

GEOLOGIC AND HYDROLOGIC CONTROLS ON KARST AND CAVE DEVELOPMENT IN BELIZE

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0.1 Nearly 3000 km² of Belize display well-developed karst that occurs dominantly on Cretaceous limestones distributed on the periphery of the Maya Mountains. Other exposed carbonates in Belize, sharing the same tropical climate and heavy rainfall, are not karsted. The Mayas represent a horst structure raised by movement of the Caribbean-North American plate boundary. In excess of 150 km of large cave passage has been mapped, often exhibiting multi-level development likely related to this regional tectonic motion. Passages are dominantly trunk conduits solutionally bored through the lower-lying limestones by integrated allogenic streams from the Mayas. Other large, independent caves and collapse chambers are also known. Limited U-series dating of speleothem gives minimum ages of 176 KaBP for cave development. The karst surfaces are dominated by disaggregated remnants of previous fluvial networks, but also contain spectacular collapse dolines. The karst aquifers appear to be solutionally "open" systems of relatively high porosity (>1%). Boosting of carbon dioxide levels above surface soil CO₂ occurs within aquifers, perhaps due to decay of washed-in vegetation. Mean solutional erosion is estimated at 0.10-0.13 m/Ka for these karsts.

Belize consists of the ancient, escarpment-bounded Maya Mountains, which rise to 1,100 m and are encircled by lower and younger sedimentary rocks, chiefly carbonates. Of primary importance to karst and cave development is the broad belt of Cretaceous limestones and dolomites which routes all but the largest highland streams underground. The remainder of Belize is mostly a seasonally swampy plain (0-80 m elevation) of soft Tertiary and Quaternary carbonates. The coastline is bordered by a 250-km-long barrier reef. Of the country's 23,000 km², about 3,000 km² has well-developed karst.

Knowledge of the Belizean karst has come chiefly from sporadic but often intense cave exploration within the past 40 years. More than 150 km of cave passages have been surveyed by various groups. Investigations of the development of the karst surface and the carbonate water chemistry have been considerably briefer and areally-confined.

Some information in this report has appeared in scattered international caving or cave-science publications, often only as abstracts accompanying presentations. The majority of the karst information is from unpublished monographs submitted as reports to funding agencies, and is published here for the first time. Substantial data remain unpublished and unanalyzed.

The following is intended to be a general review of the range of these karst-related studies in Belize, rather than an in-depth discussion of the enormous subject of karst and cave genesis in that country. However, much that is presented or collated here appears together, also for the first time. The regional geology contributing to the presence of karst in Belize is emphasized in more detail than has been presented elsewhere, as are the details of cave morphology and, to a lesser extent, surface karst development.

REGIONAL CLIMATE AND HYDROLOGY

Belize is divided by the boundary between the tropical savanna climate of its northern half (very similar to that of the Mexican Yucatan) and tropical rainforest to the south (Hartshorn et al., 1984). Annual rainfall in Belize increases with elevation and more southerly latitude, affected by the large topographic bulk of the Maya Mountains in the southern half of the country (Figure 1). Walker (1973) cites mean annual rainfall of 130 cm near Corozal, in the north, to more than 450 cm at Punta Gorda, in the south. Prevailing winds are easterly from the Caribbean, and deposit sodium and chloride ions in decreasing amounts landward.

Density fronts, common in temperate latitudes, are rare in the tropics due to the uniform temperatures. Although occasional outbreaks of polar air, called "northers," can produce heavy rains; thunderstorms and other convergences of similar, high-temperature saturated air masses are the primary causes of precipitation. Hurricanes can create heavy rain but hit Belize infrequently, with seven landfalls from 1931-1978 (Hartshorn et al., 1984), and most recently in 1995.

Daily temperature variations are due primarily to changes in cloud cover; only 63% of the possible solar insolation is received at the ground due to cloud interception, a major inhibitor of high temperatures. The northers sometimes lower temperatures to less than 10°C during the winter months. Temperature spans monthly minima of 16°C to monthly maxima of 33°C in the lowlands. Higher elevations are cooler, but freezing temperatures have never been recorded in Belize (Walker, 1973).

Figure 2 shows monthly temperature and rainfall for three representative sites in central Belize that range from sea level to 560 m elevation. The highest, Cooma Cairn, is located in the

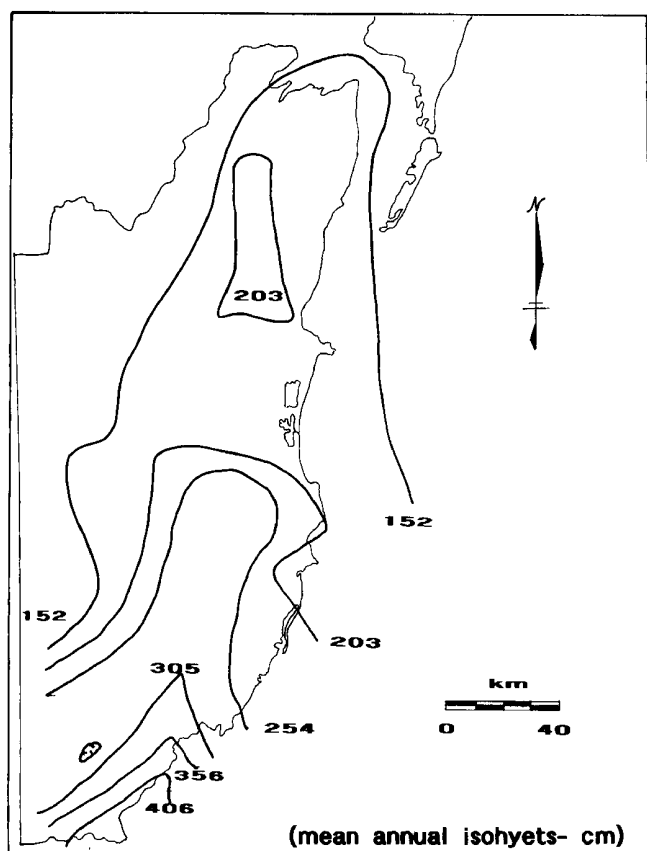


Figure 1. Rainfall isohyets, Belize (after Hartshorn et al., 1984).

northern Maya Mountains above the Boundary Fault Karst. All have precipitation greater than 100 cm/yr and mean temperatures above 20°C. March and April are the driest months at all three sites, with May being the month with the most variable rainfall pattern. The wet season occurs from June through December. Because of the abundant precipitation and vegetation, evapotranspiration operates nearly at maximum rates all year except for the short dry season.

A stream-gauging network has been established in Belize, but few streamflow data have been published (Government of Belize, 1982). For the water year 1981-1982, the mean annual flow of the Belize River, the largest in the country, was calculated at 155 m³/sec (Hartshorn et al., 1984). Unit catchment sizes needed to produce 10 m³/sec mean annual discharges ranged from 160-525 km², generally with the smaller areas in the higher rainfall regions of the south.

REGIONAL GEOLOGY AND ORIGIN OF THE MAJOR KARSTED ROCKS

All known caves and karst in Belize are developed in carbonate rocks, primarily Cretaceous limestone. Much less frequently, Tertiary dolomites and Quaternary carbonates contain solutional features. Most prior geologic attention has concen-

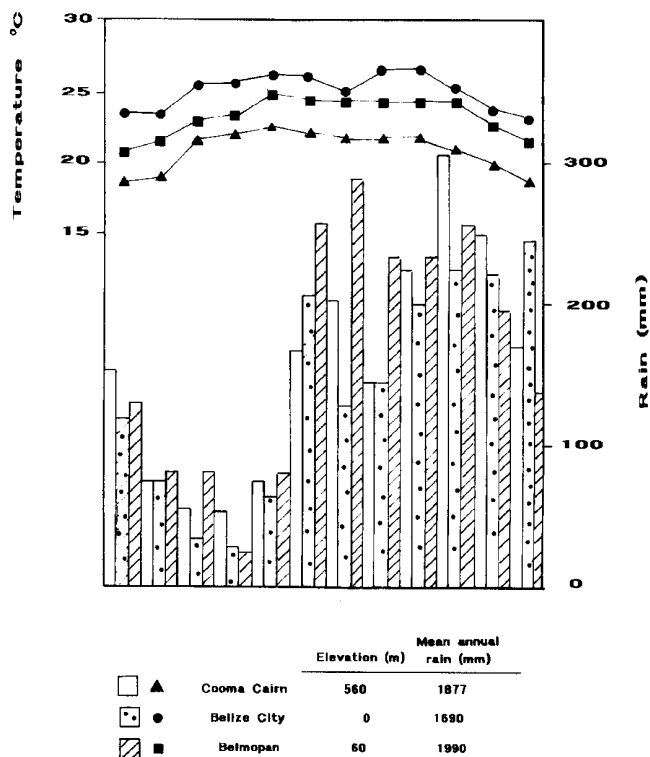


Figure 2. Climate data, Belize: three selected sites (from Miller, 1981a).

trated on the mineral potential of the Maya Mountains, the petrocarbons of the deeply-buried Cretaceous carbonates of northern Belize, or the ecologically-interesting barrier reef. Consequently, basic stratigraphic knowledge of the Cretaceous limestones has scarcely advanced beyond Ower's (1928) fossil collecting, and most is of peripheral value to karst investigations. The several units of Cretaceous carbonates continue to remain undifferentiated on most geologic maps (Figure 3).

Although preliminary geologic work was begun in Belize near the turn of the twentieth century, the first detailed studies were by Ower (1928). These were followed by Flores (1952) and numerous reports beginning in the late 1960s. The total number of geologic studies increased dramatically in the 1970s, and in the 1980s the Office of Geology and Petroleum (Ministry of Natural Resources) was established by the government of Belize.

TECTONIC HISTORY

The geologic structure of Belize is dominated by the Maya Mountains (or *Mayas*). Although underlain chiefly by essentially non-soluble metasediments and igneous intrusives, the evolution of the range played a major role in the location of later carbonate rocks, as well as the topographic situations most favorable to cavern development in Belize.

The Mayas are an uplifted block of Paleozoic metasedi-

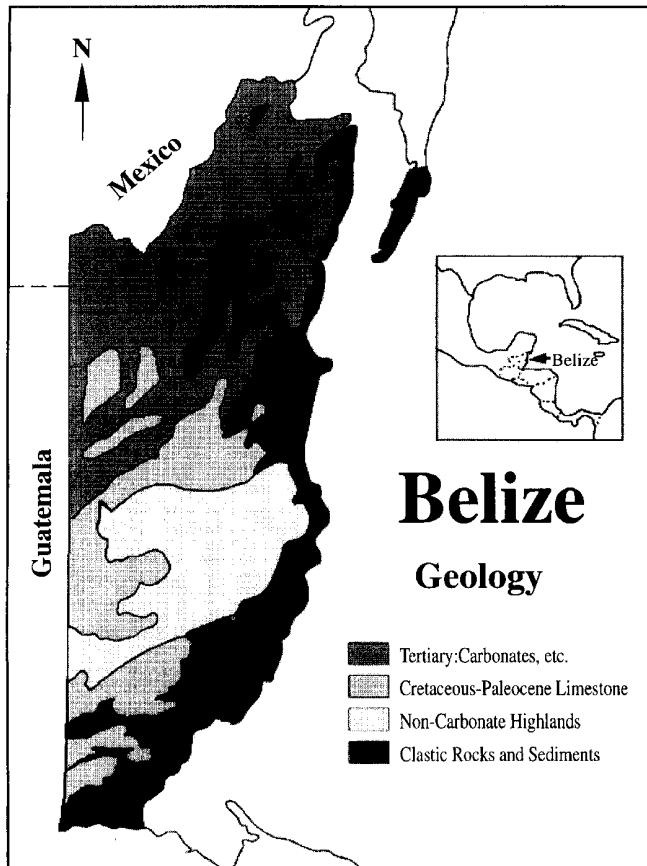


Figure 3. Generalized geology of Belize, detailing the carbonates most important for karst.

ments and Triassic intrusives that is bounded on the north and south by major faults striking east-west (Dixon, 1955). The eastern boundary is also probably a major fault. The underlying structure of the sloping western edge of the mountains is obscured by Cretaceous and Tertiary carbonates. The Mayas are the eastern terminus of the anticlinal La Libertad Arch, which extends into Guatemala. The present horst structure of the Mayas dates from the mid-Cretaceous, influenced by Paleozoic age lineaments apparently related to initiation of the La Libertad Arch. The block was affected by periodic relative uplift until the mid-Tertiary (Bateson & Hall, 1971).

Fewer than 25 km from the southern end of the Mayas, and paralleling the La Libertad Arch, is the Cayman Trench and the extensive complex of the Motagua Fault Zone. This 2,200-km-long complex is the boundary between the North American and Caribbean plates, a transform fault with left-lateral motion. It was probably initiated in the Permian, when north-south compression in the Mayas forcefully intruded granites with associated volcanism and basalt outflow. This episode lasted until the late Triassic (Dillon & Vedder, 1973) and included the initiation of block faulting. Major fault development also occurred in the Cretaceous (Meyerhoff, 1966; Dengo &

Bohnenberger, 1969; Malfait & Dinkelman, 1972; Dengo 1975; Newcomb, 1977).

The La Libertad Arch and the Maya Mountains parallel the plate boundary for 200 km and share a history of Paleozoic origin and major Mesozoic fault activity. They almost certainly have a causal relation to activity along the Cayman-Motagua Complex, but with a greater uplift. Quaternary movement along the Motagua Fault has been estimated at 0.5 cm/yr (Kupfer & Godoy, 1967; Schwartz, 1977).

CRETACEOUS CARBONATE DEPOSITION

Although limited Jurassic sedimentation occurred, the local event of greatest karst significance began with massive deposition of Cretaceous evaporites and marine carbonates throughout the Caribbean. These grade upward into reef facies in Guatemala and Belize that surrounded the then-extant islands of the Maya Mountains (Dillon & Vedder, 1973). The Cretaceous deposition is as much as 3,200 m thick westward from the Maya Mountains in the Peten of Guatemala, yet thins to only 900 m at the mountain fringes (Viniegra O., 1971). At the close of the Cretaceous, the west end of the Mayas was submerged and covered by limestone and dolomite (Bateson, 1972). Viniegra O. (1971) identified three major divisions of the Cretaceous carbonates in Guatemala, which he also applied to Belize. The oldest unit, the Coban Limestone, has been reported in outcrops north of the Mayas, possibly in the Yalbac Hills (Hartshorn et al., 1984). Most of the rest of the Cretaceous outcrops, including the Caves Branch area, the Vaca Plateau, and in southern Belize, were identified as the middle unit, the Campur Limestone.

RECENT GEOLOGIC HISTORY

Intense folding and thrusting occurred in Guatemala and Mexico during and after the late Cretaceous. Only minor tectonic activity affected Belize in the Tertiary, and shales, siltstone and limestones were deposited over much of the area (Dillon & Vedder, 1973). Northern Belize has since been characterized by slow subsidence and attendant carbonate deposition through most of the Tertiary. The primary deposition episode was in the late Paleocene to Eocene (Pusey, 1975; Dillon & Vedder, 1973). Late Cenozoic uplift in the Mayas has raised Oligocene carbonates to 50 m above sea level, and further recent uplift is demonstrated by numerous river terraces, cave levels, and modern marine faunal remains in inland sediments (Jean Cornec, Office of Geology and Petroleum, personal communication, 1986). "Tilted" stalactites in the Blue Hole, a drowned doline on Belize's barrier reef, have been cited as evidence of recent and continued tectonic activity (Dillon & Vedder, 1973). However, such features are common in large inland cave entrances, apparently due to differential calcite precipitation. Most recently, Quaternary alluvium from the Maya Mountains filled in an arm of the ocean that had

extended into central Belize.

In summary, the events of chief geological significance to karst development in Belize are:

1. deposition of clastic sediments, and subsequent uplift and intrusions by granites;
2. massive Cretaceous carbonate deposition, around and on the Maya Mountains; and
3. the uplift, faulting, and fracturing related to the nearby plate tectonic boundary.

Sizable volumes of runoff from highlands of poorly soluble metasediments and crystalline rocks entered large areas of lower-lying soluble rocks. Large caves formed as these streams sank underground. Extensive areas of carbonate rock that are not peripheral to the Mayas, primarily in northern Belize, do not display pronounced karst.

KARST REGIONS OF BELIZE

Eight karst regions have been identified in Belize and cover about half of its area (Miller, 1986a). The regions are shown in Figure 4 and a summary of their characteristics is given in Table 1. Although all eight regions share similarities in climate and geology, only five are dramatically karsted; these cover about 3,000 km² of a total land area of 23,000 km². In the following brief individual discussions of these regions, it is evident that the most dramatic expressions of karst topography and cave development occur in those Cretaceous carbonates downslope of catchments integrated on the intrusive and metamorphic highlands of the Maya Mountains. Other hydrogeologic factors particular to each region have played relatively minor roles in their development.

The two karsts most examined in Belize are those centered on the southern Vaca Plateau and on the Caves Branch section of the Boundary Fault Karst. These areas will be discussed in more detail as type examples of the surface formation of karst in Belize. Caves Branch best demonstrates subsurface development.

Several features are common to most Belize karsts. Large areas contain sinking allogenic streams (Figure 5), integrated dry valley networks of fluvial origin, "hanging valleys," and poljes with through-flowing allogenic rivers. Other areas contain thousands of closed depressions of seemingly chaotic distribution.

Those areas in Belize dominated by closed depressions of at least 30 m relief, surrounded by residual hills, are similar in appearance to areas elsewhere called kegelkarst, or conekarst. Because the *depressions* are the dynamic foci of surface erosion, and are termed "cockpits" in Jamaica, these areas are here referred to as "cockpit karsts" in keeping with the terminology of their nearby analogues.

Scores of vertical-walled depressions scattered throughout Belize are sited over and near known cave networks, and are likely collapse features (Figure 6). They are impressive, but of minor total area. The densest grouping is in the Chiquibul area

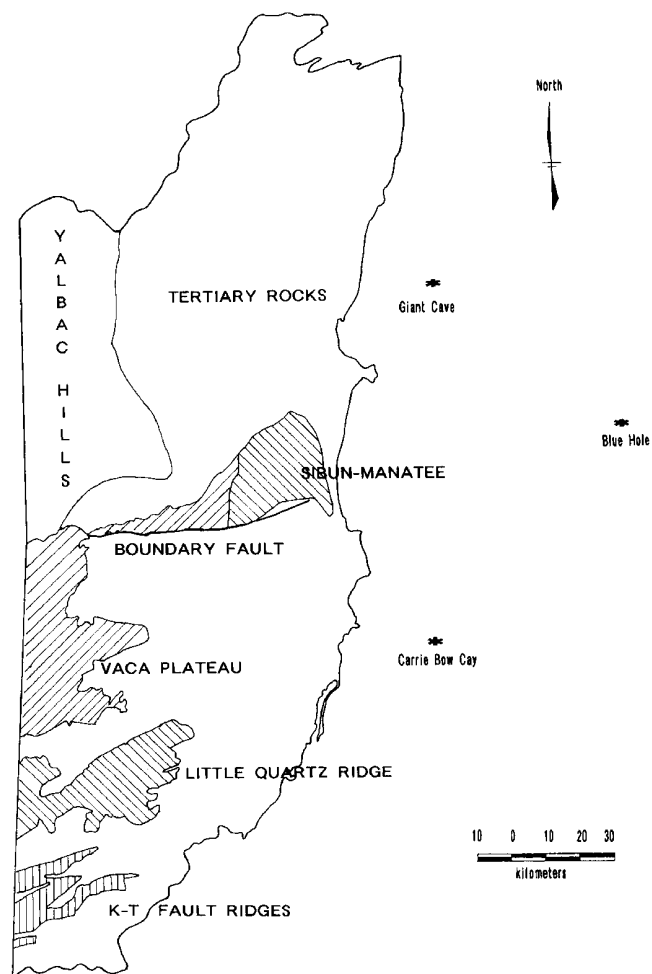


Figure 4. The major inland karst areas of Belize. Three of the Offshore Karst sites are shown.



Figure 5. The ponor of the Caves Branch River at the north end of its polje. The hills are about 50 meters high.

Table 1. Characteristics of Major Karsts of Belize.

Location	Area (km ²)	Relief (m)	Erosion	Features
1. Boundary Fault	300	350	100	C,P,F
2. Vaca Plateau	1000	400	130	C,F
3. Sibun-Manatee	550	200	—	P,T
4. Little Quartz Ridge	750	600	—	C,F
5. K-T Fault Ridges	300	250	120	C,F
6. Cayes/Barrier Reef	—	150?	—	—
7. Yalbac Hills	1950	200	—	—
8. Tertiary Rocks	7000	70	—	—

where: area is in km² within Belize, maximum areal relief is in meters, erosion is the rate of solutional removal of CaCO₃ (m²/km³/yr), and C (cockpits), P (poljes), F (fluviokarst), and T (towers) are landform features common to the surfaces of these karsts.

of the Vaca Plateau, where 20 known collapses cover only 2% of the 30 km² in which they occur.

The large allogenic streams that enter the carbonates frequently bore through at local base level to emerge on the plains near sea level. They flow through large cave passages—*trunk conduits*—that developed independently of internal runoff from the karst surfaces. None of the allogenic streams merge below ground.

1. BOUNDARY FAULT KARST

The Boundary Fault Karst is sharply delineated. It is bounded on the south at 200-300 m elevation by the Northern Boundary Fault. This east-west trending fault spans the width of the country, has a downward throw to the north of at least 900 m (Dixon, 1955), and forms a 700- to 800-m-high escarpment. The region's northern margin is a relatively abrupt termination at the contact with younger, chiefly carbonate, Paleocene-Eocene formations that continue northward as rolling plains. The Cretaceous limestone ends in hills 30 m or more in height at an elevation of 40 m a.s.l. A few isolated towers extend into the alluvium-covered plains.

The Boundary Fault region is lithologically and structurally almost identical to the Sibun-Manatee Karst, but is distinguished morphologically from the latter. The difference results chiefly from the Boundary Fault Karst's higher elevation and steeper slope due to its closer proximity to the highest and most pronounced portion of the Northern Boundary Fault. Structurally, the area is a northward-dipping shelf of Cretaceous Campur Formation carbonates, marked by north- or northeast-trending faults. The Northern Boundary Fault disappears northward beneath the Cretaceous carbonates, and is believed by Cuche and Glaus (1967) to pre-date them.

Major valleys aligned along the north-trending faults are cut by small rivers descending onto the carbonates from dendritic catchments on the granites and metasediments of the Mountain Pine Ridge to the south. Smaller valleys are also cut by lesser streams that enter the karst. These streams penetrate distances proportional to their catchment areas and discharge (Miller, 1981a), before disappearing into poljes and trunk conduits. The larger rivers, Barton, Roaring, and Sibun, are all

through-flowing to the sea; the Caves Branch is pirated underground, but a wide flat opening in the hills at the northern end of its polje suggests this river was also through-flowing in the past.

The geologic conditions of the Boundary Fault region are conducive to the formation of trunk conduits. Well-integrated streams discharge large volumes of solutionally-aggressive water from the Mountain Pine Ridge onto the limestone. At present, perhaps 70 km of active and abandoned trunk passages have been mapped in this karst (Miller, 1990a; Marochov & Williams, 1992; Hollings, 1994).

Although Day (1979, 1987) has examined surface depression development further west, currently the Caves Branch section of the Boundary Fault Karst has been studied in the greatest detail (Miller, 1977, 1981a). An overview of its hydrology, hydrochemistry, and geomorphology follows as a summary of the common conditions that prevail throughout the karst region.

CAVES BRANCH GEOLOGY AND MORPHOLOGY

The Caves Branch River originates in the Mountain Pine Ridge in the center of Belize, with a noncarbonate catchment area of 64 km². Two other allogenic streams flow from these highlands through major trunk conduits to the Caves Branch, with respective catchments of 20.3 and 3.3 km². The remaining area of the river's karst catchment is vaguely defined as ~100 km² because its drainage is internal. The Caves Branch disappears into the Cretaceous limestone at a large ponor, or open conduit sinkpoint, after flowing 10 km through a prominent polje floored with clay, sand, and cobbles derived from the highlands (Figure 7).

The limestone of the Caves Branch has a restricted fauna typical of lagoonal to back-reef deposition (Flores, 1952). The majority of exposures are 2-15 cm (often larger) gray or cream-colored limestone breccias cemented in a red calcite matrix. Anderson et al. (1973) described a similarly-appearing breccia of lower Cretaceous age in Guatemala that he identified as "clearly depositional." In Caves Branch, bedding is rarely encountered, and is infrequently more than 40 meters thick. The rock is well-fractured. Slickensides give evidence of faulting, which is difficult to observe because brecciation



Figure 6. The collapse doline of Nohoch Ch'en (Great Well), on the Vaca Plateau, possibly overlying a segment of the Chiquibul System. The doline is 300 meters in diameter and about 50 meters deep.

obscures relative movement and the amount of displacement. Where bedding is present, it usually dips 5° or less, most frequently to the northeast. Of three local samples of Cretaceous limestone (Table 2, Miller, 1981a), two were micritic clasts in the breccia which resembled rock exposed in bedded areas and one was a mixture of clast and matrix. All were very pure calcitic rock.

Table 2. Analysis of Three Rocks from the Caves Branch Valley.

General Description	CO ₂	MgO	CaO
Micritic Clast	41.70	0.24	57.32
Micritic Clast	43.16	0.36	58.09
Breccia	41.80	0.92	57.08

all values given in %, (from Miller, 1981a)

SURFACE MORPHOLOGY

Hundreds of cockpits in the Caves Branch area, most surrounded by hills, have been outlined from airphotos (Miller, 1981a). Smaller dolines frequently nest within the larger depressions. Visible differences in texture separate groups; large dolines are common, but depressions may occur as numerous, smaller, densely-packed clusters.

Beneath heavy vegetation, the hilltop ground surfaces are often bare rock, deeply fissured to several meters along joints. The cockpit floors contain clayey soils reaching depths of tens of centimeters. Many cockpits, but not all, contain simple integrated drainages terminating in vertical bedrock swallets (sink-points which may or may not be open cave entrances).

Nearest neighbor analyses were performed on 210 dolines identified from aerial photographs (40-m contour intervals on topographic maps were too large for adequate interpretation) in the Caves Branch area. In a similar section of the southern Vaca Plateau, 160 dolines were analyzed (identified from topographic maps because contour intervals were a useable 20 m and aerial photographs could not be obtained). The patterns in both areas differed significantly from a purely random distribution, with a trend towards uniform patterns of dispersion (Miller, 1981a).

In the Caves Branch, a 20-km²-area was chosen to identify influences of major joints and faults upon cockpit siting, as interpreted from photo-lineations. The 255 depressions within this area highly correlated with the lineations (Miller, 1981a). The cockpit karst appears to be the likely result of non-random processes of fluvial dissection centered by points of lithologic weakness; it has presumably advanced in dissection until past evidence of fluvial networks was largely obscured.

HYDROLOGY AND CARBONATE WATER CHEMISTRY

Data collected from 1976-1979 by Miller (1981a), com-

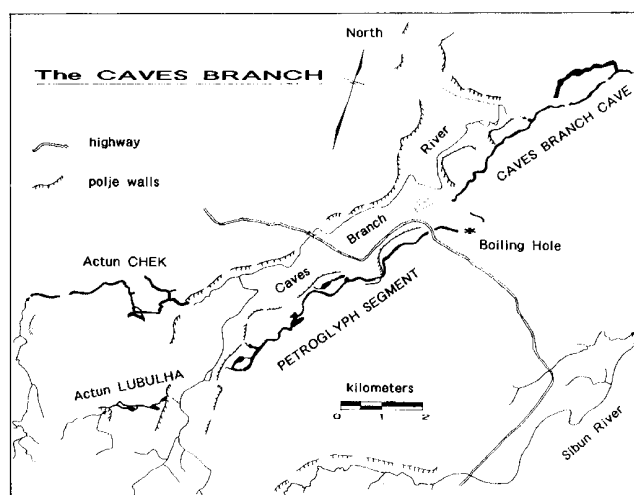


Figure 7. Major caves of the Caves Branch Valley (after Miller, 1981a).

prise most of the hydrology information about the Caves Branch area. Daily rainfall records were also kept during most of the 1950s to the 1970s at three sites along the Hummingbird Highway: Roaring Creek, Caves Branch River, and Sibun River (Walker, 1973). Mean annual precipitation was 207, 236, and 264 cm respectively, with wet season conditions dominating from June to November. Mean annual temperature, as estimated from caves, is 24°C. Precipitation in the Caves Branch drainage basin is concentrated in a slightly longer June-December wet season with convective storms producing rainfalls >5 cm/hr. Dry season discharge of the Caves Branch River was stable at 0.5 m³/sec, with wet season floods exceeding 100 m³/sec.

Scores of tributaries and uncounted stalactite drips feed the trunk conduits. Their sources are autogenic water derived from rainfall onto the karst hills bordering the polje. The combined allogenic and autogenic recharge of the area resurges 5 km to the northeast at the termination of the karst.

Surface flow on the karst is infrequent, even though most large cockpits contain stream channels integrated on the clay floors. The permeability of the karst is such that flow occurs only when rainfall exceeds 12 mm per day. The range of hardness of these streams was a low 10-40 mg/L (as CaCO₃), as was PCO₂ at 0.05-0.35%, and they were undersaturated with respect to calcite (SIc -2.54 to -1.05) and dolomite (SI_d -2.86 to -1.77).

The autogenic streams and drips display a pronounced, delayed response in discharge at the start of each wet season (Figure 8 and Miller, 1983). The mass volume of early wet season rain, falling prior to hydrograph response, closely approximates calculated losses from aquifer storage due to unreplenished base flow during the dry season. A deterministic computer model was able to correlate volumes and temporal

responses of discharge to rainfall, and enable calculations of a minimum effective porosity of 2-3% for the Caves Branch karst. A mean residence time of up to seven months was indicated (Miller, 1981a).

The amount of limestone solution by allogenic highland water was obscured by mixing with autogenic waters in the trunk conduits. These allogenic streams all had hardnesses of less than 35 mg/L (as CaCO₃) prior to contacting the carbonates, pH <7.0, and were undersaturated with respect to calcite (SIc -3.79 to -0.82) and dolomite (SI_d -3.64 to -0.87).

Most waters entering the trunk conduits were supersaturated and depositing travertine, with markedly higher hardnesses (means of 187 mg/L as CaCO₃, and PCO₂ 1.1%) than either the cockpit source runoff ranges noted above, or mean measured local soil CO₂ of 0.7%. A subsurface enrichment of PCO₂ is indicated, possibly through decay of vegetation washed into the aquifer. Combining these data with open-system carbonate solution (per Langmuir, 1971) as indicated by the high internal porosity, led to a calculation of a relatively high denudation rate of ~100 m³/km²/yr (Miller, 1986b).

CAVE MORPHOLOGY

Extensive cave exploration and mapping has occurred in the Caves Branch River valley and its environs. At least 60 caves are known, totaling about 50 km explored with about 45 km of these mapped. Because the Caves Branch area is well-studied and contains numerous features common to other karst areas of Belize, the characteristics of its caves are examined below in detail. Much of this discussion is from Miller (1981a).

Morphologic and hydrologic criteria were used to establish cavern categories for the Caves Branch area, largely based on phreatic versus vadose features of individual passages. Relevant characteristics are outlined for each cave and respective group in Table 3. Because the trunk conduits are so extensive, they often intersect other cave types, forming aggregates or systems (Figure 9). These merging cave passages have been treated as separate caves in Table 3.

PHREATIC CAVES

Four cave types of chiefly phreatic origin can be distinguished. Two are inactive or fossil. The other two are only seasonally active, but owe most of their features to solution under phreatic conditions.

Isolated Phreatic Caves. This group is composed of fossil chambers scattered at moderate to high elevations of 50-150 m above local base level. They are generally three-dimensionally complex and consist primarily of rooms rather than passages. No scalloping or fluvial sediments are present to identify localized stream flow, and the solutional pocketing, discordant elevations, and elevationally nongraded floors all indicate an isolated, nonintegrated phreatic origin. Joint control appears predominant with only minor bedding effects. Any collapse and/or sedimentation present is due to breaching and invasion related to surface erosion, rather than to phases of cavern formation.

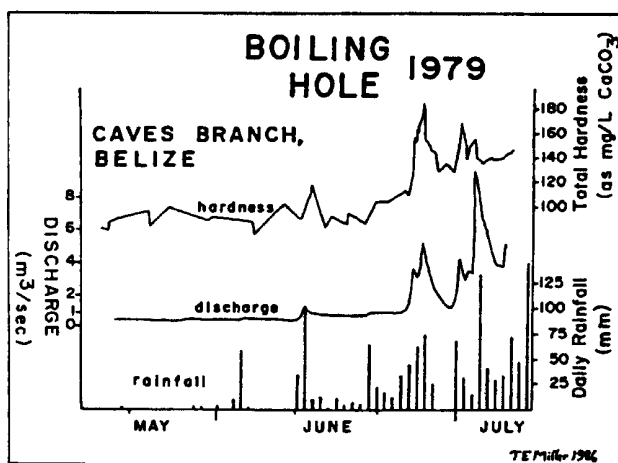


Figure 8. Hydrograph and total hardness as related to valley rainfall of the Boiling Hole trunk conduit stream, located midway on the east side of the Caves Branch polje (from Miller, 1986a)

Table 3. **Some Type Examples of Cavern Morphologic Classes, Caves Branch**

Class	Name	ID	UTM Location	1 Phreatic	2 Vadose	3 Plan Type	4 Size	5 Collapse	6 Speleothem Development	7 Sediments
Zuhuyha	Toh	Z-4	997218	Cs	s	H	60	-	-	-
	5% Solution	Z-7	971187	C	?	?	?	-	-	-
	Crooked Bend	Z-31	943184	Cs		2	150+			au
Isolated Phreatic	Swiss Cheese	0-3	004227	Cf		3	200?			
	Candlestick	0-12	947193	If		3	1-200	M1	M3	
	Cave-Around-The-Bend	0-17	912146	If		3	150?	M1	M2	
Swallet	-	S-1	997225		s	V	20			
	Swallowet Hole	S-4	955194		s	V	40			au
	VICEG	S-5	956191		s	V	100?			
Pirate	Thunder Road	P-4	007221	Cs	s	2	200+			al
	Buccaneer Alley	P-5	004218	Cs	s	2	500			al
	Zephyr Zig-Zag	P-8	956185	Cf,s(?)	f,s(?)	2	300			al
Margin Swallet	-	M-2	001217	Cs	?	?	?			
	-	M-7	965197		s	V?	?			
	-	M-11		f?		2	40		M1	
Trunk Conduit	Tuxmanu Yocmac, Chek		940152	Cs	s	2	1100		M2	al
	High Levels, Lubul Ha		915150	Cf	f	2	300	M1		al
	Petroglyph			C	P	2	3000+	M1	M2	
Collapse Chamber	Cantzicnal Caan, Lubul Ha		918157	If		2	200	M3	M3	
	Burial Chamber, Petroglyph		983175	If		2	300	M3	M2	
	Mtn. Cow		958188	If		2	1000	M3	M3	

1 Phreatic
2 Vadose
3 Plan Type
4 Size
5 Collapse
6 Speleothem Development
7 Sediments

C - conduit; I - isolated; f - fossil, s - seasonally active
P - permanent stream; s - seasonally active, f - fossil
H - linear horizontal; V - linear vertical; 2 - two dimensional (horizontal) 3 - three (dimensional)
(known passage length, in meters)
M - 3,2,1 major, moderate, minor
M - 3,2,1 major, moderate, minor a - active f - fossil
Co - cobble fill; D - dirt; al - allogenic source, au - authigenic

Speleothem development is variable in extent and activity, though generally common.

Chamber Stratum Caves. Many massive collapse areas exist underground that share similarities in their general alignment with the trunk conduits. In most instances, the collapses consist of rubble-floored chambers with extensive active and inactive speleothems (Figure 10). With rare exception, ceilings occur at elevations of 50 m or less above neighboring trunk conduits. It is not possible to determine the elevations of the bottoms of the collapses, but they appear to be no lower than, and sometimes above, the floors of the trunk conduits. Nearly all these rooms are parts of cave systems that include trunk conduits. Sizes of the chambers range up to 300 m in length, with ceiling heights often reaching 20 m. Because of widespread collapse, undisturbed sections of bedrock are almost entirely absent. High portions of these caves sometimes show undisturbed phreatic tubes and chambers with little or no evidence (e.g. scalloping) of localized conduit flow. The collapse material nearly always lacks markings from any solutional activity subsequent to collapse. Clastic sediment accumula-

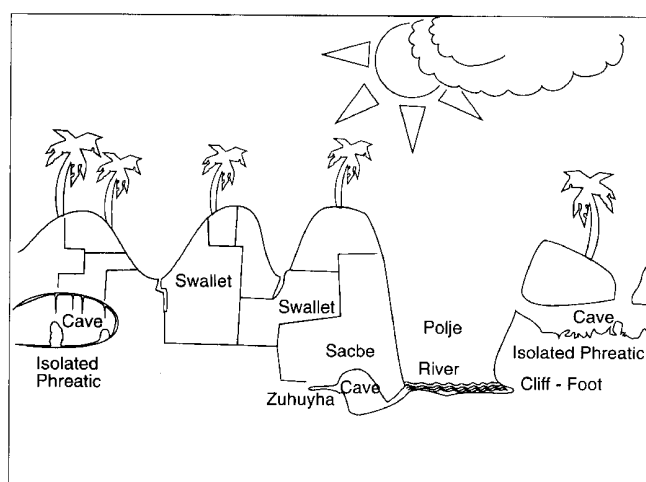


Figure 9. Generalized relations of cave and passage types in the Caves Branch.



Figure 10. A collapse chamber intersected by the trunk conduit of Petroglyph Cave.

tions are absent except where bordered by a trunk conduit.

Generally, the collapsed chambers clearly predate the trunk conduit channels. For example, the modern, hydrologically active trunk conduit at the Petroglyph Cave entrance flows briefly in a symmetrical tunnel, 15-20 m in diameter, with a roof composed of breakdown blocks in the sink above, and a floor cut in bedrock. In most other chamber/trunk conduit intersections the conduit has cut into bedrock slightly below the apparent base of the collapse. Widespread collapse on a massive scale obscures bedrock clues concerning their development.

Some examples exist of collapse after trunk conduit formation and intersection. In the Dead Room of Actun Lubul Ha

(Figure 11), collapse has filled a former stream passage and presumably forced its abandonment as an active channel. Streams have cut smaller channels on both sides of the blockage upstream, but failed to link up again with the former downstream segment. No clastic sediments or remnants, buried by collapse or otherwise, have been found in collapse chambers except directly alongside active trunk conduits. Huge speleothems are additional evidence of the great age and relative stability of most collapse chambers.

Zuhuyhas ("zu-hu-e-ha," from Yucatec Maya for "virgin water"). These are chemically diffuse flows that have the hydrological character of trunk conduits. They are active conduits of autogenic flow generally found at the lowest levels of the explorable karst. Most discharge into the trunk conduits, where they often deposit travertine (Figure 12), but several emerge as surface springs. Internal speleothem or calcite deposition is rare. No clastic sediments of obvious allogenic origin are ever present. *Zuhuyhas* are probably dendritic collectors of long residence karst water from the overlying karst surface, and are subject to runoff pulse transmission and expulsion during the wet season. They undergo seasonal to continuous modification, and, when active, consist of flooded segments (sumps) with intervening air-filled sections, except in highest flow. These passages are occasionally anastomosing, frequently tubular in form, scalloped, irregularly pocketed, joint-guided, and lack graded profiles. Travertine deposition (into trunk conduits for example) is common at their termini, but other calcite precipitation is rare. At present only one *zuhuyha* has been penetrated during the dry season to these predicted inner regions. Most are enterable no more than 50 to 100 m.

Figure 11. Western end of Actun Lubul Ha showing multi-level character of trunk conduit, collapse chamber, entrenchment, and piracy (from Miller, 1981a)

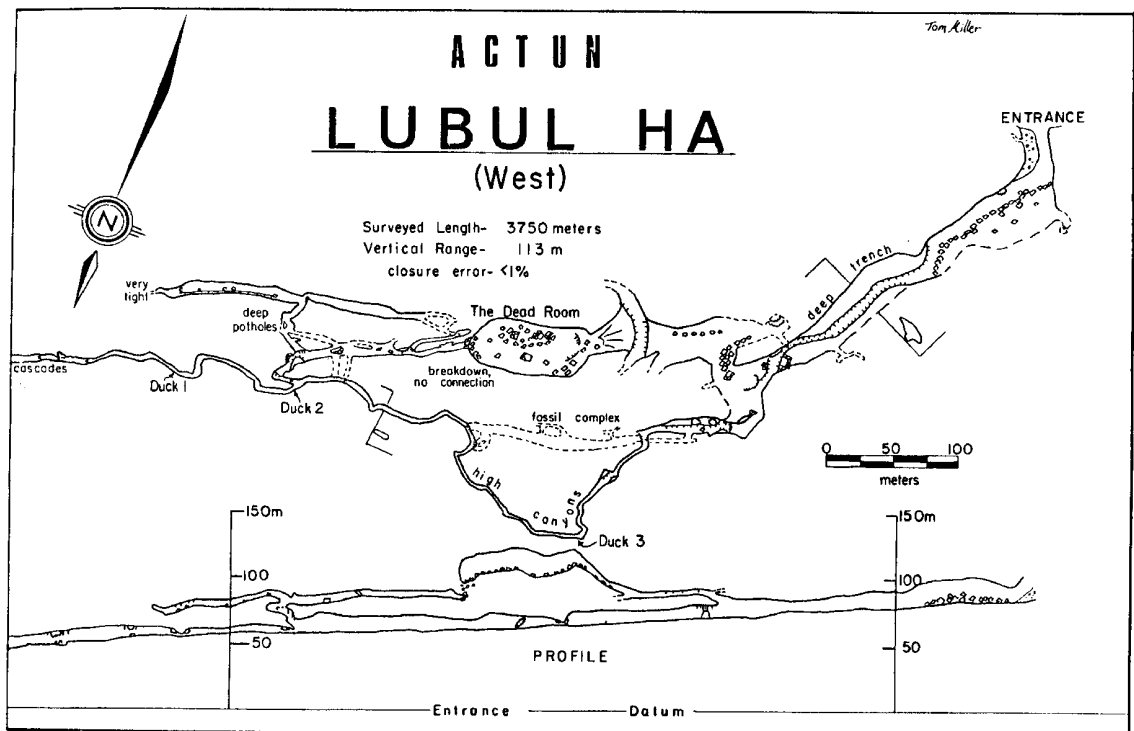




Figure 12. A wet season *zuhuyha* depositing travertine where it enters above the floor of the trunk conduit of Saint Herman's Cave in the Caves Branch area.

Karst Margin Swallets. These caves are found at or near local base levels, and function as intake conduits into the limestone for solutionally aggressive runoff from valley clays and clastics. They are commonly phreatic and anastomotic in plan, and rapidly lead to sumps with seasonally fluctuating levels.

EPIPHREATIC/VADOSE CHANNELS

These cave passages form the majority of the passages known in Belize because of their attractive size and ease of exploration. Though they may contain sumps, they generally have ample airspace except during seasonal flooding. Three passage types are known: trunk conduits, swallets, and piratic conduits.

Trunk conduits. The bulk of the known Caves Branch area cave passages belong to this category (Figure 13). Trunk conduits are the allogenic counterpart of the *zuhuyhas*, functioning to transport water and sediment from the highlands through the karst. Because of the large areal coverage provided by these lengthy conduit networks, much autogenic water is intercepted by them.

By far the largest trunk conduit in the Caves Branch area is within the 30-km-long Caves Branch Cave System, but the trunk conduits of Actun Chek (~9 km) and Actun Lubulha (~4 km) are also major karst throughways.

In Caves Branch, trunk conduits parallel photo-lineations, are similarly oriented to the regional fault trends, and also parallel the local topographic dip, which is generally to the north-east. In the brecciated bedrock there are no aquitards and bedding planes to encourage lateral development and truncate vertical fractures. However, Lubulha and Chek near the Northern Boundary Fault show examples of offset multi-level development, as opposed to the entrenchment in the trunk conduits of the main Caves Branch Cave System. In both caves, the fossil channels lie up-dip and topographically higher than the present active channels, and down-dip migration appears to have

occurred.

Swallets. These shaft caves function as transport channels for runoff from the karst's surface to its subsurface drainage system. They are almost exclusively vadose in morphology, with vertical, fluted walls and minor clastic deposits. Those presently known are located at or near cockpit bottoms, frequently at the end of a gully cut into the floor. Streams flow in the gullies only during prolonged or very intense rainfall. Passage orientation in the swallets is exclusively controlled by joints in the bedrock. Collapse occurs in solutionally-"rotted" limestone, but is not common. In contrast to the other cave types, swallets diminish in size along their courses. They end either in sediment chokes or impassably narrow fissures. Those known are all less than 30 m deep.

Piratic Conduits. The extent and function of these conduits in Belize are largely unique to the Caves Branch area. They are distinguished from the trunk conduits chiefly by smaller size, location, relative age, and the transport of predominantly allogenic water. They exist only where the Caves Branch River parallels a major cave conduit, and feed extracted river water

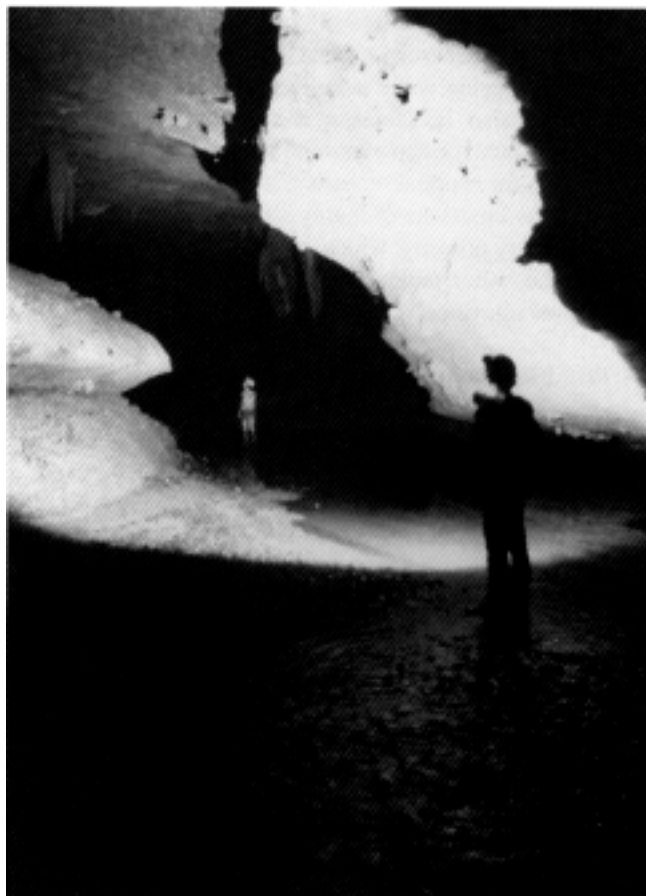


Figure 13. The main passage of Petroglyph Cave. Note the allogenic clastic sediments on the floor and the incised wall niches. The lowest 1.5-m-high niche is common to all trunk conduits of the valley.

to the neighboring trunk conduit. All have joint-controlled courses and sizes averaging 2-3 m high by 1-2 m wide. They are always located on the polje-ward side of the trunk conduit into which they empty, have sediments of Mountain Pine Ridge origin, low solute loads of less than 100 mg/L total hardness (as CaCO₃), and comparatively high water temperatures of about 25°C. Finally, the mean solute content of each piratic conduit stream increases with distance downstream in the polje and mimics that of the nearby Caves Branch River. Except for short sump sections, all are presently in states of active vadose entrenchment and all but one enter flush with the trunk conduit floor. These last four characteristics are opposite those of *zuhuyhas* off the same trunk channels.

The major cave network change presently occurring in the upper Caves Branch Cave System (e.g. Petroglyph Segment) is the growing complexity of the network through growth of piratic conduits. The main trunk conduit is laterally offset and lower than the surface river channel that it parallels, giving it a hydraulically advantageous position relative to the independent surface stream. This is likely due to insoluble sediments armor-ing the polje floor. This appears to be common elsewhere. LeGrand and Stringfield (1963) have noted that the lower course of the Río Cobres, in Jamaica, lies on alluvium higher than the neighboring water table in the limestone. Brown and Ford (1973), also in Jamaica, and McDonald (1976a), in Belize, have noted the apparent affinity of many polje and open polje streams for residual limestone masses. McDonald postulates that "the limestone is highly soluble and has developed much secondary porosity, which allows for freer movement of runoff to the water tables than the relatively insoluble and impermeable alluvium."

CAVES BRANCH SUMMARY

In the Caves Branch area, the high caves are isolated and unintegrated in the top 70-150 m of the aquifer. They are abruptly replaced in the bottom 20-30 m by the well-integrated present network, where the function and relationships of all conduits types are known. There is no apparent evidence of headward integration of the various components, or gradual evolution of the aquifer to the present low-gradient state.

The initial siting of the surface river channel was followed by:

1. development of large allogenic phreatic or epiphreatic trunk conduits
2. *zuhuyha* integration with the trunk conduits
3. vadose entrenchment and/or development of lateral cut-off
4. formation and integration of piratic conduits in the upper Caves Branch Cave system, followed by a phase of sedimentary infilling

The surface depressions have demonstrated a significantly greater occurrence near photo-lineations and the northeast-southwest trending fracture system, and are presumably located at favorable sites for the movement and penetration of

groundwater. However, there appears to be little correlation between surface and subsurface features. Observed photo-lineations seldom correlate with cave passages, and except for rare instances where massive collapse occurs to the surface, most breakdown chambers in the caves have no surface expression.

While some *zuhuyhas* demonstrate a tendency to occur at sites where a large doline was located near a conduit, trunk conduits rarely pass beneath surface dolines, and never follow surface valleys. Surprisingly, much of the course of the upper Caves Branch Cave System strongly correlates with surface ridges, in spite of a limestone thickness exceeding 100 m. Brown and Ford (1973) described a similar situation in Jamaica where conduits tended to locate beneath hills rather than depressions. It is unclear why the obviously joint-guided cave passages have an affinity with surface ridges, rather than beneath the dolines which are demonstrably favorable locations for water movement.

2. VACA PLATEAU KARST

The Vaca Plateau, containing the Chiquibul area, is the largest of Belize's five major karsts (1,000 km²) and is the eastward end of a broad platform of Cretaceous carbonates extending from central Guatemala. It spreads 10 km west into Guatemala, to the gorge of the Chiquibul River, and extends south and east to the Maya Mountains. To the north, it is defined as ending at the Northern Boundary Fault where it indistinctly merges into non-Cretaceous carbonates and clastic sediments in the plain of the Belize River. This limestone plateau has relatively uniform summit elevations, but its intervening areas are quite rugged with steep local reliefs of 100-150 m. It increases in general elevation from about 400 m in the north to about 700 m in the south, near the contact with the noncarbonates of the Maya Mountains.

VACA PLATEAU GEOLOGY

No in-depth studies exist of the limestone. (*Editors note: See Reeder, Brinkmann, and Alt in this issue for recent petrologic analyses.*) Previous geologic work has concentrated upon the mineralogy of the surrounding Maya Mountain's Paleozoic metasediments and Triassic granites (Flanders, 1978). The limestone Campur Formation dips gently westward, lying unconformably over these older noncarbonate units.

The Vaca Plateau is crossed by several major faults striking southwest-northeast. Aerial photographs of the Chiquibul section, in the southern plateau, show numerous linear features. Flanders (1978) stated that the streams on the noncarbonates to the south are fully structurally controlled by joints, faults, and bedding planes. Faults and major joints are likely the causes of linear features noted in the limestone. Identification of faults in the field, and verification of their influence, are hampered by the thick vegetation, and in the caves, by the ubiquitous brecciated bedrock, inaccessibility of many walls and ceilings by

Table 4. Rock, Soil, and Sediment Analyses from the Chiquibul, Belize, 1984.

Class/Type	n	SiO ₂	Al ₂ O ₃	Fe-oxides	CaO	MgO	Na ₂ O
Cockpit sediments	5	61.1	24.1	9.5	1.5	0.8	0.3
Bedrock	3	0.0	0.0	0.0	68.2	25.7	5.9
Cavern sediments	3	85.4	6.9	3.1	0.3	<0.1	0.5
Highlands soil	1	68.7	16.7	9.7	1.7	0.5	0.3

n = number of samples; figures are %, only 6 variables analyzed (after Miller, 1987).

large passage dimensions, and the massive deposition of sediment and speleothem on exposed surfaces.

The Chiquibul expeditions (Miller, 1984, 1986c; Miller, McNatt & Veni, 1987) identified two common lithologic units. The first is that of a dense, micritic, often-crystallized bedded limestone of dark gray to white hue. The second is a highly brecciated, usually recrystallized rock composed apparently of clasts derived from the bedded limestone, set in a matrix of orange-brown calcite. This second unit was the most commonly encountered in the area, perhaps because it was also the unit in which all of the major cave exploration occurred. Table 4 (Miller, 1987) lists several analyses of the bedrock from the southern Vaca Plateau, showing the bedrock is a high-magnesian limestone.

SURFACE MORPHOLOGY

The Vaca Plateau can be separated into two distinct areas (Figure 14). The northern two-thirds is a fluvio-karst in which integrated, dendritic valley networks are clearly visible from aerial photos. These valleys are fossil; the local gradients of their former thalwegs now contain closed depressions, though remaining graded overall.

Most of the southern area is a cockpit karst, with considerably less evidence of a fluvial past. Remnant limestone hills rising above alluviated plains run up the eastern margin of the southern karst in a several-kilometer-wide strip. The cockpits contain short (<100 m) channels, ending in swallets and short caves that likely direct surface runoff into the underlying trunk conduits.

The present distinction between the two karst surfaces of the plateau may simply be the result of their fluvial history — the southern area receives discharge from several integrated allogenic streams from higher-elevation noncarbonates to the east. Table 4 demonstrates the similarity in composition between soils on the noncarbonate highlands, soils in the cockpits, and sediments in the Chiquibul caves. Sediments from the highlands have clearly been carried onto the eastern strip of the karst and deposited into Chiquibul cockpits. Soils in the southern section of the plateau display a very strong similarity with soils and sediments developed in-situ on neighboring noncarbonate rocks, and a strong dissimilarity to insoluble residues of the local limestone bedrock. Initially, this area likely hosted a

fluvial network until the allogenic streams were pirated underground and induced the development of cockpit topography and drainage.

In this scenario, the northern area of the Vaca Plateau remains in a far less dissected state because the substantial 200-300 m incisions of the Macal and Raspaculo Rivers buffered the limestone from incursions of aggressive allogenic runoff. Well-integrated internal drainage focusing on trunk conduits would not have occurred, which is consistent with the

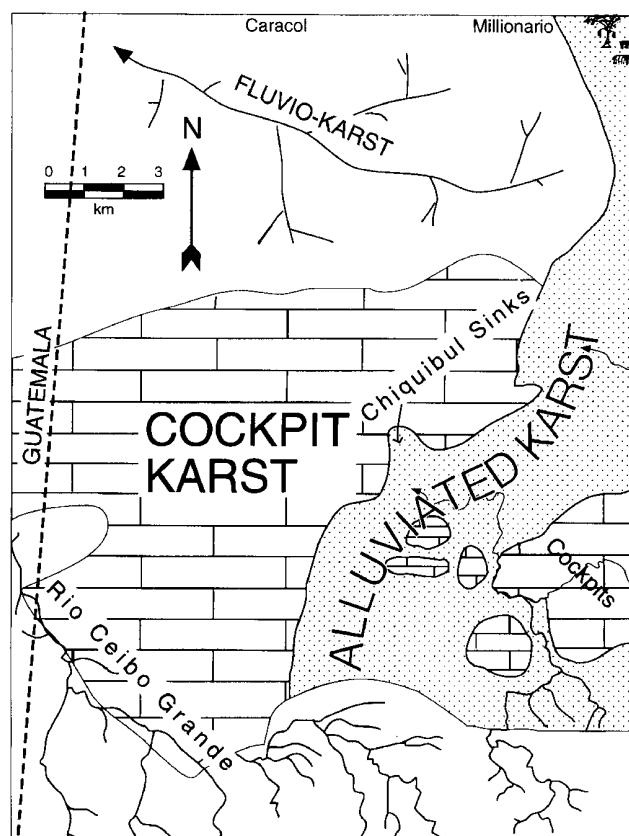


Figure 14. Boundaries of different sub-areas of the karst in the Chiquibul area, in the southern Vaca Plateau (from Miller, 1984a).

results of explorations in the area that have found few and relatively small caves (Reeder, 1993).

CAVE GEOMORPHOLOGY

At over 55 km in length and with a vertical relief of 300 m through its four major caves, the Chiquibul System is the largest hydrologically-linked cave network in Central America (Figure 15). The passages in the western half of the system are hydrologically active portions of the underground Chiquibul River; most known passages in the eastern half are abandoned channels. The river's ponor has moved upstream with time, regressing 5 km to its present position, and largely bypassing the eastern passages.

The eastern section of the system is the most complex, the result of vertical and lateral migration of the river. Various sections of the system display at least four levels that can be correlated from cave to cave. The western section has the greatest vertical development and the largest diameter passages—occasionally exceeding 100 m in width. Only a few kilometers of the total mapped passages are independent tributaries. These usually enter at or slightly above the floor of the trunk conduits.

Except in some of the large rooms, there is surprisingly little bedrock collapse for the size of the passages. Most breakdown is the result of massive stalagmites undermined by repeated floods in the trunk conduits (Figure 16). The active channels of the trunk passages are floored with sand and pebbles derived from the highlands. Most of the trunks are occu-

piated by large, lengthy clay banks tens of meters high and wide.

Isolated caves occur in the area, some of large size, but they form only a small percentage of the known total. Only one is an old high level river cave, the others being of isolated phreatic origin.

CLIMATE AND HYDROLOGY

The Vaca Plateau is largely uninhabited, and long-term climate data are few. Data collected from 1956-1959 at Millionario (Johnson and Chaffey, 1973) indicate a mean precipitation of only 148 cm/yr, and a wet season that begins in May and lasts into December. Because these years were slightly drier than average along the Hummingbird Highway, and assuming a proportional relationship with the Millionario data, which probably reflect a slight rainshadow from the Maya Mountains, 200 cm/yr may be slightly closer to the long-term mean rainfall of the Vaca Plateau as a whole. At the slightly cooler elevations at the southern part of the plateau, annual runoff is estimated at 110 cm of the 200 cm total. Mean annual temperature, as estimated from caves, is 22-22.5°C.

During the dry season, baseflow of the Chiquibul River was measured at 2 m³/sec. Perhaps another 400-500 L/sec was contributed by stalactite drips and the short tributaries carrying autogenic water. Surface runoff was of short duration after heavy rainfall.

All waters analyzed in the Chiquibul were alkaline. The Chiquibul River, both before and after sinking, was the lowest in bicarbonate at 90-107 mg/L (as CaCO₃), and undersaturated

Figure 15. The meandering course of the Chiquibul System, longest (55 km) and deepest (300 m) in Central America (after Miller, 1986c).

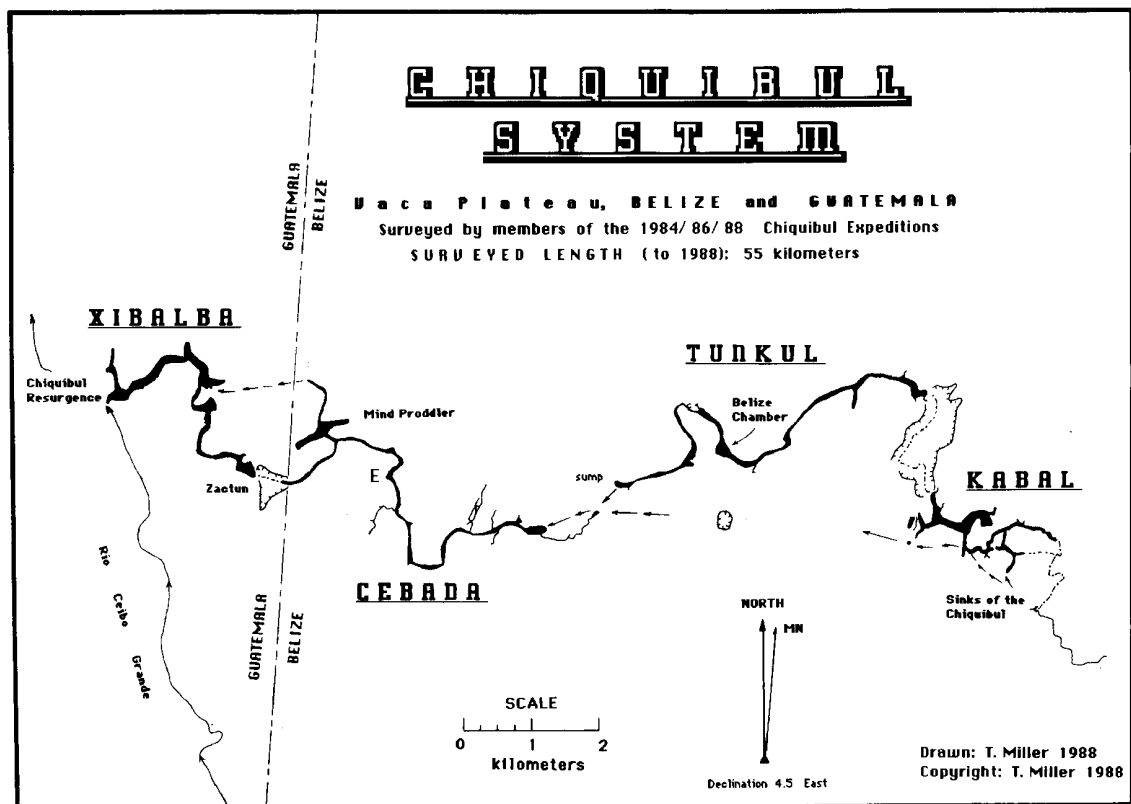




Figure 16. An undermined and fallen stalagmite typical of the Chiquibul System, as well as in many other trunk conduits in Belize. Sumps and low ceilings in this cave are located in synclinal areas.

for both calcite (SIc -0.68 to -0.19) and dolomite (SI_d -0.71 to -0.24). The autogenic waters, however, were often in the 300-400 mg/L range for bicarbonate, and PCO₂ frequently exceeded 1%. These waters contained substantial amounts of magnesium, and were always oversaturated for calcite (SIc 0.18 to 0.98) and dolomite (SI_d ranging to 0.88). A combination of degassing in the trunk atmospheres, and incongruent dissolution of calcite and dolomite may be indicated. Nearly always, these streams were depositing calcite where they entered the main passages (Miller, 1984). Using a mean total hardness of 300 mg/L and mean runoff of 110 cm/yr, an approximation of mean annual surface solutional removal of about 130 m³/km²/yr can be calculated :

$$E = [QA(H/d)]/100 \quad [\text{Eq. 1}]$$

where

E = erosion rate (solute mass removed per year), m³/km²/yr, inserting the absolute values of the following units:

QA = mean surface discharge, cm (precipitation - evapotranspiration),

H = mean hardness of local discharges, as mg/L CaCO₃, and

d = 2.5 (assumed 2.5 g/cm³ density of the dissolved rock).

3. SIBUN-MANATEE KARST

The Sibun-Manatee is in many ways simply the eastern extension of the Boundary Fault Karst. It does differ in two important respects: rocks in its northeast corner are regarded to be Tertiary dolomites (Cornec, 1986), and in surface appearance most of it is tower karst. The region is bounded on the west by the north-south line between Dry Creek and the Sibun River, and by the contact with the noncarbonate highland to the south. The tower karst summits rise to 200 m above flat valley

floors that descend to sea level from less than 40 m inland.

SIBUN-MANATEE GEOLOGY

The southern half of the Sibun-Manatee region is in the Cretaceous limestone of the Campur Formation that forms most of the karst in Belize. If Cornec's (1986) identification of the northern half as Tertiary dolomite is true, it would be a rare example in Belize of significant karst development on non-Cretaceous rock. Several major faults in the area may be responsible for uplifting the rock to the elevation of the Cretaceous outcrops. However, a rock sample from the Gracy Rock area, in this northern section, showed an almost pure calcite rather than dolomite, where CaO = 55.64%, MgO = 0.14%, and CO₂ = 43.6% (Miller, 1981a).

CLIMATE AND HYDROLOGY

Rainfall is variable in this karst, declining from 210 cm/yr at the southeastern corner to about 170 cm/yr near the coast. This is among the driest of the major Belize karsts.

The majority of this area, unlike the Boundary Fault Karst, is relatively remote from the noncarbonate highlands. Major streams do entirely traverse the area, from Indian Creek on the west, to the Manatee River, Bayman, Big, and Quamina creeks on the east. These allogenic streams carry a high sand bedload, and are associated with nearly all the large caves known in this karst, although most of the runoff is likely of autogenic origin.

SURFACE MORPHOLOGY

The area consists of thousands of hills, a mixture of cockpits, small classical towers rising from flat floors, and skeins of hills surrounding flat-floored depressions. The mixture may result from tectonic juxtaposition of differing Cretaceous rock units. Several north-south faults have been identified, and numerous dominantly east-west linear features traverse the hills. The lineaments separate tracts of hills with differing textures, either "smooth" with relatively similar summit elevations, or with rough and broken cockpit topography.

Neighboring flat areas share similar elevations, and are floored with insoluble clays. The clay source of those near the through-flowing streams is presumably deposited material from the highlands. The few interior valleys visited may contain in-situ residuum from the carbonates, or deposits from base level conduits that connect with the rivers. A few valleys appear to have the integration associated with fluviokarst.

CAVE MORPHOLOGY

The major caves of the Sibun-Manatee region are dominantly trunk conduits entered by allogenic highland streams. Examples are Actun Kimin Cab, Manatee River Cave, the White Ridges System (Darby Pat), and the five caves traversed by Indian Creek. Caves abandoned by the allogenic streams occur as far as several hundred meters from the present river courses. The largest of these caves are multi-level, such as Actun Kimin Cab and Gargantuan Cave (Miller, 1991) and the

White Ridges System (Marochov & Williams, 1992), and are reminiscent of the Caves Branch caves.

Other caves have formed where the major streams abut bedrock, but do not use it as a throughway. These passages tend to be smaller, of phreatic origin, and parallel the cliff face. They may also be multi-level, such as The Lost World (Miller, 1991), indicating a long period of development and adjustment to incising base level streams.

Flat-floored depressions, surrounded by towers and floored by insoluble clays, are often drained through small caves to the major river caves. They may also drain to what appear to be small conduits developed within the karst hills that are independent of the allogenic streams.

Isolated higher level caves have also been mapped to 600 m long and 30 m high. They are located as much as a kilometer or more from present river courses, do not contain river sediments, and their walls and ceilings are of obvious phreatic origin. They may represent an eastward extent of the large isolated phreatic cavities of the Boundary Fault Karst.

McDonald (1976a, 1976b) described ponded depressions in the northern Sibun-Manatee Karst and cave streams in Sulawesi, Indonesia, that appeared to preferentially enlarge cavernous openings in limestone bordering alluviated valleys. He believed that the limestone presented hydraulically more efficient pathways to streams perched on non-soluble alluvium. The caves on Manatee River, Mahogany Creek, and the three caves of upper Indian Creek are likely examples of this phenomenon. In all of these cases, the through-flowing stream should have experienced little difficulty in flowing around the isolated hills in which they occur.

4. LITTLE QUARTZ RIDGE KARST

Covering an expanse of ~750 km², this karst is the second-largest in Belize, and extends westward into Guatemala. Although only the interior of its western half is dominated by the non-soluble rocks of the Little Quartz Ridge, this name has been extended to the whole region.

LITTLE QUARTZ RIDGE KARST GEOLOGY

The surface is presumably underlain by the same group of Cretaceous limestones of the Campur Formation that form major karst elsewhere in Belize. Faulting plays an obvious role in some areas, particularly along the Bladen Branch, whose course, and many of its tributaries, is largely fault-controlled. The sinkpoint of the Central River, draining the Little Quartz Ridge, is at one end of a fault that extends 40 km southwest into Guatemala. The two major fault orientations in the area are at approximate right angles (southwest to northeast and northwest to southeast), although airphotos show other lineations running east-west.

SURFACE MORPHOLOGY

There are three main elements of the Little Quartz Ridge

karst. The western half is dominated by the Little Quartz Ridge, a faulted ridge of upper Paleozoic metasediments and volcanics. The streams formed on its relatively high summits (>1,000 m) flow into the surrounding carbonates 300 m below and at most penetrate a few kilometers before sinking. South and west of the ridge the carbonates form a fluviokarst; other areas are broad expanses with little relief. Many large vertically-walled dolines are scattered south and east of the ridge.

Eastward, the Bladen Branch river and its fault-controlled tributaries drain a mixed surface of fluviokarst and cockpit. Valley bottoms are at about 80 m msl, with karst summits to 400 m. A few large collapse dolines are present. South of the Bladen is a little-explored region of several hundred square kilometers, also a fluviokarst with some linear features.

CLIMATE AND HYDROLOGY

The climate in the Little Quartz Ridge region is likely similar to that of the K-T Fault-Ridges Karst to the south, with a longer and considerably more humid wet season than the Vaca Plateau to the north. Estimations of mean rainfall as high as 500 cm/yr have been made for these mountainous areas.

With such precipitation, large volumes of runoff enter the karst, and four substantial rivers drain it, beginning in the west with the Machaquila which continues into Guatemala. In Belize, the Bladen Branch, Rio Grande, and Columbia Branch are fed by numerous resurgences, and rise and sink throughout their courses. The fluviokarst south of the Bladen is likely drained by Deep River and Golden Stream.

CAVE MORPHOLOGY

Presently, the largest caves in the Little Quartz Ridge Karst are associated with the Rio Grande River. These include Tiger Cave, the longest surveyed at 4 km. Tiger Cave is described as a lengthy fossil trunk of the Rio Grande, with lower connections to the active river (Dougherty, 1985). Several small stream tributaries were noted in the cave.

The entire Rio Grande valley begins 8-10 km upstream, at the mouth of an abandoned resurgence. The valley is normally dry, but is fed during floods by short surface streams and by large overflow shafts, from which groundwater rises and discharges.

This Rio Grande source cave is apparently the end of the trunk that leads from the downstream sump of Yax Ta' Ha, a complex multi-level, 3-km-long cave (Figure 17). Dry season flow in both caves is from local autogenic karst drainage. Yax Ta' Ha is remarkable in Belize because it occurs entirely in bedded limestone. Folds in the bedrock control changes in passage elevation, and the present sump terminations at either end of the cave are due to local down-dipping strata. The cave formed under phreatic conditions, and was later invaded by downcutting surface streams in the partial fluviokarst overhead. Further up-valley toward the Little Quartz Ridge is Dead Gibnut Cave, also formed under phreatic conditions. It serves as an overflow for large wet-season discharges that likely feed

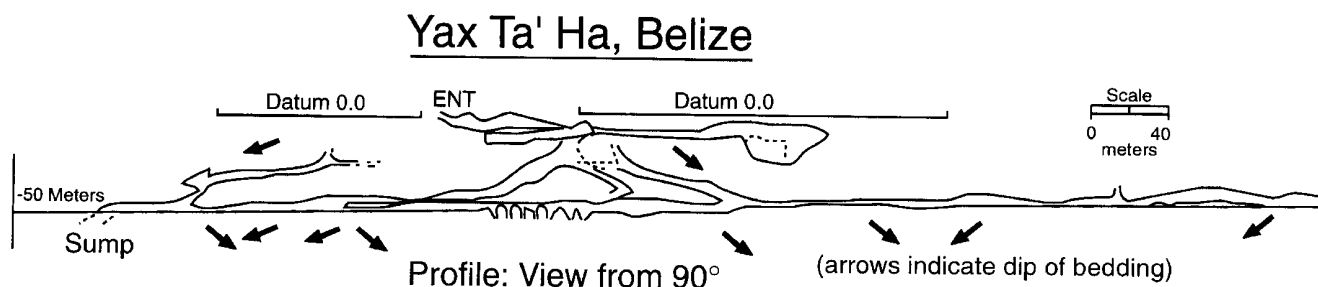


Figure 17. Profile of the multi-level trunk conduit passages of Yax Ta'Ha, the largest cave (3 km) in bedded limestones in Belize. Sumps and low ceilings in this cave are located in synclinal areas.

the sump at the upper end of Yax Ta' Ha.

Several massive vertical-walled dolines exist between Dead Gibnut Cave and the sinks of the Central River. No ponor was located at the sinks, which is an alluviated blind valley. Given the characteristics of the Rio Grande's caves and resurgences between the Central River Sinks (at 500 m elevation) and Tiger Cave (~15 m msl), and the size of its discharge from Tiger Cave (10-15 m³/sec), the presence of a large, active integrated conduit system is implied. This may be as much as 100 m below the surface. The present passages are insufficient to channel flood flow, which emerges either into higher fossil channels, or onto the surface up vertical shafts. The resurgence flow suggests it integrates the sinking Central River, scores of kilometers of autogenic drainage, and perhaps some of the other sinking Little Quartz Ridge runoff in the 14-km-distance that it traverses to the plains. While only relatively minor caves have been explored in the Little Quartz Ridge karst, the deeper, unexplored conduit system of the Rio Grande may be comparable to that of the Chiquibul in size and complexity.

The observed lack of cave development immediately surrounding the Little Quartz Ridge is anomalous in Belize. In spite of high rainfall on the non-carbonate ridge, and substantial runoff into the surrounding soluble limestones, only a few hundred meters of enterable cave passage was found by the 1990 Queen Mary Expedition (Williams, 1992). Although these potential ponors may simply be plugged by alluvial debris, the smallness of such apertures is a surprise in Belize.

The Bladen is an area difficult to access. Visits by the author in 1988, 1994, and 1996 (Miller, 1996), and more detailed explorations by the Maya Mountains Archeological Project (Dunham et al., 1995) have revealed complex systems potentially rivaling those of the Rio Grande River. With the completion of the 1996 field season, several caves now exceed 2 km in surveyed length, with the longest approaching 4 km. Several independent systems currently occupy the disaggregated Snake Creek-Bladen catchment; the largest known parallels the course of the Bladen River. The bedrock hosting the caves is a mixture of brecciated and bedded carbonates.

In the Bladen area, runoff from the non-carbonate Maya Mountains enters the lower limestone hills on armored alluvial

beds before sinking in swallets or caves, then combines with autogenic tributaries underground. Analyses by the author show total dissolved loads ranging from about 40-80 mg/L (as CaCO₃) for allogenic waters, to 300 mg/L for cave waters. All were moderately alkaline (pH 7.5-8.0), with the cave waters approximating saturation with respect to calcite. Cave water temperatures were 23-25°C.

5. K-T FAULT RIDGES KARST

K-T FAULT RIDGES GEOLOGY

The carbonates of the K-T Fault Ridges differ significantly from the other karsts of Belize in both age and structural setting. Cornec (1986) assigns these primarily to the La Cumbre Formation of Late Cretaceous to Tertiary Paleocene age, thus the name "K-T." They consist of long, isolated, block-fault ridges, trending southwest to northeast, the largest being 20 km long. The ridges total about 300 km² and rise above plains of the Toledo Series, a suite of Quaternary shales, mudstones and sandstones.

Most knowledge of the karst and caves of this area is the result of visits to the longest ridge, which contains Blue Creek Cave (also known by its Mayan name *Hokeb Ha*). Walters (1988) has described small caves of unknown genesis (possibly isolated phreatic caves) from the ridges south from Blue Creek.

SURFACE MORPHOLOGY

The Toledo Series plains are generally less than 100 m in elevation, with the intervening limestone ridges at 220-380 m. The ridges exhibit cockpit topography, with some cross-cutting valleys suggesting former fluvio-karst. Only one surface stream presently crosses through any ridge, that of Jalacte Creek at the southwest end of the ridge containing Blue Creek Cave.

The streams of the area all appear to originate on the Toledo Series, some to the west in Guatemala. The largest catchments with the most direct downstream course to limestone are those in the Pueblo Viejo-San Antonio valley, and they may be fed by outflow from the Little Quartz Ridge Karst. These streams plunge into ponors and flow in classic trunk

conduit fashion to emerge at resurgence caves such as Ochochpec and Blue Creek.

CAVE MORPHOLOGY

Two small blocks of Cretaceous limestone have been faulted into the longest ridge, outlined by the villages of Pueblo Viejo, Aguacate, Blue Creek, and San Antonio. The ridge is traversed by at least two large caves. Ochochpec, and the large ponor that appears to feed it, are simple huge trunk conduits. Blue Creek Cave, however, is among the most complicated in Belize with 9 km of mapped passages. It developed as the White River abandoned flow through a limestone gorge in the ridge above the cave, to dissolve open a subsurface route and emerge as Blue Creek (Miller, 1981b, 1995). At least four progressively-abandoned levels developed in the brecciated limestone, three of which are periodically flooded by waters exceeding 30 m in depth.

HYDROLOGY AND CARBONATE WATER CHEMISTRY

The wet season in the southern Toledo District is long and pronounced. Mean rainfalls of 200-450 cm/yr, and their consequently greater runoffs, substantially exceed the 100-150 cm/yr of the northern karst regions. Estimations of mean rainfall as high as 500 cm/yr have been made for the mountainous areas northwest of Punta Gorda.

Waters from Blue Creek Cave were analyzed as part of the Jason Project (Miller, 1995). The waters were generally bicarbonate, calcite-saturated with pH of 7.5-8.2, and dissolved solids of 160-260 mg/L. Nutrients (orthophosphate and nitrate) each averaged 0.2 mg/L, except for two pools containing guano, which exceeded 1 mg/L. Traces of dissolved sulfate, iron, and copper were found.

A large, ~300 L/sec, autogenic resurgence known as Cliff Source is located near the resurgence of Blue Creek Cave. Its water was saturated with respect to calcite, and had a high PCO_2 of ~1.5%. Its mean temperature was 25.5°C, likely reflecting the mean annual temperature of its low elevation and latitude. Given its size, the spring is probably a reasonable gauge of local solution rates. At a total hardness of 220 mg/L ($CaCO_3$), and local runoff of perhaps 150 cm/yr, the K-T Fault Ridges Karst would have a mean surface solution rate of ~1.20 $m^3/km^2/yr$, comparable to other Belizean karsts (as per Equation 1).

6. CAYES AND BARRIER REEF

The low-lying islands (cayes) and 250-km-long barrier reef fronting Belize form a significant shelf of soluble Pleistocene to Holocene carbonates. To date, few caves have been reported, probably because of the difficulty attendant to underwater cave exploration. Some caves on the cayes of Belize seem to represent development during lower sea level stands, while others may still be developing at the fresh/salt water interface.

CAYES AND BARRIER REEF GEOLOGY

The underlying reef foundation appears to be Cretaceous carbonates similar to the mainland. For example, nearly 1,800 m of the Coban Formation were exposed in a well drilled on Ambergris Cay (Dillon & Vedder, 1973).

There are two main views of the recent development of the cayes and reef. Purdy (1974) described the relief on the Belize shelf as influenced by an inherited, pre-Holocene limestone surface that eroded when the entire shelf was exposed during lower sea-level stands. Purdy stated that a pre-existing karst surface has been "accentuated... through an accelerated ... carbonate deposition on the highs."

Choi and Holmes (1982) cited a few drilling cores to support their contention that the Quaternary reef pattern was located on topographic highs of deltas, bars, river levees, and other siliciclastic depositional highs spread over the previously exposed shelf. Some mixed carbonate-siliciclastic deposition, supplied by rivers, occurs today off Placentia Cay (Wiedemeier, 1989).

CAVE MORPHOLOGY

The Blue Hole of Lighthouse Reef is a major example of a drowned offshore karst feature (Dill, 1971; Mathews, 1991). It is approximately 120 m deep, and a circular 300 m in diameter. "Tilted" stalactites beneath the overhanging lip have been cited as evidence for Holocene tectonic activity (Dillon & Vedder, 1973), although in many mainland cave entrances tilting is due to local factors of speleothem growth. The large size of this cavity and its speleothem development supports the idea of subaerial cavern development on the cayes.

Caye Caulker contains a large underwater cave on the east side of the island. Exley (1994) described the cave as over 3 km long, with several large conduits extending from a 50-m-diameter room. Later work by Coke found problems with the survey and described the cave as a room that could be as much as 600 m in diameter (Coke, 1986, 1987, 1988). The cave was subaerially exposed by low sea levels during the Pleistocene glaciations, as indicated by its abundant speleothems. Although the cave covers a large area and exceeds depths of 30 m, it has a relatively low average ceiling height of 10-13 m.

Giant Cave, small reported depressions, and some other known but minor caves of the cayes are of unknown origin. They could be the result of subaerial development on an exposed karst surface, or due to subaqueous solution at the freshwater/seawater interface. Freshwater lenses described on many cayes have been in long use as water supplies (e.g. Carrie Bow Caye [Urish, 1987]).

7. YALBAC HILLS

The surface of the northern third of Belize is formed on rocks that are generally progressively younger in age with increasing distance north from the Maya Mountains. Most of the topography is <100 m msl, with local relief on the order of

10 m or less; the surface is often swampy. The exceptions are the Yalbac Hills and the area north of Gallon Jug along the Guatemalan border west of the Booth River escarpment.

The Yalbac Hills rise to elevations of 200-250 m, with most drainage on the surface. Hartshorn et al. (1984) have reported outcrops of the Coban Formation (Cretaceous), perhaps covering about 300 km² of a total 2,000 km². In spite of their lithologic similarities to the Cretaceous carbonates further south, a cockpit karst has not developed to any degree. North of San Ignacio near the Guatemalan border a line of several vertical-walled dolines in Paleocene-Eocene carbonates have been explored. They exceed 100 m in depth but no caves were found in the vicinity (Albert & MacLeod, 1971). Areas to the north are about 100 m lower, with a "modest karst topography" developed on the early Eocene Santa Amelia Formation (Hartshorn et al., 1984).

8. TERTIARY ROCKS

All epochs of the Tertiary and Quaternary, from Paleocene to Holocene, are exposed somewhere in the rocks and sediments of northern Belize. They are largely carbonates, including marls, but bentonitic clays and poorly consolidated sands are found as a terrigenous clastic cover over much of this area. The basement rocks underlying the carbonates of northern Belize vary from Paleozoic metasediments to granites (Deguen & Schact, 1975), and are at progressively greater depths of 800 m to 3,000 m from Belmopan north to the Mexican border (Anschutz Mineral Corporation, 1976).

Most of the surface drainage (e.g. Rio Hondo, New River, and Freshwater Creek) has a distinctly northeast orientation, due to northeast-southwest parallel faulting which accompanied the general uplift of the Yucatan Platform (Pusey, 1975)

Minor shelters and shallow dolines have been reported from this region. North of Corozalito, numerous circular lakes and ponds exist, with some marked on maps as "cenote." To date, nothing about known solutional features appears to have been published, except for apparent assumptions of very immature karst present on Tertiary carbonates (Placid Oil Company, 1979). Cavernous porosity may exist at depth. Nair (1985) notes artesian flow at 150-200 m depth north of Consejo, with the hydraulic head described as 5-6 m above the ground surface, and originating in proximity to an unconformity thought to be a cave or fracture system. The shallow depth indicates flow in Tertiary carbonates.

GENERAL OBSERVATIONS OF BELIZE KARSTS

SURFACE MORPHOLOGY

Because of the widespread occurrence of carbonate rocks in the humid climate of Belize, the majority of the country can be defined as having at least minimal karst development. Westward, the karsts extend for great distances into Guatemala. The elevations of the major karsts range eastward

from near 800 m above to 100 m below sea level.

Most major karst surfaces display obvious fluvial features or influence: through-flowing streams, poljes, dry dendritic valley networks, and abandoned gorges above caves. Most of the remaining surfaces are similar to the cockpits of the Caves Branch and Chiquibul and usually abut the fluviokarsts. Analysis of sediments and morphologic studies support the idea that these areas were initially developed by non-random fluvial networks centered on points of lithologic weakness. Gradually, the allogenic streams were pirated underground, and evidence of the fluvial networks has been obscured (Miller, 1988).

Isolated limestone towers, and the sizes and extents of flat-floored alluviated dolines, increase with proximity to the lower elevations of the coast. This suggests an evolutionary sequence of fluviokarst to cockpits to towers as downcutting to base level progresses. Large collapse dolines are frequent in Belize, but minor in terms of area. Many are directly attributable to collapse into pre-existing caves.

Runoff in the karsts of Belize is an infrequent occurrence due to the convective nature of most precipitation. In the Caves Branch area, a minimum 12 mm/day of rainfall is needed to generate surface flow into cockpit swallets. Most solute removal takes place internally in what are solutionally "open" systems of relatively high porosity. Boosting of carbon dioxide levels within the aquifer occurs, perhaps due to decay of washed-in vegetation. Resurgent waters are alkaline and usually supersaturated with respect to calcite and dolomite. Overall denudation rates are high, calculated at 0.10-0.13 m/Ka.

CAVES

More than 150 km of cave passage have been surveyed in Belize. The majority are massive tunnels from 20 m to as much as 100 m in width, and have developed on the downfaulted north and south peripheries and western backslope of the horst-structured Maya Mountains. The southernmost systems are sandwiched in the 80 km between the Southern Boundary Fault and the North American-Caribbean tectonic plate margin. The caves are well-mapped, inland, regionally extensive, contain substantial deposits of speleothem, and are in proximity to regional tectonic activity.

These cave populations and cave sizes cannot be known with certainty—there are certainly thousands of unreported caves in Belize. Because of the relative ease of finding trunk conduits, they are likely emphasized out of proportion to their importance, and distort perceptions and conclusions about Belize cave development. The evolution of individual caves are unique to a particular extent beyond general regional patterns, and considerable information about growth and development may be lost through erosion. The known caves may not be representative of the whole.

The oldest caves in Belize appear to be isolated chambers and passages of phreatic origin with minor vertical relief. Trunk conduits developed next, most of which cut through to

the coastal plain at the base of the karsts. These conduits occur as discrete independent systems, each formed by an integrated stream invading from the Maya Mountains, which have karst regions distributed around their north, west, and south sides. The cave systems pass completely beneath the width of individual karsts, with linear extents of up to 15 km.

Every known trunk conduit in Belize is associated with the sinking of chemically aggressive allogenic water originating on the Maya Mountains. These streams are already large, integrated networks before they encounter a limestone where the near-absence of bedding planes provides little resistance to vertical flow in the well-jointed rock. Jointing and topographic dip appear to be the major controls as defined bedding is rare. Although many sections are obviously controlled by a joint visible in the roof, in most instances the initial joint or joints responsible for alignment have been obscured by the size to which the passage has developed. The locations of swallets, *zuhuyhas*, and piratic conduits were influenced by the siting of the trunk conduits, which were targeted for integration of the internal karst runoff.

Large trunk conduits, and apparently even large isolated phreatic chambers, are rare in those areas such as the Yalbac Hills and northern Vaca Plateau. Even though they are lithologically similar to rocks with trunk conduits in other areas, the main difference appears to be the lack of allogenic runoff. Other areas, such as the region continuing north to the Yucatan, may be too low-lying to provide sufficient hydraulic head for widespread subsurface solution at the present elevation of sea level.

COMMON CAVE FEATURES

Briefly, it should be noted that Belize caves commonly contain several types of internal features that are rare elsewhere in the world, yet have not been emphasized in publication about Belizean caves.

“Shields” or “palettes” are frequently large (up to 5 m in diameter) and widespread in Belize, and can be of surprising density—more than 60 were counted in a 100-m-traverse of a cave near Indian Creek, and another 150 were noted in neighboring caves.

“Bellholes” are ubiquitous to every large cave in Belize, occurring in both bedrock and speleothem. These cylindrical, upwardly-tapering ceiling or wall cavities are most likely due to local long-term effects of bat occupation (Miller, 1990b). Their flat, circular counterparts, “bellbasins,” are often found vertically beneath bellholes, always containing bat guano. Both features generally decrease in frequency with distance from entrances.

Travertine or speleothem, undermined by floodwaters or toppled by earth movements, form slabs or boulders. They form the majority of collapse materials in many Belize caves, rather than bedrock.

The large, high-ceiling, multi-entrance passages in Belize commonly contain narrow, linear stalagmites aligned with the

passage axes. The passage profiles approximate a Gaussian distribution, and are called “camelbacks.” The deflection of dripwaters on their surfaces (and consequent calcite precipitation) has been observed to be a product of wind current alternation and velocity, parallel to the passage trend.

CAVE LEVELS

All of the major karsts of Belize contain multi-level, often regionally-extensive, cave systems. All of the major trunk conduits display the presence of at least two to three levels, and as many as four. Internal vertical relief averages about 100 m, with clearly separated individual levels up to 20-30 m apart. Although the rock is extremely hard, it has also been heavily brecciated with bedding almost nonexistent; the individual levels are thus not controlled by stratigraphic perching.

The vertical relief between levels of similar geomorphic characteristics, but hydrologically independent catchments, is broadly concordant across the entire range of the karst in spite of large differences in elevation. It implies synchronous development by the same general cause. Together with evidence of recent, continuing uplift, the concordant cave levels supports the idea of regional response to episodic tectonic uplift of the Maya Mountains, rather than simple local downcutting responses to erosional lowering of base level.

CAVE AGES

Uranium series dating of speleothem from Belize has only been reported from the Caves Branch area (Miller, 1981a). The base of the oldest of two small stalagmites from Mountain Cow Cave (a high isolated phreatic chamber) gave a date of 176 (+49/-36) KaBP. Two others were dated from trunk conduit passages. One was a small stalagmite growing on cemented cobbles 2 m above the present floor of Actun Chek, and was radiometrically dated to 72.5 (+12.9/-11.6) KaBP. The other was a stalagmite from Lubul Ha. It had been overturned and largely covered by sediment, and gave a date of 102 (+3.9/-3.8) KaBP. These dates show that major cavernous development in the basal 30 m of the Caves Branch Karst was well advanced by about 102 KaBP. Filling episodes of unknown regional significance occurred between 60-105 KaBP in very large, mature trunk conduits.

Clays for paleomagnetic analysis were collected from the higher levels of trunk conduits in the Chiquibul, and from Yax Ta' Ha in the Little Quartz Ridge Karst. These were analyzed by W. Steele of Eastern Washington University and all showed a polarity similar to the present (Miller, 1988).

SUMMARY

Belize has proven a fruitful location for a combination of scientific studies and cave exploration. An integration of the processes that interrelate both the surface and subsurface has been possible, in no small degree due to the great amount of cave exploration and mapping that has occurred during the past

four decades. The overriding importance of fluvial processes in the development of surface karst landforms in Belize have important implications for understanding similar landscapes elsewhere in the tropics and near-tropics. This is also true for the importance of open-system solution within the local Belize aquifers, and the consequent magnitude of dissolution in these tropical waters. The regional scope of the amount of caves surveyed, and the recognition of widespread, concordant cave levels, will eventually lead to determination of any causal effect from the nearby tectonic plate boundary.

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