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Cover Photo: Outcrop showing Pleistocene soil profile,
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QUANTITATIVE ANALYSIS OF CAVES AS A GEOLOGIC HAZARD, SAN SALVADOR ISLAND, BAHAMAS

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ABSTRACT

San Salvador Island has a surface area of 156 km^2, and is composed entirely of young (Pleistocene and Holocene) limestones. The Pleistocene limestone, of which about half has been explored, contains seventy-seven known caves. The relatively extensive cave exploration and mapping efforts on San Salvador document the minimum frequency of cave occurrence and the cave size distribution better than anywhere else in the Bahama islands. The caves occur in three types of terrains that have different cave densities and cave types. The cave-hosting terrains and their areas of occurrence are: 1) a Sangamon Stage (last interglacial) marine terrace (1-7 m amsl), 77 km^2 (49%); 2) lithified carbonate dunes or eolianites (>7 m amsl), 33 km^2 (21%); 3) lakes and a restricted bay or tidal creek (Pigeon Creek), 35 km^2 (22%). The 11 km^2 (8%) of island area that is beach and Holocene rock is non-cavernous. Within these terrains, six types of caves are recognized: flank-margin caves (20); banana holes (21); pits (21); lake drains (10), blue holes (4) and a paleosol cave (1). The flank-margin caves and most pit caves occur in the dunes. Banana hole caves and blue holes occur in the terrace. Lake drain caves occur in the lakes and Pigeon Creek, but probably extend beneath the other terrains. The Holocene rocks and modern beaches have no known caves, but may be underlain by water-filled caves developed in Pleistocene rocks. The three cave-hosting terrains have the following minimum mean cave densities: terraces - 0.54 banana holes km^{-2}, 0.10 blue holes km^{-2}; dunes - 1.1 flank-margin caves km^{-2}, 1.2 pit caves km^{-2}; lakes and tidal creeks - 1.1 lake drain caves km^{-2}. The combined cave density is 0.67 caves km^{-2} for the terrace; 2.3 caves km^{-2} for the dunes and 1.2 caves km^{-2} for the entire island, excluding beaches and Holocene rocks. The actual cave densities may be significantly higher because not all existing caves have been discovered in the explored areas, and many areas have not been searched for caves at all. The median floor areas of the three main air-filled cave types are: banana holes - 28 m^2; flank-margin caves - 96 m^2; and pit caves - 10 m^2. The largest known caves in each category are: banana holes - 327 m^2; flank-margin caves - 1,700 m^2; and pit caves - 134 m^2. Banana holes are thought to pose the greatest potential collapse hazard because they occur beneath the relatively level terrace where most development is likely to take place and because they have thin roofs (typically 0.3-1.5 m thick) spanning oval-shaped chambers that are commonly more than 5 m wide. Until similar studies are performed for other islands, cave densities and cave size distributions determined from San Salvador Island should be used throughout the Bahamas to estimate the probability of cave occurrence beneath proposed man-made structures and the potential damage that could occur. Estimates of the potential financial loss from cave collapse will assist in justifying a prudent

amount of funding to assess and mitigate this geologic hazard.

INTRODUCTION

Caves represent a potential ground stability hazard to surface structures or engineering works. Thinly-roofed caves, developed in the weakly-cemented late Pleistocene limestone of the Bahama islands, pose a risk for collapse, and potentially dangerous shallow dissolution caves are abundant throughout the Bahama islands (Palmer and others, 1986; Mylroie, 1988; Carew and Mylroie, 1989; Vogel and others, 1990; Mylroie, and others, 1991).

On San Salvador Island, caves have been intensively studied (Mylroie, 1988; Vogel and others, 1990; Schwabe and others, 1993; Pace and others, 1993). The available data are sufficient for a quantitative analysis of cave density and cumulative size distribution to be performed with a higher degree of reliability than elsewhere in the Bahamas.

The purpose of this report is to present a quantitative analysis of the potential geologic hazard caused by the occurrence of caves on San Salvador Island. Consideration of cave density, the area of a development project, and the potential loss from cave collapse, can be used to estimate the amount that should be prudently allocated to search for caves that might constitute a potential collapse problem. The discovery of a cave beneath an existing or proposed project and the characterization of cave size and depth, will help establish the degree of risk for a particular land use. It is the intention of this report to provide a quantitative estimate of cave density and size distribution to assist engineers and developers in formulating rational land-use decisions and to assist with wise land-use planning throughout the Bahamas and similar carbonate settings.

SETTING

San Salvador Island is one of many islands in the Bahamian Archipelago. The island is located at 24° North latitude, 74.5° West longitude, approximately 650 km southeast of Miami, Florida.

Topography

San Salvador Island is approximately 11 km wide and 19 km long (Figure 1). The total area is approximately 156 km^2, including restricted bays, such as Pigeon Creek.

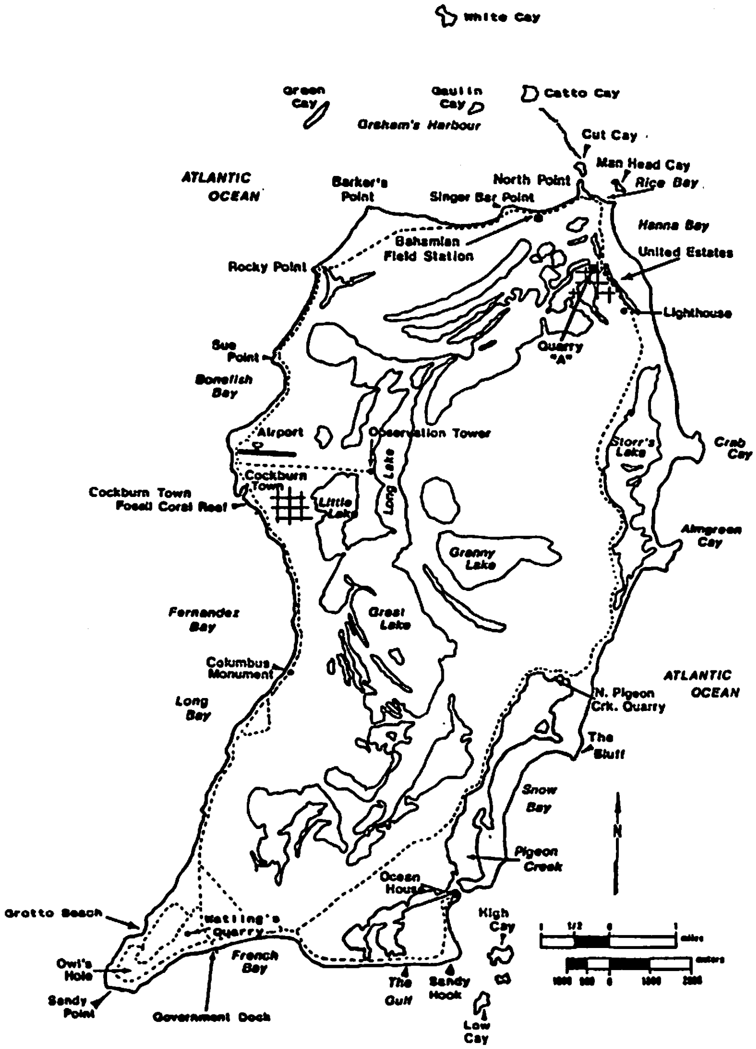

Figure 1. Map of San Salvador Island, Bahamas.

The topography of the island is dominated by arcuate, cemented, eolian (wind-blown) carbonate dune ridges that attain elevations of up to 40 meters above sea level, but most are 10-20 meters high. The land surface covers an area of approximately 105 km^2 or about 67% of the island (Table 1). Surface streams are completely absent.

The low areas between most dune ridges are occupied by lakes and ponds that cover an area of approximately 40 km^2 or about 26% of the island (Table 1). These water bodies range from less than 1 meter to approximately 3 meters deep. Occasionally,

Table 1. **TYPES OF TERRAIN ON SAN SALVADOR ISLAND**

TYPE OF TERRAIN	ELEVATION (M AMSL)	AREA (KM2)	AREA (%)
BEACH	0-1	4	2.6
HOLOCENE ROCKS	0-2	7	4.5
SANGAMON TERRACE	1-7	77	49
EOLIANITE DUNES	7-50	33	21
LAKES & TIDAL CREEKS	0-1	35	22
TOTAL	0-50	156	≈100

lake drain caves may lead deeper. Seeps commonly occur around the edges of the lakes where freshwater discharges from the surrounding dunes. The salinity of these lake waters ranges from slightly less than seawater (35 ppt) to more than 200 ppt. The salinity varies with the seasons, and from water body to water body.

Underwater cave passages connect some lakes and ponds to the ocean, and water is exchanged between the lake and ocean as the tidal stage changes (Davis and Johnson, 1989). All of the known caves that convey water to-and-from the lakes are too small to be passable by humans, and therefore little is known about their routes. On other islands, however, such caves are known to lead to extensive passages (e.g. Palmer, 1986).

Surrounding the island is a narrow subtidal shelf ranging from 0.2 km to 5.6 km in width. The shelf is covered by up to 15 m of water, containing a variety of coral reefs. The shelf edge breaks sharply to near vertical and descends to water depths greater than 2,000 m on the west and south. The upper part of the slope is steep, but it is somewhat more ramp-like on the east side of the island.

Stratigraphy

The stratigraphy of San Salvador Island has been extensively studied, and a stratigraphic column has been developed (Carew and Mylroie, 1985; 1994a; 1995). The Owl's Hole Formation (Figure 2) is the lower of two Pleistocene formations and comprises the oldest subaerial rocks on San Salvador. It is a peloidal bioclastic eolian deposit. Very few ooids are present in these rocks. The Owl's Hole Formation is currently thought to be about 220,000 years old or older (Carew and Mylroie, 1994a; 1995). The Owl's Hole Formation is capped by a paleosol that separates it from the overlying Grotto Beach Formation in most places.

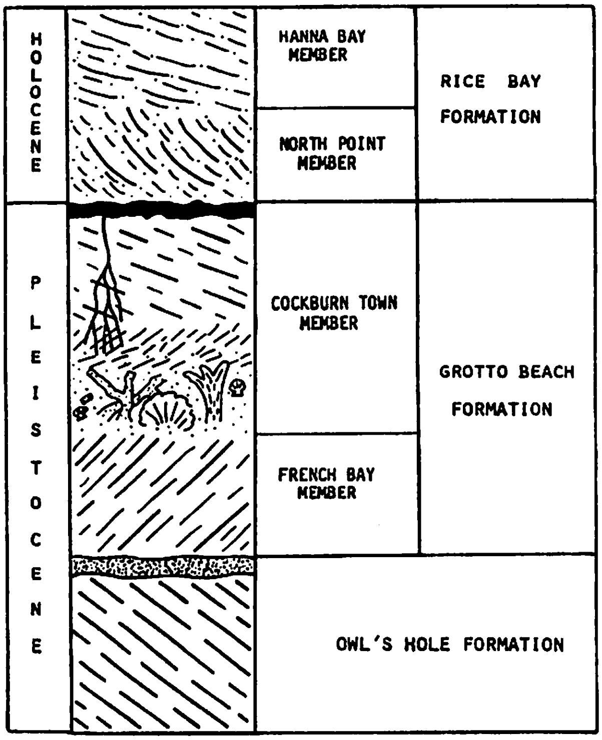

Figure 2. Geologic column for San Salvador Island.

The Grotto Beach Formation (Pleistocene) is divided into two members. The French Bay Member is a fossiliferous oosparite deposited as transgressive-phase beach, back beach and eolian deposits. The Cockburn Town Member consists of subtidal sands, coral reefs covered by regressional subtidal reef-fill, beach, back-beach and regressive-phase eolianite deposits. Fossil corals from this formation yield U/Th ages of 131,000 to 119,000 years (Chen and others, 1991), which is consistent with deposition during oxygen isotope substage 5e (Shackleton and Opdyke, 1973; Carew and Mylroie, 1994b).

Grotto Beach Formation rocks are also capped by a paleosol which marks the Pleistocene/Holocene boundary. The paleosol is composed of one or more laminations of orange-red to grayish-brown micrite, and can vary from thin crusts on dune crests to thick, complex multilayer deposits in dune swales (Carew and Mylroie, 1991).

The Holocene is represented by the Rice Bay Formation. It is also divided into two members. The North Point Member is a transgressive-phase eolian pelsparite. The Hanna Bay Member includes all rocks deposited in association with present-day sea level and consists of beach and back-beach eolianites and modern beachrock. The Rice Bay Formation is not covered by a paleosol. Whole rock ^{14}C dates indicate that the North Point Member sands formed approximately 5,000 years ago, and the Hanna Bay Member sands approximately 3,000 years ago (Carew and Mylroie, 1994a; 1995).

Hydrology

Precipitation on San Salvador Island averages between 1000 and 1250 mm per year. The majority of rainfall occurs from late May to January. Potential evaporation averages between 1250 and 1375 mm per year (Sealey, 1985). Because evaporation exceeds annual precipitation, there is a yearly deficit. During the rainy season, however, precipitation exceeds evaporation, so there is a temporary surplus of freshwater. During the dry season, potential evaporation is greater than precipitation, and conditions then are arid. The seasonal alternation of surplus and deficit water supply causes large seasonal variations in the water chemistry of the inland lakes and ground water.

The classic model of island hydrology is the Ghyben-Herzberg model (Figure 3). It shows a fresh (or brackish) ground water lens underlain by saline water from the ocean. The lens forms because of the density difference between the upper and lower water bodies. The interface between the upper water body and the underlying saline water can be an abrupt halocline, or a broader mixing zone.

The model predicts that the halocline will be located at a depth below sea-level of almost 40 times the height of the freshwater lens above sea level because of the 1 part in 40 density contrast of fresh and saline water. Thus, if the water table is at an elevation of 1 meter, then the halocline should approach an elevation of minus 40 meters (Fetter, 1988). Differences in porosity and permeability do not affect the 1 in 40 relationship, but they do affect the thickness of the lens.

The Ghyben-Herzberg model is an idealized construct that depicts an oversimplified description of the freshwater lens in a carbonate environment. Preliminary field work and sampling suggest that this model does not always fit the actual conditions on San Salvador (Davis and Johnson, 1989). The freshwater lens on San Salvador is partitioned by interior saline and hypersaline lakes with the larger portions of the lens located beneath dune ridges.

Ground water on the island may be fresh or brackish. The wells and caves, where ground water is accessible, are located predominantly along the coast. For the most part, water table elevations at accessible locations, are less than 1.5 meters above sea level. The Ghyben-Herzberg model predicts an 18 meter-thick freshwater lens, but electrical resistivity values in wells (Kunze and Weir, 1987) indicate that the lens is less than 11 meters thick.

Along the coast of San Salvador Island, ocean tides range from 0.3 to 1 meter, depending on lunar phase and season. A difference of more than 0.5 meter may occur between the heights of the two high tides on a given day. The height of the tides exerts a significant influence on the exchange of water through caves that link some lakes and blue holes to the ocean (Davis and Johnson, 1989).

TYPES OF CAVES

Caves in the Bahamas can be divided into four main types that have different morphologies and occur in different terrains on the islands. For practical analysis of caves as a geologic hazard, the following four types of caves warrant consideration:

1) banana holes
2) flank-margin caves
3) pit caves
4) blue holes

The four main types of caves each have a different potential for collapse.

Sea caves, formed by coastal wave erosion, are not discussed herein. Paleosol caves, such as Crab Cay Cave (Mylroie, 1988), although interesting, are oddities that occur too infrequently, and are too closely tied to coastal erosion processes, to merit consideration as a geologic hazard. Lake drains are features

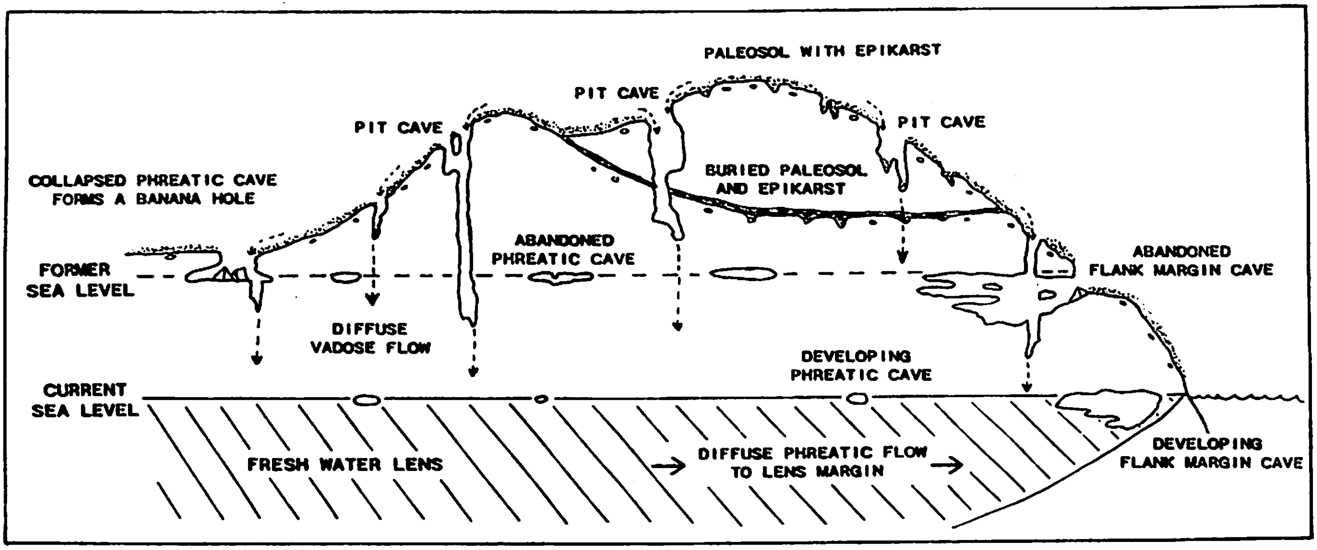

Figure 3. Diagrammatic representation of the freshwater lens within a carbonate Island, and of the karst features that develop in and above the freshwater lens.

developed by conditions associated with blue holes, and will be included in that category. Table 2 contains definitions and characteristics of all these cave types. Space does not allow for illustration of all these cave types; so the reader is referred to Mylroie (1988); Vogel and others (1990); Schwabe and others (1993); Pace and others (1993) for illustrations of specific cave types, and to Carew and Mylroie (1994a) and Mylroie and Carew (1995) for a general discussion. A synopsis follows.

Banana Holes

Banana holes are generally found in areas less than 7 m above sea level and are usually distant from the flanks of eolian ridges. Banana holes often contain collapsed roof material that partially fills their chambers. The roof collapse may be complete, producing a vertical-walled depression; or incomplete, leaving an overhung partial roof. Completely collapsed banana holes no longer represent a collapse hazard; merely a topographic depression. Many such features are included in the analysis presented in this report, because the collapsed banana holes are thought to be representative of other unknown voids of similar nature that may still have complete thin roofs.

The chambers of banana holes are round to ovoid in plan and usually are no more than 12 m in diameter. Depths are usually less than 4 m. They have a depth to width ratio of less than 1. Banana holes are named for the plant commonly cultivated in their rich soil-covered bottoms. Banana holes contain dissolution morphologies such as curvilinear dissolution surfaces, bedrock spans, thin wall partitions, and wall pockets that are consistent with phreatic development. Wall rock samples analyzed from banana holes lack dolomite, which suggests the absence of marine influence. Therefore, it appears that banana holes formed at the top of a past freshwater lens where only vadose-phreatic mixing occurred (Pace and others, 1993; Mylroie and Carew, 1995). Once the caves had developed in that lens, a fall in sea level drained the void, with subsequent roof collapse into the chamber (in the case of those caves exposed today). This collapse would allow organic matter to accumulate and surface water to enter the chamber. The water, along with CO_2 produced by decomposing organic matter may have enlarged and deepened the void as described by Smart and Whitaker (1989), but did not significantly contribute to the morphology seen today until collapse of the chamber ceiling became nearly complete (Pace and others, 1993).

Flank Margin Caves

Flank margin caves were defined and described by Mylroie and Carew (1990). Flank

Table 2.

BAHAMIAN CAVES

TYPE OF CAVE	CHARACTERISTICS
BANANA HOLE	CIRCULAR, ELLIPTICAL OR OVAL ROOMS. DEPTH/WIDTH LESS THAN ONE. THIN ROOFS - USUALLY LESS THAN 2 M THICK. COMMONLY MORE THAN 5 M WIDE. OCCUR BENEATH THE SANGAMON TERRACE AT ELEVATIONS BELOW 7 M. HIGHEST RISK FOR COLLAPSE.
PIT	GENERALLY CYLINDRICAL SHAFT THAT MAY LEAD TO A SMALL ROOM OR SHORT PASSAGE. DEPTH/WIDTH GREATER THAN ONE. SHAFTS ARE COMMONLY 1-2 M IN DIAMETER, BUT END IN ROOMS MORE THAN 3 M WIDE. VERY COMMON ON DUNE RIDGES AT ELEVATIONS ABOVE 7 M. GENERALLY LOW RISK FOR COLLAPSE.
FLANK MARGIN	IRREGULARLY-SHAPED ROOMS WITH DEAD-END PASSAGES RADIATING AWAY. ENTRANCES OCCUR ON FLANKS OF DUNES. CAVES EXTEND BENEATH DUNES AND MAY HAVE THIN TO THICK ROOFS. ROOMS ARE COMMONLY MORE THAN 10 M WIDE, PASSAGES ARE 1-2 M WIDE. GENERALLY MODERATE RISK FOR COLLAPSE
INLAND BLUE HOLE	PIT THAT EXTENDS BELOW SEA LEVEL FOR A MAJORITY OF ITS DEPTH. FORMS AN ISOLATED POND OR LAKE . DEPTH/WIDTH RATIO GREATER THAN ONE. USUALLY MORE THAN 2 M WIDE. OCCUR ONLY IN THE SANGAMON TERRACE ON SAN SALVADOR, BUT ALSO OCCUR IN DUNES ON OTHER ISLANDS. LOW RISK FOR COLLAPSE.
OCEAN BLUE HOLE	SAME AS ABOVE, EXCEPT THE PIT OPENS DIRECTLY INTO A LAGOON OR THE OCEAN. USUALLY EASY TO SEE BECAUSE OF COLOR CONTRAST - DARK BLUE IN HOLE AND LIGHT BLUE IN SURROUNDING SHALLOWER WATER. COMMONLY CONNECT TO EXTENSIVE CAVE SYSTEMS AT DEPTHS OF 20-110 M. LOW RISK FOR COLLAPSE.
LAKE DRAIN	GENERALLY SMALL HORIZONTAL PASSAGES BELOW WATER TABLE OR SEA LEVEL. COMMONLY TOO SMALL TO ENTER. ENTRANCES USUALLY FOUND ALONG MARGINS OF LAKES, BUT MAY OPEN ANY WHERE ON LAKE OR TIDAL CREEK FLOOR. LOW RISK FOR COLLAPSE.
PALEOSOL	IRREGULARLY-SHAPED ROOM ROOFED WITH THIN, MICRITIC, PALEOSOL CRUST. ONLY ONE IS KNOWN (CRAB CAY CAVE). RAREST TYPE OF CAVE. VERY HIGH RISK FOR COLLAPSE.

margin caves are found from 0 to 7 m above present sea level. They formed when sea leve was higher than at present. They occur mostly in the flanks of Pleistocene dunes and arealigned with the dune axis (Figure 3). Those that have been breached by surface erosion usually have a low elongate entrance that leads into a large central chamber or chambers. The size of the chamber can vary from several meters wide and long and about one meter high to as large as the Aeolian Chamber in Lighthouse Cave, which is 37 m long, 15 m wide and 5 m high (Mylroie, 1988; Mylroie and Carew, 1994). The chambers are interpreted as an indicator of the former position of the margin of the discharging freshwater lens where dissolution was at a maximum (Mylroie and Carew, 1990). From this chamber(s) smaller dead-end passages lead into the dune. Mylroie and Carew (1990) hypothesize that the passages leaving the back of the chambers represent sites of concentrated movement of water from the freshwater lens toward the dune margin. The concentration of flow was produced by preferential movement along bedding planes and other heterogenieties in the dune. Dissolution ended abruptly when sea level fell. Entrances to the known flank margin caves formed by slope retreat, which eventually breached the outer walls of the main cave chamber(s). Advanced stages of this erosion can erode away all but the back portion of the flank margin cave, to produce notch-like features that can be misinterpreted as bioerosion notches (Mylroie and Carew, 1991).

Pit Caves

Pit caves have a depth-to-width ratio greater than one (Pace and others, 1993). In plan view, the shafts are nearly circular to elliptical. In some cases, segments of the shaft may be slightly offset laterally from segments above or below. Pits range in diameter from less than one meter to approximately 7 m. Depths range from about 1 m to at least 10 m.

Most pit caves are found in clusters along the tops and sides of dune ridges above elevations of 7 m. They often initiate in oolitic limestone (Grotto Beach Formation), and may penetrate into lower peloidal-bioclastic rock (Owl's Hole Formation). Their commonplace origin in rocks of the Grotto Beach Formation indicate that they developed since the last interglacial 125,000 years ago. Pit caves usually end in sediment, and have not been shown to couple directly to a conduit flow system at depth.

In some instances, pit caves penetrate into flank-margin caves lower in the dune, and often continue through the rock of the bottom of the flank margin cave passage. This indicates that the penetration of the pit cave into the phreatic flank-margin cave occurred after sea level fell and the flank margin cave was in the vadose zone (Mylroie, 1988; Carew and Mylroie, 1990)). Such penetration is a random phenomenon, and no evidence has been discovered to indicate a hydrologic connection between pit cave development and flank margin cave development. Their hydrologic histories are independent (Pace and others, 1993).

The morphology of pit caves, including vertical grooves and incised slots, suggests a primarily vadose origin. Water budgets for pit cave development were initially thought to be insufficient because of the limited catchment area (Mylroie, 1988). However, field observations during rainstorm events showed that, even near the crests of ridges, there is significant surface and subcutaneous flow (epikarst; see Williams, 1983, and Figure 3) to feed pits on the perimeter of the pit fields. The clustering of pits appears to be the result of sequential piracy of storm water into new pits on the margin of the pit field, so that older abandoned pits are toward the center (Pace and others, 1993). This is analogous to what is seen in classical vadose shaft development in continental karst (White, 1988).

Pit cave development occurs above sea level and is largely independent of sea level for areas having elevation of more than 6 m. Pit caves could be initiated as soon as a dune formed and was lithified, or concurrently with eolianite formation, a phenomenon called syngenetic karst (Jennings, 1968). Formation could then continue, and is still active today. Paleosols on top of the lithified dunes, which formed during substage 5e (Grotto Beach Formation), have been shown by Carew and Mylroie (1985) to be the Pleistocene/Holocene boundary. The fact that some pit caves have a paleosol draping into them is clear indication that some pit caves were initiated after the last interglacial (Grotto Beach Formation) rocks were deposited, but before the end of the Pleistocene.

Blue Holes

The Bahamas are famous for the blue holes that are found throughout the islands (Palmer, 1986). They are characterized by a cave entrance, usually a pit, that opens on the ocean floor in water that is sufficiently clear and shallow for the entrance to be seen. The deeper water in the submarine pit or cave entrance depression usually has a dark blue color that contrasts with the light blue color of the surrounding ocean floor. In general, the name "blue hole" has also been applied to sinkhole ponds and lakes located in the interior of the islands. Blue holes can be subdivided into two types, based on location (Burkeen and Mylroie, 1992): inland blue holes, which open onto the land surface, and ocean blue holes, that open into lagoons or the open ocean.

Blue Holes have a depth to width ratio greater than one (Burkeen and Mylroie, 1992). Some connect with complex cave systems, while others end in sediment or collapse. The blue holes may result from upward stoping of deep dissolution conduits, fractures voids produced by collapse of the bank margin, or pit caves formed during Pleistocene low sea levels that are flooded today (Burkeen and Mylroie, 1992; Mylroie and Carew, 1995).

Ocean blue holes that open on the sea floor, so water can flow in or out of the hole depending on the tidal stage. Generally, the water flows out as the tide ebbs and flows in as the tide rises. However, usually the ebb and flow cycles are at least slightly out of synchronization with the tide, because of hydrodynamic conditions in the cave system to which the blue hole is connected.

The water of ocean blue holes is usually near-normal marine unless they discharge significant water from an island interior, in which case they may be fresh or brackish. Water in inland blue holes may be fresh, brackish, hypersaline, or marine. If the surface water is fresh, or brackish, then it is usually stratified according to salinity and density differences. At some depth a halocline usually exists, below which, the water has near-normal marine salinity.

The largest and most significant blue hole recognized on San Salvador Island is called Watlings Blue Hole. It is a sinkhole pond on the southwest side of the island near Sandy Point. The pond is approximately 40 m wide and is generally circular in shape. At the center of the pond, the water is 10 m deep. A horizontal cave passage opens at the center of the floor of the pond and extends north. The entrance is 2.5 m wide and 1.3 m high. The cave extends approximately 10 m north before becoming to low for cave divers to follow. The floor of the cave is dark gray silt (Mylroie, 1988). The water level in the pool rises and falls with the tide. Salinity of the water is usually near-normal marine or slightly brackish.

CAVES AS A GEOLOGIC HAZARD

Caves and karst are recognized as a geologic hazard (Beck, 1989; White, 1988). Subsidence, groundwater contamination, and flooding are problems common to many karst areas. In the Bahamas, the caves develop primarily as a result of vadose flow or phreatic mixing of groundwaters, as opposed to true integrated conduit systems. For these reasons, Bahamian caves are not the type of hazard as regards contaminant transport or flooding in an island freshwater lens environment, that exists for the conduit flow systems found in continents. Collapse and subsidence is the major hazard. To evaluate collapse potential, the nature of the various types of caves must be considered, as well as their distribution. To that end, the existing data base of caves on San Salvador Island, the most geologically studied island in the Bahamas, was analyzed. As certain types of Bahamian caves are found associated with certain types of Bahamian terrains, the distribution of terrains was examined as well.

Caves and Their Terrains

The various types of terrains are shown in Table 1. Beach and Holocene rock areas can be eliminated from the analysis, as these areas do not yet contain caves developed by dissolution processes (sea caves and related structures in Holocene and Pleistocene rocks are ignored in this analysis). Paleosol caves have been ignored for similar reasons. The Sangamon Terrace includes low lying areas between 1 and 7 m elevation. The vast majority of these rocks are Grotto Beach Formation deposits formed during the last interglacial, or Sangamon (oxygen isotope substage 5e, centered about 125,000 years ago), when sea level was about 6 m above present, hence the name of the terrace.

The eolianites are defined as those deposits that reach above 7 m elevation (although they have flanks that extend below that elevation). They consist of rocks of the Grotto Beach Formation and the Owl's Hole Formation. The lakes and tidal creeks make up the remainder of the island area.

This study examined the data on 77 known caves on San Salvador Island. Blue holes and lake drains have not been given an in-depth treatment, as their submerged character nature requires cave diver investigation. Also, blue holes are obvious features that are easily located, and can be explored by cave divers, if need be, to assess their potential geologic hazard. The data on banana holes, pit caves, and lake drains are presented in Table 3; and the cumulative size distribution is presented as Figure 4. It is very important to note that these data do not represent all of the caves on San Salvador Island, just those that have been found in areas that have been explored. Many areas of San Salvador have not been searched for caves, and in those areas that have been searched, it cannot be assumed that all caves were located. This caveat is especially important in regard to banana holes, many of which may still have entirely intact roofs. The presence of "hidden" banana holes can only be estimated from analysis of those that have total or partially collapsed roofs. Therefore, the data presented here represent only a <u>minimum</u> assessment of risk, and in all likelihood, the risk is significantly higher than that presented here. This study does, however, provide insight into the potential for caves to be geologic hazards in the Bahamas.

The cave data are presented in a variety of formats, as follows. Table 4, and Figure 5 are data for banana holes; Table 5, and Figure 6 are data for pit caves; Table 6, and Figure 7 are data for flank margin caves. All these data, including paleosol caves, blue holes, and lake drains are summarized in Table 7.

The median floor areas of the three main cave types are: banana holes, 28 m^2; pit caves, 10 m^2; and flank margin caves, 96 m^2. The largest floor areas for the three main cave types are: banana holes, 327 m^2; pit caves, 134 m^2; flank margin caves, 1,700 m^2. Although these data are representative of the known caves on San Salvador, the reader should be aware that much larger examples of these cave types are known on other Bahamian islands (Mylroie, 1988; Mylroie and others, 1991), and larger caves, as yet not located, may exist on San Salvador. For example, Clifton Banana Hole on New Providence Island, Hatchet Bay Cave on Eleuthera, and Salt Pond Cave on Long Island represent much larger features than the largest now known on San Salvador.

Analysis of Cave Hazard

Given that a substantial cave data base does exist on San Salvador, an estimate of <u>minimum</u> risk can be made. The caves posing the greatest risk to land use are the banana holes. Pit caves are known primarily from the eolianite terrain, but they may exist at lower elevations on the Sangamon terrace terrain, where they are likely to be either water-filled and appear as blue holes, or sediment choked and appear as banana holes. So, low elevation pit caves will appear in the cave counts as another cave type. On the eolian ridges, a few pit caves are very large, and building a structure over them would be difficult. Most, however, are small, and their openings can easily be bridged or engineered around. As pit caves have a depth much greater than their width, they have are more mechanically stable than banana holes. Pit caves also have a surface expression that is the result of their capture of vadose water. Thorough field examination should be able to locate them. Despite these reassurances, some pit caves are known to have lateral passages that lead to pits that do not breach the surface. Such situations do pose a risk, but because pit caves are generally located on ridges, which are less likely to be developed, they represent a minimal geologic hazard.

Flank margin caves are, by definition, located in the flanks of eolianite ridges. This location greatly reduces the possible area that must be examined for this type of cave. The ascending nature of the dune surface in which the caves form indicates that the deeper these caves penetrate the dune, the more rock there is overhead, and hence the greater the cave stability. Risks remain real, however, as the largest air-filled dissolution voids known in the Bahamas today are flank margin caves. One chamber in Salt Pond Cave on Long Island, Bahamas, has a volume of over 14,000 m^3 (Mylroie and others, 1991). If the chamber is large, and the dune slope low, the roof may be thin. If the underlying chamber is

TABLE 3

GENERALIZED DIMENSIONS OF KNOWN CAVES ON SAN SALVADOR ISLAND, BAHAMAS, RANKED BY AREA AND SHOWING CUMMULATIVE DISTRIBUTION

Compiled by William L. Wilson, Geologist, Subsurface Evaluations, Inc., From Various Sources, June 15, 1993.

Name	Length (meters)	Width (meters)	Height (meters)	Elevation (meters)	Depth (meters)	Area (Square m)	General, Simplified Description	Rank	Cummulative Distribution (Rank/63 x 100)
Lighthouse Cave	100	17	NA	7	NA	1700	Irrg Chambers w/Intercon Pass	62	98.4
Beach Cave	57	15	3.5	NA	NA	855	Irregular Chamber	61	96.8
Altar Cave	48	11	NA	2.5	1	528	Single Passage	60	95.2
Dripping Rock Cave	24	24	NA	2.5	1	484	Single Chamber	59	93.7
George Storr's Cave	20	20	3.5	4	NA	400	One Chamber	58	92.1
Viente Palm B. H.	23	19	5	NA	2.5	327	One Elliptical Chamber	57	90.5
Water Hole B.H.	24	16	NA	NA	6	300		56	88.9
Reckley Hill Pond Cave	17	13	2	2	NA	221	One Chamber	55	87.3
Cave B.H.	23	9	1	NA	1	190		54	85.7
Palm Tree B.H.	16	13	NA	NA	NA	163		53	84.1
Habitat Cave	16.4	9.1	5.5	NA	1.4	149	Two Pits to One Chamber	52	82.5
Triple Shaft Cave	26	13	5	NA	4	134		51	81
Sliver Cave	31	28	1	NA	NA	134		50	79.4
Dance Hall Cave	17	7	1.5	3	NA	119	Chamber and One Passage	49	77.8
Cresent Top Cave	18	14	1.8	3	NA	108		48	76.1
Blow Hole	19	5.4	NA	0.9	1	103	One Chamber	47	74.6
Garden Cave	48	2	1.5	NA	NA	96		46	73
Hole to the Sea 2	26	3.7	NA	2.5	1	96	Pit with One Passage	45	71.4
Try Tried Cave	14.5	6.4	2.9	NA	2	93	Two Pits One Passage	44	69.8
Berney's Cave	11	8.2	NA	8	4	83	Two Chambers	43	68.3
Old Bottle Cave	20	4	1	NA	2	80	Three Pits One Passage	42	66.7
Chinese Fire Drill Cave	20	3.6	NA	2	1	72	Pit with One Passage	41	65.1
Deep Hole Cave	20	3.5	2	12	2.5	70	Pit with Two Chambers	40	63.5
Ficus Tree B.H.	9	9	1	NA	1	64		39	61.9
Double Shaft Pit	10.4	10	1.1	NA	2	58.5		38	60.3
Plummet Hole	8	7	2	NA	1.3	56	Pit to One Chamber	37	58.7
Bug City	22	2.25	1.5	3	NA	49.5	Two Short Passages	36	57.1
Reckley Hill Pond Maze	8	5.75	1.2	2	NA	46	Maze	35	55.6
Midget Horror Hole	14	2	1.2	4	0.8	41		34	54
Little Owl's Hole	8.2	6.4	NA	NA	NA	41		33	52.4
Hanna's Banana Pit	6	6	7.5	NA	NA	36	Pit to One Chamber	32	50.8
Emerald Cave	12	7	1	4	1	35	One Chamber	31	49.2
Not Got Cave	7.3	4.7	2	NA	2	34.3	One Chamber	30	47.6
Indian Well	7	4	3	NA	NA	28	One Chamber	29	46
Hole to the Sea 1	15	1.8	NA	2.5	1	27	Pit with One Passage	28	44.4
Pipe Cave	13	2.5	0.75	3	NA	27		27	42.9
Hole to the Sea 3	11	2.3	NA	2.5	1	25	Pit with One Passage	26	41.3
Just Off Jake Jone's Rd.	5.5	4	1	NA	0.2	22	One Slopping Chamber	25	39.7
Wasp Cave	8.4	8	1	NA	NA	22		24	38.1
North Little Lake B.H.	5.2	5	1.6	NA	1	19	One Elliptical Chamber	23	36.5
My Water Hole	9	2	1.5	NA	2.5	18	Pit with One Passage	22	34.9
Hole to the Sea 4	8	2.3	NA	2.5	1	18	Pit with One Passage	21	33.3
South Breezy Hill Cave	7	2.5	1	NA	0.5	17.5	Pit with One Passage	20	31.7
Sharp Rock Cave	6	5.2	1.7	NA	0.5	16		19	30.2
Owl's Hole Cave	7.2	2.3	NA	NA	NA	13	Pit	18	28.6
Tight Hole Cave	4	2.5	1	NA	NA	10	Pit to One Chamber	17	27
Owl's Nest Cave	6	1.5	1.5	NA	NA	9	Pit with One Passage	16	25.4
Double Drop Cave	8	1	1	NA	NA	9	Pit with One Passage	15	23.8
Ectasy Cave	5	2.5	2.2	NA	NA	8.7	Pit with One Passage	14	22.2
Winter's Pit	4	4	12	12	3	8	Deepest Pit	13	20.6
Hanna's Hole	4.5	1.75	1.5	NA	NA	8	Pit to One Chamber	12	19
Two Dead Cow Hole	2.2	4.4	4	NA	NA	7.6	One Elliptical Pit	11	17.5
Roger's Hole	6	1	1.5	NA	NA	6	One Sloping Passage	10	15.9
Winter's Hole	5.5	1	3	NA	NA	5.5	One Sloping Passage	9	14.3
Hornet B.H.	3	2	0.7	NA	0.5	4.7		8	12.7
Old Well B.H.	2.5	2.1	NA	NA	0.5	4	One Elliptical Pit	7	11.1
Bat Pits	5	1.5	0.8	NA	NA	4		6	9.5
Top O' the Hill B.H.	2.5	2.1	0.9	NA	0.5	4		5	7.9
Lizard Hole	4.8	0.8	1	NA	NA	3.8	One Sloping Passage	4	6.3
Dune Ridge Pit	3	1	5	NA	3.1	3		3	4.8
Spider Splash Pit	2.5	1.2	4	NA	NA	3	Pit	2	3.2
Bat Window Cave	2	0.75	0.6	NA	NA	1.5	Small Chamber	1	1.6
Minimum						0		0	0

Abbreviations: B.H. = Banana Hole, NA = Not Available, Irreg = Irregular, Intercon = Interconnected, Pass = Passages

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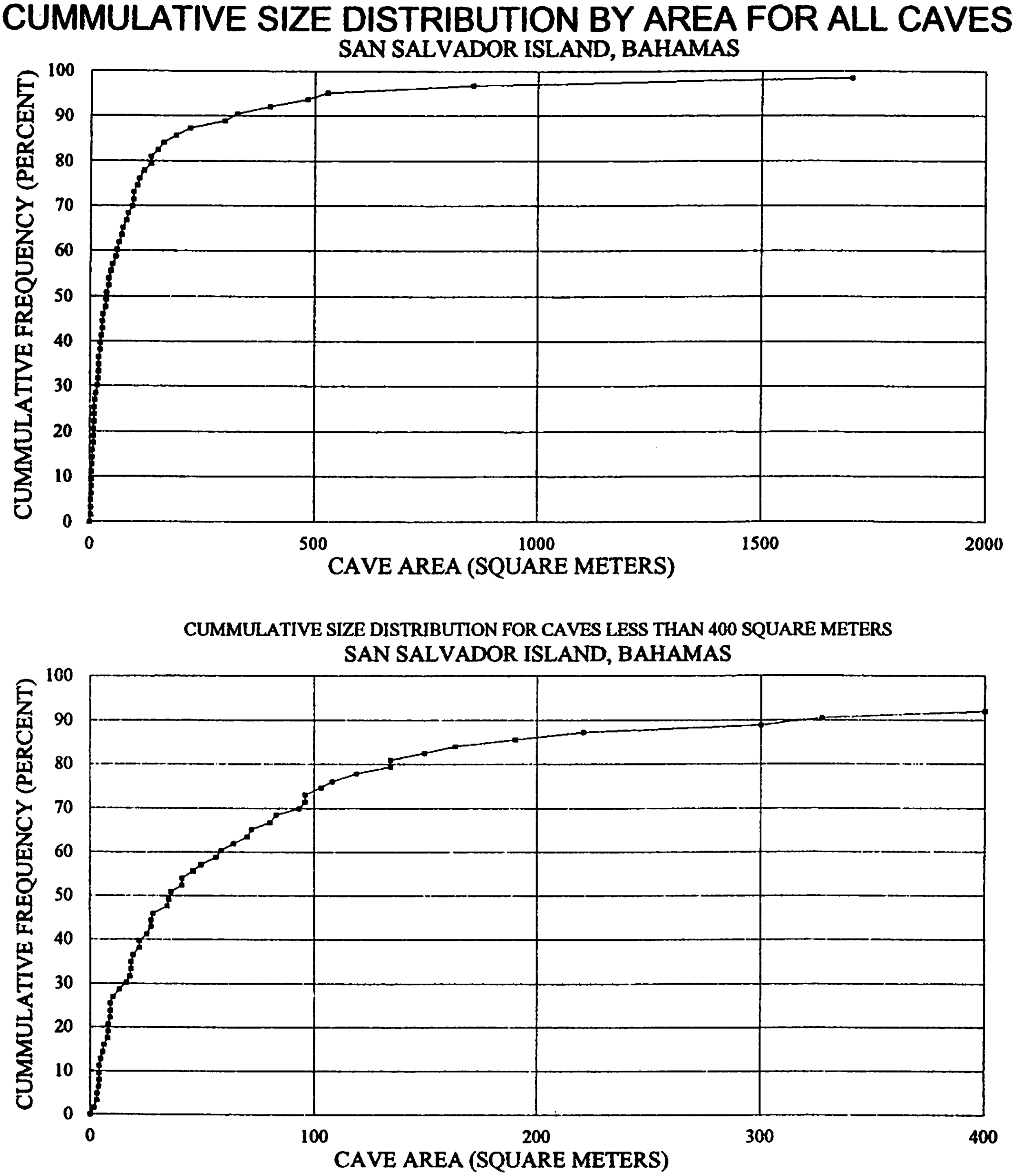

Figure 4. Cumulative size distributions for caves on San Salvador Island: A - for all caves; B - for caves with surface areas less than 400 m.

Table 4.

GENERALIZED DIMENSIONS OF KNOWN BANANA HOLE CAVES, SAN SALVADOR ISLAND, BAHAMAS, RANKED BY AREA AND SHOWING CUMMULATIVE DISTRIBUTION

Compiled by William L. Wilson, Geologist, Subsurface Evaluations, Inc., From Various Sources, March 15, 1994.

Name	Length (meters)	Width (meters)	Height (meters)	Elevation (meters)	Depth (meters)	Area (Sq m)	General, Simplified Description	Rank	Cummulative Distribution % Smaller
Hornet Banana Hole	23	19	5	NA	2.5	327	One Elliptical Chamber	21	95.5
Just Off Jake Jone's Rd.	24	16	NA	NA	6	300		20	90.9
Old Well Banana Hole	23	9	1	NA	1	190		19	86.4
North Little Lake B.H.	16	13	NA	NA	NA	163		18	81.8
Habitat Cave	16.4	9.1	5.5	NA	1.4	149	Two Pits to One Chamber	17	77.3
Cave Banana Hole	14.5	6.4	2.9	NA	2	93	Two Pits One Passage	16	72.7
Bemey's Cave	11	8.2	NA	8	4	83	Two Chambers	15	68.2
Plummet Hole	9	9	1	NA	1	64		14	63.6
Ficus Tree Banana Hole	8	7	2	NA	1.3	56	Pit to One Chamber	13	59.1
Not Got Cave	7.3	4.7	2	NA	2	34.3	One Chamber	12	54.5
Indian Well	7	4	3	NA	NA	28	One Chamber	11	50
Wasp Cave	8.4	8	1	NA	NA	22		10	45.5
Palm Tree Banana Hole	5.5	4	1	NA	0.2	22	One Slopping Chamber	9	40.9
Try Tried Cave	5.2	5	1.6	NA	1	19	One Elliptical Chamber	8	36.4
My Water Hole	9	2	1.5	NA	2.5	18	Pit with One Passage	7	31.8
Sharp Rock Cave	6	5.2	1.7	NA	0.5	16		6	27.3
Ectasy Cave	5	2.5	2.2	NA	NA	8.7	Pit with One Passage	5	22.7
Water Hole B.H.	2.2	4.4	4	NA	NA	7.6	One Elliptical Pit	4	18.2
Top O' the Hill B.H.	3	2	0.7	NA	0.5	4.7		3	13.6
Viente Palm B. H.	2.5	2.1	0.9	NA	0.5	4		2	9.1
Two Dead Cow Hole	2.5	2.1	NA	NA	0.5	4	One Elliptical Pit	1	4.5
						0		0	0

Abbreviations: BH = Banana Hole; NA = Not Available; Rd = Road; Sq = Square; m = meter

Table 5.

GENERALIZED DIMENSIONS OF KNOWN PIT CAVES ON SAN SALVADOR ISLAND, BAHAMAS, RANKED BY AREA AND SHOWING CUMMULATIVE DISTRIBUTION

Compiled by William L. Wilson, Geologist, Subsurface Evaluations, Inc., From Various Sources, March 15, 1994.

Name	Length (meters)	Width (meters)	Height (meters)	Elevation (meters)	Depth (meters)	Area (Sq m)	General, Simplified Description	Rank	Cummulative Distribution % Smaller
Triple Shaft Cave	26	13	5	NA	4	134	Largest Area for a Pit Cave	21	95.5
Hole to the Sea 2	26	3.7	NA	2.5	1	96	Pit with One Passage	20	90.9
Double Shaft Pit	10.4	10	1.1	NA	2	63		19	86.4
Owl's Hole	7	6	NA	NA	10	33	Pit	18	81.8
Hanna's Banana Pit	6	6	7.5	NA	NA	28.3	Pit to One Chamber	17	77.3
Hole to the Sea 1	15	1.8	NA	2.5	1	27	Pit with One Passage	16	72.7
Hole to the Sea 3	11	2.3	NA	2.5	1	25	Pit with One Passage	15	68.2
Hole to the Sea 4	8	2.3	NA	2.5	1	18	Pit with One Passage	14	63.6
Little Owl's Hole	5	5	NA	NA	6	18		13	59.1
Winter's Pit	5.5	3	12	12	12	11	Deepest Pit	12	54.5
Tight Hole Cave	4	2.5	1	NA	NA	10	Pit to One Chamber	11	50
Owl's Nest Cave	6	1.5	1.5	NA	NA	9	Pit with One Passage	10	45.5
Double Drop Cave	8	1	1	NA	NA	9	Pit with One Passage	9	40.9
Hanna's Hole	4.5	1.75	1.5	NA	NA	8	Pit to One Chamber	8	36.4
Roger's Hole	6	1	1.5	NA	NA	6	One Sloping Passage	7	31.8
Winter's Hole	5.5	1	3	NA	NA	5.5	One Sloping Passage	6	27.3
Bat Cave	5	1.5	0.8	NA	NA	4		5	22.7
Lizard Hole	4.8	0.8	1	NA	NA	3.8	One Sloping Passage	4	18.2
Spider Splash Pit	2.5	1.2	4	NA	NA	3	Pit	3	13.6
Dune Ridge Pit	3	1	5	NA	3.1	3		2	9.1
Bat Window Cave	2	0.75	0.6	NA	NA	1.5	Small Chamber	1	4.5
Minimum						0		0	0

Abbreviations: NA = Not Available; sq = square; m = meter

Table 6.

GENERALIZED DIMENSIONS OF KNOWN FLANK-MARGIN CAVES, SAN SALVADOR ISLAND, BAHAMAS, RANKED BY AREA AND SHOWING CUMMULATIVE DISTRIBUTION

Compiled by William L. Wilson, Geologist, Subsurface Evaluations, Inc., From Various Sources, March 15, 1994.

Name	Length (meters)	Width (meters)	Height (meters)	Elevation (meters)	Depth (meters)	Area (Sq m)	General, Simplified Description	Rank	Cummulative Distribution % Smaller
Lighthouse Cave	100	17	NA	7	NA	1700	Irrg Chambers w/Intercon Pass	20	95.2
Beach Cave	57	15	3.5	NA	NA	855	Irregular Chamber	19	90.5
Altar Cave	48	11	NA	2.5	1	528	Single Passage	18	85.7
Dripping Rock Cave	24	24	NA	2.5	1	484	Single Chamber	17	81
George Storr's Cave	20	20	3.5	4	NA	400	One Chamber	16	76.2
Reckley Hill Pond Cave	17	13	2	2	NA	221	One Chamber	15	71.4
Sliver Cave	31	28	1	NA	NA	134		14	66.7
Dance Hall Cave	17	7	1.5	3	NA	119	Chamber and One Passage	13	61.9
Cresent Top Cave	18	14	1.3	3	NA	108		12	57.1
Blow Hole	19	5.4	NA	0.9	1	103	One Chamber	11	52.4
Garden Cave	48	2	1.5	NA	NA	96		10	47.6
Old Bottle Cave	20	4	1	NA	2	80	Three Pits One Passage	9	42.9
Chinese Fire Drill Cave	20	3.6	NA	2	1	72	Pit with One Passage	8	38.1
Deep Hole Cave	20	3.5	2	12	2.5	70	Pit with Two Chambers	7	33.3
Bug City Cave	22	2.25	1.5	3	NA	49.5	Two Short Passages	6	28.6
Reckley Hill Pond Maze	8	5.75	1.2	2	NA	46	Maze	5	23.8
Midget Horror Hole	14	2	1.2	4	0.8	41		4	19
Emerald Cave	12	7	1	4	1	35	One Chamber	3	14.3
Pipe Cave	13	2.5	0.75	3	NA	27		2	9.5
South Breezy Hill Cave	7	2.5	1	NA	0.5	17.5	Pit with One Passage	1	4.8
Minimum						0		0	0

Abbreviations: NA = Not Available; sq = square; m = meter; Irreg = Irregular; w/ = with; Intercon = Interconnected; Pass = Passages

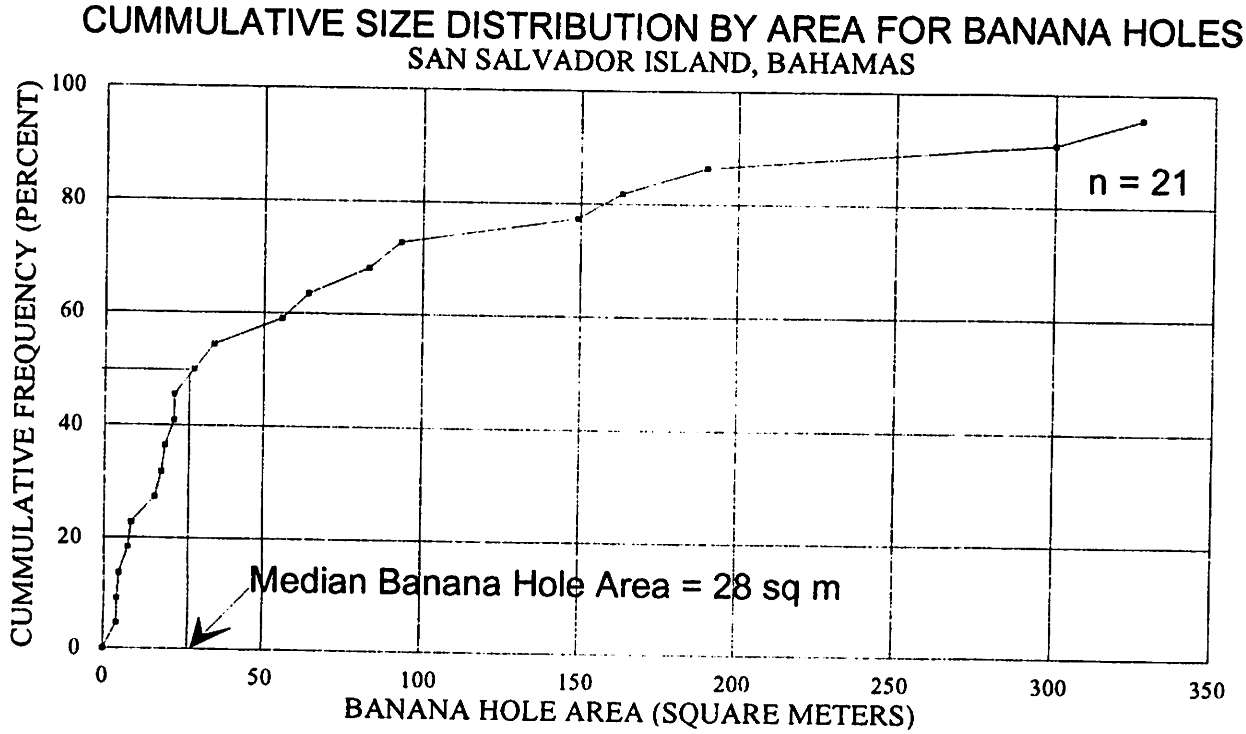

Figure 5. Cumulative size distribution of banana holes on San Salvador Island.

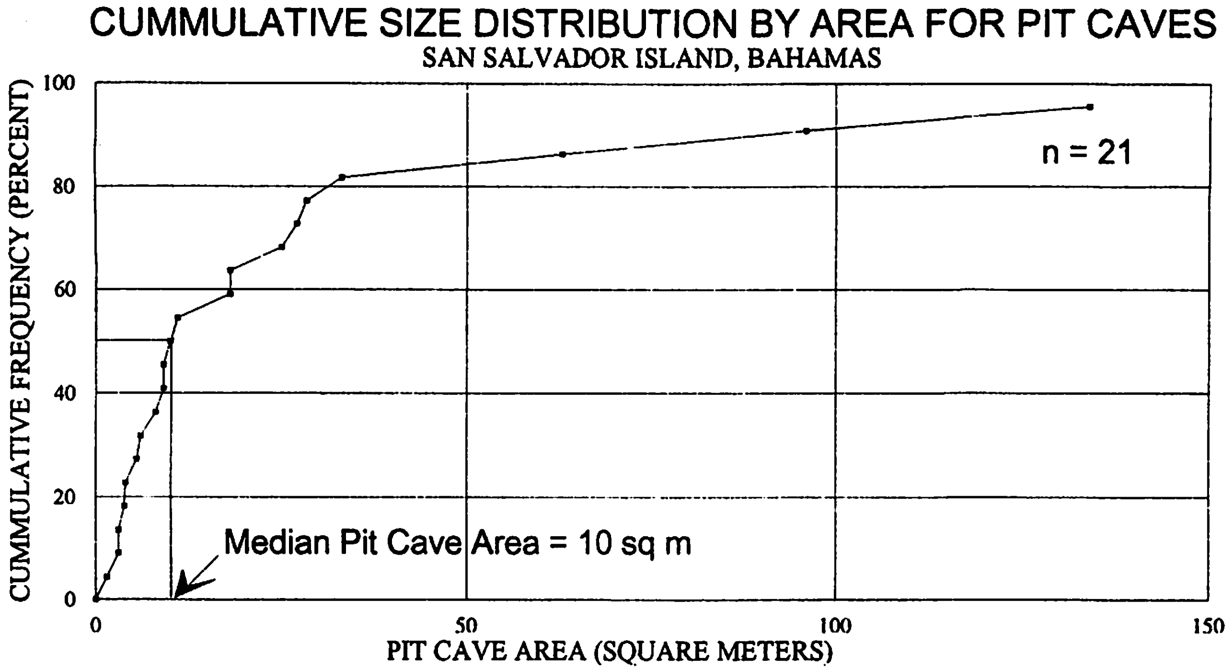

Figure 6. Cumulative size distribution of pit caves on San Salvador Island.

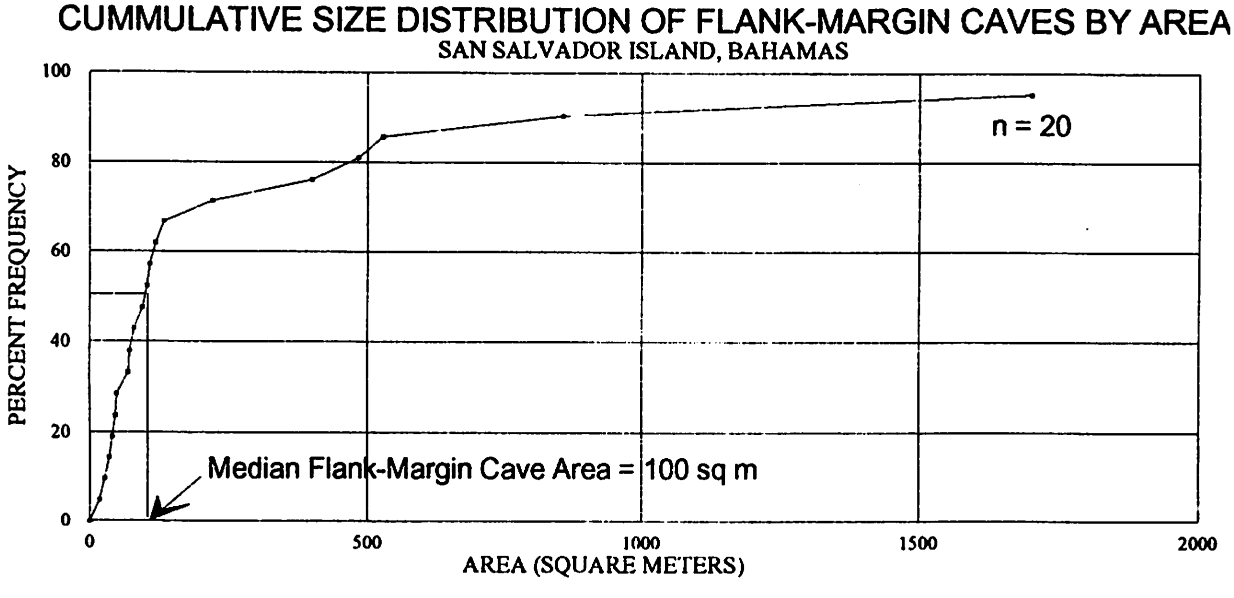

Figure 7. Cumulative size distribution of flank-margin caves on San Salvador Island.

Table 7.

CAVE DENSITIES ON SAN SALVADOR ISLAND

TYPE OF CAVE	NUMBER KNOWN	TERRAIN	EXPLORED AREA (KM2)	MINIMUM DENSITY (C/KM2)	COMBINED DENSITY (C/KM2)
BANANA HOLE	21	TERRACE	39	0.54	0.67
BLUE HOLES	4	TERRACE	39	0.10	
PALEOSOL	1	TERRACE	39	0.026	
FLANK MARGIN	20	DUNES	18	1.1	2.3
PIT	21	DUNES	18	1.2	
LAKE DRAINS	10	LAKES	9	1.1	1.1
TOTAL	77	------------	66	----	----
AVERAGE	----	------------	----	----	1.2

extensive, collapse is a very real risk.

For a variety of reasons, banana holes represent the greatest collapse risk. First, they are developed in the Sangamon Terrace, which by area is the largest of all the terrains (Table 1). Second, they typically form with thin roofs, and need no further surface erosion tomake them weak or unstable. Third, unlike flank margin caves, they do not form at a specific site in the freshwater lens, hence predicting their location is difficult. Fourth, they are normally discovered only when the roof has partially or completely collapsed, so estimating the number hidden beneath intact, but vulnerable, roofs is very difficult.

Table 8 shows an example of the calculation of cave risk and potential cost for a runway extension on San Salvador Island, Bahamas. Remembering that the cave data represents a minimum value (1.2 caves/km^2), it can be seen that a sum in excess of $100,000 could be prudently justified to assess the risk of cave collapse for the runway. The potential cost of collapse most certainly would be higher, given the minimal value of risk used, and that there may be many as yet uncollapsed banana holes which would enhance the risk factor.

Dealing With Cave Hazard

If a portion of a Bahamian island, or similar carbonate island, is to be developed, it is clear that the cave risk must be assessed and dealt with. The initial task should be to conduct a ground survey of the area to see if there are caves that are open to the surface. This can be labor intensive, but there is no substitute for ample ground-truth in this situation. If the ground survey reveals no caves it cannot be assumed that there are no caves, especially banana holes. It merely means that there is no current expression of subsurface voids.

To locate existing, but unexpressed subsurface voids or caves, geophysical techniques can be used. Gravity survey has proven successful in locating unknown voids on San Salvador (Kunze and Mylroie, 1991), but the technique is very labor intensive and time consuming. Ground penetrating radar (GPR) has been used with success in the Bahamas by one of the authors [Wilson]. Theoretically, both seismic and resistivity methods should also work, as the caves of interest tend to be shallow. Boreholes provide the best data, but at the greatest cost of time and money. A key question for any such survey is, "What is the minimum sampling regime to follow in order to satisfactorily assess cave risk?" The question assumes that the technique being used does successfully indicate existing caves that have no surface expression. The data presented here provides a minimum estimate of how many caves are to be expected per unit area. From these numbers, the investigator can decide how much ground needs to be covered, and at what sampling density, to attain the risk assessment appropriate for the situation.

SUMMARY

The data presented here provides an initial

Table 8.

ESTIMATED APPROPRIATE FUNDING TO ASSESS AND MITIGATE CAVE COLLAPSE AT THE SAN SALVADOR ISLAND AIRPORT

FACILITY	WIDTH & LENGTH (FEET)	AREA (ACRES)
RUNWAY	150 X 7,800	26.86
AIRCRAFT PARKING	400 X 600	5.51
TAXIWAY	65 X 150	0.22
TOTAL		34.59 = 0.14 KM^2

PROBABILITY OF CAVE OCCURRENCE:

$$= 0.14\ \mathrm{KM}^2 \times 1.2\ \mathrm{CAVES/KM}^2 = 0.17$$

REASONABLE MINIMAL ACCIDENT SECENARIO CAUSED BY CAVE COLLAPSE SHORTLY AFTER AIRPORT OPENS:

> ONE-TIME, CATASTROPHIC DESTRUCTION OF TWIN-ENGINED, PROPELLER-DRIVEN AIRCRAFT RESULTING IN DEATH OF PILOT AND TWO PASSENGERS

MINIMUM COST OF ACCIDENT INCLUDING LOSS OF LIFE AND PROPERTY DAMAGE:

$$\approx \$5\ \mathrm{MILLION}$$

EXPECTED LOSS FROM CAVE COLLAPSE:

$$\$5{,}000{,}000 \times 0.17 = \$850{,}000$$

MINIMUM PRUDENT FUNDING TO ASSESS AND MITIGATE CAVE COLLAPSE (ASSUMING 15% ROR):

$$\$850{,}000 \times 0.15 = \$127{,}500$$

estimate of cave density that may be used for the assessment of the risk of cave collapse in carbonate island settings such as the Bahamas. We again wish to emphasize that the data presented here represents a minimum value for cave density. Currently, we are conducting further research over a substantial area of San Salvador Island to obtain a greater volume of data that can be used to generate a better estimate of cave density for the whole island. The collection of cave data used in this paper was the result of research conducted for purposes other than the assessment of cave density and the risk of cave collapse. Our current research will consist of a systematic search for caves in selected areas, particularly the Sangamon Terrace terrain, as it has the highest potential for development, and the highest potential risk. After a ground survey has been completed, selected areas will be examined by one or more geophysical techniques to determine how many caves (banana holes) exist that have no surface expression. With that data in hand more reliable estimates of the risk of cave collapse can be generated.

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