BLUE HOLES: DEFINITION AND GENESIS

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ABSTRACT: Blue holes are karst features that were initially described from Bahamian islands and banks, which have been documented for over 100 years. They are water-filled vertical openings in the carbonate rock that exhibit complex morphologies, ecologies, and water chemistries. Their deep blue color, for which they are named, is the result of their great depth, and they may lead to cave systems below sea level. Blue holes are polygenetic in origin, having formed: by drowning of dissolutional sinkholes and shafts developed in the vadose zone; by phreatic dissolution along an ascending halocline; by progradational collapse upward from deep dissolution voids produced in the phreatic zone; or by fracture of the bank margin. Blue holes are the cumulative result of carbonate deposition and dissolution cycles which have been controlled by Quaternary glacioeustatic fluctuations of sea-level.

Blue holes have been widely studied during the past 30 years, and they have provided information regarding karst processes, global climate change, marine ecology, and carbonate geochemistry. The literature contains a wealth of references regarding blue holes that are at times misleading, and often confusing. To standardize use of the term blue hole, and to familiarize the scientific community with their nature, we herein define them as follows: "Blue holes are subsurface voids that are developed in carbonate banks and islands; are open to the earth's surface; contain tidally-influenced waters of fresh, marine, or mixed chemistry; extend below sea level for a majority of their depth; and may provide access to submerged cave passages." Blue holes are found in two settings: ocean holes open directly into the present marine environment and usually contain marine water with tidal flow; inland blue holes are isolated by present topography from surface marine conditions, and open directly onto the land surface or into an isolated pond or lake, and contain tidally-influenced water of a variety of chemistries from fresh to marine.

INTRODUCTION

A search of the scientific literature on the karst features of the Bahamas reveals a great number of references to features called blue holes. Original use of this term in the Bahamas can be traced back to a descriptive label on British navigation charts from 1843 and 1844, where it was initially used to describe a water-filled depression differentiated from its surroundings by its deep blue color (Shaw 1993). However, blue hole has also been used to describe artesian springs in Jamaica, a karst setting different than that of the blue holes of the Bahamas (Zans 1951; Sweeting 1973). In addition, features of similar morphology, that contain water, such as the cenotes of Mexico, are interpreted by some authors as a form of blue hole (Ford and Williams 1989). Recently, use of the term blue hole has proliferated because of increased scientific research on karst environments in the Bahamas. The resulting variety of uses is misleading and confusing.

This paper first provides a discussion of the origin of the term blue hole, and many of the ways the term has been applied, both within and outside the Bahama Islands. Then, mechanisms of blue hole formation are discussed, and finally we propose a definition of blue holes to standardize use of the term for the variety of scientific researchers that work with them. This paper is not intended to provide an exhaustive review of the term and its uses, but rather, to present a representative discussion of the variety of terminology.

Blue holes have been defined based on their position, shape, developmental history, water-flow characteristics, connection to caves, and water chemistry. To find a common definition that is both specific enough to describe the phenomena, and general enough to serve all users, is a problematic task.

The term blue hole is associated primarily with the carbonate islands of the Bahamas. The karst experience of most geologists is with fluvial karst landscapes developed on Paleozoic and Mesozoic carbonates from interior continental settings. In contrast, the Bahama islands consist of late Quaternary limestones and their associated dissolutional landforms. Both Quaternary carbonate deposition and dissolution in the Bahamas are tied to sea-level position. Carbonate deposition occurs when sea level is high, and the platform tops are partially or totally submerged. Karst processes that result from meteoric dissolution can occur only when some portion of the carbonate platform is subaerially exposed. Vadose dissolution occurs on any exposed island surface, and downward through the carbonate rock to the water table. The water table in carbonate islands is represented by the top of the fresh-water lens, which floats on underlying marine ground water. Phreatic dissolutional processes occur within the fresh-water lens, especially at its upper boundary with the vadose zone, and its lower boundary with marine water. This lower boundary is referred to as the halocline, or mixing zone. Over time, the lens migrates vertically as sea level migrates up and down during continental glaciation and deglaciation. Glacioeustatic change (global sea level fluctation that results from glaciation and deglaciation) has had a major impact on karst development in the Bahamas, including the formation of blue holes. For a review of Bahamian geology and karst processes, see Mylroie and Carew (1995b).

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ORIGIN AND USE OF THE TERM "BLUE HOLE"

Early Descriptions

The first reference in the literature to blue holes is by Catesby in 1725 (Shaw 1993), who used the word "pit" to describe them, a term used by island inhabitants at that time to describe deep holes filled with water that fluctuated with the tides. Such fluctuating water level in deep depressions was also reported by Nelson (1853). The term blue hole appeared on the British Admiralty charts of the Bahamas in 1843 and 1844 (Shaw 1993). Northrup reported in 1890 that the term "ocean hole" was used by inhabitants of the Bahamas, and also commented on water flow into and out of these features, using the term "boiling hole" (Shaw 1993). Agassiz (1893) used the term blue hole in conjunction with ocean hole, to describe deep holes in the floor of Bahamian lagoons and banks. He gave no other definition or description. Maynard made observations he reported in 1894, describing features he called ocean holes, noting their deep indigo color (Shaw 1993). Shattuck and Miller (1905) used the terms ocean hole and blue hole to describe deep holes, found on the Bahama banks, whose sides flare-out beneath the opening and which usually have a constant circulation of water. The water in some of the blue holes they described responded in harmony with tidal fluctuations. Doran (1913) referred to blue hole as a local name given to ocean holes. Stoddart (1962) described a blue hole in Belize as a deep depression in the floor of the lagoon which is perfectly round and reputedly bottomless. Stoddart preferred to use the term blue hole, rather than ocean hole, because of the deep blue color associated with the features. While they are obvious features of the Bahamas, blue holes did not receive much early scientific study (Sealey 1991). Discussions of blue holes are now routine in textbooks about Bahamian geology and geomorphology (e.g. Sealey 1994).

The Influence of George Benjamin

The synonymous use of the terms blue hole and ocean hole changed in 1970, when George Benjamin published an article on blue holes in *National Geographic Magazine* (Benjamin 1970). That article was followed by the abstract for a talk presented to the National Speleological Society (Benjamin, 1971). He used the term blue hole to refer to submarine caves entered from flooded deep shafts found in Bahamian lagoons (Benjamin 1970), and subsequently described blue holes as being different from springs in that they have strong reversing currents (Benjamin 1971). He later catalogued the blue hole sites he had described between 1967 and 1972 (Benjamin 1984). A number of later articles by other authors on blue hole deposits refer back to Benjamin (1970) as the source for blue hole definition and description (e.g. Dill 1977; Gascoyne et al. 1979; Gascoyne 1984; Palmer 1984). The impact of Benjamin's work can be seen by comparing the first and second editions of the textbooks on karst written by Jennings (1971; 1985). Jennings (1971) described vertically-walled collapse dolines, some of which were filled with deep water, but did not at that time refer to these dolines as blue holes. He compared them to cenotes of the Yucatan, Mexico, and to similar features in southeast Australia. In 1985, Jennings described blue holes as deep circular holes in reefs, which are recognized by their dark blue color, and which formed as a result of drowning of subaerial dolines (sinkholes) by sea level rise. He also reported that they commonly had caves leading from them.

Purdy (1974) recognized that blue holes were also called ocean holes, but he preferred to use the term blue hole to describe the circular features which could be recognized from the air by their dark blue color. Dill (1977) also recognized that the term blue hole was in reference to color, but he defined blue holes as being submerged karst features, such as an isolated atoll sinkhole. Gascoyne et al. (1979) suggested that blue holes are underwater karstic caves which had formed in fresh water and which consist of subhorizontal passages and vertical pits extending more than 100 m below sea level. Kieser et al. (1982) described blue holes as elliptical to circular, bowl-shaped depressions with a central vertical tube connected to the sea via deep conduits.

Contributions of Rob Palmer and Later Workers

Scientific investigation of blue holes underwent a major advance in the 1980's when Rob Palmer led a series of expeditions to the Bahamas for the purpose of examining and exploring blue holes. This work produced a series of popular books on blue holes in the Bahamas (Palmer 1985; 1989), and a large number of scientific studies published in the journal *Cave Science* [now titled *Cave and Karst Science*]. In 1984 an entire issue of *Cave Science* was devoted to the exploration, biology, and geochemistry of blue holes (see Palmer 1984). What is notable about that special issue and later papers, are the various ways the authors from different disciplines defined blue holes. Farr and Palmer (1984) defined blue holes as cavernous features, and divided them into two types: inland blue holes (cenotes) and oceanic blue holes ("boiling holes"). The inland types were described as circular deep shafts which bell out into a wider cavern. The oceanic ones were defined as cave systems which opened out below sea level, and which have strong tidally-related, but out of phase, currents (origin of the term "boiling hole"). Smart (1984) defined blue holes as lakes that are deeper than the thickness of the fresh-water lens, some of which have a deep blue color, are circular in plan, and have vertical or sloping sides that are overhung at depth. Warner and Moore (1984) defined blue holes as entrances to complex cave systems with strong tidally-related currents. Cunliffe (1985) differentiated between oceanic Bahamian blue holes and inland anchialine caves (those with no surface connection to the open sea, but which contain salt or brackish water and a water level which fluctuates with the tides). Heath and Palmer (1985) differentiated between marine blue holes (which had a "suck and blow" effect in response to tides), and inland anchialine blue hole caves (which had little or no tidal time lag and little or no "suck and blow" effect). Palmer and Heath (1985) also described blue holes as cave entrances, some of which open into inland anchialine caves. In a series of articles by Palmer (1985; 1986a; 1986b), blue holes were variously described as being found both in the ocean and in inland lakes, and as underwater caves which descend into the fresh-water zone. He further reported that some blue holes were long and complex, which he called lens base, and others were circular deep shafts he called cenotes, and some were fractures he called fault controlled. He reported that most blue holes are the cenote type and can be entered through large water-filled openings. Palmer et al. (1986a) described inland blue holes, some of which had a fresh-water lens on top. Palmer et al. (1986b) described blue holes as underwater caves of two types: marine (having strong, tidally related currents) and inland (having entrances lying within fresh water or saline lakes). Trott and Warner (1986) described marine blue holes which were affected, with a time lag, by tidal currents; and used the term doughnut holes for blue holes whose entrances are surrounded by corals and their associated flora and fauna.

As a result of Rob Palmer's work, the general level of knowledge of blue holes within the karst scientific community improved. In their textbook on karst, Ford and Williams (1989) described blue holes as shaft-like depressions, deeply flooded by sea water, which resemble cenotes. They suggested that not all blue holes are formed by karst processes, but that some are formed by bank-margin fracture. In contrast, White's (1988) textbook on karst did not mention blue holes.

In parallel with Rob Palmer's work, done primarily on the large islands and platforms of the northwest Bahamas, other research efforts in blue holes were initiated. Dennis Williams began extensive cave diving in the Bahamas in the 1970's, and gave a number of presentations on blue holes and the flooded cave systems with which they commonly connect (e.g. Williams 1980a; 1980b; 1988). He offered no unique definition for blue holes, but he greatly expanded the data base on blue hole locations, characteristics, and configurations. Williams collaborated with Palmer and wrote a very important paper that laid the foundation for understanding cave development, including blue holes, in carbonate islands (Palmer and Williams 1984).

In the late 1970's, two of the authors of this paper (Carew and Mylroie) began examining Bahamian karst through field work done at the Bahamian Field Station on San Salvador Island. In the first comprehensive study of Bahamian karst, Mylroie (1980) defined blue holes as flooded sinkholes or flooded vadose shafts that may lead to extensive cave systems at depth. Subsequent work largely focused on caves above sea level (Mylroie and Carew 1988; 1990; 1995b). They collaborated with Rob Palmer to study the surface geology for the 1987 *Andros Project* (Palmer 1989) which investigated blue hole development associated with bank-margin fracture on South Andros Island (Carew and Mylroie 1989). At that time Peter Smart and Fiona Whitaker of Bristol University began detailed geochemical studies of blue holes as an outgrowth of the *Andros Project*, and they subsequently produced the first detailed models of blue hole geochemistry (Smart et al. 1988) and flow characteristics (e.g. Whitaker and Smart 1990). Also, a number of ecological studies of Bahamian blue holes were conducted through the auspices of the Bahamian Field Station on San Salvador Island (e.g. Teeter et al. 1986).

Alternative Use of the Term Blue Hole

Unfortunately, the term blue hole has also been used in the literature to describe vaclusian or artesian springs in karst areas. As with Bahamian blue holes, the term originated in reference to the blue color associated with deep water. In this case the fresh water flows upward from a deep karst aquifer, as described in the textbook on karst by Sweeting (1973). Sweeting (1973) makes no mention of blue holes associated with carbonate islands or banks. Instead, she developed the term based on usage in Jamaica (Zans 1951), where ironically, it appears only twice in an atlas of Jamaican karst (Fincham 1977). This usage of the term became the basis of one of two definitions for blue hole found in the Glossary of Geology (Bates and Jackson 1987): "...a Jamaican term for a *resurgence* that does not fountain". The other definition in the Glossary is: "...a term used on the Bahama Banks for a drowned sinkhole". The use of the term blue hole for a deep karst resurgence or karst window can be found in reports on many areas in North America, such as McMillon Blue Hole and Boggs Blue Hole in West Virginia (Dasher and Balfour 1994) and Turner's Blue Hole, Kentucky (Mason et al. 1984). Northern Florida, with its many karst windows and springs that lead deep into a karst aquifer, also has features which have been compared to blue holes (Lane 1986). Use of the term blue hole for artesian karst springs or karst windows in settings where the limestone is dense, the flow is entirely freshwater, and the recharge has an allogenic component (from insoluble areas adjacent to the limestone) is a completely different environment from that of places like the Bahamas. We suggest that use of the term blue hole in this context should be discontinued. The remainder of this paper will refer to blue holes in the Bahamian sense.

Blue Holes and Other Related Karst Features

The previous discussion deals with different features that have been given the same name. On the other hand, examination of the literature indicates that there may be features of different names from a variety of localities that have many or all of the characteristics of Bahamian blue holes as described in the current literature.

In the Mount Gambier area of southeastern Australia there are numerous flooded deep shafts known locally as "sinkholes" (Lewis and Stace 1980). Many of those "sinkholes", such as Little Blue, and Black Hole, have names derived from the color of very deep water. Lewis and Stace

(1980) refer to the blue holes of the Bahamas, the karst springs of Florida, and the cenotes of Yucatan, Mexico, as containing similar features. Based on the diagrams of those features, they are in many respects identical to blue holes and cenotes.

The term cenote repeatedly appears in papers discussing blue holes. The *Glossary of Geology* (Bates and Jackson 1989) defines cenote as: "In Yucatan, Mexico, a vertical shaft in limestone, open to the surface, that contains standing water." The word originates from the Mayan word "tzonot" (Bates and Jackson 1989). Major textbooks on karst (Jennings 1971; 1985; White 1988; Ford and Williams 1989) merely refer to cenotes as collapse sinkholes that lead to water in the Yucatan, Mexico. Ollier (1975), in discussing karst of the Trobriand Islands (between New Guinea and the Solomon Islands) described circular pits that lead to water, which he called cenotes. He defined cenotes as, "cylindrical pits on limestone plateaus ... having water at their base;" and compared them to cenotes of the Yucatan, "obruk" lakes of Turkey, and caves of south-east Australia (see Lewis and Stace 1980). Sweeting (1973) believed that cenotes are a type of abandoned spring, and was uncomfortable with the collapse model of cenote origin, "...since their distribution and frequency are not characteristic of collapse phenomena" (p. 216). However, springs, active or abandoned, also do not have such a distribution and frequency.

The most complete treatment of the term cenote can be found in Reddell (1977). Reddell demonstrated that the Mayan term "tzonot" meant any subterranean chamber that contained permanent water. Reddell felt that cenotes had two major origins. One was by dissolution at depth which produced a void that later became expressed at the surface by collapse. He said that such collapse, or stoping, could produce a variety of morphologies, from small openings into large chambers, to deep shafts, to wide vertical-walled ponds. The second method of origin was described as typical doline or sinkhole development in the subaerial environment. Partial flooding of the sinkhole to produce sloping sides that led to water was attributed to a subsequent rise in base level.

The common factor in all these definitions and descriptions is the presence of water in the cenote. The major difference between Yucatan cenotes and Bahamian blue holes appears to be the elevation of the land containing the features, and their proximity to the ocean. The Yucatan has a higher elevation, locally in excess of 15 m (Reddell 1977), whereas in the Bahamas the average landform is less than 7 m above sea level (Wilson et al. 1995). To reach from the surface to water in the Bahamas, the subaerial portion of an inland blue hole need only penetrate about 6 m of rock at most, whereas in the Yucatan the subaerial portion of many cenotes commonly exceeds 15 m. In addition, the hydrology of the Bahamas differs from that of the Yucatan. In the Bahamas, all phreatic dissolution occurs in a fresh-water lens that is entirely dependent on a small local catchment. In the Yucatan, phreatic dissolution is driven by a large autogenic catchment, as well as allogenic input from non-carbonate highlands to the west (Mylroie and Carew 1995a). It is clear that in morphology, and perhaps in origin, Yucatan cenotes are similar to Bahamian blue holes, and the differences between them are due to geographical differences in the host environment.

Reversing Flow

While blue holes originally gained notice as a result of their depth, which produces the characteristic deep blue color (Agassiz 1893; Shattuck and Miller 1905; Doran 1913), reversing flow was also recognized as a significant feature of some blue holes. Maynard in 1894 (Shaw 1993), and Shattuck and Miller (1905) were the first to discuss in detail the reversing nature of water flow in blue holes; while Benjamin (1970; 1971) presented the first modern discussion of reversing flow in blue holes, a factor critical to safety for the cave diving he pioneered while investigating blue holes near Andros Island, Bahamas. As previously discussed, a decade later Rob Palmer, Dennis Williams, and co-workers conducted numerous studies of blue holes that demonstrated the importance of reversing flow on blue hole ecology, exploration, and geochemistry. The reversing flow of blue holes has been viewed as an aspect of sub-platform water flow in the carbonate banks of the Bahamas; however, flow in some blue holes does not reverse, but instead continuously discharges (Whitaker and Smart 1990; 1995). The reversing flow of blue holes does not appear to be a factor in their formation, but rather, a result of their penetration of tidal and ground-water flow patterns.

BLUE HOLE GENESIS

The formation of blue holes has been ascribed by various authors to four major processes: 1) drowning of surface and vadose karst features such as sinkholes; 2) phreatic dissolution along an ascending halocline; 3) collapse of deep-seated phreatic dissolution voids or conduits; and 4) voids formed by fracture associated with bank-margin failure (Figs. 1-4). It appears that blue holes are of polygenetic origin, that is, they may form from any one of these four processes, or even a combination of them (Mylroie et al. 1995).

Dill (1977) and Jennings (1985) suggested that blue holes were merely drowned dolines or sinkholes. Their view proposed the development of sinkholes by surficial dissolution, a process common in karst areas. The sinkholes developed subaerially during times of glaciation and corresponding low sea level in the Bahamas. They were then thought to be flooded to form blue holes during subsequent times of deglaciation and sea level rise. Mylroie (1980) also thought blue holes might be flooded sinkholes, but in addition suggested that they could be flooded vadose shafts. In this latter model, meteoric water drained from the surface by vadose shafts connected to deep phreatic passages that developed in a fresh-water lens during past glacioeustatic lowstands. These shafts later became flooded by the rise of sea level to its present position (Carew et al. 1982). Dry vadose shafts of a similar

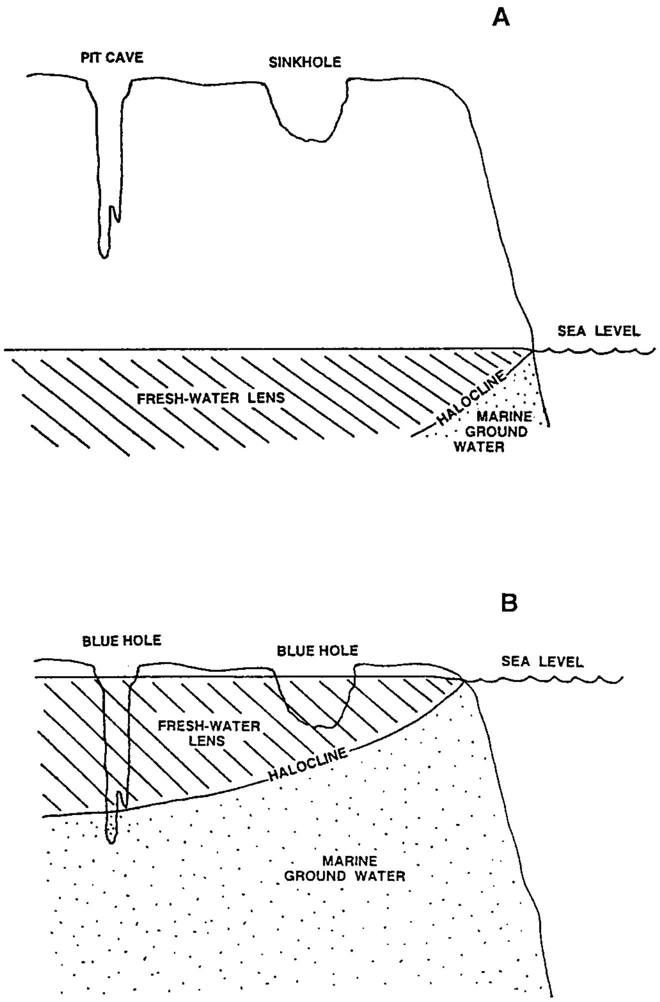

Figure 1. During glacioeustatic lowstands, vadose karst features such as pit caves and sinkholes develop (A). When sea level rises, these depressions flood to become inland blue holes (B). If sea level rises far enough to cover the platform, the inland blue holes would become ocean holes.

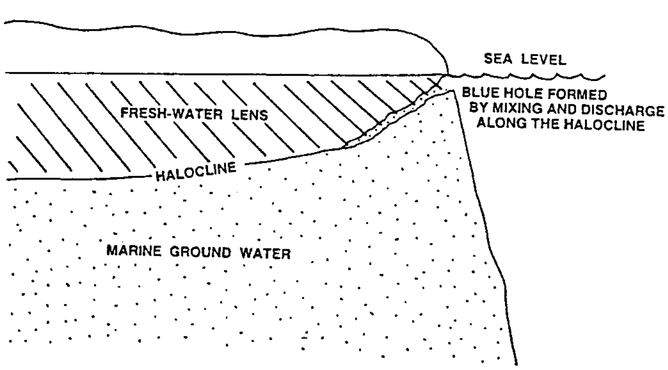

Figure 2. At a given sea level position, phreatic dissolution along the halocline produces a descending void that may enlarge to blue hole dimensions (after Palmer and Williams 1984).

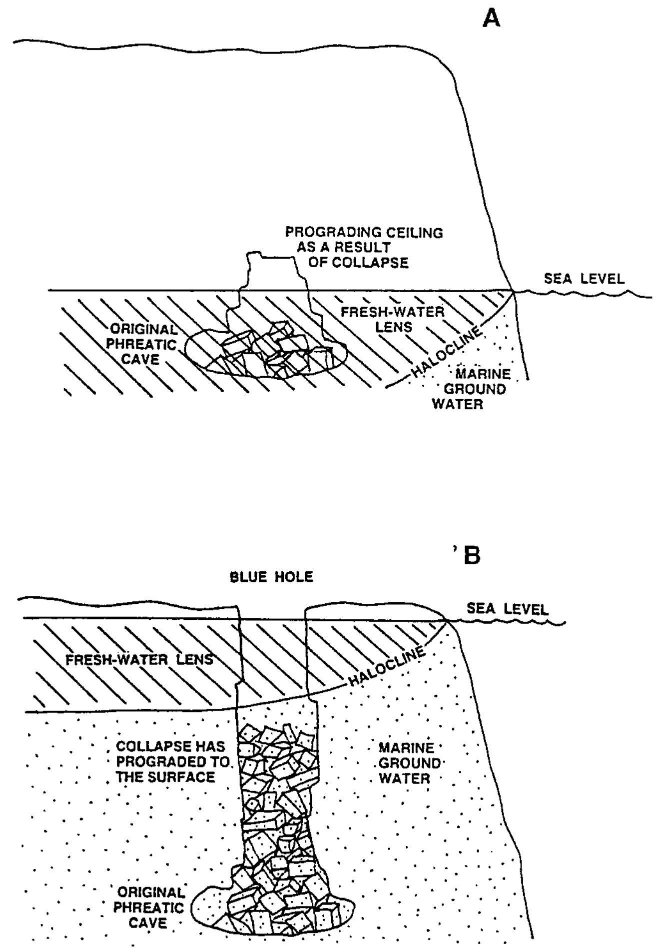

Figure 3. Voids produced at depth by phreatic dissolution (or that formed at shallow levels but later subsided to depth) may undergo progradational collapse (A). If this collapse reaches the surface, an inland blue hole will be created during glacioeustatic highstands (B). If sea level rises far enough to cover the platform, the inland blue hole would become an ocean hole.

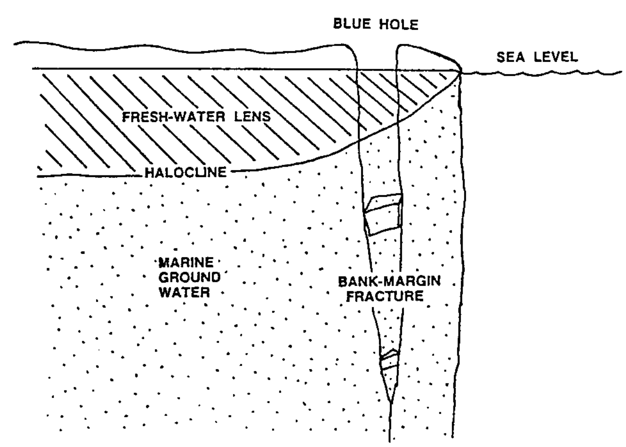

Figure 4. Mechanical failure of the steep sides of carbonate banks produces deep fissures parallel to the bank margin; at glacioeustatic highstands these fissures flood to produce inland blue holes. If sea level rises far enough to cover the platform, the inland blue hole would become an ocean hole.

nature are found on eolian ridges today in the Bahamas, and they have been named "pit caves" (Mylroie and Carew 1995a; 1995b; Mylroie et al. 1995).

In contrast to drowned sinkholes and pit caves, Gascoyne et al. (1979) suggested that blue holes formed in the phreatic zone within a fresh-water lens, and were part of a complex system of sub-horizontal passages and vertical pits. Palmer and Williams (1984), and Palmer (1985; 1986a; 1986b) elaborated on the fresh-water lens origin, by explaining how long caves could develop along the lens base, and trend upward to the platform surface following the halocline as it trends upward at the seaward edge of the fresh-water lens. Shaw (1993) presented only a fresh-water lens mechanism for blue hole formation. The importance of the fresh-water lens and its potential for developing phreatic caves has been widely discussed (Mylroie and Carew 1988; 1990; 1995a; 1995b).

Palmer and Williams (1984), Smart (1984), and Palmer (1986b) also felt that the deep, flooded shafts that form many blue holes could be the result of progradational collapse (or stoping) from deep-seated phreatic dissolutional voids formed in past, lower fresh-water lens positions at times of stillstand during Quaternary rises and falls of sea level. These collapse structures had been called "aston" development by Jimenz (1967, *in* Palmer 1986b). In the collapse model, the void develops in a past fresh-water lens, preferentially at the halocline. Then, sea level falls, and the loss of buoyant support of the water promotes roof collapse (Smart 1984). If the collapse progrades to the surface it may be expressed as a large collapse structure. With a later rise in sea level, it becomes a blue hole. Progradational collapse, or stoping, is considered responsible for the development of the large cave chambers of Bermuda (Mylroie 1984; Mylroie et al. 1995), and of Rat Bat Cave on South Andros Island, Bahamas (Carew and Mylroie 1989). Large voids clearly exist at depth in the Bahamas, as they have been reported from well-drilling logs. In the Bahamas, large voids have been encountered at depths of 21 to 4082 m; the deepest of these voids was large enough to accommodate 2430 m of drill pipe (Meyerhoff and Hatten 1974). Voids at such depth are well below the greatest Quaternary glacioeustatic sea-level lowstand, believed to have been about 125 m below present (e.g. Carew and Mylroie 1987). The voids probably originated at relatively shallow depths and subsequently subsided to their current position (Mylroie and Carew 1995a). The deepest known blue hole in the Bahamas, Dean's Blue Hole on Long Island, is 202 m deep (Wilson 1994). If it is a collapse feature, then the host void must be very large and very deep and the blue hole is merely the current void at the top of a breccia pipe (White 1988).

Work in the northwestern Bahamas has shown that many blue holes are located along faults or fractures (Palmer, 1986b). These fractures are generally arranged *en echelon* and often in the form of grabens parallel to the bank margin. Palmer (1986b) hypothesized that mechanical failure of the steep bank margin produced these fractures. Surface openings along these fractures provide access to flooded voids, or blue holes. Such fracture-oriented blue holes have been documented on South Andros Island (Carew and Mylroie 1989) and New Providence Island (Carew et al. 1992). Supporting evidence in the Bahamas for this fracture theory comes from mapped fractures and joints that show a trend parallel to the bank-margins (Daugherty et al 1987). Mullins and Hine (1989) have suggested such bank-margin failures may be significant in the evolution of the banks and troughs currently seen in the Bahamas.

DEFINING BLUE HOLES

A blue hole, as first identified by scientists over a century ago, is a deep hole in a lake, land surface, or shallow lagoon. All that is needed to form a blue hole is a mechanism that produces a deep, flooded void that is open to the surface. All of the mechanisms presented here (vadose processes, phreatic processes, collapse, and bank-margin fracture) are capable of producing the deep void, and the origin of blue holes is clearly polygenetic. Moreover, as a result of glacioeustatic rise and fall in the Quaternary, many different cave-forming environments (vadose, fresh-water phreatic, mixing-zone phreatic, and marine phreatic) have been superimposed upon blue holes. Therefore, blue holes as seen today may represent the over-printed composite outcome of many different cave-forming situations. Based on U/Th age dating of stalagmites, some blue holes have ages in excess of 350,000 years (Carew and Mylroie, 1995). Sea-level changes may also have promoted bank-margin fracture as a result of loss of buoyant support for the steep bank margin during glacioeustatic lowstands.

As blue holes are polygenetic and over-printed, the term blue hole is not easily defined. The initial portion of this paper reviewed how blue holes have been characterized and defined in the past. None of those definitions are adequate. In an attempt to clarify the situation, Burkeen and Mylroie (1992) offered the following definition of blue holes: "...pits developed in carbonate rock which have a depth to width ratio greater than one that extend below sea-level for the majority of their depth." Use of the depth to width ratio in the definition was an attempt to emphasize the verticality and depth of blue holes, and to discourage the labelling of ponds and lakes containing a blue hole, as blue holes themselves. The characterization of blue holes as pits that "extend below sea level for the majority of their depth" was an attempt to differentiate them from the Yucatan cenotes. The low-lying nature of the land of the Bahamas allows little subaerial exposure of blue hole walls, but the higher land surface of the Yucatan allows cenotes to have high subaerial bedrock walls. Burkeen and Mylroie (1992) adopted and modified the Farr and Palmer (1984) separation of blue holes into ocean holes and inland blue holes as follows: "An ocean hole opens directly into a lagoon or the ocean, is usually tidally influenced, and contains marine water. An inland blue hole opens directly onto the land surface or into an isolated pond or lake, may be tidally influenced, and may contain a variety of water chemistries from fresh water to marine."

When developing their definition, Burkeen and Mylroie (1992) had corresponded with the other major workers in Bahamian blue holes. Based on their various perspectives, each correspondent had specific aspects of blue holes that dominated their idea of an acceptable definition. Those workers with an explorational focus felt that a blue hole had to connect with a conduit or cave at depth; whereas those with a geographical perspective felt that the earliest historical use of the term should control the scope of the definition. Those with a scientific interest believed that as a first approximation, the form or morphology should dominate the definition; as a second approximation, the genesis of the blue hole should be considered. Smart and Whitaker (personal communication) offered a ternary plan as the basis of a genetic classification. It uses the three aspects of dissolution (phreatic and vadose), collapse, and fracture as the end members of a ternary continuum that operates over space and time to produce the observed blue holes. As regards the Burkeen and Mylroie (1992) definition, most of the correspondents had difficulty with the use of a depth to width ratio, the use of the term "pit", and the requirement that they be flooded for the "majority of their depth." There was general agreement that the geochemical and tidal components of the definition were useful.

The term blue hole is most associated with the Bahama islands and similar carbonate bank settings. On first observation, the single dominant aspect of a blue hole is its deep blue color. To characterize blue holes further requires detailed study to determine morphology, connections to caves, and genesis. We therefore offer the following definition of blue holes that can be used in the field by a variety of natural scientists: "Blue holes are subsurface voids that are developed in carbonate banks and islands; are open to the earth's surface; contain tidally-influenced waters of fresh, marine or mixed chemistry; extend below sea level for a majority of their depth; and may provide access to cave passages."

We continue the Farr and Palmer (1984) and the Burkeen and Mylroie (1992) practice of separating inland from marine blue holes, as such separation is obvious in the field, and the location has important geochemical and ecological implications. We suggest a modification of the Burkeen and Mylroie (1992) definition as follows: "An ocean hole is a blue hole that opens directly into the present marine environment and usually contains marine water with tidal flow. An inland blue hole is a blue hole isolated by present topography from surface marine conditions, which opens directly onto the land surface or into an isolated pond or lake, and which contains tidally-influenced water of a variety of chemistries from fresh to marine."

The definition can be expanded as follows to recognize the polygenetic origin of blue holes: "Blue holes may form by drowning of dissolutional sinkholes and shafts formed in the vadose zone, by phreatic dissolution along a rising halocline, by progradational collapse of deep dissolution voids produced in the phreatic zone, and by fracture of the bank margin."

Blue holes are scientifically interesting, visually awe-inspiring, and explorationally challenging. The continued study of these natural features can be facilitated if we understand how they have been referred to in the past, and how they have developed. This paper has been an attempt to pull the various threads of documentation about blue holes together in one place, and to offer a simple way to describe blue holes to others.

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