Cave Surveys, Cave Size, and Flank Margin Caves

by John Mylroie

The standard measure of cave size, from which the United States, and World, long caves lists are derived, is surveyed length. There have been numerous discussions over the years, in this newsletter and elsewhere, about what portions of the actual survey are considered part of the cave length. The issue of projection of the cave onto a two-dimensional plane, THC or "True Horizontal Cave", must also be considered in a discussion of cave survey length. Modern computer techniques have bypassed this projection problem, at least visually, by 3-D presentations of cave surveys.

Survey length is also used as a filter for state cave surveys. States with many long caves tend to set their filter high, for example, some exclude any cave with less than 10 m of survey, while cave-poor states tend to count almost anything, using a lower filter, such as 2 m, as the inclusion limit. This filter effect has a couple of outcomes. First, it can make state-to-state comparisons of the total number of caves in each state unrealistic, as the ground rules are different. Second, it uses an arbitrary length value as the determiner of cave importance. For example, a 3 m diameter cave passage opening on a hill side, and going in for 9 m to a breakdown blockage, might not be entered in a data base at all as it is less than 10 m in length. However, the cave's significance to understanding, and exploring, an overall cave system could be immense.

Explorational bias also plays a role in cave length discussions. If two caves are segmented by a short, untraversable collapse, their lengths are treated as independent measurements. In the past few decades, this problem has been somewhat mitigated by use of the "cave system" approach, which while still logging the individual explorable cave segments as individual lengths, the length of such segments is commonly summed to give a known minimum length value for the entire cave system. The greatest degree of discussion in this regard has been with lava tube segments, separated by collapsed lava trenches.

Despite the concerns mentioned above, for long stream caves, the overall survey distance is the single most representative value of cave size, for the length of the passage is a dimension much greater than the passage width, or height. The same is partially true for rectilinear maze caves, especially if the length is stated with respect to the area enclosing the maze, as it yields a passage density value. Is a maze cave big because it has a high passage density, or because it has a large areal extent? Some cavers dismiss maze caves with a high surveyed length value as not actually long caves, because although there is a lot of passage, it doesn't really seem to go anywhere.

While cave survey length is the routine indicator of cave size, there are some problems with that use, as indicated above. There are applications where summed cave survey length is not really useful in indicating cave size. How does one consider a large room? Most are surveyed as either a line run around the perimeter of the room, or a series of splay shots taken from a central point or points (or both). For a long stream cave system, a few large rooms surveyed by either method don't change the overall cave length much even if the survey shots for the entire cave are simply summed.

For certain cave types, such as flank margin caves, issues of survey length and cave size take on significant importance. Flank margin caves form in the margin of the fresh-water lens that is found just inside the limestone coasts of landmasses, from continents to islands. The fresh-water lens is a body of water that floats on underlying sea water, as it is slightly less dense. A full explanation of these caves can be found in the recent 65th Anniversary issue of the Journal of Cave and Karst Studies (Mylroie and Mylroie, 2007). For the purposes of this article, flank margin caves form by dissolution caused by mixing of fresh and marine waters within the rock. They are not stream caves, and do not have turbulent water flow. The caves are mixing chambers, and grow and become complex as a result of the enlargement and intersection of these chambers. The caves lack a linear form and are a collection of chambers and rooms. They do not form with entrances, which are a later result of surface erosion or collapse. A portion of a typical flank margin cave, Cueva Aleman from Isla de Mona, Puerto Rico, is shown in Figure 1A. The cave has two main levels, the larger lower level is displayed here (see Frank *et al*, 1998, and Mylroie et al, 1995, for a complete description of the cave). Cueva Aleman is a large cave as flank margin caves go, and when these caves get large, they assume a degree of linearity because the cave chambers only form in the margin of the fresh-water lens, and cannot grow very far inland from the coast. As the chambers enlarge and connect, they form a chain of chambers that are parallel and proximal to the shoreline. This pattern has been called "beads on a string", as shown in Figure 2.

As the caves are a series of globular chambers (Figure 3), to accurately survey them requires that each chamber be properly measured. Perimeter surveys are difficult, as the chambers tend to have very low ceilings on their periphery, and the preferred technique has been to establish a central station or stations, and shoot splay shots of sufficient number to establish the room's dimensions so that the sketch is accurate. Figure 1B is the same as Figure 1A, except that passage detail has been removed and the survey lines added to show how the cave dimensions have been quantitatively fixed by numerous splay shots. The number of stations shown is 190, the number of shots is 233, and the total survey length of those shots is 2,820.67 m, for an average shot distance of 12.1 m. The cave trends ESE to WNW, and the linear distance, taken from the final map, from end-to-end is 325 m. A "width", taken perpendicular to the end-to-end line is 92 m, for an aspect ratio (length over width) for the cave map of 3.53.

The upper level of the cave, shown in Figures 4, is less extensive, but still consists of 124 stations, with 139 shots to produce a sum of 1,475.78 m. The total survey summation for the cave is 4296.45 m. The survey was done by a team of four people in five in-cave days. The cave was surveyed from the WNW end to the ESE end, and the astute observer will see that survey station and shot density drops a little at the ESE end, as time on the expedition was running out, and we rushed to complete the survey. Figure 5 shows the cross sections derived from the survey. A surface survey from the Rio Mona Entrance in the ESE to the West Entrance at the WNW took 16 stations and 16 shots with 376.25 m of survey.

So, how big is the cave? What value should be taken from the survey data to indicate how big the cave is, so that it can be compared to other flank margin caves on Isla de Mona, to flank margin caves elsewhere in the world, and to the more traditional stream caves of continental interiors? While simple summed survey length may be a decent size indicator for long, linear stream caves, it is obvious that simple summation will not work with the intersecting chamber configuration found in flank margin caves. One could go over the final map with a ruler (or plot lines in a computer display), and determine how many linear segments the cave contains, and come up with a derived length that way, but would it be meaningful?

As part of a scientific research project involving Mississippi State University graduate student Monica Roth (Roth, 2004, Roth et al., 2006), a technique was developed to assess flank margin cave size so that the governing factors of cave formation could be discovered. The plan was to determine the areal footprint of the caves. To determine this value, the cave map was scanned, and the cave area was determined by measuring the cave perimeter. This can be done in a variety of computer programs, Monica Roth used AutoCad,

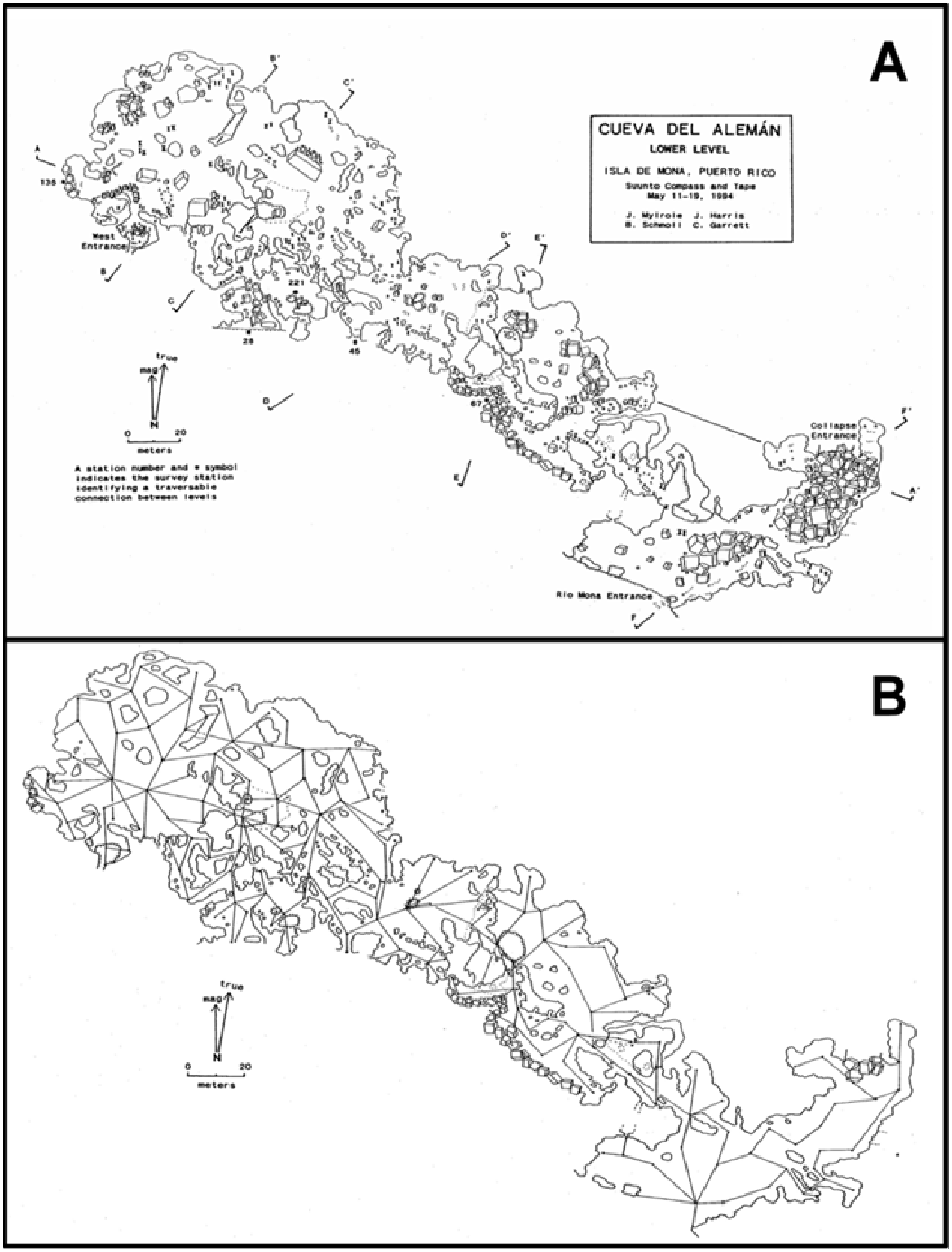

Figure 1. Map of the lower level of Cueva Aleman, Isla de Mona, Puerto Rico. A – Map showing internal cave detail and cross section locations. B – Same as (A) with internal detail removed, and survey station and survey shots displayed.

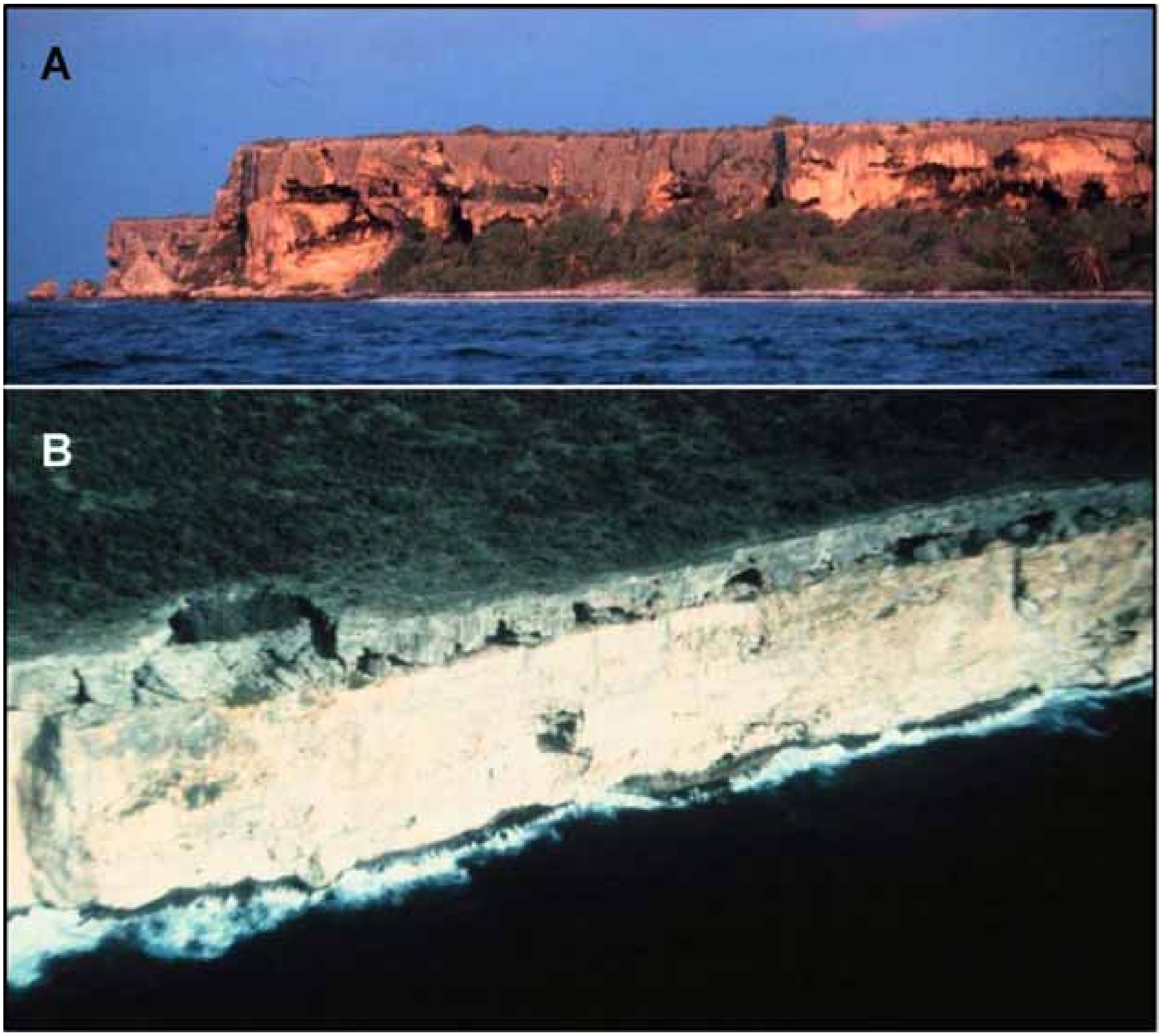

Figure 2. Sea cliffs on the coast of Isla de Mona, Puerto Rico. A – Cliffs at Parajos, 30 m high, showing caves developed in the Lirio Limestone at linear horizons that equate to a past sea level position. B – The southeast coast of Isla de Mona, with sea cliffs 60 m high, and caves developed at the Lirio Limestone and Mona Dolomite contact. Cliff retreat has opened the caves, such that individual chambers appear as "beads on a string".

but we have since switched at the recommendation of Mike Lace to a program from the National Institutes of Health used to map cell interiors, as it is very easy to learn and use. The overall cave area was determined this way, and then the area of any interior bedrock column, pillar, or bedrock body caught within a loop was subtracted out. As these area data were collected by using perimeter measurements, the outer perimeter of the cave was measured, as was the perimeter of each of the bedrock columns, pillars, and bedrock bodies caught in passage loops. While the internal bedrock area values were *subtracted* from the area total, the internal bedrock perimeter values were *added* to the perimeter total as these surfaces were part of the bedrock/water interaction that helped form the cave.

Subsequent analysis of these data by Monica Roth established that flank margin caves had some unusual mathematical properties. The ratio of cave area to perimeter, for flank margin caves of different sizes, produced a straight-line plot. Given

Figure 3. Large Chamber in Cueva Aleman, Isla de Mona, Puerto Rico. The photograph was taken from the B to B' cross section line of Figure 1A, looking WNW into a large chamber. Light from the West Entrance is visible to the left of the person in the photograph. Above and to the right of the person, two circular openings, with flagging tape hanging down, lead into passages of the upper level (Figure 4A & B).

that area is in square meters, and perimeter is in linear meters, the plot was expected to be curved (as it would be for circles or squares of increasing sizes). The significance of that plot is discussed in Roth (2004), Roth *et al* (2006), and in Mylroie and Mylroie (2007), but it is sufficient here to say that this outcome was a very big surprise. It helps explain flank margin cave formation as occurring by the joining of chambers with very irregular perimeters, such that when joined, the increase in cave area is balanced by the increased complexity of the cave wall.

Monica Roth's work also lead to another surprise. When flank margin caves from the Bahamas were plotted as a rank-order graph, that is, the smallest cave to the largest cave, by area, the plot showed three distinct line segments. Again, these results are discussed in the papers mentioned in the paragraph above, but what they show is that these flank margin caves begin as small, simple voids dissolving out in the fresh-water lens. As they grow, they begin to intersect their neighbors, and the gradual increase in size is replaced by a jump in size as two or more chambers connect. These combined chambers continue to grow in size, and then intersect with other chamber combinations, and the cave makes another sudden increase in size. A very interesting outcome of this work is that when flank margin cave genesis and growth was modeled on a supercomputer, using sophisticated programs that took into account water flow, geochemistry, lens geometry, etc., the computer model produced exactly the same size distribution segments as had been derived from Monica Roth's field data (Labourdette, et al, 2007). In addition, it predicted a fourth straight-line segment, down at the very small cave size, in the range of a few square meters in size. Those voids exist, they are present on all the islands where we have done field work. But they are too

CAVE	LENGTH	AREA	PERIMETER	A/P RATIO
McFails Cave, NY	**10,470 m**	**36,245 m^2**	**14,786 m**	**2.45**
Schoharie Caverns, NY	**1,239 m**	**1,279 m^2**	**1,345 m**	**0.95**
Nelson Cave, WV	**603 m**	**1,616 m^2**	**1,379 m**	**1.17**
Yokum Soakum Cave, WV	**621 m**	**1,608 m^2**	**1,341 m**	**1.20**
Cueva Aleman, Isla de Mona	**4,296 m**	**14,523 m^2**	**3,344 m**	**4.34**
Cueva del Agua, Isla de Mona	*****	**8,508 m^2**	**1,879 m**	**4.53**
Hamiltons Cave, Bahamas	*****	**8,931 m^2**	**2,083 m**	**4.29**
Hatchet Bay Cave, Bahamas	*****	**5,934 m^2**	**1,383 m**	**4.29**

Table 1. Comparison of four stream caves in the continental United States with four flank margin caves on Isla de Mona, Puerto Rico, and the Bahamas. The A/P ratio is distinct for flank margin caves, and very consistent (* indicates that total survey shot length is no longer recorded for flank margin caves).

small to be fun, so we never mapped them, and they weren't in our database. But the computer demonstrated that it "knew" those little caves were there. Our island work had filtered out the very small caves by explorational bias.

So, once again, how big is Cueva Aleman? It has an areal footprint of 14,533.75 m^2, and a perimeter of 3,343.77 m. The A/P ratio is 4.34. As a comparison, see a few similar measurements (Table 1) done by Monica Roth from linear stream caves in the United States. The A/P ratios are much lower as stream caves do not have complex perimeters. On an A/P graph, they form a separate field from the one produced by flank margin caves.

Because flank margin caves form on the thin margin of a fresh-water lens, they tend to be horizontally extensive but vertically restricted. If the fresh-water lens changes elevation as a result of a sea-level change, and new flank margin cave forms, it may have a connection or two to a flank margin cave produced on an earlier, but slightly different sea-level position and hence, fresh-water lens elevation. Cueva Aleman is such an example, it shows two distinct levels with evidence of a lower third level at the ESE end of the cave (Figure 4). Each level is horizontally extensive and vertically restricted. The significance of this wide-but-low configuration is that areal footprint of the cave is a proxy for cave volume. From a cave science perspective, the cave map becomes a tool for the amount of rock carried away by dissolution, and allows geochemical models to be tested.

Mapping of flank margin caves started out pretty much as a one-team operation as Mylroie and Mylroie (2007) explain. Since the late 1990's, beginning on Isla de Mona and spreading to the Bahamas, mainland Puerto Rico, and the Mariana Islands, cavers have discovered the fun of mapping flank margin caves, as much for the joys of the island locations as for the unique character of the caves themselves. These survey teams have produced hundreds of flank margin cave maps, which keep expanding the database that can be geometrically analyzed to learn more about how such caves form. These cave survey teams understand how the cave maps will be used, and so recognize that passage wall detail, and the presence of isolated bedrock columns and pillars, are important to how the cave is later analyzed. The cave surveying techniques developed on Isla de Mona and elsewhere, primarily attention to passage detail and the use of numerous splay shots, create a mapping strategy. As can be seen from Figures 1 and 4, the cave surveys generate a large number of loops. The abundance of loop closures, and the many splay shots, allows the option of reducing the number of back sights taken, which speeds up the survey. Survey speed can be an issue when on a remote island for a limited amount of time, with limited resources. For example, expeditions to Isla de Mona must bring everything along, including all fresh water. Team

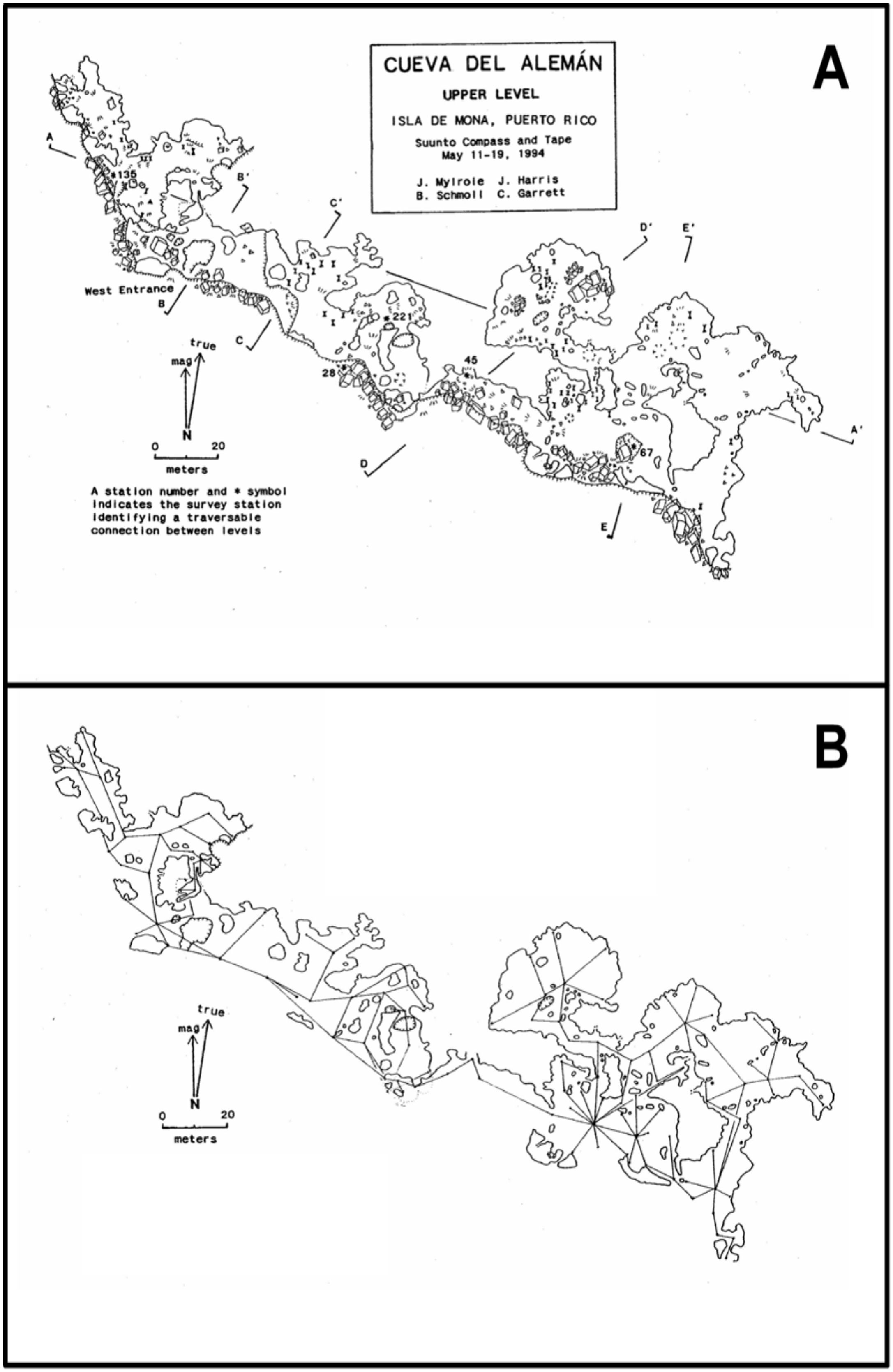

Figure 4. Map of the upper level of Cueva Aleman, Isla de Mona, Puerto Rico. (A) and (B) display the same features as in Figure 1.

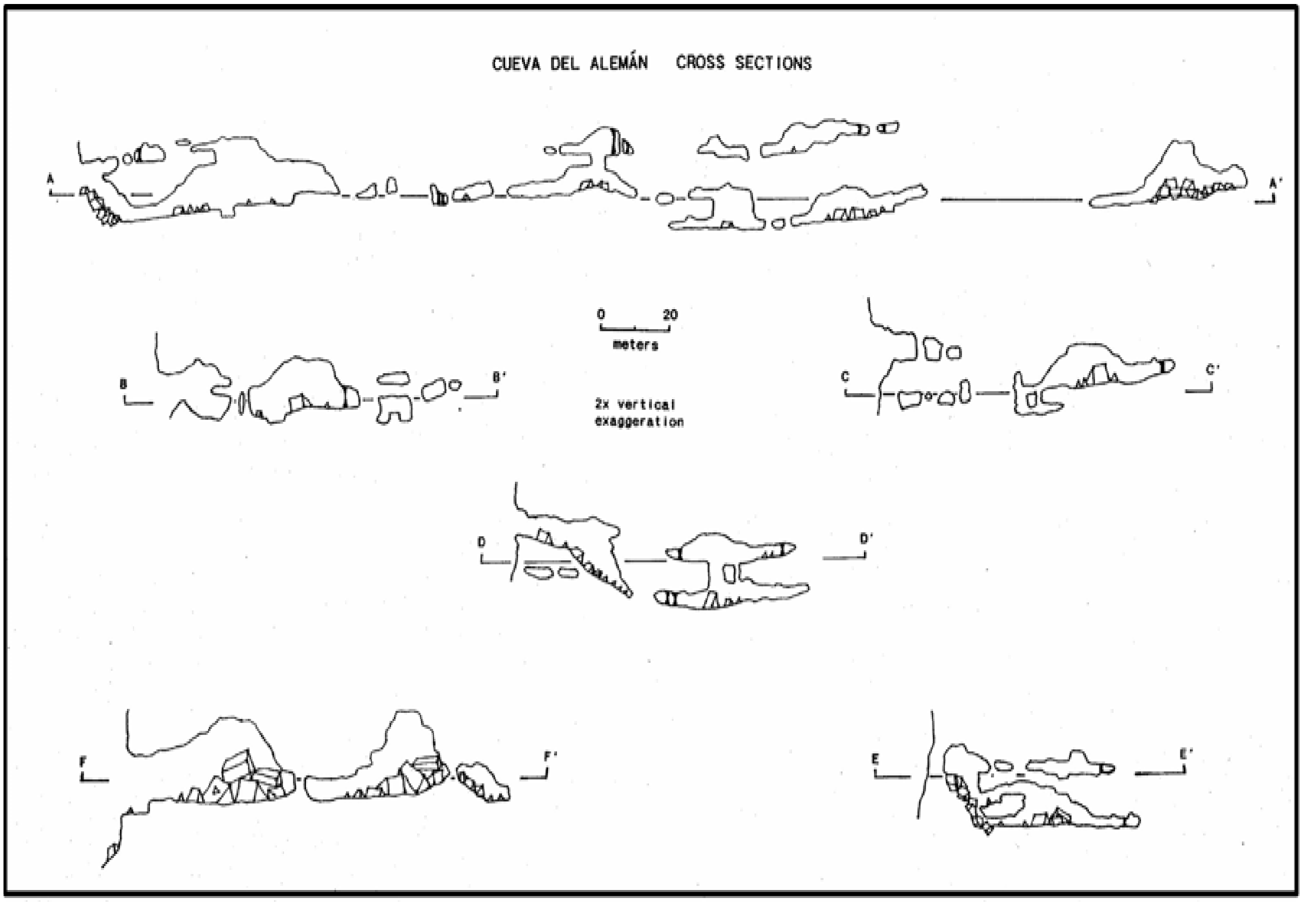

Figure 5. Cross sections for Cueva Aleman, Isla de Mona, Puerto Rico. See Figure 1A for location of the cross sections. The cross sections have a 2X vertical exaggeration.

endurance becomes an issue, even though flank margin caves are among the easiest caves in the world to traverse. The cave map manipulation techniques devised by Monica Roth have recently been applied to other cave types, such as sea caves (Waterstrat, 2007) and tafoni caves (Owen, 2007), and by workers elsewhere, such as on mainland Puerto Rico (Lace, in press), to differentiate these cave types and to help in explaining their genesis.

So cave size is determined in part by how that size can be measured, and how the cave size value will be used in the study of caves. For long, linear stream caves, or lava tubes, simple surveyed lengths, correcting for the relatively few splay shots, produces a reliable and useful answer. For caves that form not as stream conduits, but from the mixing of waters in a non-turbulent environment, the large, irregular chambers thus formed require a different assessment. Cave area appears the best size measure for these type of caves, called "hypogenic" by Art Palmer (1991). Flank margin caves are easily studied by this technique, as they are dominated by length and width, but have a limited vertical extent. But other types of hypogenic caves, such as those of the Guadalupe Mountains of New Mexico, are not restricted in the third dimension, and simple areal footprint is not as successful a measure. The next step is to adequately characterize these three-dimensional chamber complexes.

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