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3D Outcrop Study of Hypogene Karst Caves of Brazil using LIDAR and Drone Imagery

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We would like to thank Stichting Molengraaff Fonds (STMF) for their generous support for our speleological expedition to Brazil in July 2018 (Grant: Hoop S de and Prabhakaran R – 3D Outcrop Study of Hypogene Karst Caves of Brazil using LIDAR and Drone Imagery). The following field work report outlines a summary of the activities performed, data acquisition and way forward to convert the field work data and knowledge gained into referred works of literature.
1. Introduction

The fieldwork was focussed on quantification of the morphological features of hypogenic karst caves in Brazil using 3D LIDAR (Light Detection and Ranging) and Drone Imagery. The fieldwork was conducted along with several partners as part of the Porocarste 3D project which is a consortium of three Brazilian universities (UFRN, UFRJ and UnB) and Shell.

Hypogene karst caves are suitable analogues for karstic reservoirs that have been observed globally in many different settings. Geomodeling of such settings has always been problematic because of the uncertain nature in seismic. The use of caves as analogues for karst reservoirs requires a precise quantification of the volumetrics and the complex 3D morphology. The conventional methods of hand mapping using laser range finders and manual measurements have so far been painstaking in which years of effort were expended in creating useful cave maps.

To the best of our knowledge, our expedition was the first ever attempt to use mobile LIDAR technology in a speleological setting in South America. Compared to terrestrial LIDAR systems (TLS), mobile LIDAR has the advantage that the user can traverse complex cave passages while simultaneously capturing 3D point clouds of the passage geometry without the need for cumbersome setup and movement of apparatus. Also the intricate and tortuous passages that are common in cave terrain makes it difficult or near impossible to use TLS. Our fieldwork planning had included recording of drone photogrammetry on the surface exposures of the hypogene caves to study any possible relation between fracture patterns on the exposures and the cave paths. Such pavement exposures were not visible and hence this component of the fieldwork could not be carried out.

2. Mobile LIDAR – The GeoSLAM System

To constrain in a quantitative manner the geometry of the cave, we employed a mobile handheld mobile mapping system (MMS), the Geoslam ZEB REVO®, commercialized by the GeoSLAM company (GeoSLAM, 2018), to obtain 3D point clouds of the cave interior geometry. Portable laser scanner systems such as the ZEB Revo® allows rapid and easy mapping of complex 3D geometry of cave interiors without the presence of an active GPS signal (Zlot and Bosse, 2014a). The ZEB REVO captures raw laser ranging measurements and inertial data to generate real time point clouds while the operator is moving through the cave terrain.

The portable MMS comprises of a laser range scanner coupled to an inertial measurement unit (IMU) mounted on a rotating drive. The rotation of the scanning head produces the third dimension, necessary to generate 3D data. The device uses a 3D SLAM (Simultaneous Location and Mapping) algorithm (Bosse et al, 2012; Zlot and Bosse, 2014b) to fuse the 2D laser scan data with the IMU data to generate the 3D point clouds (GeoSLAM, 2017).

Figure 1: Mobile LiDAR equipment (ZEB-REVO GeoSLAM).

The acquired data from the handheld LIDAR device shows in high resolution the complex 3D cave morphology and speleogenetic features. The datasets we have recorded help in understanding the primary controls on cave formation. Another positive aspect of having a 3D point cloud dataset, compared to a 2D (hand-drawn) map, is the ease at which a full 3D meshed surface can be obtained for further analysis such as geomechanical / flow
simulations. This modern data acquisition technique can also help to possibly constrain different types of uncertain manual measurements (e.g. compass) of planar features such as fractures and bedding orientation.

Recording of a single survey requires prior planning of a survey path that traverses the regions of interest. Initialization of the device is performed at a stationary location that marks the beginning of the planned trajectory. After initialization, the operator commences the scan mode during which the rotating head is activated and the data is recorded and stored into the data logging unit as the operator walks through the planned trajectory. The survey ends at the exact location where the device is de-initialized. The survey trajectory starts and ends at the same location for loop closure and to minimize drift (Zlot and Bosse, 2014b). The raw data is transferred out from the data logger for further processing to a laptop using a USB stick.

The main challenges in acquiring the data were primarily related to the accessibility of some locations in the caves, particularly in the vicinity of sudden steep changes in elevation where both hands were required to safely proceed. This led to splitting the caves up into more surveys, which eventually led to increased complexity in processing the data (point cloud registration steps).

3. Surveyed Caves
A total of 6 carbonate caves were surveyed over a period of 6 days. An attempt to survey a seventh siliciclastic cave was unsuccessful since the cave entry point was not found.

3.1 Cave Lapa de Morro Vermelho (The Red Hill Cave)

The Morro Vermelho cave is located in the municipality of Canarana, state of Bahia, Brazil. The cave is located inside a hill approximately 100 m high by 600 m in an ellipsoidal fashion and oriented in the WNW / ESSE direction. Access to the cave is through a narrow, restricted vertical passage of around 2 metres. No map existed for the Morro Vermelho cave prior to our expedition. Since no map was available, the LiDAR survey was used to outline the cave interior, see Figure 2. This figure was taken from the still unpublished paper by Bertotti et al. based on the results obtained in this fieldwork.

![Figure 2 Aerial View of the Red Hill Cave taken from W-E direction](image)

![Figure 3: Location Map of the Red Hill Cave located in the municipality of Canarana, Bahia](image)
Out of all the six caves which have been investigated, this is the most complex cave in terms of 3D architecture. The cave possibly formed along inclined bedding planes, which along with cross formation flow, resulted in the complex 3D architecture.

Several observations regarding en-echelon veins (conjugate shear deformation zones) and other fractures present in the cave, have been identified in order to constrain the possible orientation of the paleo stress. Large planar deformation features are easily recognized in the LiDAR dataset and help to further unravel the structural history of the cave environment, see Figure 4 and Figure 5.

No extensive pavement type exposures around the vicinity of the cave mouth was present. Measurements were performed on limited outcrops on the periphery of the cave entrance.

Most of the data acquired in the cave is currently being used for (at least two) publications, expected to be published somewhere in 2019.

### 3.2 Cave Diva De Maura

The Diva De Maura cave is located in the municipality of Seabra, in the state of Bahia, Brazil. Access to the cave is made by a steep descent in the escarpment of a dolina. The entrance of the cave is located at the base of the cave in the area corresponding to the bottom of the dolina. The cave comprises of large halls separated by constricted ducts with low ceilings.
Collapsed breccia was observed in many parts of the cave as well as sedimentary stylolites (burial related). Hydrothermal minerals were also found, suggesting the possibility of involvement of hypogenic processes in the formation of the cave system. However some of the cave chambers had extensive presence of epigenic overprint features like stalagtites and stalagmites.

3.3 Cave Ioiô

The Ioiô Cave is located in the Patos Lagoon Village, in the municipality of Palmeiras, in the state of Bahia, Brazil. The entrance of the Ioiô Cave is located at the base of the slope of a semicircular dolina. The Ioiô cave is characterized by narrow, sub-parallel cave conduits. All passages of the cave was not explored because of the presence of a lake. The lake could be a location for preferred fluid ascent and indicative of its hypogenic origin.
3.4 Cave Torrinha

Torrinha is located in the municipality of Iraquara, in the state of Bahia, Brazil. The cave has 12 km long passageways. The fact that it is a tourist attraction prevented access to all passages and only certain areas of interest were visited.
The cave forming mechanisms are believed to be a combination of hypogenic and epigenic processes. Deeper into the cave, a seemingly (hypogenic) maze network can be found, with very regular spacing between each cave tunnel. This spacing will be further analysed in the future, both statistically and numerically (see also section 4.3).

3.5 Cave Lapinha

The Lapinha cave is located in the municipality of Ibiquera, in the state of Bahia, Brazil. The cave is a religious cave housing a church which is also a popular tourist attraction.

The Lapinha cave has a series of rectilinear conduits with large internal spaces that seem to have developed around a system of orthogonal fractures. The labyrinthine pattern indicate that it probably has an exclusive hypogenic origin.
3.6 Cave Paixão

The Paixão Cave is located in the municipality of Andaraí, in the state of Bahia, Brazil. The cave has a series of conduits that are oriented in a predominant N-S direction with smaller ducts in the orthogonal direction. The cave had many interesting features like the presence of bubble trails (indicative of corrosion due to air flow) and scallops on cave speleothems (indicative of water flow through the cave). The orthogonal nature of the passages suggest a hypogenic origin.
4. Future Work

The concluded cave expedition was highly beneficial in terms of gaining scientific knowledge, imparting practical fieldwork data acquisition and processing experience for the authors and exposure to working within in an multidisciplinary and multicultural team in a challenging environment. The method of data acquisition, namely, use of mobile LiDAR in enclosed settings, is a major technological breakthrough in the study of caves enabling rapid digitization of complex cave geometries. The data collected is highly valuable and can lead to quite a few research directions and potential publications. Despite the obvious advantages of mobile LiDAR there were still some shortcomings in the data acquisition which needs to be mentioned. These are:

- The lack of a coherent workflow to efficiently convert the recorded data into meshed surfaces automatically.
- The non-availability of real time display of recorded point clouds

For the first deficiency, specific point cloud processing algorithms need to be developed for point cloud de-noising, clustering and surface fitting. For the second point, it is planned to use and advanced version of the GeoSlam that has real time display of point clouds. In a future cave expedition, this would allow the operator to uniformly sample cave regions and increase / decrease point cloud density as per the geological significance. Apart from the data acquisition, a few of the anticipated research themes which we are interested in exploring are discussed here.

4.1 Topological Analysis of Cave Pathways

Previous studies by Jouves et al. (2017) and Collon et al. (2017) have shown the use of topology and various statistical metrics in identifying the diagenetic history of a cave purely from its geometric configuration. The various speleologists which were part of this fieldwork have identified some of the main cave forming mechanisms. It would be extremely useful to compare these findings and the detailed topology of the cave, with the previously mentioned works. Currently, two MSc. students (Lynn El Ahmar and Hanif Dinul Islam) are currently also working on part of the LiDAR dataset and will manage to deduce the required topological and statistical data to perform this analysis.

4.2 Geomechanical Stability Analysis of Maze Structures

Understanding the geometric relations governing the spatial distribution of these encountered karst features is an important asset. However, one of the main applications of this knowledge would be improving the reservoir modelling workflow of karstic reservoirs, i.e. improving their predictability regarding spatial distribution in the subsurface. Several pilot projects in the Netherlands have targeted the lower Carboniferous (Dinantian) carbonates and encountered such karstic reservoirs (Reijmer et
These reservoirs are located at great depth and it is not entirely clear in which condition the karst features occur in these reservoirs. I.e. improving our understanding of the geomechanical stability of such caves at depth is another important contribution to the reservoir modelling workflow. The plan is to perform several geomechanical modelling studies, using a Finite Element Method (FEM) or Discrete Element Method (DEM) approach, and utilizing these realistic cave geometries obtained from the LiDAR dataset. The result of this modelling study will help with a more realistic population strategy of the reservoir model parameters and improve the accuracy of the resulting fluid flow simulations.

### 4.3 Numerical Simulation of Passage Formation

A reactive transport model is currently developed at the TU Delft as a module for the Delft Advanced Reservoir Terra Simulation framework. Part of this work involves understanding the dissolution structures encountered in acid simulation, but also natural dissolution phenomena such as the encountered hypogenic karst in Brazil. Numerical models will be validated with fieldwork observations and the LiDAR dataset in order to better understand the main controls on the cave forming mechanisms.

### 4.4 Case Study of Hypogenic Morro Vermelho cave

One of the most interesting caves which was investigated is the Morro Vermelho. The interplay between stratigraphy, fractures, and flow configuration in a strike-slip structural setting is evaluated in a paper which is currently being written (Bertotti et al.). The LiDAR dataset is of paramount importance to this study, since it provides a detailed description of the highly complex 3D cave interior. Something which be (nearly) impossible to acquire with TLS or other mapping tools.

### References


