PROCEEDINGS OF THE SEVENTH SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS

Edited by
Mark Boardman

Production Editor
Daniel R. Suchy

Bahamian Field Station, Ltd.
San Salvador, Bahamas
1995

Cover Photo: Outcrop showing Pleistocene soil profile,
caliche crust, and rhizocretions,
San Salvador, Bahamas.
Photo taken by Daniel R. Suchy.

Printed in USA by Don Heuer

ISBN 0-935909-55-9

DEVELOPMENT OF FLANK MARGIN CAVES ON SAN SALVADOR ISLAND, BAHAMAS AND ISLA DE MONA, PUERTO RICO

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ABSTRACT

San Salvador Island, Bahamas is a 161 km^2, tectonically stable late Quaternary carbonate island located 600 km east-southeast of Miami, Florida. San Salvador contains numerous flank margin caves (phreatic karst features) that developed primarily in late Pleistocene eolianites. These caves developed during a short time in very small fresh-water lenses. Cave elevations and Uranium-series ages from stalagmites indicate that all currently subaerial flank margin caves developed during the last interglacial sea-level highstand that was 6 m above current mean sea level 125,000 years ago (oxygen isotope substage 5e), which lasted no more than 15,000 years. The caves were formed by dissolution in the mixing zone at the margin of a freshwater lens that was elevated by the substage 5e highstand, and which resided within the small emergent portions of eolianite ridges. The flank margin caves have chambers with volumes greater than 1000 m^3 on San Salvador; on other Bahamian islands, chambers as large as 14,000 m^3 are known.

Isla de Mona is a 55 km^2, uplifted Late Miocene-Pleistocene carbonate platform located in the Mona Passage 60 km west of Puerto Rico. Most of the island has 40 to 80 m high vertical cliffs to the sea which contain numerous flank margin caves at various elevations. A few cave chambers have volumes in excess of 100,000 m^3. Paleomagnetic reversals observed in cave deposits and speleothems indicate the caves are at least 780,000 years old (Matuyama Reversal), and may be as old as pre-Pleistocene. This age indicates that the caves may have developed in a stable, freshwater lens prior to Pleistocene glacio-eustasy, and have been subsequently tectonically elevated to their current position. The great size of the flank margin caves indicate mixing-zone dissolution in a large freshwater lens over an extended period of time.

Flank margin caves on Isla de Mona, and some in the Bahamas contain evidence of two cycles of dissolution, in that speleothems and the cave wall rock to which they are attached show evidence of contemporaneous phreatic dissolution. In the Bahamas, the cause is most likely a minor change in sea level during the last interglacial highstand which caused a brief period of emergence, during which the subaerial speleothems grew, followed by re-submergence and dissolution. On Isla de

Mona, either tectonic motion, or the onset of glacio-eustasy, created the conditions that caused renewed phreatic dissolution after a period of subaerial exposure and speleothem precipitation.

Despite differences in rock age and geologic setting, both San Salvador and Isla de Mona show evidence of re-invasion of the flank margin caves by dissolutionally aggressive water following a vadose interval. The flank margin caves have very similar morphologies and characteristics, and the only major difference is that the Isla de Mona caves are more voluminous. This volume difference is attributable to the larger lens size and the longer duration of stable lens position on Isla de Mona. The data indicate that dissolution occurs rapidly in these environments, and despite the development of large voids, the same geochemical environment can be re-established after an emergence episode.

INTRODUCTION

The development of phreatic dissolution caves in carbonate islands occurs within the freshwater lens, which floats on the denser underlying marine water (Figure 1). As relative sea level changes, either as a result of local tectonics, or glacio-eustasy, the position of the lens changes as well. Consequently, phreatic cave development within the freshwater lens is tied to sea level.

The mixing of two water masses, each of which is saturated with respect to $CaCO_3$, can result in an undersaturated mixture. This phenomenon is true for the mixing of two freshwater masses (Bogli, 1964) and for the mixing of fresh and saline water (Plummer 1975). This mixing-produced undersaturation creates two favored sites for carbonate dissolution: the top of the lens (water table) where vadose and phreatic freshwaters mix, and the bottom of the lens (halocline or mixing zone) where fresh and saline waters mix (Mylroie and Carew, 1988). Even with the additional carbonate dissolution that is possible under these two conditions, there is only a small, finite amount of dissolution per unit time that can be accomplished by simple inorganic mixing of these waters (Sanford and Konikow, 1989).

In settings such as the Bahamas, the elevation and timing of past glacio-eustatic sea-level highstands allows constraints to be placed on freshwater lens history. The amount of phreatic dissolution observed under these conditions (Smart and others, 1988; Mylroie and Carew, 1990; Mylroie and others, 1991; Wicks and others, 1993; Wicks and Troester, 1994) indicates that mixing-produced undersaturation may not be sufficient to produce the observed amount of phreatic cave development in the limited time available. The top and bottom of the freshwater lens are density interfaces, which tend to trap organic material. The oxidation of these organics can lead to localized anoxic conditions, and as the density interfaces migrate slightly in response to changes in sea level, complex oxidation and reduction reactions can occur. These reactions can result in the production of significant acidity, which may double the dissolution rate at the interfaces (Bottrell and others, 1991). Field investigations in the Bahamas have shown that the necessary organic material is present in the current freshwater lens (Mylroie and Balcerzak, 1992) and that oxidation and reduction reactions involving sulfur have assisted phreatic cave development (Bottrell and others, 1993).

This paper compares the development of a specific type of phreatic dissolution cave, flank margin caves (Mylroie and Carew, 1990), in the Bahama Islands (San Salvador Island in particular), with those found on Isla de Mona, Puerto Rico. The Bahamas represent a well-constrained situation where lens size, amplitude, and duration are known. On the other hand, Isla de Mona is an older island that has experienced tectonic uplift. As a result, conditions are different and have produced caves with greater size than those seen in the Bahamas, but the Isla de Mona caves are still compatible with the overall flank margin model of cave development.

SETTING

Bahamas

The Bahama Islands are a 1000 km long portion of a NW-SE trending archipelago that extends from Little Bahama Bank off the coast of south Florida to Great Inagua Island, just off the coast of Cuba (Figure 2). The northwestern Bahamas are isolated landmasses that project above sea level from two large carbonate platforms, Little Bahama Bank and Great Bahama Bank. To the southeast, beginning in the area of San Salvador Island,

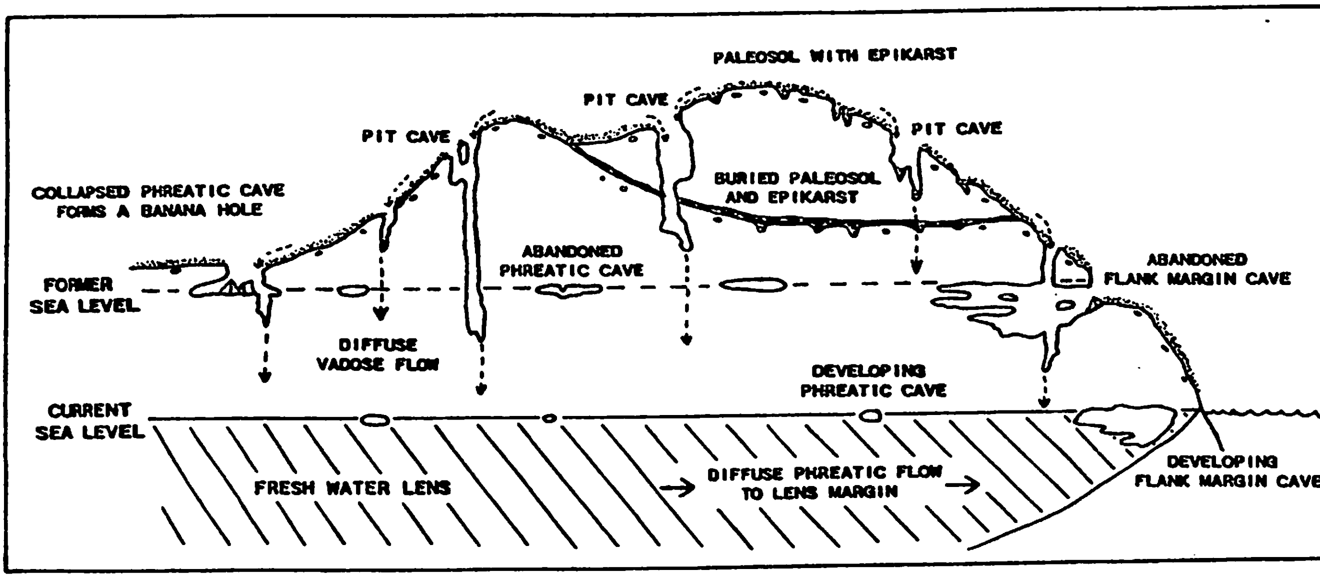


Figure 1. Diagrammatic representation of the freshwater lens within a carbonate Island, showing vadose versus phreatic environments, a sea-level change, and the resultant products.

Figure 2. Map of Caribbean and the Bahamas, showing the location of San Salvador Island and Isla de Mona.

the Bahamas comprise small isolated platforms many of which are capped by islands that make up a significant portion of the available platform area. The Bahamian platforms have been sites of carbonate deposition since at least the Cretaceous, and have a minimum thickness of 5.4 km (Meyerhoff and Hatten, 1974) and perhaps as much as 10 km (Uchupi and others, 1971). The large platforms to the northwest are dissected by deep channels and troughs; the isolated platforms to the south are surrounded by deep water. Water depth on the platforms is generally less than 10 m.

The surficial rocks of the Bahamas are late Quaternary carbonates, which are a mosaic of subtidal, beach, eolian and paleosol facies (Carew and Mylroie, 1995). All land greater than 6 m elevation above mean sea level is eolianite. All subaerially-exposed subtidal facies formed during the last interglacial (oxygen isotope substage 5e) approximately 125,000 years ago. The Bahama Islands show no structural deformation, are tectonically stable, and may be currently subsiding at a rate of 1 to 2 m per 100,000 years or less (Carew and Mylroie, 1994).

San Salvador Island (Figures 2 and 3) has been the site of extensive geological research under the auspices of the Bahamian Field Station, which has produced an excellent geologic data base (Carew and Mylroie, 1995). San Salvador is on a platform only slightly larger than the island itself; therefore it did not change size appreciably during glacio-eustatic sea-level lowstands. Today, San Salvador encompasses 161 km^2 of area, with a maximum elevation of 40 m above mean sea level. The island topography is dominated by numerous eolianite ridges, with intervening swales that often extend below sea level and are occupied by saline to hypersaline lakes (Figure 3). The island contains many phreatic caves that formed when sea level was higher than it is today. Those caves are now dry, and many have been located, mapped, and characterized by Vogel and others (1990).

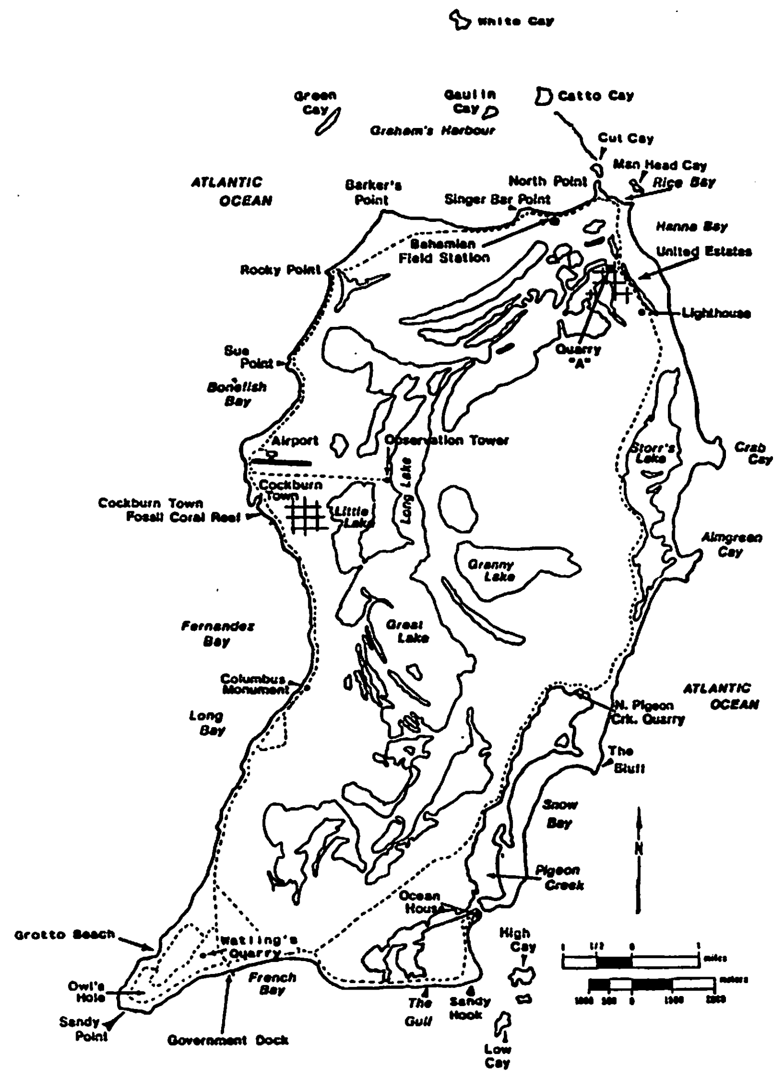


Figure 3. Map of San Salvador Island, Bahamas.

Isla de Mona, Puerto Rico

Isla de Mona, Puerto Rico, is a nearly circular, 55 km^2 uplifted Miocene-Pleistocene carbonate platform. It is located in Mona Passage, midway between Puerto Rico and Hispaniola (Figures 2 and 4). Except for a narrow coastal plain of Pleistocene limestones along the south coast, the island is bounded by 40 to 80 m vertical cliffs that continue at least another 40 m below sea level (Briggs and Seiders, 1972). The top of the island is planar, with a few closed depressions (Figure 4).

The bulk of Isla de Mona consists of carbonate rocks that were originally thought to be Miocene in age (Kaye, 1959; Briggs, 1974), but are now considered to consist of Miocene-Pliocene rocks (Gonzalez and others, 1993; Ruiz, 1993; Taggart and Gonzalez, 1994). The rocks that form the narrow coastal plain along the south side of the island are late Pleistocene in age, correlative with the last interglacial 125,000 years ago (Taggart and Moore, in press). Older Pleistocene outcrops are found at higher elevations on the Miocene-Pliocene plateau (Gonzalez and others, 1993; Ruiz, 1993). The Miocene-Pliocene rocks have been divided into two units, the Isla de Mona Dolomite, and the overlying Lirio Limestone. Paleosols are found within the Isla de Mona Dolomite, and on the surface of the Lirio Limestone. The Lirio Limestone is the more cavernous of the two units.

Isla de Mona, which is located on one of several small plate fragments containing Puerto Rico and Hispaniola, has been tectonically uplifted because that plate is rotating counter-

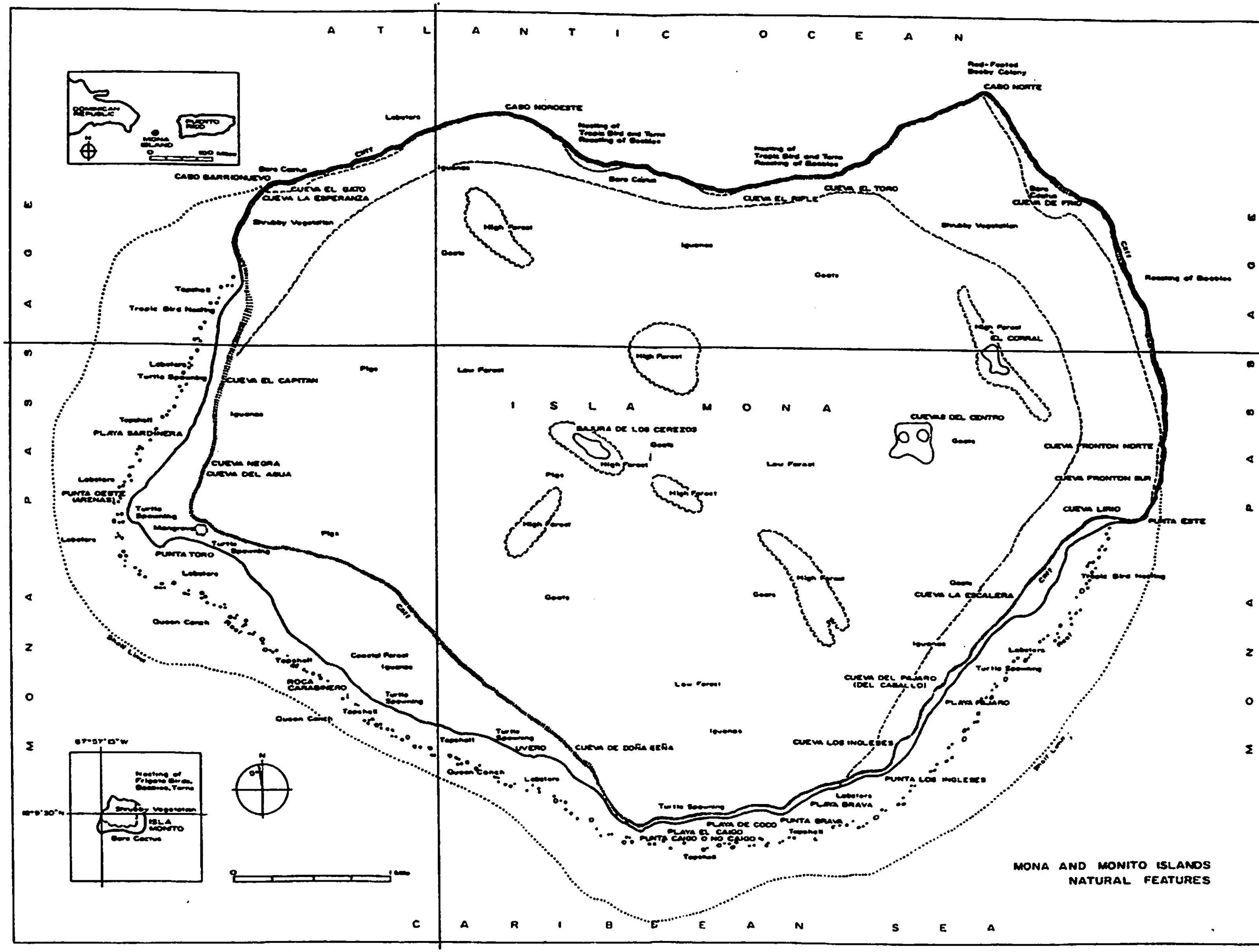


Figure 4. Map of Isla de Mona, Puerto Rico.

clockwise as a result of the oblique strike-slip motion of the surrounding Caribbean and North American plates (Masson and Scanlon, 1991). The tectonic movement has produced broad synclines and anticlines that on Isla de Mona plunge gently to the south or southeast (Kaye, 1959). There are also a series of SE-trending faults, with up to 10 m of vertical displacement (Briggs and Seiders, 1972).

Isla de Mona is especially notable for the large and extensive caves that extend inward from the vertical cliffs of the Miocene-Pliocene carbonate rocks. The periphery of the island is literally ringed with cave entrances at a variety of elevations. The current subaerial exposure of the caves today is largely the result of tectonic uplift rather than the result of glacio-eustasy in the Quaternary. Thus, the comparison of San Salvador Island to Isla de Mona allows the importance of tectonic uplift in the formation and evolution of these caves to be determined.

FLANK MARGIN CAVES

Flank margin caves are phreatic dissolution caves developed at the margins of the freshwater lens of carbonate islands. The term is derived from their environment of development in the Bahamas: under the flanks of eolian ridges in the distal margin of a discharging freshwater lens (Figure 1). In this environment, the freshwater lens thins at the margin and the vadose-phreatic mixing zone at the top of the lens is superimposed on the saline-freshwater mixing zone at the base of the lens, thus maximizing dissolution (Mylroie and Carew, 1990).

The morphology of the flank margin caves depends on the amount and pathway of the water discharge from the freshwater lens, the water chemistry, and the time available. In the Bahamas, the caves generally consist of globular chambers located just inside the eolian ridge (Figure 5). A series of such chambers may interconnect along the strike of the eolian ridge. The back of these chambers generally consists of a maze of small interconnecting passages that subdivide into tiny tubes. In some cases, large passages extend some distance into the ridge before abruptly terminating. Flank margin caves formed from the outside in; that is, as the various mixing processes dissolve the rock, a chamber forms. The mixing front then migrates toward the back wall of the chamber, and the chamber enlarges headward, up into the flow of discharging freshwater. This process routinely produces thin bedrock partitions and pillars in the main chamber of the cave (Figure 5). The large dead-end passages formed along preferential flow routes for the discharging fresh water. Their abrupt end marks the site of the mixing front when sea level fell and the cave was drained. Entrances to the caves are most commonly formed when erosion of the hillside breaches the main chamber.

Flank Margin Caves of the Bahamas

Flank margin caves are common throughout the Bahamas, and many have been described in detail (Palmer and others, 1986; Mylroie, 1988; Carew and Mylroie, 1989; Vogel and others, 1990; Mylroie and others, 1991). Because of the abundant existing descriptive literature, detailed cave descriptions for the Bahamas are not included here, but a brief overview follows.

During the last interglacial (125,000 years ago, oxygen isotope substage 5e), sea level was approximately 6 m higher than it is today. The only subaerially-exposed land masses in the Bahamas at that time were eolian ridges formed during earlier sea level highstands, or eolian ridges constructed on the transgression of the substage-5e highstand (Carew and Mylroie, 1995). These ridges were of limited areal extent. The substage-5e highstand lasted no more than 15,000 years (Chen and others, 1991). So, the Bahamian flank margin caves developed in very small freshwater lenses within a very brief period of time. Only the geochemical reactions associated with inorganic mixing of waters, coupled with oxidation and reduction reactions, is capable of making caves in such small lenses in so short a time.

All air-filled flank margin caves found throughout the Bahamas formed during the last interglacial sea-level highstand (Mylroie and others, 1991). The previous glacio-eustatic sea-level highstands were either not high enough (e.g. oxygen isotope stage 7, approximately 220,000 years ago), or were too long ago and any caves formed then would by now have subsided below modern sea level (e.g. oxygen isotope stage 9, approximately 330,000 years ago). These conditions

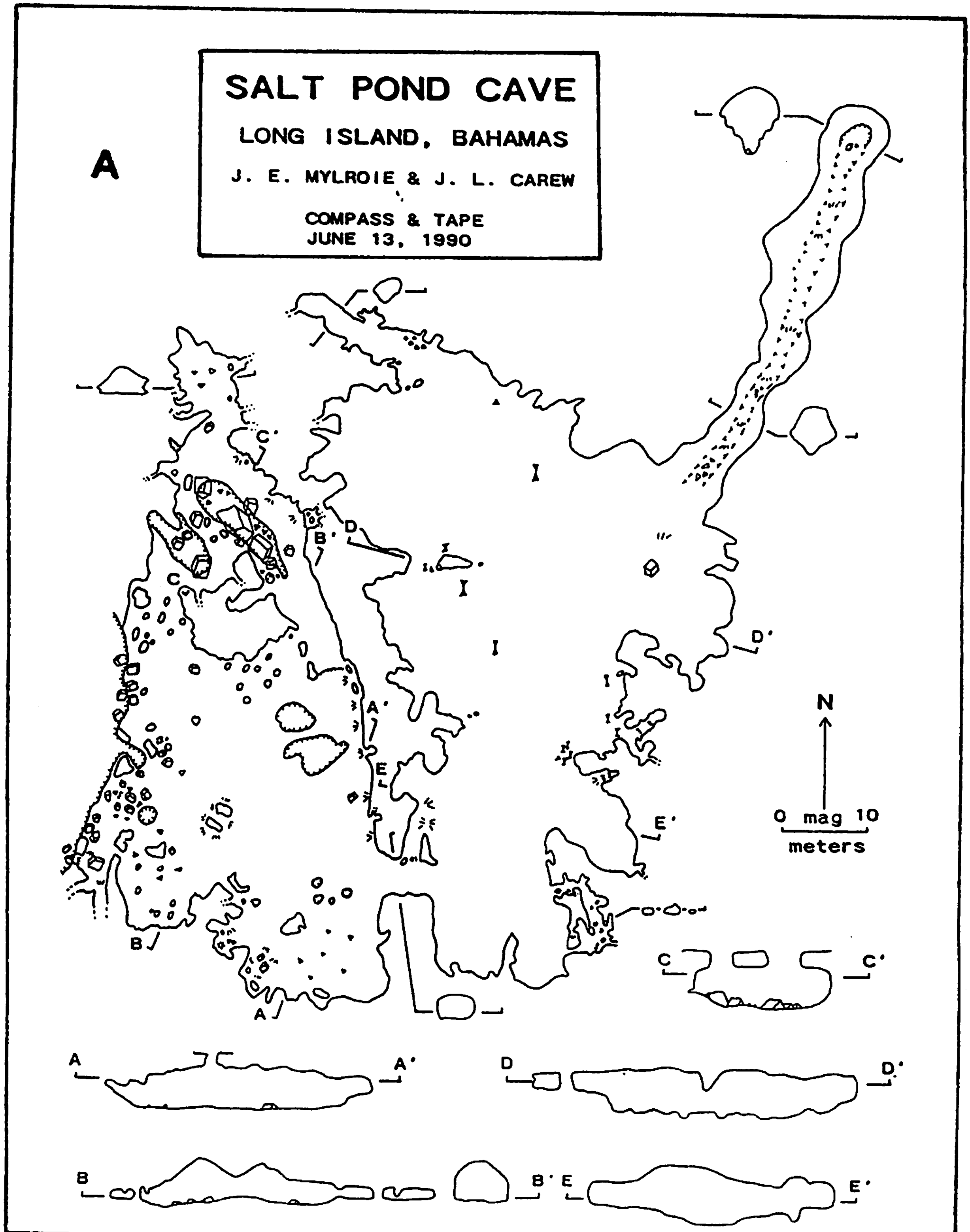
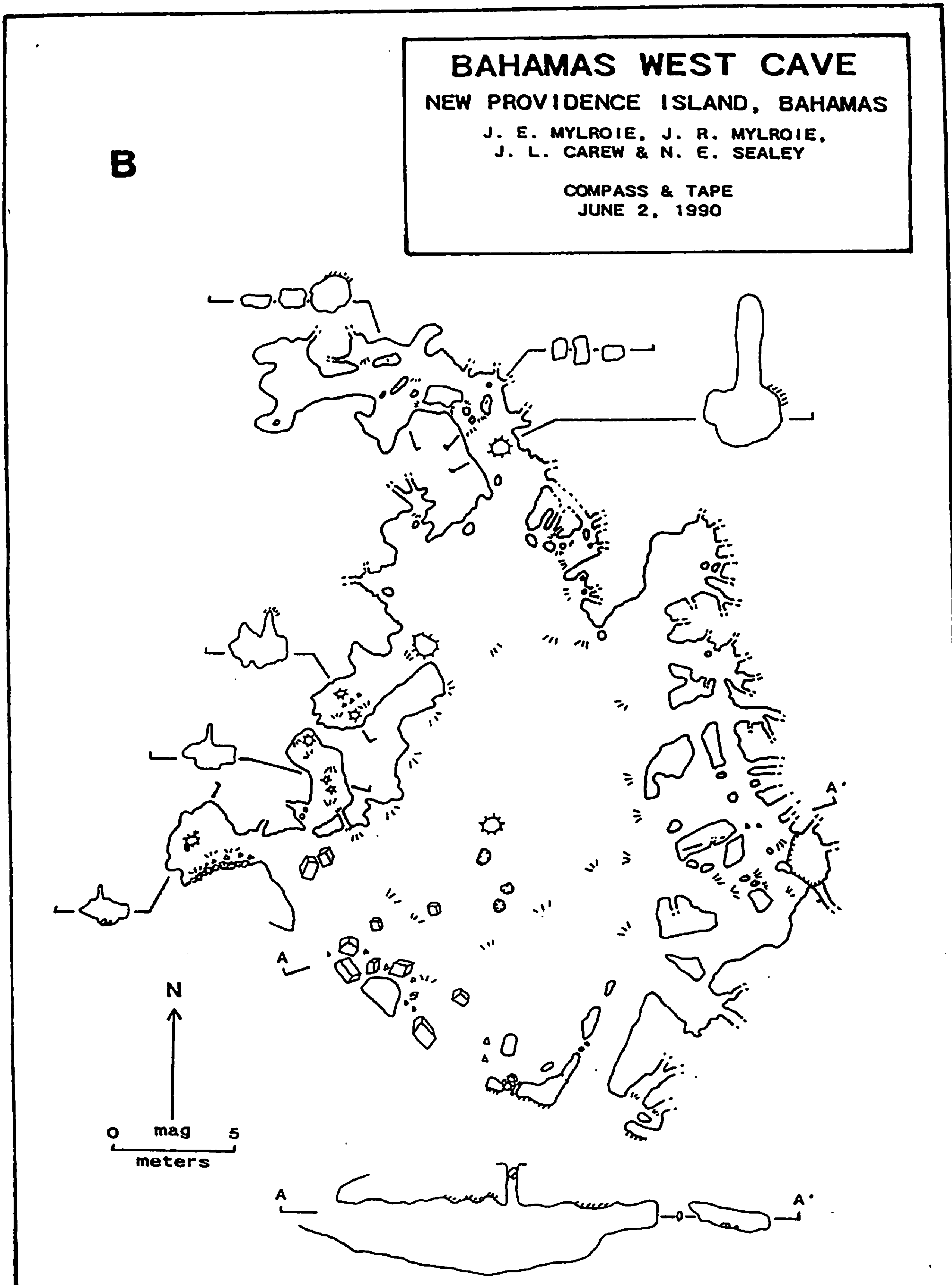


Figure 5. Maps of typical Flank Margin caves of the Bahamas. Hachured lines indicate cliff and pit entrances, and interior vertical drops; rectangular blocks and open triangles represent collapse debris; solid triangles indicate calcite speleothems; sets of three diverging lines indicate lower levels. 5A, Salt Pond Cave; 5B, Bahamas West Cave; 5C, Lighthouse Cave.



BAHAMAS WEST CAVE
NEW PROVIDENCE ISLAND, BAHAMAS
J. E. MYLROIE, J. R. MYLROIE,
J. L. CAREW & N. E. SEALEY
COMPASS & TAPE
JUNE 2, 1990
B
A
A'
N
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A
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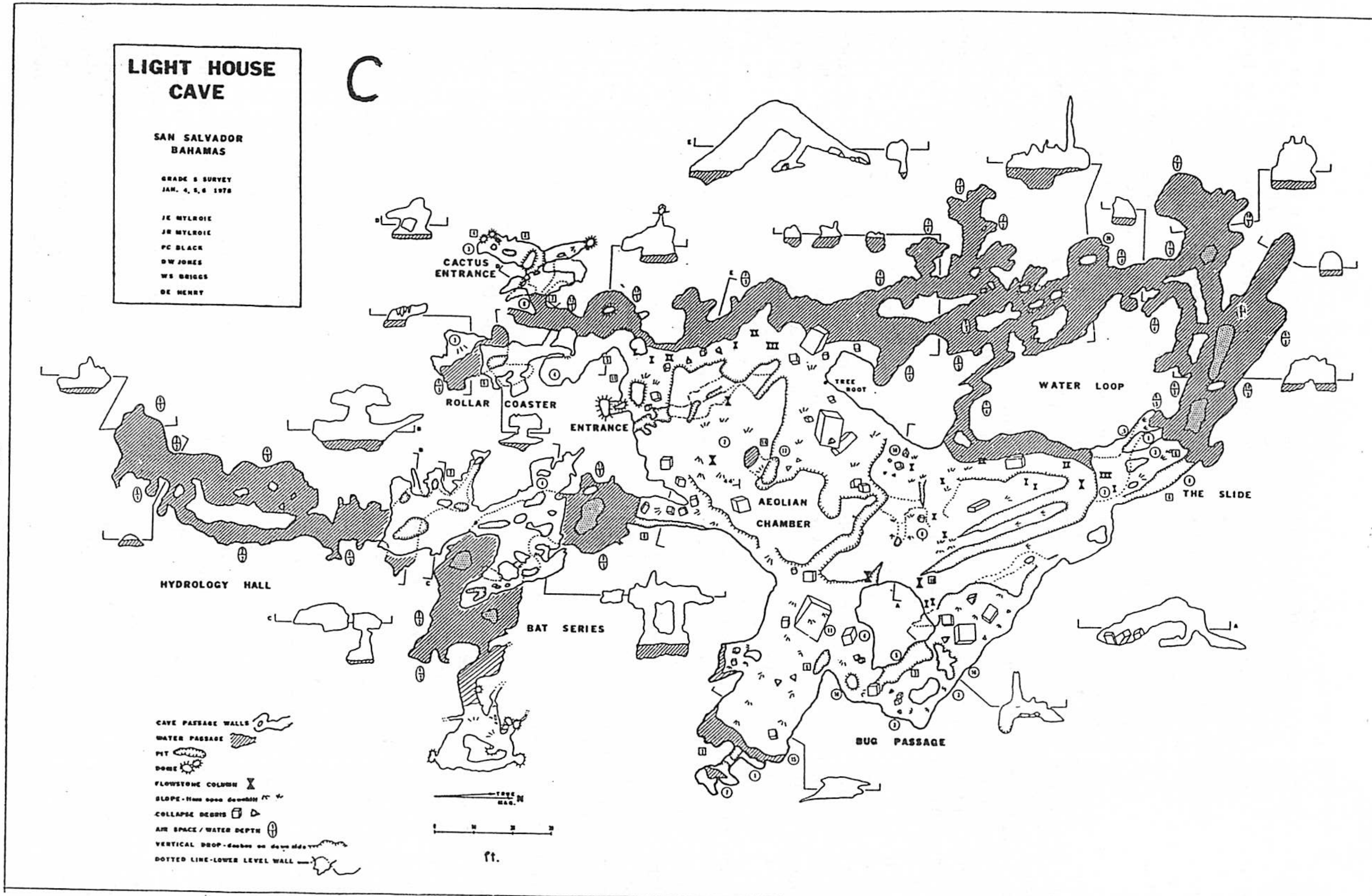

LIGHT HOUSE CAVE
SAN SALVADOR
BAHAMAS
GRADE 5 SURVEY
JAN. 4, 5, 6 1978
JE MYLROIE
JR MYLROIE
PC BLACK
DW JONES
WS BRIGGS
DE HENRY
C
CACTUS ENTRANCE
ROLLAR COASTER
ENTRANCE
TREE ROOT
WATER LOOP
THE SLIDE
AEOLIAN CHAMBER
HYDROLOGY HALL
BAT SERIES
BUG PASSAGE
CAVE PASSAGE WALLS
WATER PASSAGE
PIT
DOME
FLOWSTONE COLUMN
COLLAPSE DEBRIS
AIR SPACE / WATER DEPTH
VERTICAL DROP
DOTTED LINE-LOWER LEVEL WALL
ft.

rigorously constrain the time window available for the formation of these caves (Carew and Mylroie, 1994).

For San Salvador Island, the average plan area for the flank margin caves is 96 m^2, with a maximum of 1,700 m^2; their average density is 1.1 per km^2 (Wilson and others, 1994). The largest cave on San Salvador, Lighthouse Cave, has a main chamber with a volume greater than 1,000 m^3; the largest mapped chamber in the Bahamas is in Salt Pond Cave, Long Island (Figure 5), which has a volume of 14,000 m^3 (Mylroie and others, 1991). The vast majority of flank margin caves are found in eolianites that were in place prior to the substage 5e highstand (Schwabe and others, 1993).

The flank margin caves of the Bahamas are extremely similar. The morphology and pattern of the caves (Figure 5) is consistent from island to island (Mylroie and Carew, 1990). They all formed in a short time (15,000 years), in very small lenses, at approximately the same time in the same rock type, and at the same elevation. Their internal configuration is very similar even on islands 800 km apart. Such consistency argues for a strong, overriding control of cave development that operates effectively over a short time-frame in small lenses. The flank margin model explains what is seen in the tightly constrained setting of the Bahama Islands; but does the model work in a more complicated setting?

Flank Margin Caves of Isla de Mona

The large caves that are found in the cliffs of Isla de Mona are also flank margin caves. Other than an unpublished MSc. thesis on the caves of Isla de Mona (Frank, 1993) and a few general comments made by Kaye (1959), Briggs and Seiders (1972), and Briggs (1974), almost no detailed descriptions of these caves exist. For this reason, a few representative cave descriptions are presented in detail in Appendix I, and maps of these caves are shown as Figures 6 - 12. The caves of Isla de Mona have been breached by erosional retreat of the cliffs containing them (Figure 13). Large talus blocks, some containing complete or partial cave chambers, can be found at the foot of the cliffs along the southern coast of the island, where a terrace of Pleistocene limestone abutting the Miocene-Pliocene cliffs acts as a catchment for the talus. On the cliffs themselves, cave chambers gape seaward, their outer walls having fallen away. Stalagmites and stalactites can be seen in the open air, and can be found on the talus blocks below, pointing in random directions due to block rotation.

The Isla de Mona caves are consistent with the model for flank margin caves, that is, caves formed in the discharging margin of a fresh or brackish water lens. They each have one or more large, central chambers joined to each other by a series of arches and tubes. The periphery of the caves are marked by wide, low chambers that end in bedrock walls. These bedrock walls often contain very small tubular passages that subdivide several times, as well as cuspate wall pockets, rock pendants, bedrock partitions, and pillars (see Figures 6 - 12).

The cave descriptions (Appendix I, Figures 6 - 12) are of caves that are among the smallest on Isla de Mona. They have been mapped specifically because their small size allowed completion of the survey work during limited field seasons. As shown on the geologic map of Isla de Mona, other flank margin caves commonly have floor areas of greater than 50,000 m^2, and some range up to 128,000 m^2 (Briggs and Seiders, 1972). The ceiling height of some chambers is 8 m or more, producing single voids with volumes around 100,000 m^3. These large caves are not concentrated at any one locale on the island. They are found on the east coast (e.g. Cueva de las Losetas, Cueva al Lado del Faro, Cueva del Lirio), the south coast (e.g. Cueva de los Pajaros), the west coast (e.g. Cueva del Diamante, Cueva del Capitan) and the north coast (e.g. Cueva del Espinal, Cueva del Toro) (Briggs and Seiders, 1972).

All caves entered on Isla de Mona show extensive evidence of phreatic dissolution of speleothems or subaerial calcites (e.g. stalactites, stalagmites, flowstone) that formed under vadose conditions (Figure 14). In addition, the caves also show evidence of intersection by vertical shafts formed in the vadose zone, which in many cases led to the introduction of paleosol breccia into the caves. This breccia has also been subsequently modified by phreatic dissolution (Figure 15).

A magnetostratigraphic study of deposits in Cueva del Aleman is currently in progress (Figure 12). The initial results show a reversely magnetized dripstone column (joined stalactite and stalagmite) overlying a normally magnetized poolstone (secondary calcite

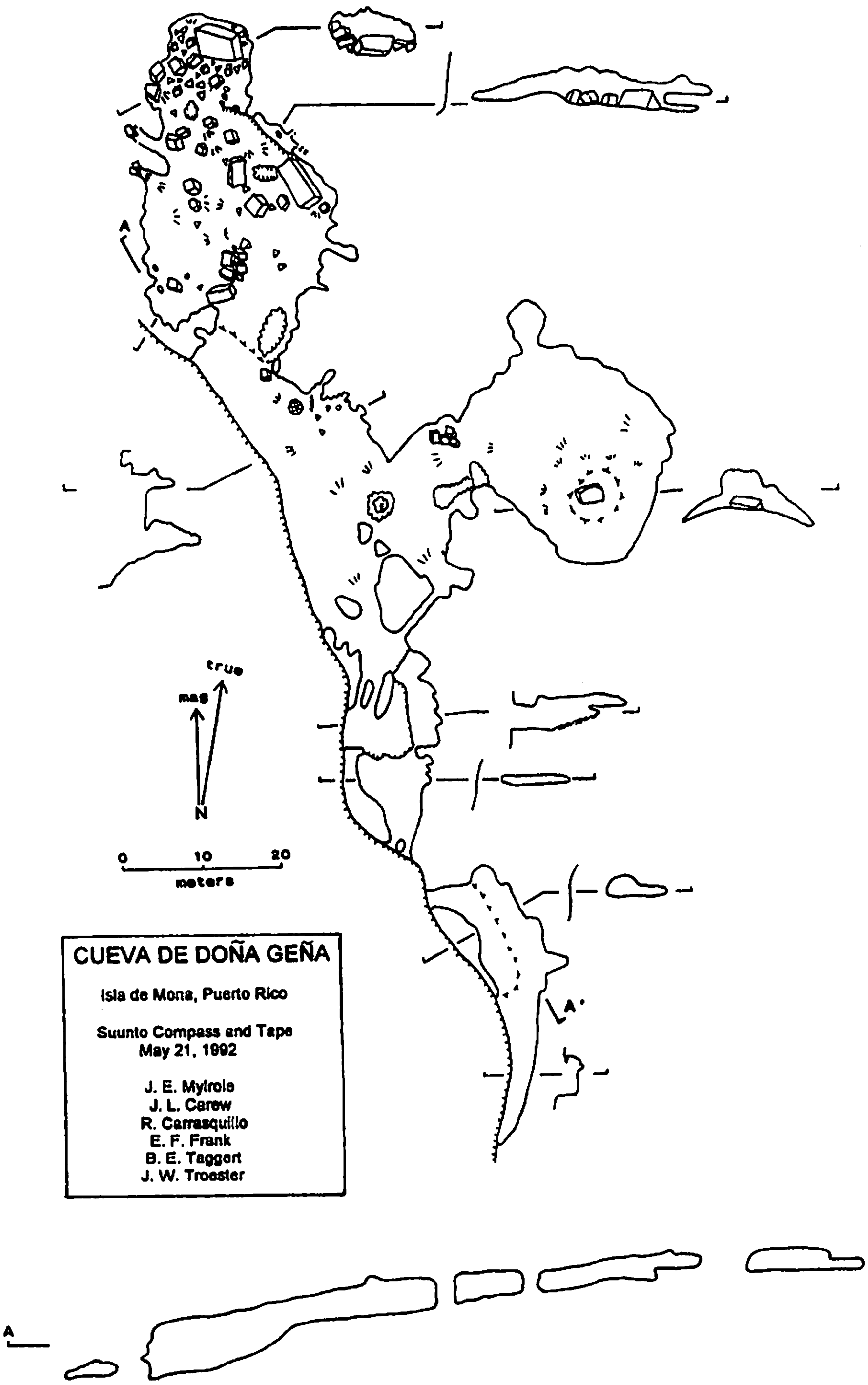


Figure 6. Map of Cueva de Dona Gena, Isla de Mona, Puerto Rico. Symbols same as for Figure 5.

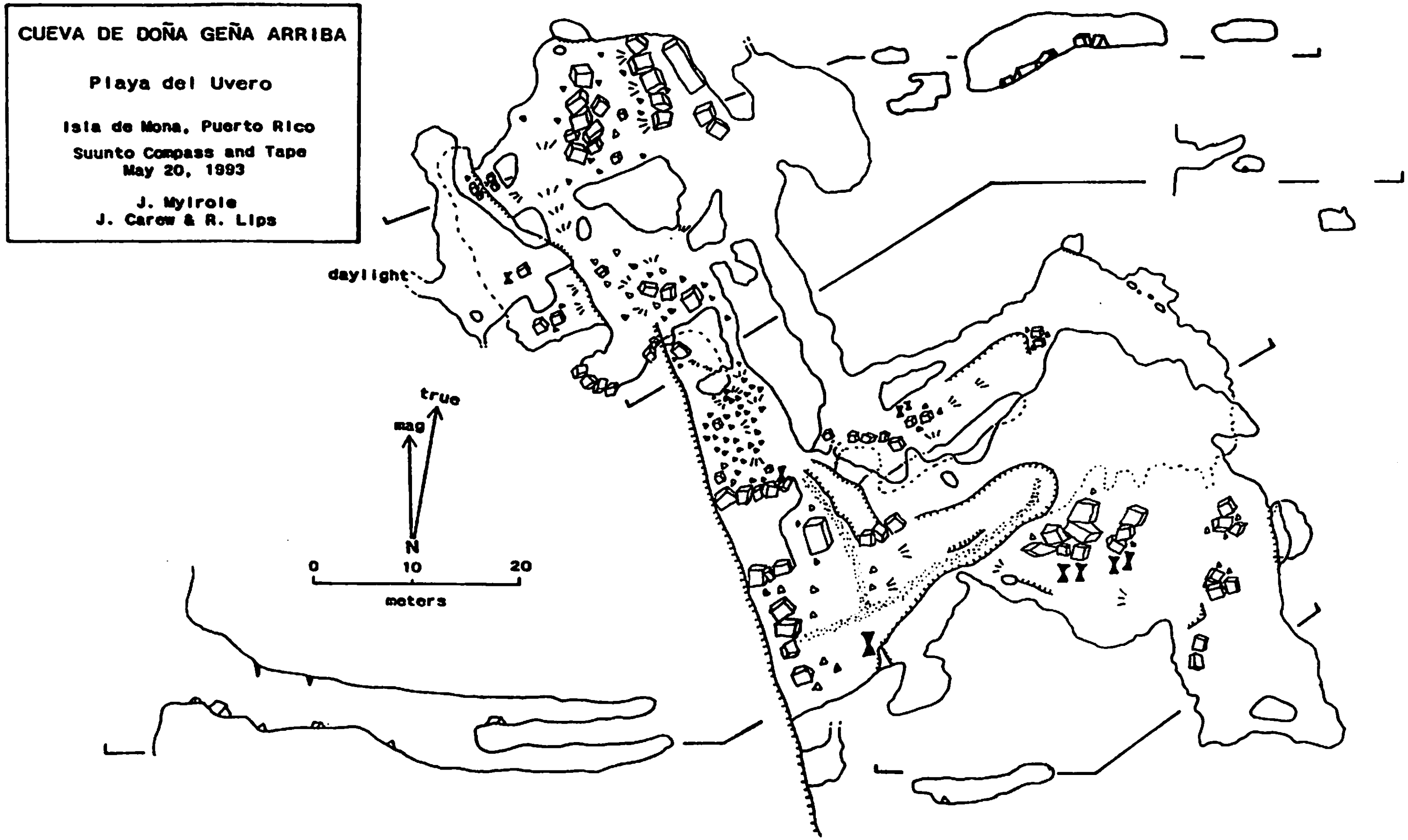


Figure 7. Map of Cueva de Dona Gena Arriba, Isla de Mona, Puerto Rico. Symbols same as for Figure 5.

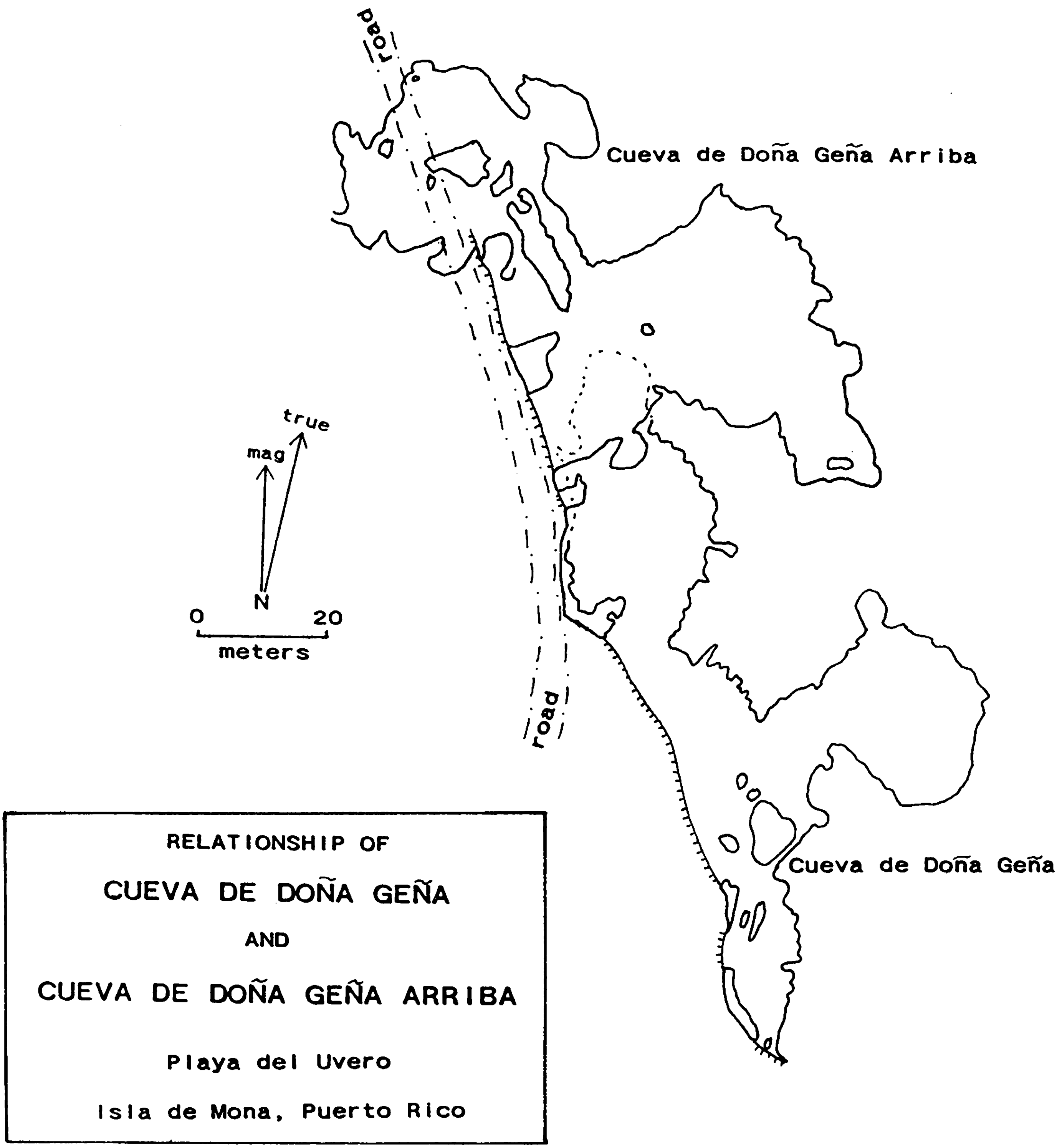


Figure 8. Outline map of Cueva de Dona Gena Arriba over Cueva de Dona Gena, Puerto Rico.

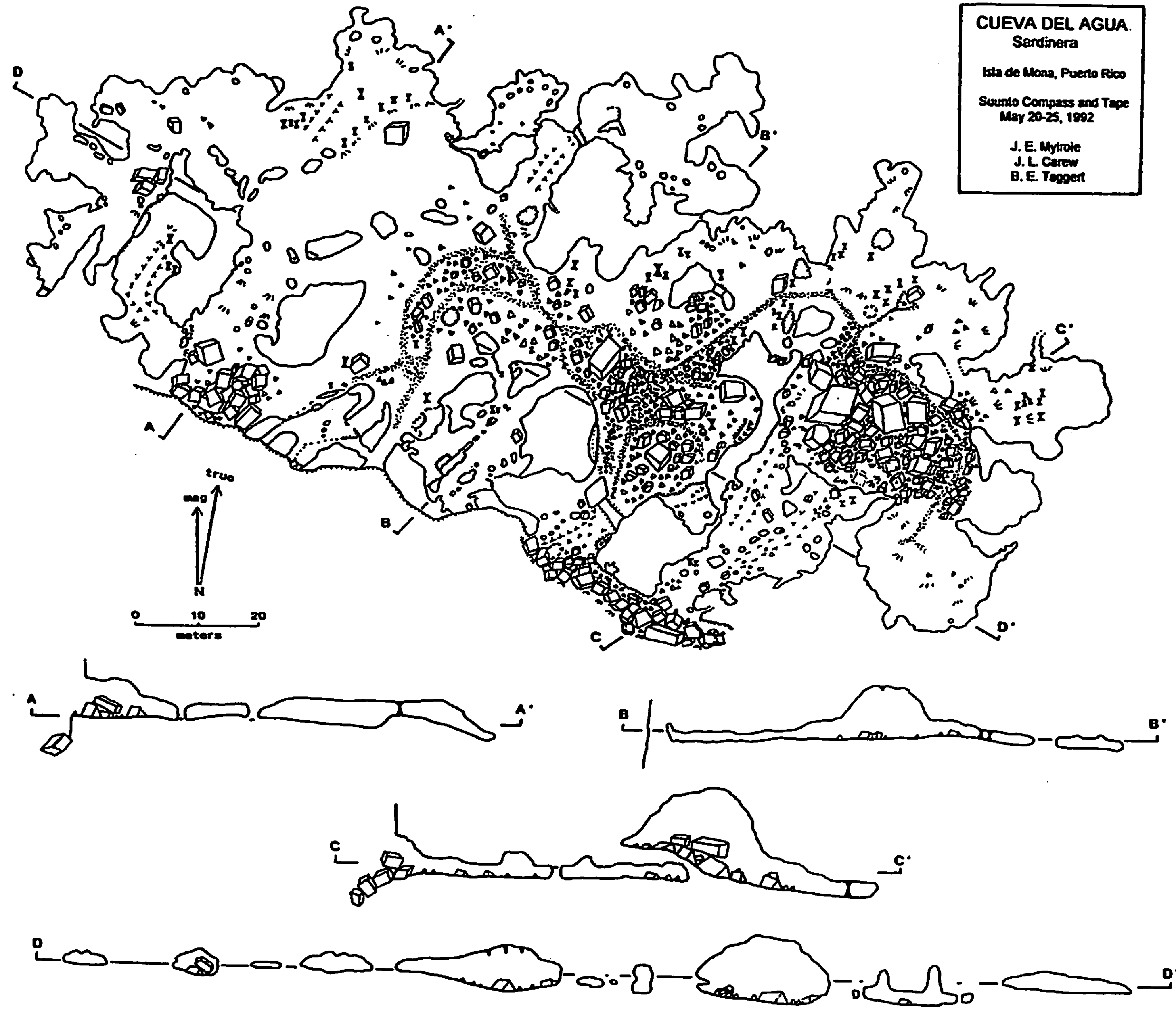


Figure 9. Map of Cueva de Sardinera, Isla de Mona, Puerto Rico. Symbols same as for Figure 5.

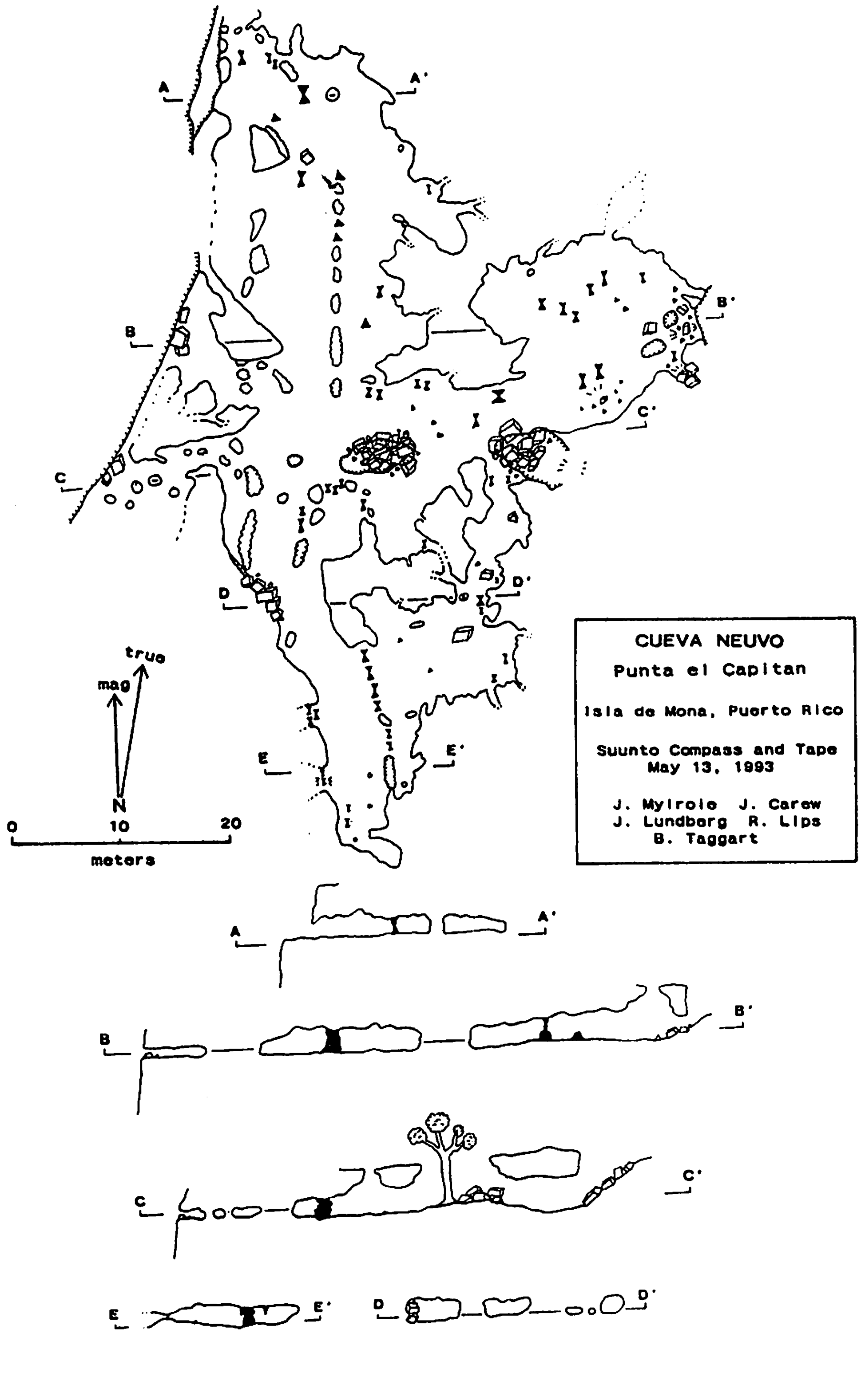


Figure 10. Map of Cueva Neuvo, Isla de Mona, Puerto Rico. Symbols same as for Figure 5.

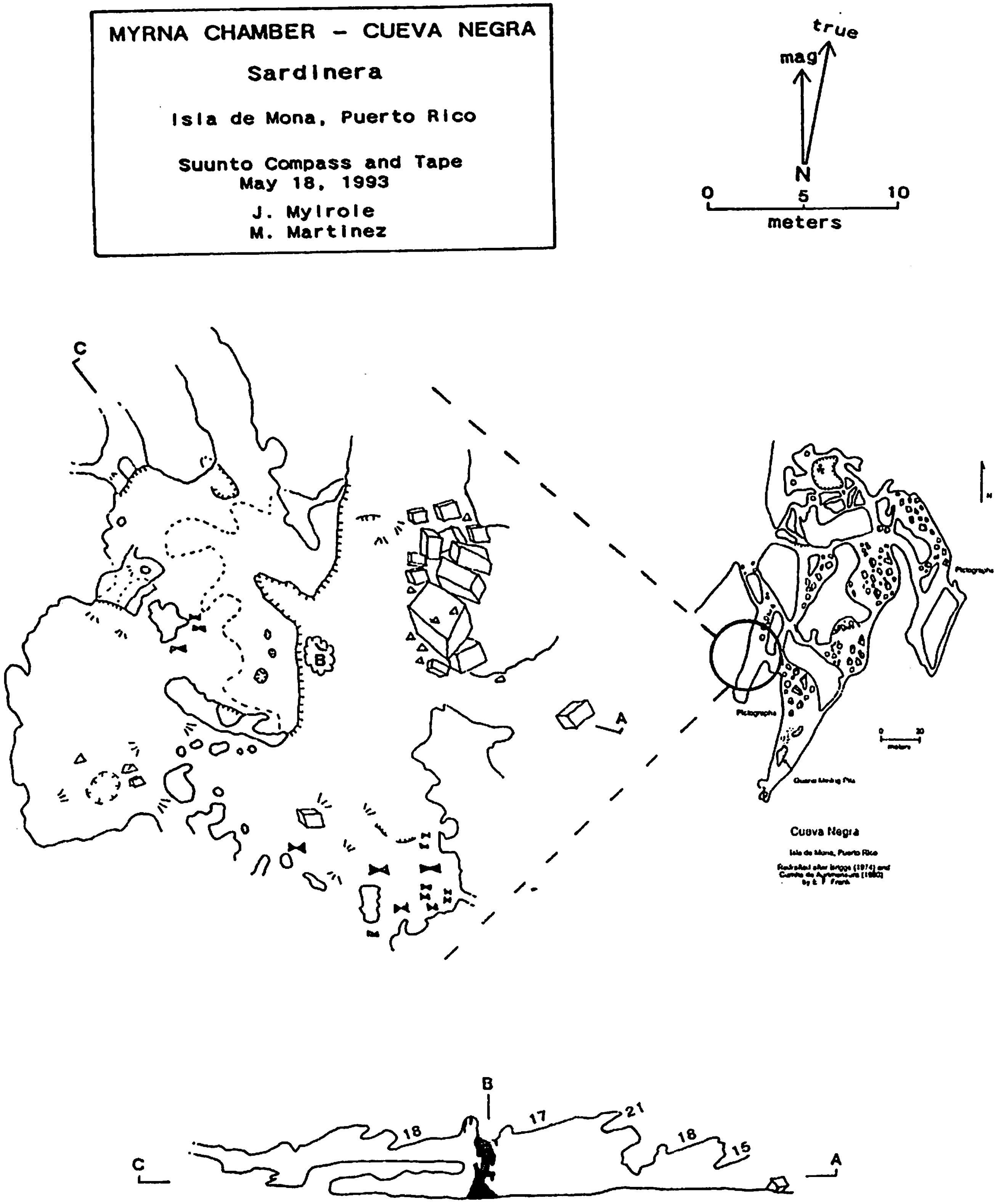


Figure 11. Map of Myrna Chamber, Cueva Negra, Isla de Mona, Puerto Rico. Symbols same as for Figure 5, numerals are measured depositional dips of the bedrock.

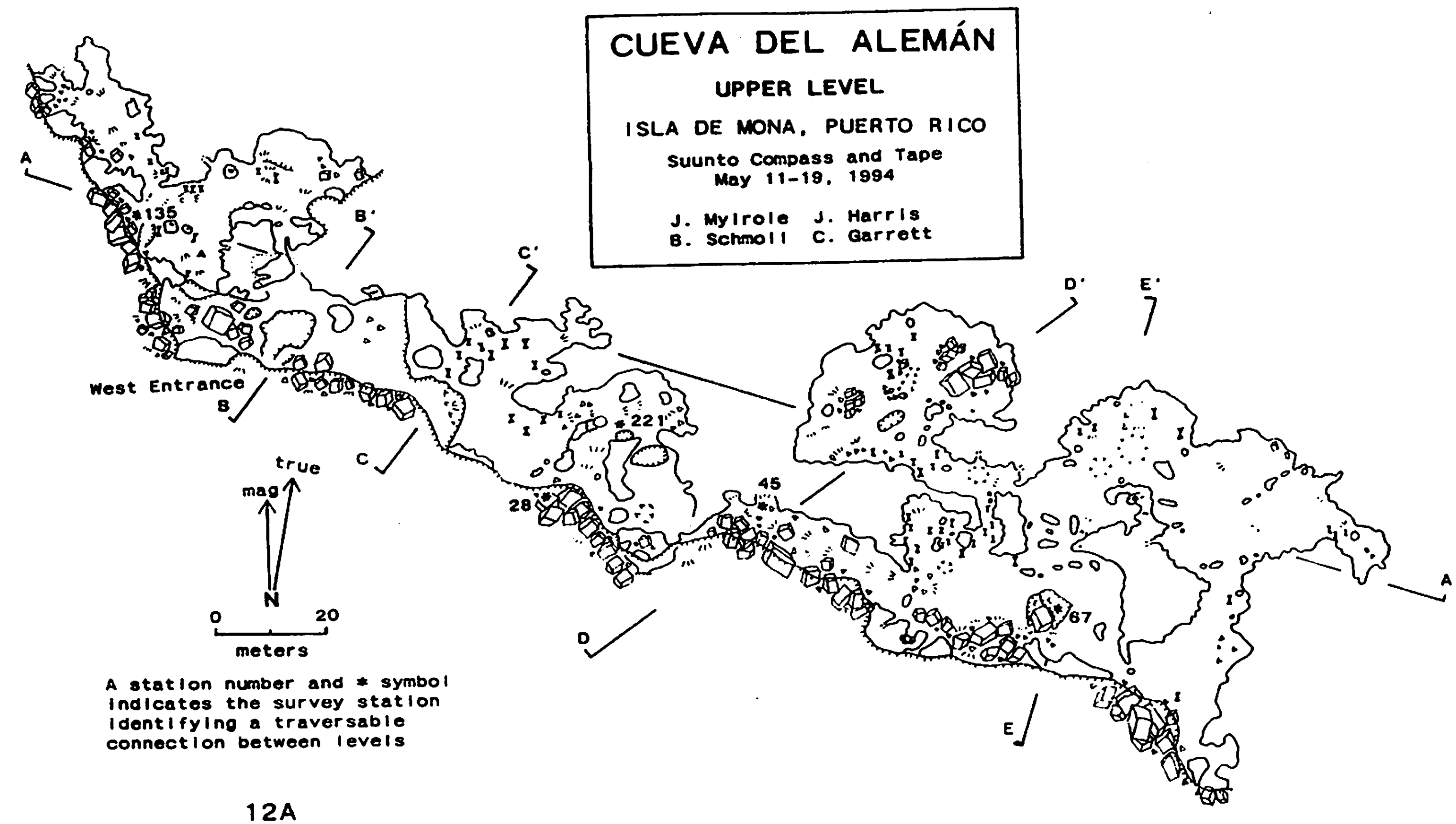
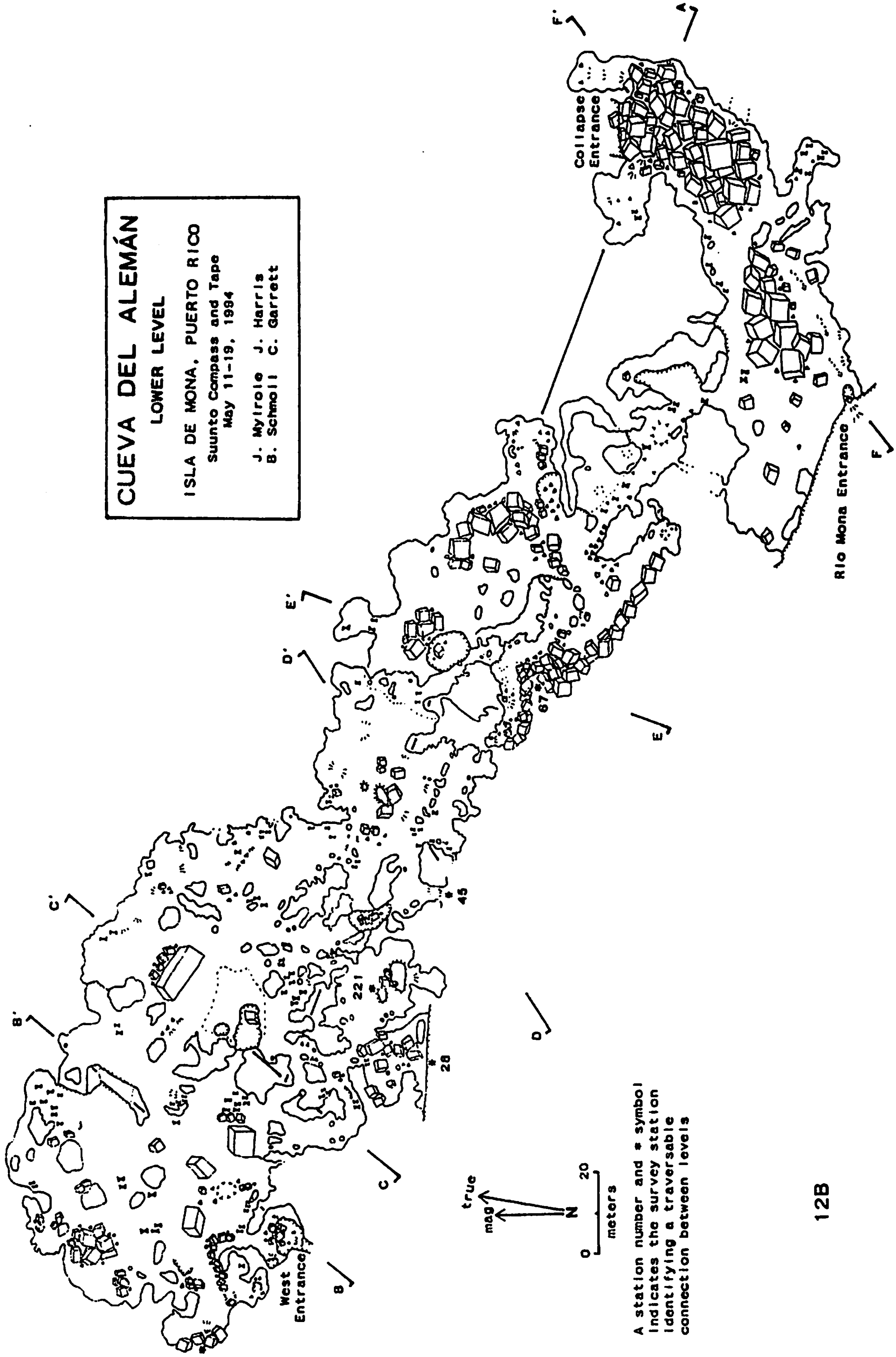
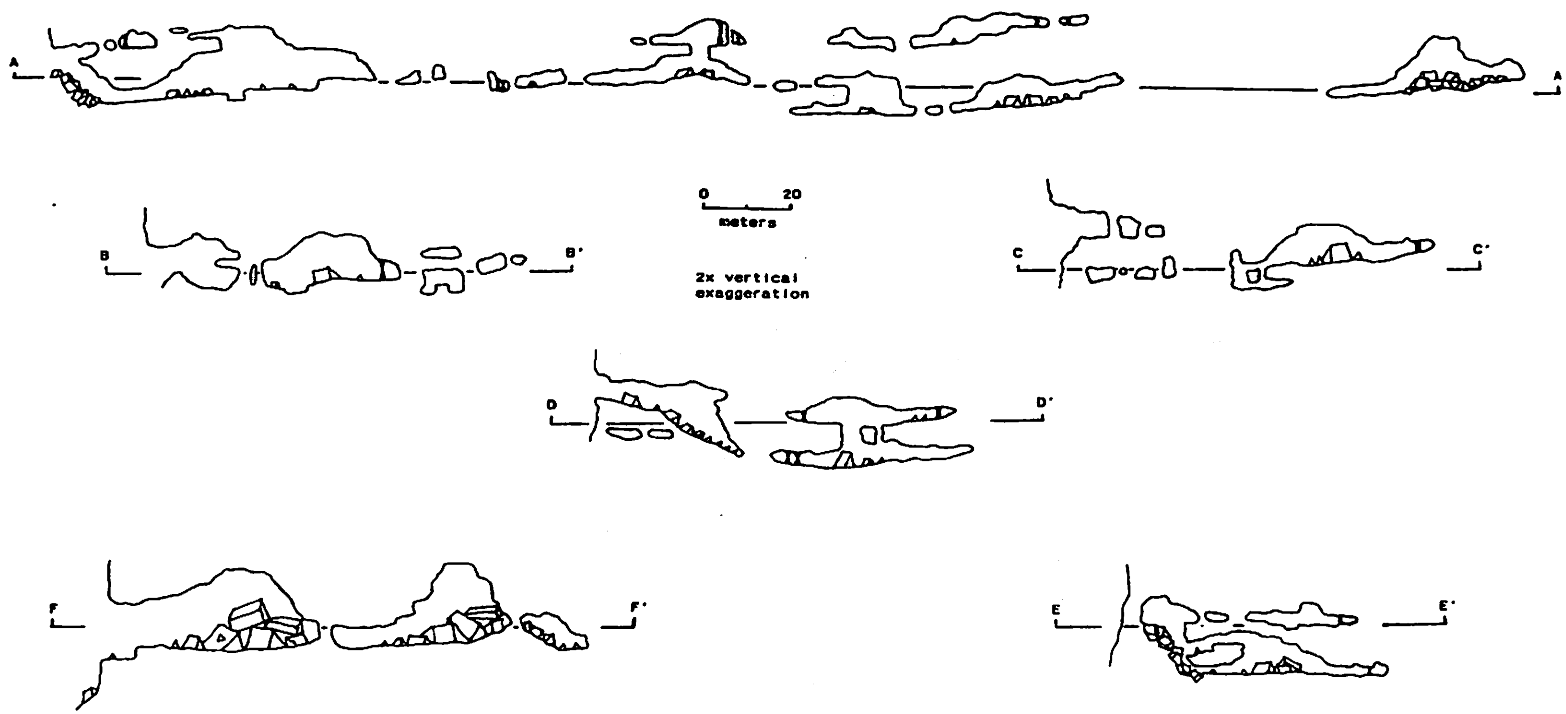


Figure 12. Map of Cueva del Aleman, Isla de Mona, Puerto Rico. 12A, upper level of Cueva del Aleman; 12B, lower level of Cueva del Aleman; 12C, cross sections of Cueva del Aleman. Symbols same as for Figure 5.


CUEVA DEL ALEMÁN
LOWER LEVEL
ISLA DE MONA, PUERTO RICO
Suunto Compass and Tape
May 11-19, 1984
J. Mylroie J. Harris
B. Schmoll C. Garrett
Collapse Entrance
Rio Mona Entrance
West Entrance
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
135
28
221
45
67
true
mag
N
0
20
meters
A station number and * symbol indicates the survey station identifying a traversable connection between levels
12B

CUEVA DEL ALEMÁN CROSS SECTIONS



12C

Figure 13. Cave entrances and cliffs on Isla de Mona, Puerto Rico. 13A, cliff at Playa Brava, southeastern coast of Isla de Mona, showing breached cave openings and talus below; note the curved surface of the former back wall of the cave chamber and the speleothems now exposed to the outside environment; cliff in foreground is 15 m high. 13B, entrances to Cueva del Lirio, on the east coast of Isla de Mona, with person at right for scale; note the cave entrances and talus receding into the background.

Figure 14. Photograph of a section of the cave wall in Cueve del Lirio, Isla de Mona, Puerto Rico, with a pocket knife for scale. The dark patches are layered flowstone deposits that have been phreatically dissolved. Note that the smooth dissolution surface cuts across both the wall rock and the flowstone, indicating that the chamber has phreatically enlarged since the flowstone deposition.

Figure 15. Photograph of a portion of the roof of a chamber in Cueva de los Pajaros, on the southeastern portion of Isla de Mona, Puerto Rico. The material consists of white limestone fragments in a reddish carbonate-soil matrix. Lens cap in upper left for scale. This limestone breccia has been phreatically dissolved; note the smooth cusp in the lower left of the photograph.

Figure 13B

Figure 13A

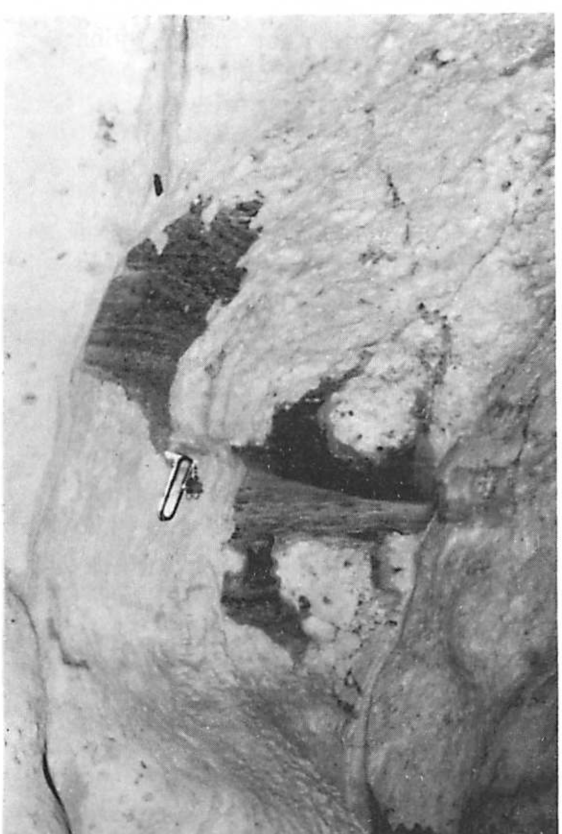


Figure 15

Figure 14

deposited by sheet flow) (Figure 16). The poolstone in turn overlies a reversely magnetized cave floor sediment fill (re-deposited surface paleosol). Below the cave floor is a 10-20 cm wide clastic dike (re-deposited paleosol breccia). This normal

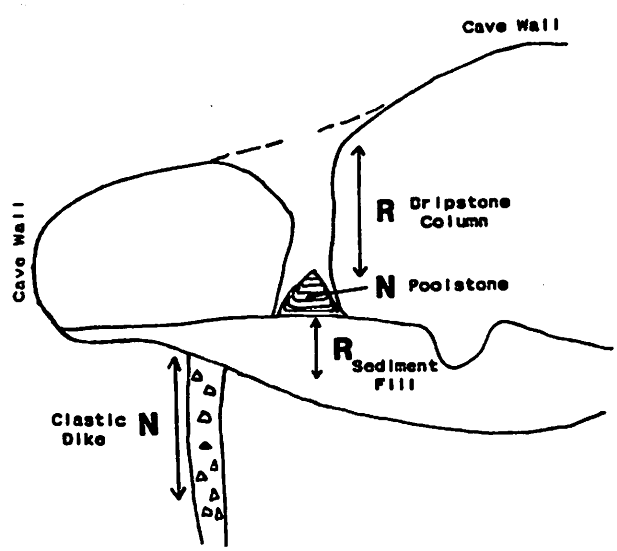


Figure 16. Diagrammatic representation of a paleomagnetic sampling site in Cueva del Aleman, referred to in the text. The R and N labels refer to reversed and normal polarity, respectively.

polarity clastic dike is in sharp, erosional contact with the overlying cave floor sediment. A conservative interpretation of the magnetostratigraphic evidence at hand places the older cave deposits in the Matuyama chronozone. According to this scenario, the clastic dike in the cave floor would be 1.67-1.87 Ma (using the magnetostratigraphic time scale in Butler, 1992) and the overlying cave floor sediment, occupying the oldest "cave passage", would be 0.97-1.67 Ma old. Assuming that Cueva del Aleman is representative of the other caves at this stratigraphic level, all caves at this level can be inferred to have a minimum age of the cave floor sediment in Cueva del Aleman.

The caves exist at elevations up to almost 70 m above sea level, which is an order of magnitude higher than any Quaternary glacio-eustatic sea-level highstand. The setting of the island in an active tectonic province, its deformation, the Miocene-Pliocene age of the cave-bearing carbonates, and the elevation of the caves all attest to tectonic uplift of Isla de Mona. The large size of the caves suggests that the caves formed during a period of prolonged stability of sea level after some initial emergence of the platform (necessary to provide subaerial catchment for the development of a freshwater lens). This stability led to a much longer period of time for flank margin cave development that produced extremely large flank margin caves. The paleomagnetic results indicate that this long time of stability might possibly have been prior to the glacio-eustatic sea-level changes of the Quaternary.

The pervasive evidence of phreatic dissolution of vadose speleothems and paleosol infills indicates that the caves on Isla de Mona were re-invaded by dissolutionally-aggressive phreatic waters after a prolonged air-filled interval in the vadose zone (Figure 17). The history of change indicates initial phreatic conditions during cave development, followed by vadose conditions that permitted speleothem growth and the introduction of cave fills, with at least one subsequent phreatic dissolution event, then the vadose conditions of today. This history implies a complex interaction between glacio-eustasy and tectonics. The occurrence of flank margin caves (with phreatically-dissolved vadose speleothems) at elevations up to 70 m above modern sea level indicates that Isla de Mona has been tectonically active since the first phreatic-vadose-phreatic series of events.

Comparison of San Salvador and Isla de Mona

The major difference between the caves of Isla de Mona and those of San Salvador Island is the very large size of the Isla de Mona caves. The larger cave size on Isla de Mona indicates not only a longer time for cave development in a stable freshwater lens, but that the lens may also have been larger in size. As noted earlier, the last interglacial sea-level highstand was 6 m above present, and only eolian ridges existed as islands in the Bahamas at that time. The freshwater lenses were correspondingly small, and lens discharge would have been correspondingly small. Therefore, small lenses existing for a short time produced flank margin caves of limited size.

On the other hand, the topography of Isla de Mona suggests that most of its 55 km^2 area was subaerially exposed at the time of cave development during or before the early Pleistocene, thus producing a lens larger than

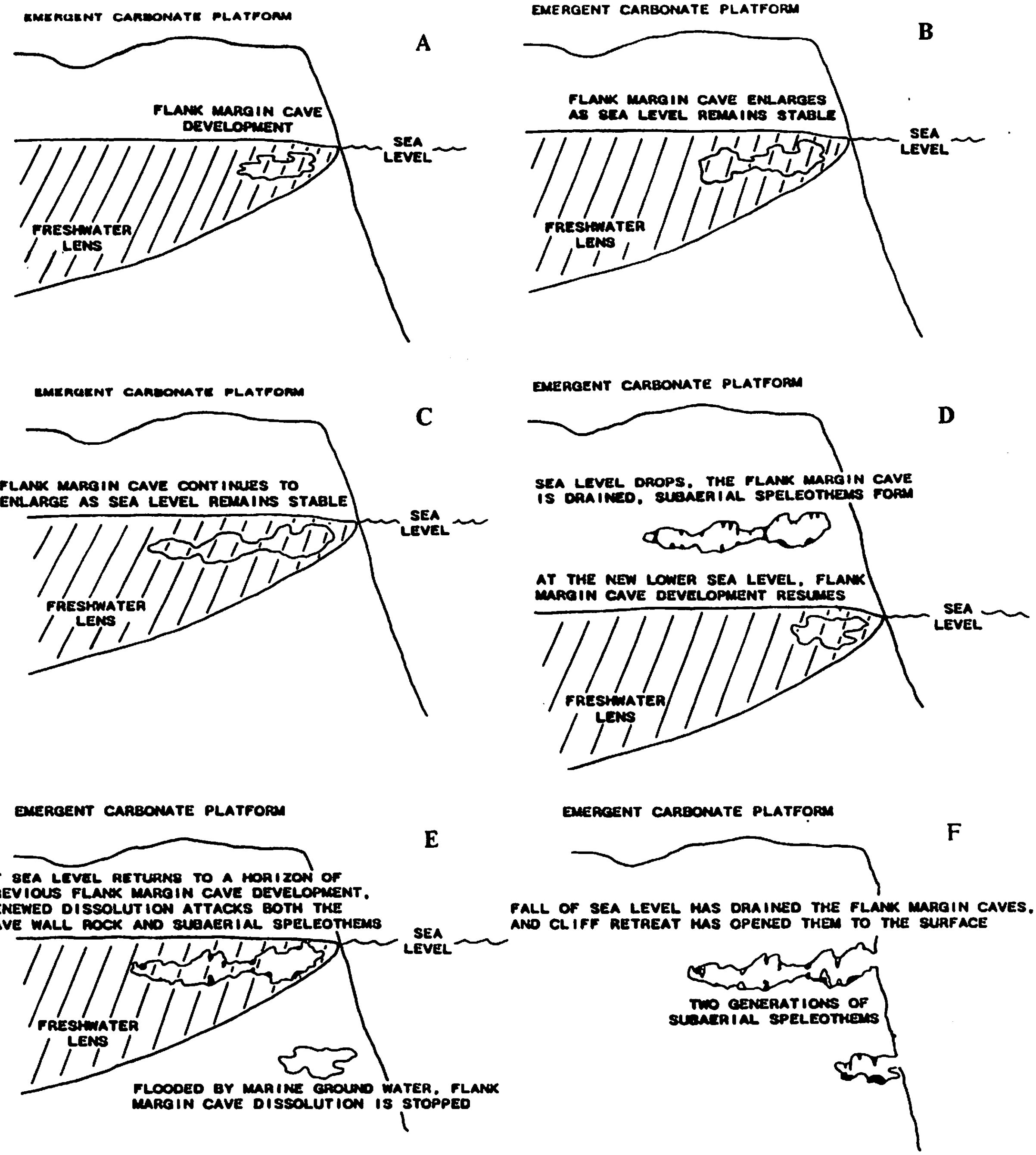


Figure 17. Diagrammatic representation of the development of flank margin caves on Isla de Mona, and their subsequent modification. 17A, initiation of flank margin cave development; 17B, flank margin caves enlarge with time; 17C, cave enlargement continues; 17D, caves are drained by a drop in sea level (tectonic or glacioeustatic) and develop vadose speleothems, new flank margin caves develop at the new, lower sea level; 17E, sea level rises again, abandoned flank margin caves are invaded by the freshwater lens, both wall rock and speleothems are modified by phreatic dissolution; 17F, a final drop in sea level exposes the caves as found today.

what was available on San Salvador and other Bahamian islands during the last interglacial. This larger lens size for Isla de Mona, combined with the longer time of a stable freshwater lens position, explains the development of larger caves on Isla de Mona.

While the history of Bahamian flank margin cave development is not as complex as for Isla de Mona, there is also evidence in the Bahamas for a brief phreatic-vadose-phreatic episode in some caves. Phreatically dissolved flowstone is found in Hunts Cave on New Providence, and phreatically-modified paleosol breccia infill is found in Benzie Hill South Cave on Long Island (Mylroie and others, 1991). These phenomena have been explained (Mylroie and others, 1991) as the result of a minor, small scale change in sea level during the last interglacial sea-level highstand 125,000 years ago. The most interesting aspect of these phreatic-vadose-phreatic cycles on both islands (Figure 17) is that they indicate that the freshwater lens can reestablish itself in flank margin caves and re-initiate the mixing-dissolution process even after an appreciable void has been produced.

The flank margin caves of Isla de Mona, and to a lesser extent those of the Bahamas, show a clear sequence of development. The caves begin as individual, isolated chambers. Through time, if conditions are stable, these chambers grow and widen. They often interconnect laterally along the margin of the lens to produce chambers that are joined by small openings dissolved through the thin bedrock partitions separating them (Figure 18). In the Bahamas, this pattern of chamber formation has been called "beads on a string" (Vogel and others, 1990). As development proceeds further, the mixing front moves inland (headward) to reach the diffuse flow of freshwater coming from the island interior. A second row of chambers develops inland of the first, and eventually a third row may form still farther inland. Such a pattern is common on Isla de Mona (Figures 6-12, 18). The pattern is less common in the Bahamas, where time limitations apparently stopped the process at the stage when a series of inward developing passages were drained by falling sea level, before they could enlarge into a second or third row of chambers (compare Figure 5 with Figure 18).

The development in both settings of large globular chambers that are horizontally

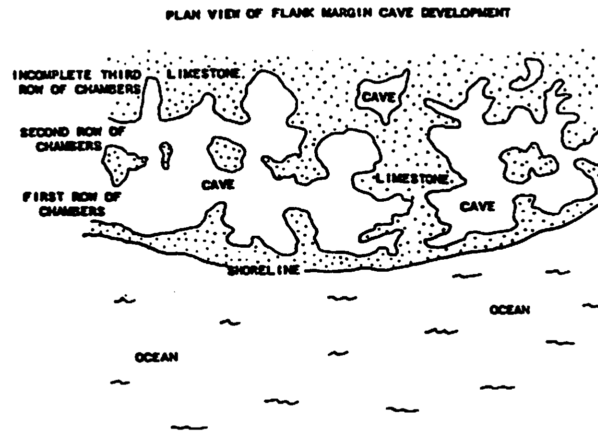


Figure 18. Plan view of flank margin cave development, showing preferential development at the lens margin, with progressive chamber development inward. Caves develop as an irregular arrangement of chambers connected by short passages. On isla de Mona, collapse of the outer cliff wall often breaches the first row of chambers.

extensive, that cut across primary structure in the rock (Figure 11), and that attenuate inland, provide evidence of the power of the mixing dissolution that takes place in the flank margin setting. Similar large-scale dissolution in a mixing zone has been described from the Yucatan (Back and others, 1986). The Yucatan offers a further extension of the flank margin model to a continental setting, where the presence of a freshwater lens, driven by allogenic recharge in land areas to the west, has produced large and abundant caves at the lens margin. As noted by Mylroie and Carew (1995), such cave development during a low order sea-level rise or fall could produce a continuous pattern of chambers that subsequently collapse and create a widespread solution-collapse breccia in the rock record.

SUMMARY

Flank margin caves have been produced on both San Salvador Island and Isla de Mona. The difference between the caves on these islands is primarily one of scale: San Salvador has small caves and Isla de Mona has large ones. The Isla de Mona caves formed prior to the large-amplitude, short-duration glacio-eustatic sea level fluctuations of the Quaternary; their large size is the result of dissolution in a large freshwater lens that was in a stable position for a long time. The San Salvador caves formed in a small freshwater lens during a relatively brief sea-level highstand (the 15,000 year-long last interglacial) of the late Quaternary; their small size is the result of dissolution in small lenses that were stable for a very short time. The flank margin caves on both islands show evidence of phreatic-vadose-phreatic conditions prior to the vadose situation they are found in today. This evidence, coupled with the similarity of passage morphology over a variety of scales, indicate the powerful control that mixing dissolution has on the development of flank margin caves.

ACKNOWLEDGMENTS

The authors wish to thank the Bahamian Field Station, Dr. Donald T. Gerace, Chief Executive Officer; the U. S. Geological Survey and Dr. William Back; the Puerto Rico Department of Environmental and Natural Resources; The University of Charleston; and Mississippi State University for logistical and technical support of the research reported herein. Discussions with Rosmarijn Lips, Joyce Lundberg, Neil Sealey, Pete Smart, Len Vacher, Fiona Whitaker, and Carol Wicks were very helpful in formulating our ideas.

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APPENDIX I

Cueva de Dona Gena and Cueva de Dona Gena Arriba

The caves are located at Playa del Uvero (Figure 4), in the cliff where the road climbs from the Pleistocene coastal plain up the Miocene carbonates to the island plateau. At this place, the road from Sardinera to the Faro lighthouse climbs the cliffs in a road cut. Immediately adjacent, to the southeast in the natural cliffs, is Cueva De Dona Gena. In the east wall of the road cut itself are the entrances to Cueva de Dona Gena Arriba.

Cueva de Dona Gena is a series of chambers that extend into the interior plateau of the island from a large outer vestibule (Figure 6). The outer vestibule starts in the west with a ceiling height of 8 meters. To the east, the floor rises, producing a cliff that drops away to the south to the coastal plain. Within 30 m the vestibule ends in a series of small chambers that intersect the cliff line in numerous spots. Two large chambers leave the outer vestibule. To the west, just above the level of the coastal plain, a low arch leads immediately into a large circular room over 20 m in diameter, with a ceiling height in the center of 5 m. The room contains substantial collapse material in spots, and some dry and desiccated flowstone. The margin of the room lowers in all directions except to the west, and closes down. To the west, the chamber rises into an area with much collapse and breakdown. This is near to the cut in the cliff made by the road as it ascends to the plateau, and underlies portions of Cueva de Dona Gena Arriba.

To the east 22 m from the initial chamber and 8 m higher in elevation up the sloping floor of the vestibule, a second large chamber heads north into the plateau. It has dimensions of 30 m by 20 m, and slopes up to the southeast, the floor of the southeast side of the chamber being above the roof of the northwest side of the chamber. There is little breakdown. Desiccated flowstone is found near the chamber entrance. The chamber averages 2 to 3 m in height, with a dome reaching 5 m in height on the east side of the room.

Continuing to the southeast, the vestibule and second chamber merge into a series of smaller passages and chambers that lower to 1 m in height and end against the cliff face. A further isolated chamber 20 m long, parallel to the cliff face, continues the trend of the cave to the southeast.

Cueva de Dona Gena Arriba

Cueva de Dona Gena Arriba has two large entrances on the northeast side of the road cut (Figure 7). Entry is most easily gained at the southern of these two entrances, as it is larger and leads directly into substantial passages. From the broad entrance archway, evidence of guano mining can be seen as well-established trails that lead both left (north) and straight ahead (east). To the south, the cave has a solid wall with a few pockets and small chambers. To the east, the cave bifurcates into an upper and a lower level. The upper level trends 40 meters east then south as a single large chamber with almost no side passage development. The ceiling averages 1.5 to 3 m high, and a loop can be made around formations and breakdown to appear back in the entrance chamber along the north wall.

Alternatively, a trail can be followed from the entrance to a lower level, which underlies the northern half of the upper level and extends to the north and northwest. This lower level consists again of a single large chamber over 20 m across and wide, with a ceiling from 1 to 2 meters high on average. The north wall of this lower chamber has a passage that leads back to the entrance room, and a passage that leads northwest to the rest of the cave. After 20 m this passage enters a series of low, wide rooms 10 to 20 m across and 1 to 1.5 m high. Sharply to the left (west) are two connections to a complex chamber. To the northwest a large chamber is reached, 20 meters wide and 15 meters across, which slopes steeply down to the west across breakdown. The chamber is up to 5 m high. At the west side of this chamber, passages can be followed into lower and upper levels. Going low leads to the deepest part of the cave, a low room 7 meters below the main entrance. The next level up leads to a series of low (1 to 1.5 meters) rooms trending west. At the extreme end of these passages, a small, breakdown-filled passage could be seen leading to daylight. This potential entrance is to the west of the road. Trending southeast from these rooms enters the complex chamber previously mentioned. Massive flowstone and large breakdown have made this chamber complicated. Passages depart on at least three levels going to all compass points. Those to the north and east lead back to previously described cave, those trending west end or loop back into known passage. To the southeast, a low passage over scree leads to the smaller northern entrance of the cave, which contains a high level alcove. Continuing southeast in 3 meter high passage along a mining trail enters the northwest side of the main entrance chamber, completing a loop of over 100 meters.

Survey data shows that the north end of Dona Gena partially underlies the main entrance chamber of Dona Gena Arriba (Figure 8). The floor of the upper cave at this point is collapse, sediment and mining debris, while the roof and back wall of the lower cave below is massive collapse. It would appear that the caves were once connected, and natural events, mining, road building, or some combination of the three has resulted in the blockage that separates the two caves. The lowest point in Dona Gena is only 2.5 m below the lowest point in Dona Gena Arriba (which is at the north end of the upper cave), the highest point is less than a meter below the highest point in Dona Gena Arriba. The large chambers of these caves approach each other without connecting. The eastern-most chambers in each cave come within 20 meters of each other, forming a second row of chamber development inland from the well-connected outer row of chambers nearer the cliff line.

Cueva Del Agua, Sardinera

The cave is located in the cliffs overlooking Anclaje Isabella, just west and above the Portuguese well, but several hundred meters east of Cueva Negra and Playa Sardinera (Figure 4). The cave is best located by going to the Portuguese well, and following the talus up and northwest to the base of the cliff, and taking any of a number of entrances northeast into the cave.

The cave consists of a series of very large chambers surrounded by smaller and lower chambers (Figure 9). The cave can be first entered by what seems to be a large shelter cave (see section C-C', Figure 9). By stooping, a wide, low passage can be reached which has a series of channels dissolved into the ceiling that allow walking. Taking the right (easterly) channel leads to a low region that can be followed up through collapse into a large chamber with many giant pieces of breakdown. Taking the left (westerly) ceiling channel is easier and leads into the west side of the same room. This large chamber is over 8 m high and 25 m in diameter. Breakdown covers almost the entire floor, except where guano miners have cleared a trail around the north and east perimeter of the room. To the southeast the miners' trail leads to a low (1 to 1.5 m), wide (20 m diameter) room essentially free of breakdown (D' area of Figure 9), that ends in bedrock walls in all directions except for the access point. Another similar room, on a smaller scale, exists just to the north. To the east-northeast, up and over a pile of breakdown from the miners' trail, leads to a low room with well-developed and active stalactites and stalagmites (C' area of Figure 9). This room ends after trending 20 m to the east.

Following the miners' trail to the northwest leads to a fork in the trail. To the right, or northeast, the trail proceeds for 10 m and forks again, each fork quickly ending. To the right (southeast) is a broad, low chamber 15 m in diameter with a tight connection to the previously described formation room. To the left (north), past a series of calcite columns, is a 10 m diameter room with a further 10 m long passage heading north that ends in bedrock walls. Back at the main fork, the left part leads northwest, then west and southwest. Desiccated calcite columns and flowstone are abundant, and to the left (east) is a route back into the large breakdown chamber. To the right (west) is a low, wide area that ends to the north and west, but which loops back to the southeast to rejoin the miner's trail.

The miners' trail leads through an arch into a very large chamber with large, scattered breakdown. To the right (northwest) is a low area that rejoins previously described passage. Ahead the miners' trail forks three ways. To the left a short trail leads 10 m to a large breakdown block, beyond which is the bedrock margin of the chamber. Straight ahead at the fork (southwest), daylight can be seen at a second entrance. Ten meters along the trail towards the entrance, the trail winds between breakdown, and a junction trail leads left (west) for 10 m, again reaching the bedrock wall of the chamber. This large chamber is at least 6 m high and 25 m in diameter. The main trail leads southeast for 15 m to a rock bridge which is crossed into an archway to the second entrance that broadens into a large vestibule chamber. To the left, over large breakdown blocks, this vestibule can be followed until it joins the shelter area where the cave can first be entered. To the southwest, the vestibule ends overlooking a large talus pile, which has a hole in the floor, requiring rigging, leading into a lower chamber. This chamber can be reached by descending the talus pile on the surface, turning northwest to the cliff, and entering an arch that proceeds to a single chamber beneath the vestibule. Low, under the wall of the northwest side of the vestibule is a low, broad passage that links up with the rest of the cave.

Back at the three way junction, the remaining portion of the miners' trail can be followed northwest to a very large breakdown block. Ahead is more open space, but by following a side trail south, entry can be made into a series of low passages, rooms and tubes that lead back to the second entrance, out to the cliff as a series of small entrances, and northwest into another large room. From the large breakdown block, the trail heads northwest, passing alcoves on the right (north) and connections on the left (south) into the warren of passages just described. Ahead is the largest chamber in the cave, with a ceiling 6 m high, many stalactites and some columns. Breakdown is present, but is less abundant than in the two preceding large rooms. Two large entrances can be seen to the southwest. The chamber has many passages and archways leading to adjacent chambers, but the main void is 30 m in diameter. The miners' trail forks, both forks curving west and south towards the large entrances, joining again after 25 m and then branching again, each leading after a further 15 m to entrances on a balcony overlooking the coastal plain. Between these entrances is another warren of small passages, often on two levels, that leads to a series of small openings on the cliff, and back into the large chamber. The southeast of the two entrances is a clean bedrock ledge in the cliff; the northwest entrance is associated with a large pile of collapse material in a vestibule, similar to that found at the first two entrances to the cave.

North out of the large chamber is a passage made up of successive chambers 1 to 2 m high that wind northeast then east into the plateau, ending in low, broad rooms with many dissolution pillars and wall partitions (B' area of Figure 9). In the northwest wall of the passage leading into this area is a small opening into an upper level, best reached by a climb up into a narrow tube in the wall of a chamber further into the cave. This short upper level is anastomotic, and resembles boneyard. It has an elevation below the roof of the large chambers, but above the roof to the subsidiary chambers to the northeast.

The large chamber passes northwest upslope and through numerous bedrock arches and past bedrock pillars into a wide room with a ceiling of 2 to 3 m height. To the northeast is access to the previously mentioned short upper level. To the north, past a row of columns and up a brief slope is a low room (A' area of Figure 9). To the south are a series of low arches to a broad, low (1 m high) passage that connects into the large, breakdown-filled entrance vestibule (A area of Figure 9).

Continuing west from the line of the cross section A-A' in Figure 9, the cave becomes a series of low chambers and tubes, with an occasional ceiling channel. Flowstone and related calcite deposits are abundant. This section of the cave trends west and northwest as a series of tubes and low chambers that all end in bedrock walls. A route can be followed around to the southeast, dropping over a ledge and re-appearing at the large, most northwesterly entrance of the cave (A area of Figure 9).

The cave is easy to traverse, the only obstacles being popcorn covered floors in some of the low, peripheral chambers. The guano miners' trails make it easy to negotiate the first two-thirds of the cave, but these trails are not found in the most northwesterly third of the cave. Here, the numerous bedrock partitions and pillars, coupled with columns and flowstone, can make route finding occasionally tricky.

Cueva Neuvo

Cueva Neuvo is located on the plateau, near the cliff edge, just north of Punta el Capitan, and south of Cabo Barrionuevo (Barrio Neuvo on the 7.5 minute quadrangle map of the island). The cave has entrances on the cliff face, and holes down from the plateau above. All entrances lie west of the main coastal trail in this area. The cave has six main entrance areas, three from the plateau surface, and three from the cliff edge to the west (Figure 10). The easiest way to locate and enter the cave is to use the eastern-most entrance. This entrance leads down a breakdown slope into a large, circular chamber 15 to 20 meters across, 2 to 4 meters high. Two skylights and a blocked entrance are immediately adjacent to the main entrance. On the north wall of the chamber a low crawl, too tight to negotiate, can be seen leading into a low chamber with a further crawl leading off to the northeast. This latter crawl is illuminated by daylight from a pit to the northeast. This pit leads into another cave to the north, and so Cuevo Neuvo definitely extends in that direction. The connecting crawl has a dirt floor and could be forced.

West from the entrance chamber a broad arch leads into a second oval chamber 15 meters wide and 20 meters long. To the left (south) on entering the chamber is another sloping collapse pile leading to the surface, while the center of the chamber has a very large skylight with a tree growing up and out. Next to the breakdown entrance is a passage that leads south for 15 meters as a walk/stoop walk to a 2 meter high oval room 15 by 10 meters. To the west, through a wall of formations, is another chamber 6 meters wide and 20 meters long, trending south. It ends to the south, but two low crawls go west into low chambers, and through one of them daylight can be seen, most likely from an entrance at the cliff edge. North loops back into the chamber with the big skylight. East from the skylight enters a low and complex area of bedrock pillars, flowstone columns, and breakdown. Two different low passages reach entrances on the cliff, which plunges 60 meters to the ocean below. To the south, a very low area continues, but was not pushed. It most likely connects to the low area seen from the southern room. Substantial passage may exist in this direction. To the north from the skylight, a 10 to 15 meter wide passage, bisected by flowstone columns, goes for 40 meters to an impressive entrance overlooking the sea. All side passages in the northern part of the cave end quickly, except for at the northern cliff entrance where small tubes lead to an unentered entrance chamber to the north. The cave may therefore extend a significant distance to the north. Cuevo Neuvo is well decorated, and shows evidence of guano mining. Old survey stations, and mining symbols, are found throughout the cave. The cave is most likely only a fragment of a larger, cliff-parallel system. To the north immediately is a similar cave system, but with more passage. Both caves contain abundant speleothems that have undergone phreatic dissolution that has continued into the adjacent wall rock of the cave.

Myrna Chamber, Cueva Negra

Cueva Negra is located in the Miocene carbonate cliff behind the mess hall at Playa Sardinera (Figure 4). A trail leads up to the entrance arch, from which four passages radiate into the main part of the cave. The largest of the southern passages leads, after 25 meters, into an area named "Myrna Chamber". This chamber was mapped in detail because of the dissolution morphology of the passages. The limestone in this area is a forereef talus, with a depositional dip of 15 to 21 degrees. While the cave is strongly controlled on the local scale by this dip, the overall trend is to cut across such primary structure. The map of Myrna Chamber (Figure 11) shows how various ceiling pockets have dissolved up along the dipping beds, but how the chamber as a whole cuts across the beds and stays within a horizontal plane. Such morphology is consistent with that expected in a thinning margin of a freshwater lens, where vertical development would be restricted, and the greatest chemical potency would be along a horizontal mixing zone.

Cueva del Aleman

Cueva del Aleman is located on the southwest side of Isla de Mona just west of the western end of the airport runway where the Pleistocene coastal plain abuts the Miocene carbonate cliff. The cave has a series of entrances in this cliff, where cliff retreat has intersected the cave. The cave has two major levels of development (Figure 12); the upper level is the most dissected by cliff retreat and has numerous entrances. In fact much of the upper level can be viewed without light sources. The lower level is accessible from a few spots within the upper level, and by a few places where it is intersected by the cliff. The lower level also has a large Collapse Entrance at the extreme eastern end of the cave, which opens directly to the plateau surface that roofs the cave.

The upper level of Cueva del Aleman is smaller than the lower level, overlying only the northwestern two-thirds of the lower level. The levels connect in two ways. There are a number of connections that occur where cliff retreat has intersected both levels, and one may work vertically in or over breakdown to make a connection. Examples are the connection at the West Entrance, station 135, and 28. The second type of connection is by vertical dissolution passages within the cave proper. At stations 157/35, 45, 67, 221, and 271/236 such connections are made; however only at stations 45, 67, and 221 can the traverse be made without vertical equipment.

Within each level are minor vertical subdivisions into partial levels. In the upper level, in the area just north of the West Entrance, the upper level has three separate components stacked on top of each other within a vertical range of only 4 meters (see the A-A' cross section). In the lower level, along the C-C' cross section there is a small level beneath the main development. At the E-E' cross section, there is a major shift downward of the main cave development. In this area the cave is most complex, as the two parts of the lower level are overlain by the southwest end of the upper level.

The cave has been mined of much of its cave earth, and evidence of mining is everywhere. A major "trade route" for the miners trends from the West Entrance through the lower level of the cave to just east of station 45. A similar "trade route" goes from the Rio Mona Entrance west to the station 67 area. The connection between the two main parts of the lower level occurs between stations 45 and 67 (see cross section A-A'), and involves a series of low passages (less than 1 m) and a pit, which prevented the development of a "trade route" from one end of the lower level to the other.

The survey of Cueva del Aleman took five complete days, involving the placement of 333 stations, with 388 shots taken for 4,250 m of survey line (see map of survey lines). An additional half-day was spent taking photographs in the cave. A complete description of the cave would take too much space, but a brief tour follows.

From the West Entrance, both the upper and lower levels can be easily reached. Up and to the west are a series of chambers open through pillars to the outside. Continuing north and then east goes into true cave; to the south are the three mini-levels previously described. Straight east leads to stations 157 and 155, which overlook the large entrance chamber of the lower level, 6.5 m below (inaccessible without vertical gear). Going east from the West Entrance, the upper level trends as a gallery open along the south wall to the sky, with an occasional bedrock pillar. Low, wide chambers trend into the cliff for a few meters. Beyond station 28, the cave development into the cliff to the north becomes more pronounced, and at station 221 are two vertical holes into the lower level (one of which is negotiable without vertical gear). The upper level constricts at this point, and subdivides into two mini levels. The lower one closes down except for a small hole out to the cliff face; the upper level is a high arch from which the airport is clearly visible. From this point towards and past station 45, the entire south wall of the cave is missing. At station 45, a sloping crawl leads down over rock fragments to the lower level. Continuing south, the cave lowers to a broad arch 1 m high, then opens again into the Pasunka Room at station 67. Near the back wall of this room is where the paleomagnetic studies have been undertaken by Bruce Panuska and co-workers. A narrow passage leads north and west from this point into a large oval room. Cave earth deposits are abundant here, as is a 5 m pit to the lower level at station 271 (upper level) and 236 (lower level). West and north of the Pasunka Room are a series of low and wide passages that make a loop. Careful examination of this room and nearby areas failed to find any continuation of the upper level to the east or south.

From the West Entrance, a downward trending slope leads to the Entrance Chamber of Cueva del Aleman. This chamber is very large, over 60 m in diameter, interrupted by remnant bedrock pillars. To the west the chamber and the lower level end in bedrock walls except at station 135, where a breakdown slope leads up to an entrance and a connection with the upper level. Northeast from the West Entrance is a large formation area, and a natural bridge, under which the guano miner "trade route" leads deeper into the cave. Following this "trade route" to the southeast passes wide rooms to the north, and mazy areas to the south. Pushing through the mazy area leads to an entrance at station 28 on the cliff (with a connection to the upper level), and to the connection to the upper level at station 221. The trade route swings more to the south and passes a few meters north of the crawl leading to station 45. The trade route then peters out in a broad room (cross section D-D') containing station 236, which is directly below the pit connection to station 271, 5 m above. Southeast from this room ends in bedrock walls (called "rimouts"), but going more easterly leads to a low area that pops out at a pit that drops 4 m to the lower part of the lower level (see cross section E-E'). By traversing the south rim of this pit, the upper part of the lower level is regained, reaching a section of passage with much original cave earth sediment layering, and a breakdown pile that leads upwards to connect to the upper level and the Pasunka Room at station 67. Going to the south east, a new "trade route" is encountered, sloping downward into the lower part of the lower level. Northeast, then northwest leads through large chambers with much breakdown until the pit connection to the upper part of the lower level is encountered from below. At this point in the cave, the two components of the lower level interfinger, but connect only at the pit (cross section E-E'). The cave narrows for a bit, with small rooms on either side, trending southeast, then suddenly opens out into the very large Rio Mona Entrance. This chamber is over 50 m in diameter, opening to the south to the open sky less than 100 m from the road and airport. The back portion of the room has huge blocks of breakdown, and the ceiling is one of the highest in the cave (10 m). Along the east wall of this chamber is a dry stream bed, the Rio Mona. Following this upstream leads through breakdown into another massive chamber totally floored by large breakdown blocks. At the north end of this room, the breakdown has breached to the surface to form the Collapse Entrance. During storms, water apparently collects on the plateau surface, enters the Collapse Entrance, and flows through the south end of the cave to the Rio Mona Entrance, where it flows back on the surface.

The cave is well decorated in spots, and like many of the caves on this island, the miners apparently took care not to do any damage to the cave beyond what was necessary to extract the cave earth. The cave contains old vadose speleothems that have clearly undergone one or more phreatic dissolution events, a feature common to all large caves on Isla de Mona.

The cave map was treated as two separate pieces, the upper level and the lower level, as superimposing the levels made for a very confusing map. The levels are presented at the same scale, and by lining up the survey stations, they may be placed one on top of the other to show the passage relationships (as a result of photo-reduction, the registration is not perfect). The map has been presented in two forms: one with all the passage detail and content information; and one with the detail removed but the survey station shot lines added. This latter presentation demonstrates the survey control over placement of the cave wall by sketch, and shows how Cueva del Aleman contains numerous cases of thin bedrock partitions separating major chambers. This pattern is common to flank margin caves. The cross sections A through E help place the levels in the proper relationship, and show how the cave is horizontally extended, but vertically restricted. Cave walls are in bold line. Breakdown is noted as blocks (large) and open triangles (small). Flowstone, stalagmites, stalactites and columns are shown as filled triangles joined at their apex (columns are the most dominant speleothem). Diverging lines of three indicate slope in the direction of divergence. Hachured line indicates a vertical change. Circles with the hachures on the inside mean a drop down; hachures on the outside mean a hole going up (note the difference for the two levels at station 221 on the map). The map gives the illusion of great detail, but is a gross over-simplification of reality. The map is meant as a guide to the cave, not a definitive description. It is at best diagrammatic.