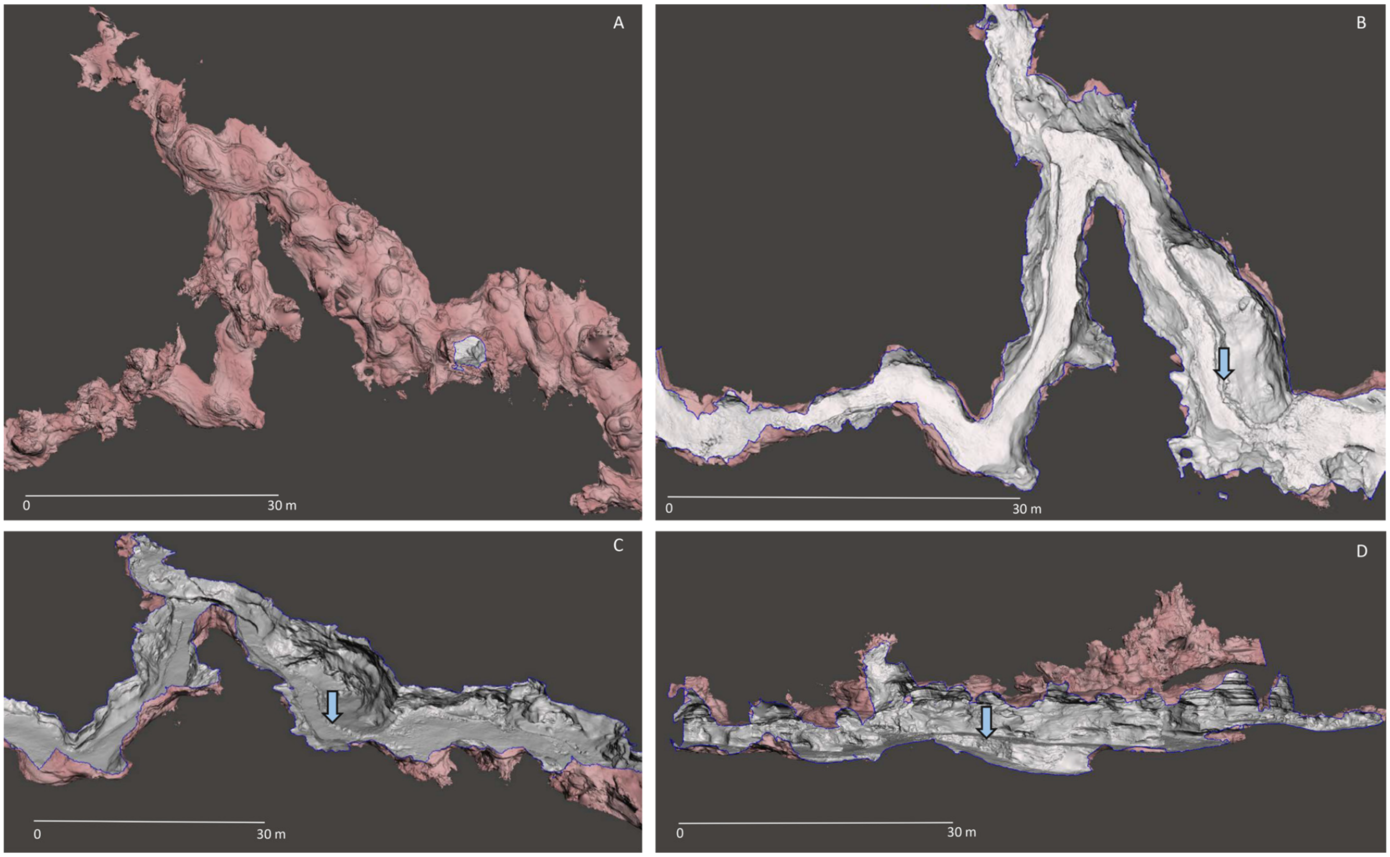

Figure 2. Mesh of section of Longhorn Cavern (Cathedral Room). Parts of mesh in ceiling region removed for bird's-eye visualization of cavern interior. Blue dot represents common point on all models. (A) Top-down view of cave (map view). (B) Top-down view of room with ceiling removed. (C) Model tilted 45° to exhibit relief. (D) Model tilted 90° to show cave in cross section.

these parameters, our final cave model's dense point clouds have a point spacing of 1 cm from which the meshes were derived.

Data Acquisition

Approximately 6000 individual images were taken throughout the cave system with a fixed-focal-length 16 mm lens to ensure overlap. A minimum of 60 percent overlap between images is required; in most cases, a much greater overlap was obtained. Overlap ensures that matches are found between images by the photogrammetry software package. All features of the cave system—including walls, floor, and ceiling—were captured. A tripod and a remote camera trigger were used to avoid any vibrations or movements that could result in motion blur while the shutter was open. Approximately 815 m of cave length was photographed using this data-acquisition method.

To establish locations of geographic reference, GPS data was captured outside of the cave entrance with a Garmin Montana unit. We also used a Leica Disto X2 survey instrument, which combines a laser distance meter, compass, and clinometer with a modified hardware/firmware package (Heeb, 2008; Kershaw, 2012). The Disto unit modification adds a three-axis compass, a clinometer, and Bluetooth connectivity. The upgrade modifies the main board shipped with the Leica Disto unit; the purpose of the board is to measure distance, direction, and inclination between locations or control points. This Disto data can then be processed to geographically link to a series of already-captured GPS points. We measured from the GPS points with the Disto unit to control points in the interior of the cave. The control points, when measured from and processed alongside GPS points, provide latitude, longitude, and altitude, which we then used to georeference the cave model. A total of 70 control points were collected with the Disto unit throughout the cave (Fig. 3).

Image acquisition was conducted prior to capturing control points to mark control locations on images taken previously. This pinpointing of exact locations ensures that each control point is registered correctly and allows the user to find common point locations across numerous images for geographic registration and image alignment of the photogrammetry model.

Data Processing

During image acquisition, all images were taken in a raw-camera format to have full control over post-processing. Images were batch-corrected in Adobe Camera Raw to maintain consistency between image exposure, ISO, and color. Images deemed of poor quality—e.g., out of focus or too dark or too grainy—were removed from the dataset.

Control points taken from the Leica Disto X2 were processed with GPS data to integrate into a geographic coordinate system. Control points were then loaded in a geographic information system (GIS) as shapefiles and compared against aerial photograph data to double-check accuracy of Leica Disto X2 points versus aboveground control points taken with a GPS unit.

Approximately 6000 images were imported into Agisoft PhotoScan Professional software. Because of hardware constraints, multiple Agisoft projects were created to facilitate ease of visualization and analysis of project exports, as well as reconstruction times of the photogrammetry model. Control points derived from Leica Disto X2 control stations were added to images for georegistration. Each individual control point was represented by an average of approximately 50 image projections per point, ranging from a minimum of 8 to a maximum to 169 projections. Alignment established a range of 200,000–320,000 tie points, or points common to each photograph, between images in each photogrammetry project. Once alignment was accomplished, a sparse point cloud remained, representing the model based on the alignment.

A dense point cloud was then created based on user specification. Dense-point-cloud reconstruction ranged from 20 million points to 180 million points; fewer or more points could be readily generated based on computing-power strengths or limitations and the amount of points desired for user analysis. In Agisoft, point-cloud filtering was conducted to remove any points with a high projection error and remove a high degree of noise from the model. Next, a 3D polygon mesh was created from the existing dense point cloud. The mesh—consisting of vertices, edges, and faces—is a polygonal reconstruction of the object based on the density of the base point-cloud model. For example, a point cloud with higher point density results in a mesh with more polygonal faces. Agisoft's mesh topology was employed to help fix any irregularities present in the mesh. Texture was then mapped to the mesh, based on the original image information, which allows viewing of the geometric and physical characteristics of a 3D digital model in a realistic virtual environment.

As mentioned previously, multiple Agisoft projects were created to divide the dataset and better handle data processing and data management. Project sections were aligned in Agisoft to ensure consistent scale and elevation throughout the project and the final product.

Numerous outputs were generated to visualize and analyze the 3D objects in different environments. For visualization of the 3D mesh, a Wavefront Object (.obj) file was used. A .obj file is a data format that represents position of vertex, vertex normal, and polygonal faces, as well as the position of textures associated with the file, if texture is being utilized for visualization. A Log ASCII Standard (LAS) binary file—a common file type used with lidar or point-cloud data—was also used for visualization and analysis of point features.

Interpretation and Analysis

LAS files were loaded into Applied Imagery's Quick Time Modeler (QT Modeler) point-cloud data software to analyze the model in 3D. The available toolsets in QT Modeler were employed to measure lengths of cave passages as well as create cross sections of cave passages. Cross-section tools allow us to specify a line width that collects points in the sample region for visualization of their horizontal and vertical (x, y, z) values in meters in a scaled environment (Fig. 4).

In Agisoft Photoscan Professional, once the 3D mesh had been built on the dense point cloud, some measurements were taken directly in the photogrammetry package to extract information from the models. Any open spaces in the mesh model were closed to create a model without any holes produced by missing data. Holes found in the mesh were introduced into the model in two places: (1) entrances inside the cave or the division between the datasets, and (2) any areas where we lacked enough information to create matches or model reconstruction (e.g., areas in the cave with inadequate light, passages where the end could not be photographed adequately, or areas with poor tie points). Once the mesh was closed, we were then able to calculate information regarding observed area (m^2) and volume (m^3) of the cave system.

Visualization was carried out using 3D software tools designed for mesh analysis. Autodesk Meshmixer was used to quickly visualize measurements within the cave system and slice the inner cave attributes. Meshlab is also a robust and powerful mesh tool that was used for manipulation and visualization of the model.

RESULTS

The modeling of a cave system at high resolution provides many opportunities to extract relevant information about the infrastructure of the cave (Fig. 4). A cave system recreated through the use of a digital photogrammetry model helps the user interrogate the digital model in a GIS environment with statistical tools that allow quantification of geologic parameters of the cave-system network. These parameters include the orientation and morphology of geologic bodies, dimensions of cave passages and rooms, and spatial distribution and patterns of cave elements. The ability to represent the cave-system network in 3D is important for hydrogeology and reservoir characterization. This finished product provides an object that can be analyzed and viewed in 3D and geographically referenced space (Fig. 5).

The flexibility of photogrammetry models and formats allows for viewing and analysis of exports in numerous software packages: remote-sensing packages, geographic information systems, and 3D modeling and design software. Having such options increases our ability to analyze data in a multitude of software systems and provides the user a robust toolkit to analyze the geology.

To create a dataset of cave-parameter statistics, we sampled the modeled cave system and generated a series of cross sections at roughly 10 m intervals. At these interval points, we measured the widths of cave passages, which resulted in 64 cross sections generated, ranging from 3 m to 27 m in width (Fig. 7). The largest passage width is associated with the Indian Council Room. The median cave passage width for this dataset was 7 m. The statistical distribution for the cave passages in Longhorn Cavern are larger than what Loucks (1999) calculated (average = 2.2 m) for four of the longest caves in the United States (Fig. 8). Our dataset consisted of significantly fewer data points than those of the Loucks study, and because of the methodology of our survey, only larger passages (over 2–3 m) were sampled. Based on the Loucks dataset, the larger size of Longhorn Cavern passageways is quite uncommon when compared to the frequency of its smaller passageways, indicating that the passages in this cave system is in the larger range. Thus, the data collected gives us the ability to quantify passage lengths and heights when measured against other similar cave systems.

The closed model of the cave was sampled to quantify the volume of the modeled cave system. The calculated cave volume from the digital model is approximately 17,240 m^3 based on approximately 815 m of cave-passage length captured. To view examples of the model, visit this link to the textured mesh of the first section of the cave: https://skfb.ly/ZtWH. A mesh-only link is also provided for viewing the model without image-data overlays: https://skfb.ly/ZtVx.

CONCLUSIONS AND DISCUSSION

The photogrammetry methodology demonstrated in this investigation allows 3D digital modeling of cave systems at a scale defined by the user's image-acquisition methods and camera quality (Fig. 6). The data-acquisition and processing time necessary to complete a photogrammetry survey is reasonable, but obviously dependent on the dimensions of the cave system. In this study, data acquisition of the Longhorn Cavern system was captured over the course of five workdays to capture the imagery and three workdays to capture the Disto X2 data measurements for georegistration. Certain isolated areas of the cave were captured over the course of a day to test feasibility of modeling the entire cave system prior to the start of the project. It is more difficult to give an estimated time for completion of data processing because it is based on computational parameters and quality level of the model. Additionally, processing has taken place in multiple iterations in order to test the data at different point densities and parameters. As an estimate, data processing

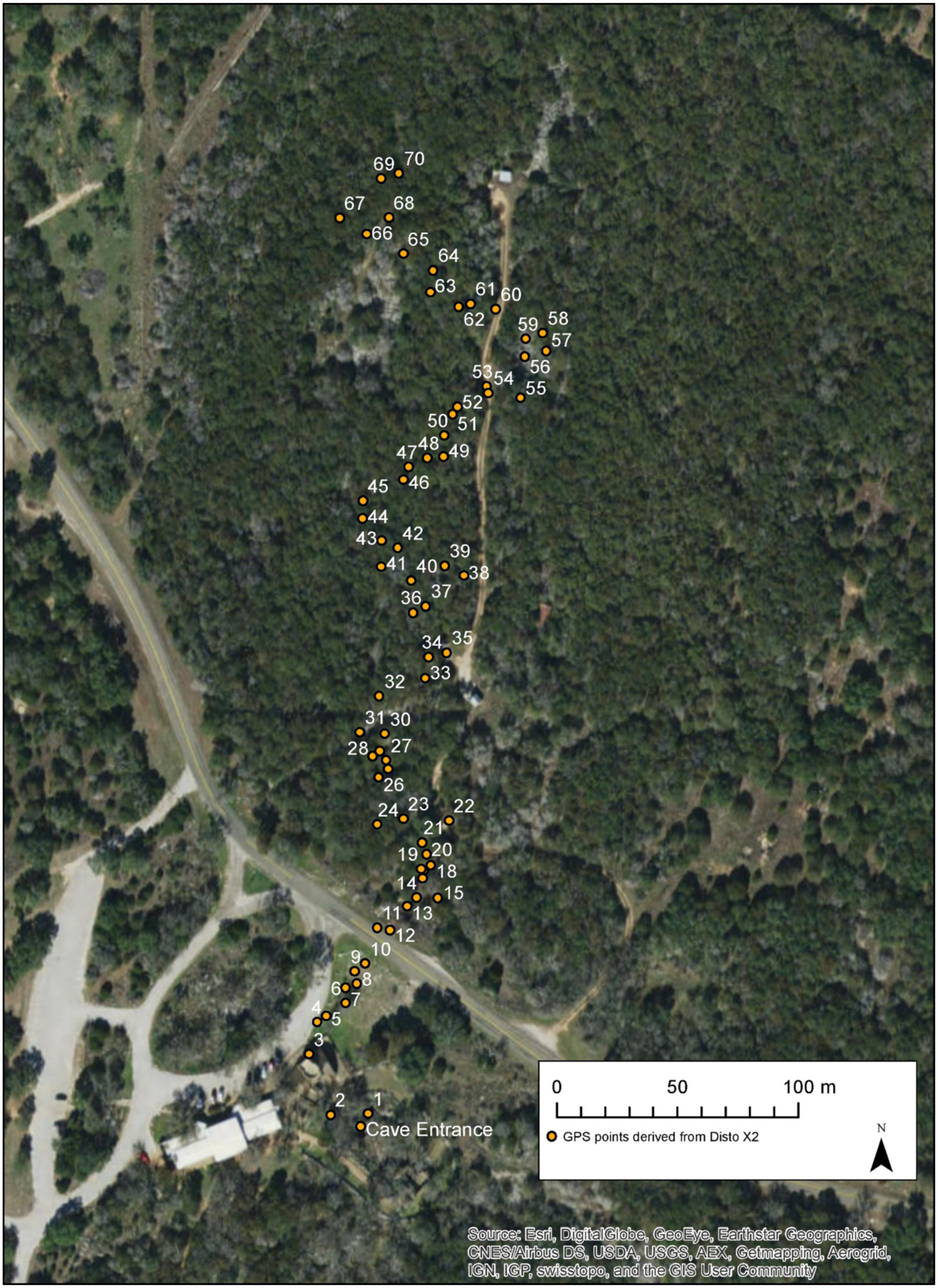

Figure 3. Longhorn Cavern, Burnet County, Texas. GPS control points surveyed with Disto X2 survey instrument.

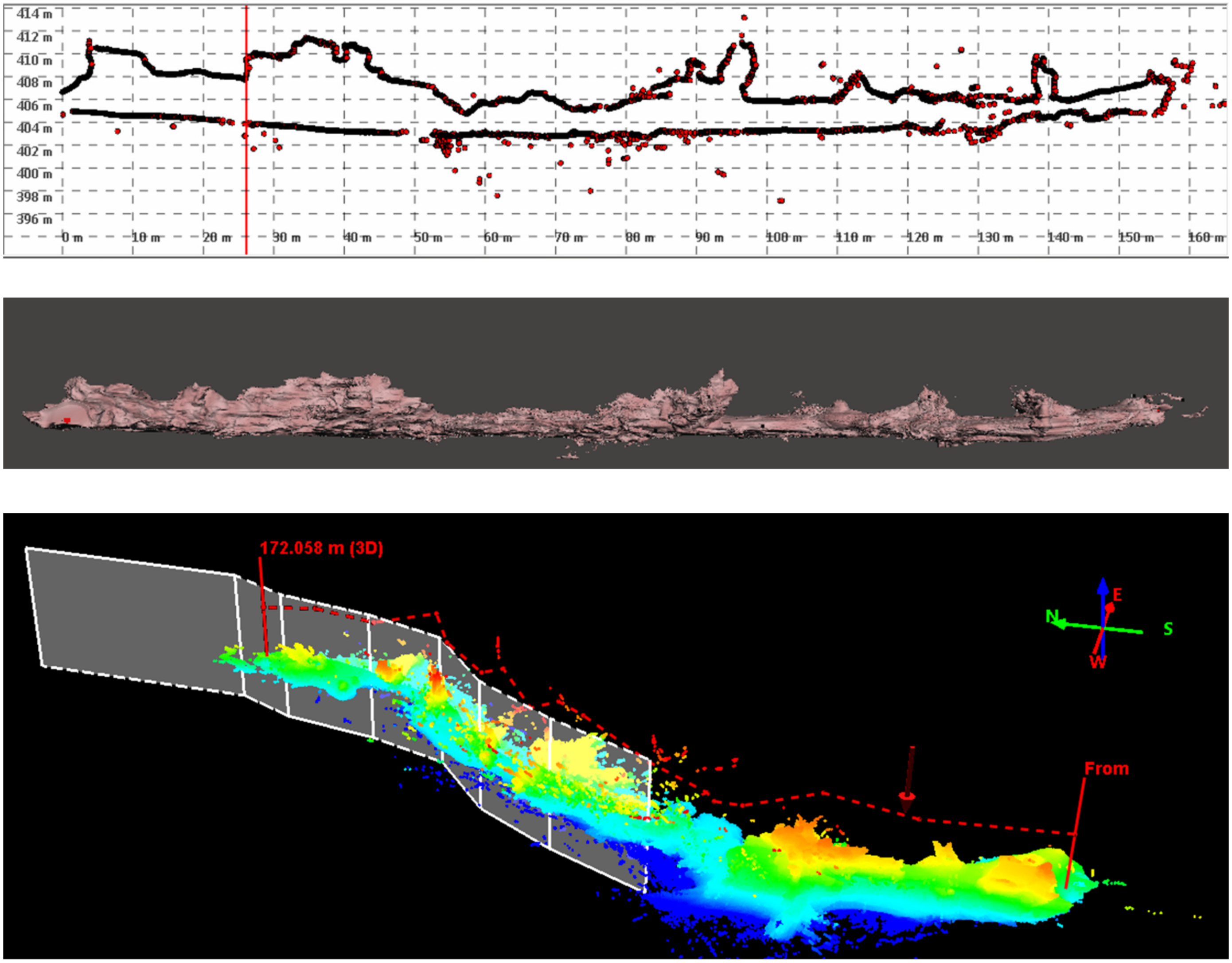

Figure 4. Portion of cave model with vertical slice taken at width of 4 cm to measure profile of model. All views represent same area. (A) Profile-analysis slice taken of point cloud to show cave area in cross section. (B) Geometry of mesh at side view. (C) Point cloud symbolizing elevation. Vertical slice shown bisecting point-cloud model.

could be accomplished in less than a week for this current dataset. Feasibly, for a smaller cave system or only select rooms within a larger cave system, a dataset could be acquired and processed within a single workday.

Using common field equipment such as a DSLR camera, tripod, and remote camera trigger kept costs of the survey down. Including the Disto unit, a similar survey could be duplicated for less than $3000 (if all gear were purchased rather than rented). Costs could be further minimized depending on type of equipment used, rental rather than purchase of equipment, and use of resources already in the surveyor's possession. Access to high-quality photogrammetry software and digital-analysis software can be more expensive, but many open-sourced alternatives (such as VisualSFM for 3D reconstruction from images or MeshLab or Blender for manipulating the 3D model data) are available to alleviate cost.

3D modeling of cave systems using photogrammetry can be used as a more cost-effective alternative to lidar surveys. This is based on the assumption that purchasing or renting a lidar unit for the high volume of data acquisition required for modeling a cavern of this size can be more expensive than using a camera and tripod setup. Time considerations can also favor a camera setup. Scan times for lidar instruments, depending on required point density (e.g., longer scan times for higher-point-density models), could take upward of 5–10 min for each scan and perspective. Acquisition of the images with a camera is a moderately fast process, with images taken in less than a second. Small rooms can be photographed in minutes, although passageways require more time and effort to image all angles (ceilings and floors). Point density of photogrammetry-derived models are dependent on the quality of the photograph and processing time of the model; because of the cramped environment of cave systems, images are commonly taken within a few meters of the point or object of interest (in this case, the cave wall), resulting in resolution high enough to allow images that are most suitable for creating a high-quality photogrammetry cave model.

Through this photogrammetry method, cave models can be used to visualize relationships between cave systems and understand geologic geometrics and other characteristics inside cave systems. This method allows the geoscientist to virtually access the cave system and interpret faults and fractures, hydraulically model groundwater flow in cave systems, view stratigraphic relations, and model as objects in other fluid-flow models. This process could be applied to rate-of-change studies to analyze and quantity differences in a cave system (such as cave-sediment deposition and erosion) throughout time. The results can be used

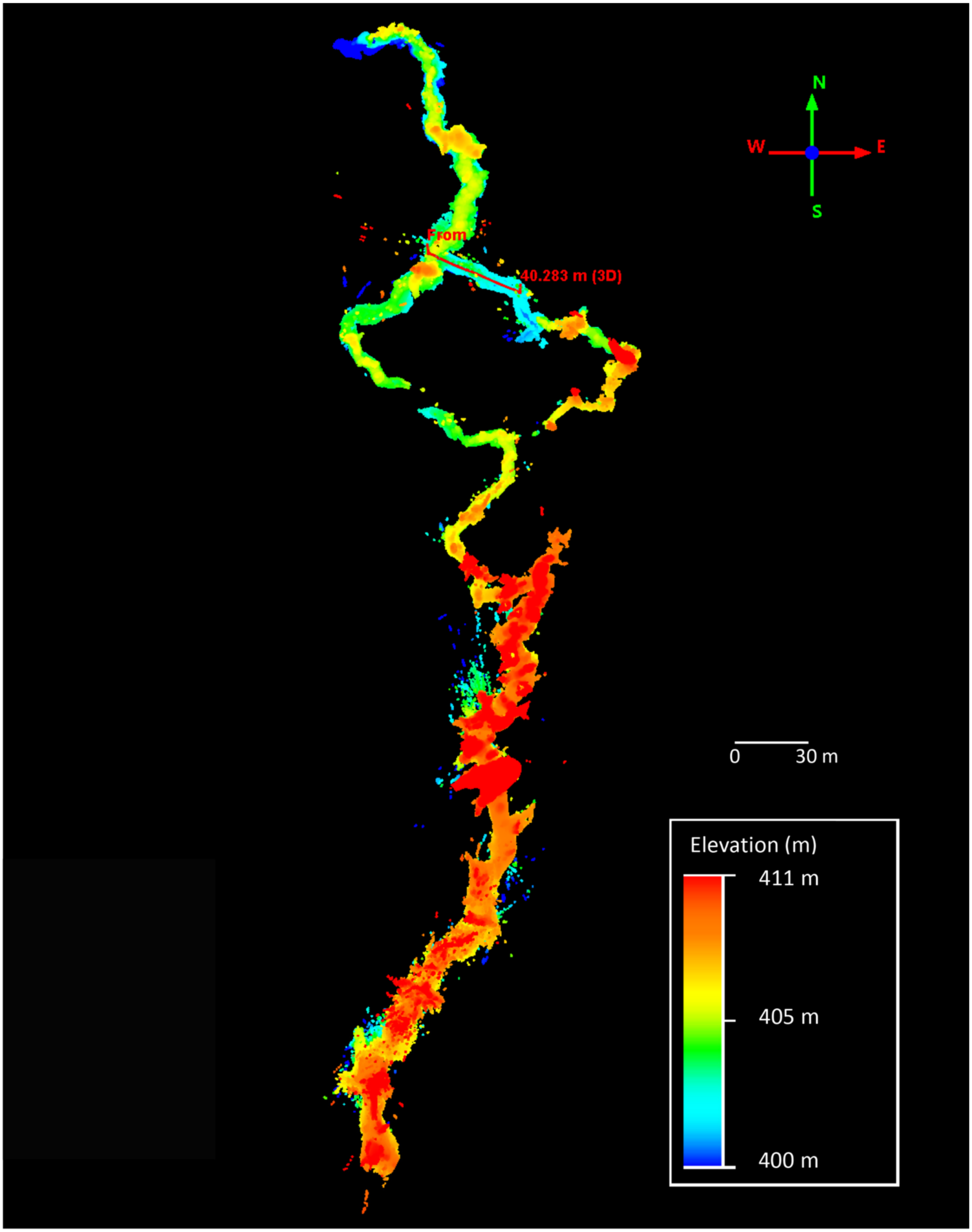

Figure 5. Point cloud of Longhorn Cavern rendered in QT Modeler software to show elevation gradient. Top-down or map view.

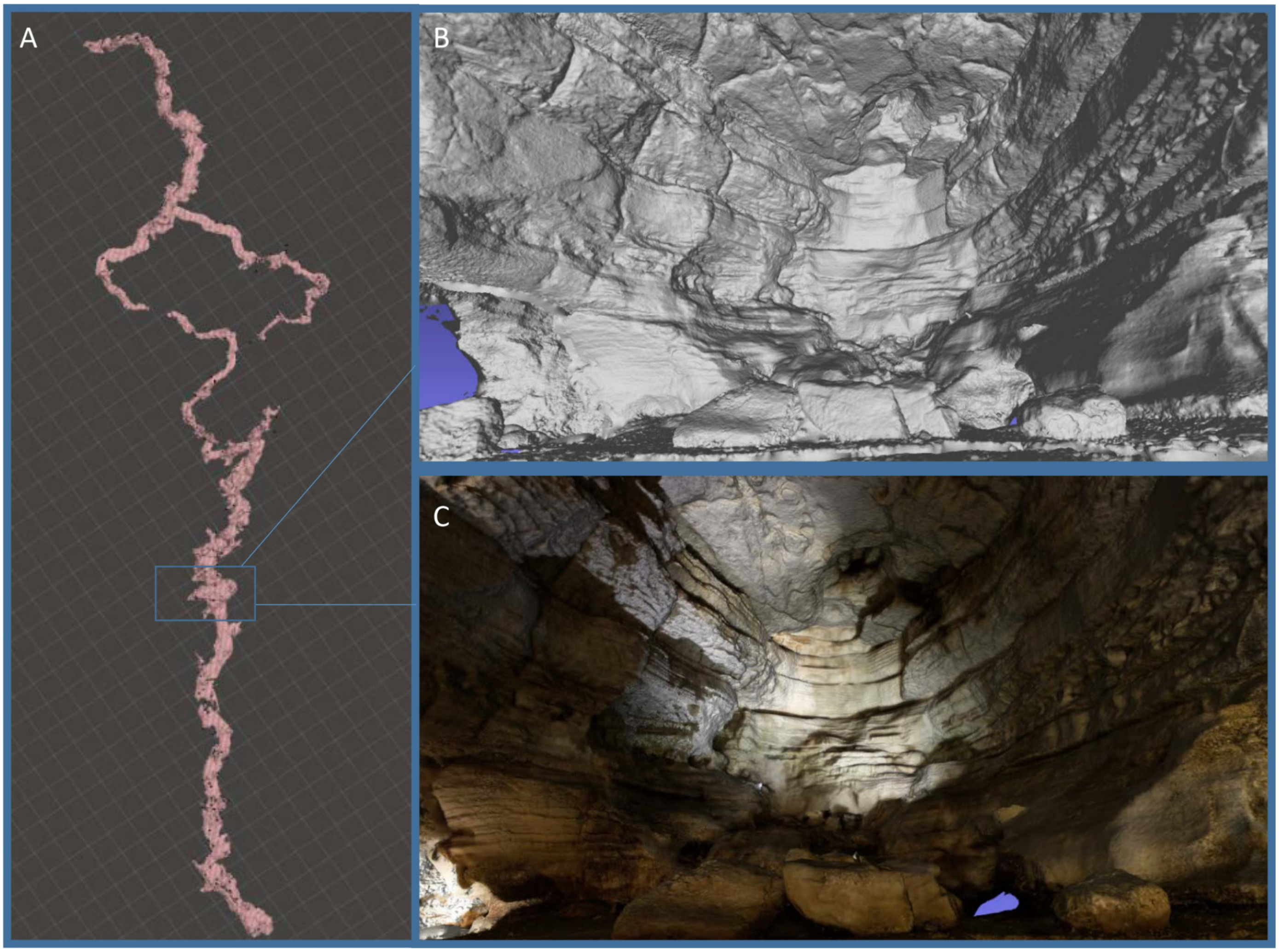

Figure 6. Extent of Longhorn Cavern survey. (A) All cave meshes of Longhorn Cavern cave system. (B) Indian Council Room viewed as mesh bottom. (C) Indian Council Room viewed as mesh with image texture mapped onto mesh surface.

for multiple purposes, such as cave management and conservation.

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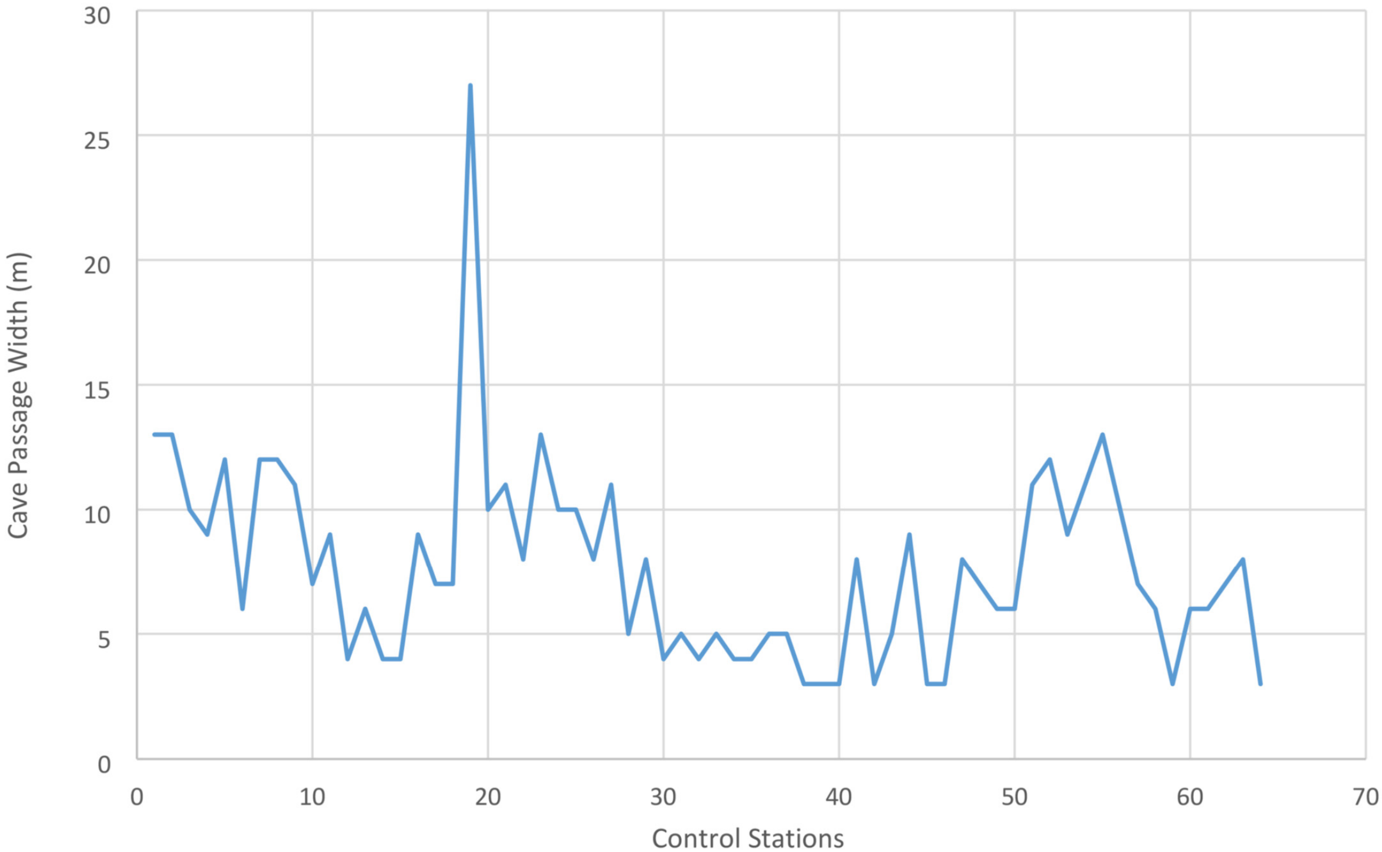

Figure 7. Cave-passage cross-section width. Samples taken at 30 m interval. Largest width is Indian Council Room. (A) Graph showing plot of cave width throughout Longhorn Cavern at 30 m intervals. (B) Table showing cave measurement width corresponding to graph.

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Figure 8. Longhorn Cavern passage width cross-plotted against Loucks' (1999) probability statistics of cave-passage widths for four of longest caves in United States. The trend of the results are similar despite differences in datasets used.