Raster Geographic Information System for the Management of Cave Reconnaissance Information

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Abstract

There are two ways in which to manage geographic information with a computer, as vector objects or as raster cells. Vector systems dominate the industry and are what most people think of when they hear, or read, the term Geographic Information System (GIS). Raster systems, however, are growing in popularity for complex map analyses. This paper will describe the application of a raster GIS to the management of topographic, hydrologic, and geologic information in the search for undiscovered caves on the eastern slope of the Santa Catalina Mountains, Arizona. The success of the procedures will be measured by their ability to "discover" the known caves in the area.

Introduction

To many people the term geographic information system or GIS is synonymous with the vector-based GIS packages that are popular with government agencies and businesses. The overwhelming market share occupied by these expensive systems eclipses the raster GIS software that is sold by smaller vendors.

The power of raster GIS systems lies in their ability to rapidly perform mathematical and logical operations on individual map layers. The layers can be considered as variables in an equation and they may be manipulated by operations of map algebra. This paper is a demonstration of the application of a raster system to the management of data that are useful in cave reconnaissance.

The focal point for this work is an area on the northeastern flanks of the Santa Catalina Mountains, which form a dramatic backdrop to the Tucson skyline (Figure 1). A number of caves in that area share a morphology that suggests a common genesis. Extensive solution is confined to a limited vertical interval at what was once at or just below the paleo water table. Joints and faults exert some control on passage direction so resulting caves begin as two-dimensional mazes. If solution is extensive, the overlying rocks collapse and large rooms form as a result of upward stoping. Continued solution of the breakdown sometimes creates dramatic, flat-floored rooms.

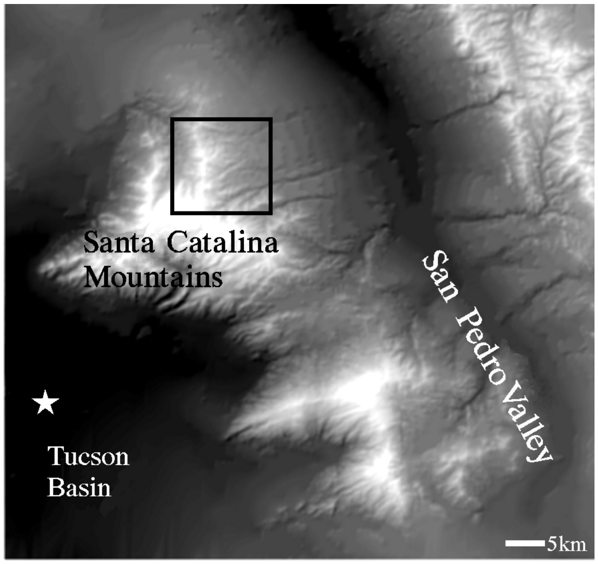

Figure 1. *Location of research area on the northeastern flank of the Santa Catalina Mountains indicated by the black square. Star indicates the site of the Symposium in Tucson, Arizona. Original scale about 1:500,000.*

Scroll Cave is a good example of this morphology. It is a horizontal maze covering an area of approximately 75,000 square meters. A large entrance room has a floor that is 20 by 30 meters in size. The cave is located directly below a flat, gently-sloping erosion surface capped by older Quaternary sediments. Kartchner Caverns, 75 kilometers southeast of Scroll Cave, also exhibits strong water-table control of solution. At Kartchner Caverns it appears that a stable water table was associated with the maximum filling of the San Pedro River Valley by the late Pleistocene St. David formation (Hill, 1999).

Information

Information for this search for caves comes from three sources: geologic mapping, digital elevation models, and information on cave morphology and speleogenesis. Utilizing this information in a cartographic model (Figure 2) will define areas with the highest potential for new cave discoveries. In addition to the above information the 1:100,000 metric topographic maps of the Mammoth, Tucson, and Fort Huachuca Quadrangles were used to provide general regional information.

The geology and tectonics of the Santa Catalina Mountains have been studied in some detail, particularly by Force (1997) and Dickinson (1991). The range is a classic metamorphic core complex in the south but is dominated by a Laramide, basement-cored uplift in the north. Here, 1.1 kilometers of middle Proterozoic to Paleozoic sedimentary rocks rest unconformably on a basement of Oracle Granite and Pinal Schist. Three Laramide aged concordant intrusions distort and partly metamorphose the sedimentary stack. Laramide and Tertiary faulting in the area is typically high-angle and normal, most notably along the Geesaman and Mogul Faults.

The 1:48,000 scale geologic map prepared by Force (1997) is of particular interest to this study since it breaks out the Paleozoic carbonates that host caves in southeastern Arizona. Also shown on the map is an area of older, Quaternary alluvium (Qa2) which may be correlated with the St. David formation exposed near Kartchner Caverns. Dickinson (1991, page 66) regards the St. David formation near Kartchner Caverns and the older Quaternary alluvium in this study area to be part of the Quiburis Formation. Even though the St. David is younger than the Quiburis, both formations are representative of the period of maximum basin filling in the San Pedro Trough; thus they define a period of water table stability on the flanks of their respective mountain ranges.

Digital elevation models of the Campo Bonito and Mount Bigelow 7.5-minute Quadrangles were acquired on line. The elevation data is in raster format with a 30-meter cell size. Information on the caves was obtained from the published maps of Scroll Cave (Thayer, undated) and Deadman Cave (Brod, 1977 survey) from visits to Scroll, Deadman, Peppersauce and Nugget Caves, and from conversations with Lang Brod of the Escabrosa Grotto.

All the information used in this work was converted to raster format for management by the geographic information system. The digital elevation model data uses a cell resolution of 30 meters. Using a cell size of less than 30 meters creates only an illusion of precision. Geologic maps at 30-meter resolution looked "blocky" and were difficult to digitize. In the end 20 meters was found to be workable for data input and processing. All data files were less than one megabyte in size. Data layers were all warped to UTM zone 12N with NAD27 and registered to each other.

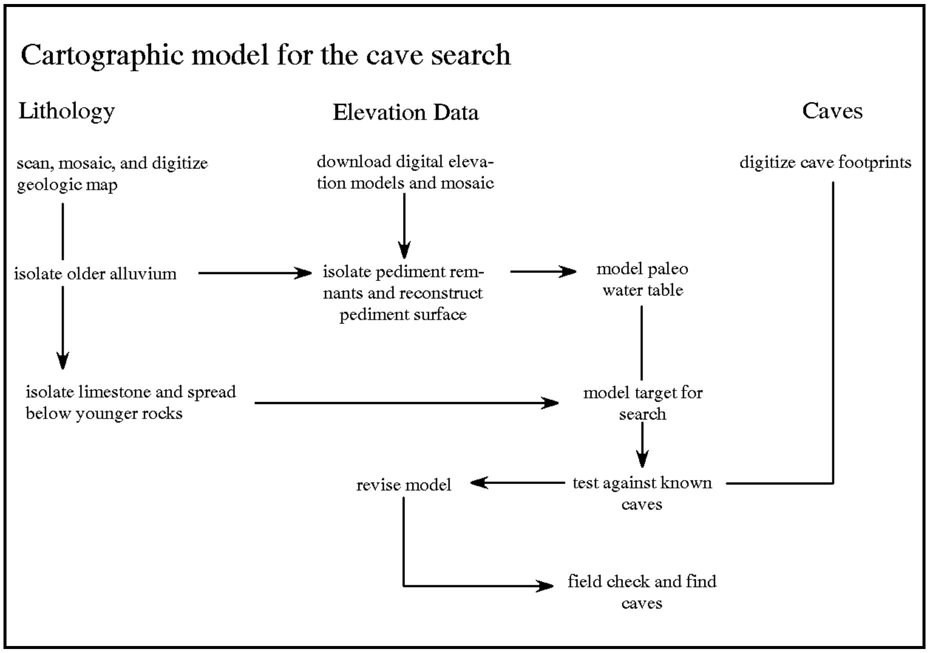

Figure 2. *Cartographic model used to guide the operations of the geographic information system.*

Data management

After the data are assembled, the process of extracting useful information can begin. Recall that the objective of this work is to define areas in which searching for undiscovered caves will be most successful. The overall search region has an area of 132 square kilometers. Even without a geographic information system it is easy to use the geologic map to eliminate areas that do not contain limestone. This reduces the search region to 9.8 square kilometers; but this is still a large area to search carefully on foot.

Developing an effective cartographic model, based on the speleogenesis of known caves, one can effectively reduce the search area within the limestones. The morphology of caves suggests that a stable water table, associated with a stable erosion surface, is important to the genesis of caves. The basic elements of the model then include soluble limestone and a stable water table (Figure 2). Discovering areas where these two factors coincide in space is the key to reducing the search area.

Solution of the limestone is controlled to some degree by faulting and joints and we felt that mapped faults would be a useful part of the cartographic model. However, filed observations show that faults are so ubiquitous in the map area that virtually every cell in the GIS will contain faults and/or joints. Limiting the model to the vicinity of mapped faults is excessively constraining.

The first step in the application of the model is to select areas containing Horquilla (Ph), Escabrosa (Me), and Mescal (Ym) Limestones from the digitized geologic map (Figure 3). Escabrosa Limestone is the most common host rock for caves in southeastern Arizona but the other limestones in the area should not be ruled out as possible hosts. The geologic map shows places where the limestones outcrop but the rocks are present beneath younger formations and there is no reason not to expect caves there. To accommodate this possibility, the extent of limestones was spread 100 meters beyond their outcrops, beneath all younger rock units.

Modeling the paleo water table presented a more challenging task. In order to accomplish this it was necessary to recreate the pediment surface that existed at the time the water table was stable. Since remnants of the pediment surface remain as geomorphic features today, the first step was to isolate these remnants on the digital elevation models.

The slopes of the remnant pediment surfaces range from almost horizontal to as much as 15 percent toward the cores of mountain ranges. Slopes in this range, with extents greater than 200 by 200 meters were isolated from the digital elevation data. These were further processed to remove those slopes that occurred at the bottoms of arroyos. The remaining areas, representing erosional remnants of the older Quaternary pediment surface, were used as seeds for an interpolation operation. The interpolation effectively replaced those parts of the pediment that had been removed by erosion. The interpolated surface was trimmed to fit any topography that extended above the surface and the result is shown in Figure 4.

Figure 3. *Geologic map of the research area. Lithologic units are shown in shades of gray, oldest units are the darkest. Horquilla (Ph), Escabrosa (Me) and Mescal (Ym) limestones are shown in black.*

The preserved pediment surface at Scroll Cave is approximately 20 meters above the level of extensive maze development. This distance was used as an estimate of the depth of the paleo water table below the older Quaternary pediment surface. Creating a model of the stable water table at the time of extensive solution of the limestones was simply a matter of subtracting 20 meters from the elevation of the restored pediment surface.

With the extent of the limestones and the level of the paleo water table modeled, it remained to find places where the two intersected. The first step in this process was to isolate the topography of areas containing limestone. The elevations of cells in these areas were subtracted from the elevations of cells in the water table surface. Negative or positive values in the result indicated that the lime-

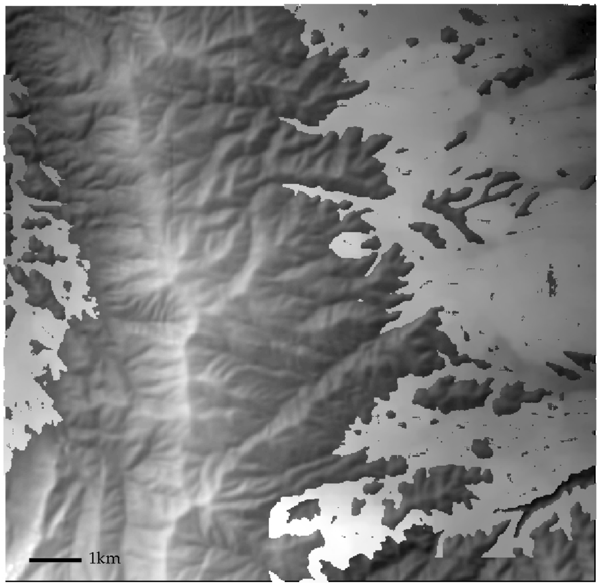

Figure 4. *Restored older Quaternary pediment surface shown in light gray tones on shaded dem background.*

stones were below or above the water table, respectively. Allowing ± five meters for margin of error, the cells at zero and above or below zero were selected as areas where the water table was in contact with the limestone, much as a lake is in contact with its topographic shore (Figure 5).

Figure 5. *Target areas shown in black. Areas of limestone outcrop, in gray are shown for reference. Targets that extend beyond the limits of limestone outcrops show potential in limestones covered by younger rocks. Tips of arrows indicate the locations of presently known caves.*

The success of the cartographic model in predicting the locations of undiscovered caves can be tested by comparing the model with the locations of known caves. The locations of entrances of known caves are indicated at the tips of arrows in Figure 5. With the exception of one cave, the entrances to known caves are within or very near the target areas. The exception is a cave that does not exhibit a strong water table control of its speleogenesis.

Since the objective of this effort is to define areas for optimum field exploration the model can be "tweaked" a bit by using the locations of known caves as evidence for the location of the paleo water table. If this were done before the model was tested it would be considered a self-fulfilling effort—the model "finds" the caves that were used in its creation. If the known solution levels in the caves are used after the model has been tested and shown to be accurate, the improvement will only improve the precision of an already accurate model.

Conclusions

Caves within a 132-square-kilometer area on the northeastern slopes of the Santa Catalina Mountains are known to contain caves with strong water table control on their speleogenesis. Simply selecting areas of limestone for field checking in this area would require the examination of 9.8 square kilometers for the existence of cave entrances.

Instead, a two component cartographic model consisting of limestone host rocks and a stable paleo water table was used. The model was developed with some trial and error but in its ultimate form it used only a geologic map and digital elevation models for input. One and one half pages of script were used to execute the cartographic model in the MFWorks raster GIS.

The application of a raster format geographic information system to the task effectively reduced the search area to 0.8 square kilometers. Most of the targets are on hillsides so ridge walking in the strictest sense would have been ineffective in finding new caves.

References

Brod, Lang, 1977 survey, *Deadman Cave*; map at 1:392.

Dickinson, WR, 1991, *Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona*;

Geological Society of America Special Paper 264, 106 pages plus map.

Force, Eric R, 1997, *Geology and Mineral Resources of the Santa Catalina Mountains, Southeastern Arizona*; Monographs in Mineral Resource Science No 1, Center for Mineral Resources, The University of Arizona and the U.S. Geological Survey, 135 pages, 2 plates.

Hill, CA, 1999, *Overview of Kartchner Caverns, Arizona*; Journal of Cave and Karst Studies, v 6, n 2, p 41-43.

Keigan Systems (formerly ThinkSpace), 2001, *MFguide*; Adobe Acrobat Document, see also http://www.keigansystems.com/Products/MFWorks/index.html

Thayer, Dave, undated, *Scroll Cave*; map at 1:1,176

USGS, 1986, *Mammoth quad, Arizona*; U.S. Geological Survey 30' x 60' metric map, 100,000.

USGS, 1994, *Fort Huachuca quad, Arizona*; U.S. Geological Survey 30' x 60' metric map, 100,000.

@REFERENCE = USGS, 1994, *Tucson quad, Arizona*; U.S. Geological Survey 30' x 60' metric map, 100,000.
USGS, undated, *Campo Bonito*; U.S. Geological Survey 30 arc-second digital elevation model.

USGS, undated, *Mt. Bigelow*; U.S. Geological Survey 30 arc-second digital elevation model.

Biographical Sketch

Dr Truebe started caving in the iron mines of New York State and in the cold, wet caves of the Schoharie Plateau. An education at Colorado School of Mines introduced him to the Rockies, the Black Hills, and the Guadalupes. A career in mineral exploration and a tour in the Peace Corps has taken him throughout the western U.S. and Oceania. He currently teaches map and aerial photo interpretation as well as providing remote sensing and raster GIS services to clients in mineral exploration and other fields.