PROCEEDINGS OF THE EIGHTH SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

Edited by
James L. Carew

Production Editors
Daniel R. Suchy
Nicole G. Suchy

Bahamian Field Station, Ltd.
San Salvador, Bahamas
1997

Front Cover: View to the SSE on White Cay in Grahams Harbour off the north coast of San Salvador, Bahamas. At this spectacularly scenic site one can see that marine erosion has removed the entire windward portion of these early Holocene eolianites (North Point Member, with an alochem age of ~5000 radiocarbon years B.P.) that were deposited when sea level was at least 2 meters below its present position.

Back Cover: Stephen Jay Gould, keynote speaker for this symposium, holds a *Cerion rodregoi* at the Chicago Herald Tribune's 1891 monument to the landfall of Christopher Colombus, which is located on the windward coast of Crab Cay on the eastern side of San Salvador Island, Bahamas. The monument consists of an obelisk constructed from local limestone which houses a carved rock sphere depicting the globe with the continents. The inscription carved in a marble slab, reads: "On this spot, Christopher Columbus first set foot upon the soil of the New World."

Printed in USA by Don Heuer

ISBN 0-935909-63-X

DETAILED WALL MORPHOLOGY OF AN INTERIOR FLANK MARGIN CAVE ROOM, ISLA DE MONA, PUERTO RICO

Scott Rice-Snow
Dept. of Geology
Ball State Univ.
Muncie, IN 47306
(ricesnow@wp.bsu.edu)

Carol M. Wicks
Dept. of Geological Sciences
Univ. of Missouri
Columbia, MO, 65211

Roosmarijn F. A. Tarhule-Lips
Dept. of Geography
McMaster Univ.
1280 Main Street W.
Hamilton, ON L8S 4K1

ABSTRACT

Wall pockets are common features in the flank margin caves of Isla de Mona, Puerto Rico. We have performed a detailed survey of one room on the inland perimeter of Cueva del Agua, Sardinera. The room is roughly semicircular in form, six meters in radius, and completely ringed with a series of wall pockets, or alcoves, varying from a few centimeters to almost two meters deep. Variation in width is relatively limited (range: 0.37-0.91 m). These observations suggest expansion of the alcoves occurred mainly by deepening rather than widening, and that there was a strong control on the scale of dissolution pocket formation such as mixing-zone thickness adjacent to the cave wall.

Extremely deep and very shallow alcoves predominate along one half of the room perimeter, while mostly similar-sized alcoves of intermediate depth occupy the remainder. This difference in dissolutional development may relate to local contrasts in the paleohydraulic conditions, possibly influenced by wall orientation relative to general direction of past groundwater flow.

The overall plan-view outline form of Cueva del Agua Sardinera is somewhat similar to that of the room, with several radiating extensions that are roughly concave in form. Fractal dimension values for the outlines of the whole cave and the room are also similar, 1.38 and 1.30 respectively, which lends some support to a concept of analogous erosional development across scales.

INTRODUCTION

Wall and ceiling pockets within cave passages and rooms are among the most widely cited erosional forms that indicate phreatic cavern development (Ford and Williams, 1989). While some types of these concave, dissolutional depressions are localized on joint traces or intersections (Quinif, 1973; Veress et al., 1992; Dreybrodt and Franke, 1994; Slabe, 1995), other types are developed on cave wall/ceiling sites within limestone that is in no apparent way more susceptible to erosion than the flat wall/ceiling areas commonly found between pockets (Bretz, 1942; White, 1988; Ford and Williams, 1989; Slabe, 1995).

Wall and ceiling pockets are common features in the carbonate island caves discussed by Mylroie and Carew (1990) in connection with their flank margin model of cave development. In this model, phreatic voids are created by fresh and saline groundwater mixing effects near the edge of the island's freshwater lens, and those voids are later opened to the surface by erosional cliff retreat.

Examples include caves of the Bahamas (Mylroie and Carew, 1990, 1995) and those of Isla de Mona, Puerto Rico (Mylroie and Carew, 1995). In the latter caves, wall pockets are so densely clustered within some areas that little or no intervening unaffected wall surface is found, and the boundaries between pockets are cuspate ridges. Most of these pockets do not coincide with joint traces, or other apparent features, that would have acted as routes of enhanced groundwater migration into the voids during their formation.

We have performed a detailed survey of one room located at the extreme interior margin of Cueva del Agua, Sardinera, a large cave that is more than 150 m wide and extends 60 m into the carbonate plateau from the WNW-ESE oriented cliff face. The room is roughly semicircular in form, 6 m in radius, and is completely ringed with a single series of wall pockets, many of significant depth, which give the appearance of abutting alcoves connected to the large, almost completely open room. The ceiling height is less than two meters, lessening to the periphery, and the height of the wall at sites of pocket entrances is less than a meter. The floor is fairly flat and clear, with the exception of one residual column in the main chamber. It extends quite levelly into all alcoves, and horizontally truncates the concave forms of the wall pockets, so that the deepest points on their back walls are at, or within 20 cm of, floor level.

THE ROOM SURVEY

The objective of the survey was to map a line of the room's maximum extent in plan view, with detail of form recorded at a near-centimeter level of resolution. The entrance to the room is an opening in a perforated, roughly linear curtain wall which forms the flat side of the room's semicircle, and which was not included in the survey.

A room-wide, compass and tape survey of the vertical cusp ridges between wall pockets gave a base map for more detailed surveys of the individual alcoves. In each of these fine-scale surveys we laid out a base line between the flanking cusp points, and made a number of depth measurements into the cavity, normal to the base line. These measurements were taken at floor level, or a height above the floor corresponding to the deepest vertical concavity of the back wall (no more than 20 cm above floor level, as noted above). If a pocket was deeper than its width, we established a secondary base line normal to the first, extending from the entrance to the back wall, from which a series of width measurements were made. The resulting set of measured location points for the wall of each alcove has a spacing of approximately 20 cm.

We plotted the wall location points for each alcove on graph paper concurrently with measurement, and then drew in the intervening wall forms by visual inspection. The alcove walls are smooth and smaller dissolution pockets in the surface are generally absent, but a single such pocket, a few centimeters across, is documented in the surveyed periphery line. (A larger number of such centimeter-scale pockets has been noted by the authors in another alcove-lined room elsewhere in Cueva del Agua.) Only one alcove was noted to coincide with a fracture line in the room wall; the remainder appear to have no such cause for development.

The compiled room wall map (Figure 1) shows a total of 25 wall pockets, ranging from slight concavities a few centimeters in depth to extensive erosional cavities more than a meter deep. They broadly radiate from the room center, but in some locations several alcoves appear to spread out from centers of larger indentations in the room wall (see wall pockets #1-5, #8-15, Figure 1). The central axes of some adjacent alcoves diverge or converge, rather than being broadly parallel in direction of erosion into the wall. In at least one location (between pockets #6 and 9) a thin rock wall is found. This is a common feature of flank-margin caves mapped at larger scales (Mylroie and Carew, 1990; Mylroie et al., 1994).

MORPHOMETRY

Width and Depth Values

In order to better examine the variations of form characteristics among the wall pockets, we have compiled various measures of depth and width. Procedures differ somewhat for shallow vs. deep alcoves

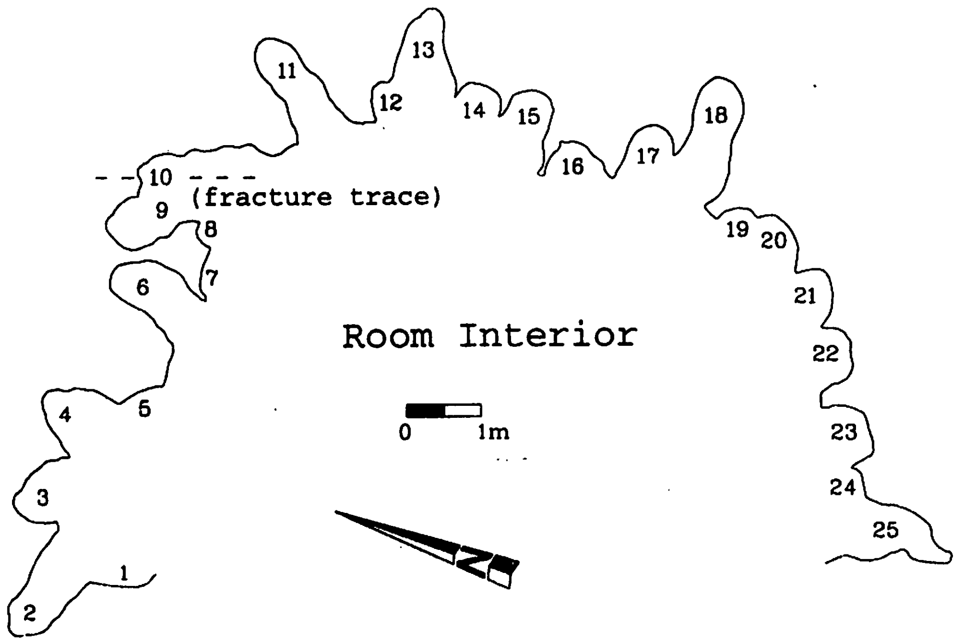


Figure 1. Detailed survey around the perimeter of a room in Cueva del Agua, Sardinera, Isla de Mona, Puerto Rico. Numbers identify individual wall pockets, or alcoves, of varying depth.

(Figure 2). For a shallow alcove, width (W) is taken to be the distance between points marking the limits of the concave form: these are in most cases the surveyed cusp points, but have been redefined in some places to exclude small lengths of straight wall surface separating adjacent wall pockets. Depth (D) is then the maximum perpendicular distance to the back wall. For a deep alcove, the depth is measured from the midpoint of the entrance base line, at whatever angle is appropriate, to the furthest point on the back wall. The midpoint of this depth measurement line, then, becomes the location for a roughly perpendicular, minimum-value measurement of alcove width.

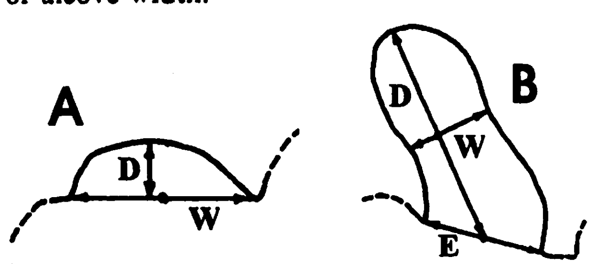


Figure 2. Measurement scheme for shallow (A) and deep (B) wall pockets. Baseline midpoints are marked by dots.

The 25 wall pockets vary little in width, with values that range from 0.37 to 0.91 m and average 0.66 m. The range in width values is considerably less for the deep alcoves. This constancy in width is striking when compared to the extreme variability in depth (Figure 3). Depth-to-width ratios fit into two classes: 0.5 or less, and 1.0 or more, providing a natural break for our shallow versus deep distinction in measurement procedure.

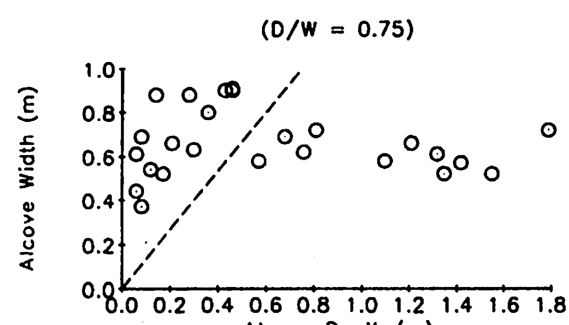


Figure 3. Width and depth values for the twenty-five wall pockets. The dashed line ($D/W = 0.75$) marks the differentiation, for measurement procedure, between shallow and deep alcoves, the latter being to the right of the line.

Alternative measures of width show somewhat broader ranges of values, although these ranges are still limited when compared to the range in depth. These measures include wall pocket entrance width (*E*, Figure 2) adopted for deep as well as shallow alcoves, and diameters of circles fit to the quasi-circular back walls of shallow and deep alcoves. The mean values for entrance width (0.79 m) and back wall diameter (0.78 m) support the qualitative observation that even the deeper wall pockets typically do not narrow with increasing depth, but instead end abruptly -- wall pocket #25 is the notable exception (Figure 1).

Considerations of Formative Process

The consistency in alcove width suggests a characteristic scale control on the initiation and subsequent development of these features. In other words, the conditions and processes responsible for the creation of the wall pockets in this room favored certain sizes of pockets within a narrow range of scale, and inhibited formation of smaller and larger pockets. Although one might argue that the larger-scale indentations in the room wall, mentioned above, are some larger version of wall pockets, one would still need to show why there are no pocket features with widths grading between these and the room's large population of identified wall pockets.

One suggestion for the cause of a characteristic scale control is that much of the fresh and saline water mixing in the cave, which created dissolutionally active mixed waters, may have occurred close to the walls where relatively fresh water flowed from the rock into the phreatic chamber. The thickness of this mixing zone could determine the sizes of developing wall pockets. At some point of locally concentrated freshwater flux from the wall, the depression being created by enhanced dissolution there would extend in either direction laterally along the wall, as far as the water dispersed before mixing was complete, and corrosive power depleted. In this scenario, smaller wall indentations marking, or within the mixing range of, high-flux sites would be erased by rapid retreat of more broadly curved wall sections encompassing the full mixing range. Creation of larger wall pockets would require close clustering of high-flux sites, or larger lateral distances of mixing in open, dispersive flow environments associated with a mixing zone extending a greater distance into the phreatic chamber from the wall.

The extreme variability of wall pocket depth, along with the consistency of width among and within the pockets, suggests that these features grow by deepening without appreciable widening. For this kind of growth to occur, continued erosion must be limited to the quasi-circular back walls of the alcoves.

In order to conceptualize how this style of erosion could be maintained, as well as how sites of locally high flux could characterize a rock wall apparently devoid of fractures, we make an analogy to the subaerial process of canyon development by groundwater sapping (Dunne, 1990). On a fairly linear cliff where erosion is dominated by weathering associated with groundwater seepage, any slight indentation in the wall will become a focus, in a very weak sense, of groundwater flow approaching the cliff face. The slight increase in flow from these indentations will cause them to erode back preferentially, which results in a focusing of more groundwater flow to that location, increasing the rate of headward expansion there in a positive-feedback process that at the same time depletes groundwater flow to the remainder of the cliff. The resulting canyons are constant in width throughout their lengths and end abruptly at semicircular, cliffed back walls.

Similarly, if the walls of a disc-shaped, water-filled phreatic void such as this cave room were almost smooth, but with minor irregularities, and the hydraulic head within the void was appreciably lower than in the surrounding rock (which might be expected if such an interior, peripheral void were already connected to a system of much larger voids extending in the seaward direction, as the flank margin model suggests), then the slight concentration of freshwater discharge toward the indentations would ultimately result in well-developed wall pockets whose back walls were foci of freshwater flow and whose widths were controlled by the scale of the mixing zones adjacent to those back walls.

The expansion of the cave volume by development of wall pockets which deepen preferentially as focal points for freshwater influx, mirrors the larger-scale development of caves and cave rooms at locations of greatest freshwater-saltwater mixing, as proposed in the flank-margin model (Mylroie and Carew, 1990).

Variations of overall room evolution can be accommodated within this scheme. It is possible that the room was dissolutionally expanded to nearly its current size with relatively smooth walls (under different prevailing conditions) before initiation of alcove development. On the other hand, the entire room development may be the result of headward growth of an ever-increasing number of alcoves. This could allow for creation and expansion of a roughly semicircular room if new alcoves were "seeded" at or near the cusps between existing alcoves; however, such locations, which would be subject to the relatively lowest differential hydraulic pressures between room and wall, would seem unlikely to be the sites of initiation of new alcoves. Seeding of new wall pockets in intermediate locations along the walls of deep alcoves, similar to the development of tributary canyons in subaerial sapping (Dunne, 1990) and branching in diffusion limited aggregation (Witten and Sander, 1981), is a better model in terms of process, but it is less likely to produce a fairly compact, open room, such as the one investigated here.

Variations Along Room Perimeter

With the general model of wall pocket development by positive-feedback concentration of freshwater flow in mind, it remains for us to examine the variations in this development around the room perimeter. By visual inspection of Figure 1, one can note that the north and northeast-facing walls of the room (alcoves #1-13) display most of the extremely deep wall pockets, which are generally separated by one or more extremely shallow pockets. The east and southeast-facing walls predominantly have alcoves of intermediate depth, although there are a couple of very deep and very shallow ones. A running standard deviation (n = 7) of depth values around the room perimeter (Figure 4) provides some statistical confirmation of this variability in wall pocket depths.

This difference in wall morphology could result from local contrasts in paleohydraulic conditions within the wall rocks adjacent to the room, specifically, contrasts in the degree to which freshwater flowlines approaching the void could be laterally diverted toward the back walls of deepening alcoves. If this diversion was limited to scales less than the characteristic scale of wall pocket development, then it would be sufficient only to favor the erosion of wall pockets at the expense of the cusps separating them (Figure 5A). A series of alcoves of approximately equal depth would be the natural result. If the diversion could occur over greater lateral distances, then freshwater flow toward the deeper alcoves could dominate to such a degree that flow to intervening, shallower wall pockets would be first partly, then entirely, pirated as the deeper pockets preferentially grew (Figure 5B). The development of the shallower pockets would end after a short time, and they would remain as slightly concave faces of the rock promontories between extremely deep alcoves (i.e., pockets #7 and 8 between deep alcoves #6 and 9, Figure 1).

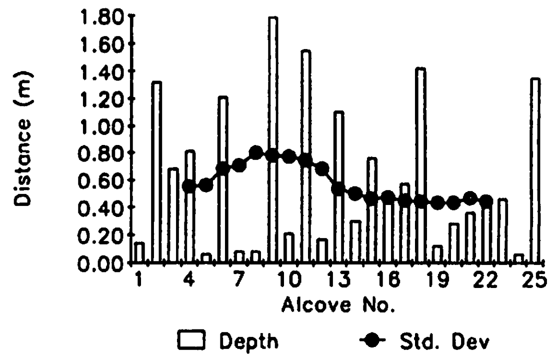


Figure 4. Depth values for the twenty-five alcoves, identified by number, proceeding clockwise around the room (Figure 1). A running standard deviation (n = 7) of depth values shows the decrease in contrast among depths of adjacent alcoves on the southeast-facing part of the room wall (alcoves #13-25).

This degree of diversion could have been affected by factors including local variations of permeability in the wall material (although the near-absence of such apparent flow-concentrating features as fractures has already been noted), different wall orientations relative to hydraulic anisotropy of the rock, or contrasts in general character of freshwater flow fields within walls on different sides of the room. Without detailed lithologic analysis, it is still possible to note some likely contrasts of flow conditions for the different walls

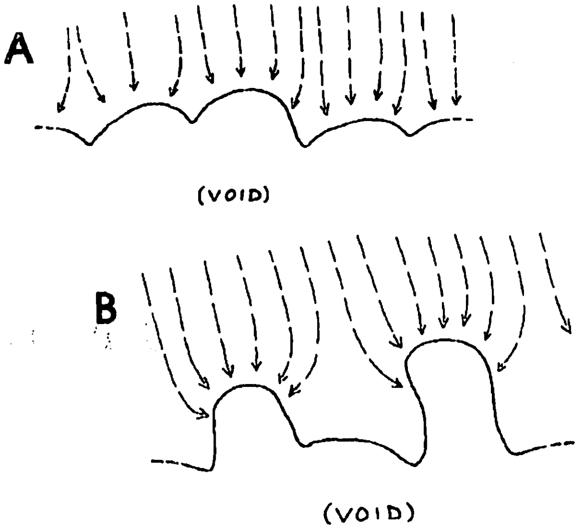


Figure 5. Variations in coupled groundwater diversion and wall pocket development, depending on scale of lateral diversion of flowlines allowed by paleohydraulic conditions. For small amounts of diversion (A), wall pockets of equal size are favored. Greater diversion of flowlines (B) encourages preferential deepening of some pockets, at the expense of others.

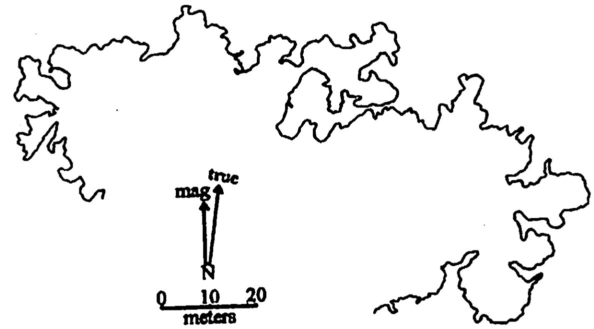


Figure 6. Perimeter outline of Cueva del Agua, Sardinera, depicted without the numerous, isolated, remnants of rock that further subdivide the cave interior. Derived from mapping by Mylroie, Carew, and Taggart (Mylroie et al., 1994).

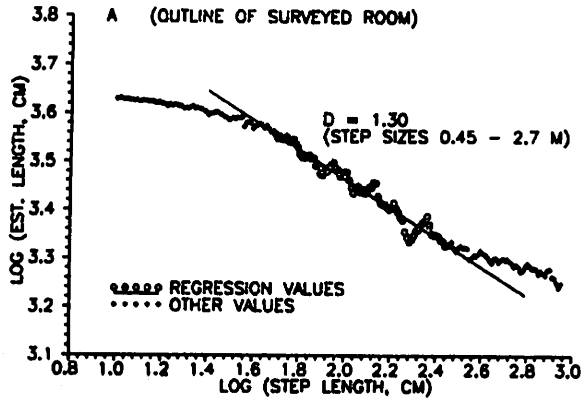
during alcove development. The north and northeast walls are the most inland, and are approximately parallel to the modern cliff face and the trend of the island shoreline. These walls were probably perpendicular to the groundwater flow direction, in contrast to the east and southeast walls, which were probably parallel to the general groundwater flow direction, were located slightly closer to the shore, and were more likely to have received freshwater flow that was being dispersed between the studied room and one or more other rooms developing nearby.

FRACTAL MORPHOMETRY

We have also applied fractal geometric analysis as a means to compare the room outline with the perimeter outline of the entire cave. This inquiry was prompted by a suggestion from J. E. Mylroie (personal communication, 1993) that the dissolutional voids comprising flank-margin caves may have similar form at many scales of inspection. The perimeter line of Cueva del Agua (Figure 6) does show a pattern of alcove-like rooms that are roughly concave in form, broadly similar to the wall features of the surveyed room, although depiction of features smaller than room scale on the map of the entire cave results in a more irregular appearance.

Divider analysis (Richardson, 1961; Mandelbrot, 1967, 1983) is an efficient means for quantification of the geometry of an irregular curve, such as the studied room or the entire cave outline, specifically identifying the degrees of curve wandering that are found at various scales of observation. The length of the curve is repeatedly walked by a real or virtual map divider, giving a suite of estimated curve lengths, each of which is keyed to a particular step size (or resolution of measurement). If a doubly-logarithmic plot of estimated curve length vs. step size, known as a *Richardson plot*, is linear, this indicates a self-similar fractal geometry for the curve, with fractal dimension (D) being a function of the plot slope. We performed the analysis digitally, including the average of 50 divider walks for each tested step size; each of the multiple walks started from a randomly chosen point along the curve, and proceeded in both directions to the curve ends.

The central portion of the Richardson plot for the surveyed room (Figure 7A) is straight, and shows a fractal dimension of 1.30 for scales (step sizes) ranging from 45 cm to 2.7 m. Remaining portions of the graph show lesser plot slopes, which correspond to a smoother curve form in the room outline. For the step sizes less than 45 cm we see the effect



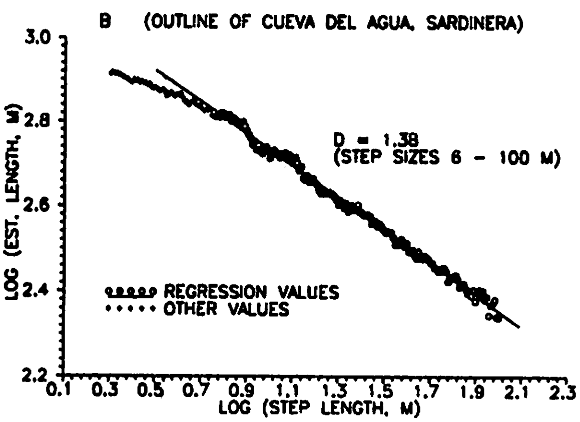


Figure 7. Richardson plots showing results from the divider method of geometric analysis. Plot A shows analysis results for the surveyed room perimeter marked by wall pockets (Figure 1). Plot B is obtained from analysis of the outer perimeter of the entire cave (Figure 6). Fractal dimension (D) values are computed from marked regression lines. Log values are base 10.

of the smooth outlines of individual alcoves. Similarly, the irregularity of the room wall becomes smoother when viewed at resolutions above 2.7 m, which are too coarse to resolve the alcoves. This implication of simpler geometry at large (room) scale, however, may be an artifact of the choice of survey area, limited as it is to the interior of a single room rather, than several rooms with intervening remnant wall partitions.

The Richardson plot for the entire cave outline (Figure 7B) is broadly linear for all tested step sizes greater than 6.0 m, and is characterized by a fractal dimension of 1.38, which is similar to the value derived for the surveyed room. We believe that generalizations of wall morphology, inherent in mapping the entire cave in lesser detail, are a significant factor that has lead to the apparently smoother geometry, indicated by Figure 7B, for scales less than 6 m.

Fractal dimension values of 1.30 and 1.38 indicate a fair degree of similarity in the irregular outlines of the surveyed room and the whole cave. The broadly fractal form of the cave outline, augmented by demonstration of similar geometric character in the outline of the studied cave room, suggests that fractal geometric models merit further application in the morphometry of flank margin caves.

ACKNOWLEDGMENTS

The Cueva del Agua room survey was made possible by funding from the U.S. Geological Survey. We wish thank J.E. Mylroie and J.W. Troester for helpful discussions and assistance, and anonymous reviewers for improvements to the manuscript.

REFERENCES CITED

Bretz, J.H., 1942, Vadose and phreatic features of limestone caverns: Journal of Geology, v. 50, p. 675-811.

Dreybrodt, W. and Franke, H.W., 1994, Joint controlled solution pockets (*laugungskolke*) in ceilings of limestone caves: A model of their genesis, growth rates and diameters: Zeitschrift für Geomorphologie, v. 38, p. 239-245.

Dunne, T., 1990, Hydrology, mechanics, and geomorphic implications of erosion by subsurface flow, *in* Higgins, C.G. and Coates, D. R., eds., Groundwater geomorphology: Geological Society of America Special Paper 252, p. 1-28.

Ford, D.C. and Williams, P.W., 1989, Karst geomorphology and hydrology: London, Unwin Hyman, 601.

Mandelbrot, B.B., 1967, How long is the coast of Britain? -- Statistical self-similarity and fractional dimension: Science, v. 156, p. 636-638.

Mandelbrot, B.B., 1983, The fractal geometry of nature: New York, Freeman and Co., 468 p.

Mylroie, J.E. and Carew, J.L., 1990, The flank margin model for dissolution cave development in carbonate platforms: Earth Surface Processes and Landforms, v. 15, p. 413-424.

Mylroie, J.E. and Carew, J.L., 1995, Karst development on carbonate islands, *in* Budd, D.A., Saller, A.H. and Harris, P.M., eds., Unconformities and porosity in carbonate strata: American Association of Petroleum Geologists Memoir 63, p. 55-76.

Mylroie, J.E., Panuska, B.C., Carew, J.L., Frank, E.F., Taggart, B.E., Troester, J.W. and Carrasquillo, R., 1995, Development of flank margin caves on San Salvador Island, Bahamas, and Isla de Mona, Puerto Rico, *in* Boardman, M.R., ed., Proceedings of the Seventh Symposium on the Geology of the Bahamas (1994): San Salvador, Bahamian Field Station, p. 49-81.

Quinif, Y., 1973, Contribution a l'étude morphologique des coupoles: Annales Spéléologie, v. 28, p. 565-573.

Richardson, L.F., 1961, The problem of contiguity: An appendix of statistics of deadly quarrels: General Systems Yearbook, v. 6, p. 139-188.

Slabe, T., 1995, Cave rocky relief and its speleogeneticalsignificance:Ljubljana, Znanstvenoraziskovalni Center SAZU, 128 p.

Veress, M., Pèntek, K. and Horvàth, T., 1992, Evolution of corrosion caverns: Ördög-lik Cave, Bakony, Hungary: Cave Science, v. 19, p. 41-50.

White, W.B., 1988, Geomorphology and hydrology of karst terrains: New York, Oxford University Press, 464 p.

Witten, T.A. and Sander, L.M., 1981, Diffusion limited aggregation, a kinetic critical phenomenon: Physical Review Letters, v. 47, p. 1400-1403.