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Cave Development on the Caribbean coast of the Yucatan Peninsula, Quintana Roo, Mexico

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ABSTRACT

Extensive flooded cave systems are developed in a zone 8–12 km inland of the east coast of the Yucatan Peninsula, Quintana Roo, Mexico. In plan, the systems comprise cross-linked anastomosing networks composed of horizontal elliptical tubes (which are actively developing where associated with the present fresh water/saline water mixing zone) and canyon-shaped passages. Both forms are heavily modified by sediment and speleothem infill, and extensive collapse. The pattern of Quintana Roo caves differs both from the mixing chamber form of flank-margin eogenetic caves, and also the dendritic and rectilinear maze patterns of epigenetic continental (telogenetic) caves. Unlike the latter, Quintana Roo caves are formed by coastal zone fresh water/saline water mixing processes. While mixing dissolution is also responsible for development of flank-margin caves, these may be typical of small islands and arid areas with limited coastal discharge, whereas Quintana Roo–type caves are formed when coastal discharge is greater.

In the Quintana Roo caves, multiple phases of cave development are associated with glacio-eustatic changes in sea level. Two critical conditions control cave development following lowstands: (1) if the passage remains occupied by the mixing zone and connected to underlying deep cave systems, and (2) for passages above the mixing zone, if active freshwater flow is maintained by tributaries. In the first case, inflow of saline water drives mixing dissolution, enabling removal of the lowstand carbonate fill and continued passage enlargement. In the second, despite limited dissolution in the fresh water, continued removal of uncemented sediments can maintain the cave void. Where neither of these conditions is met, enlargement will cease, and the cave void will become occluded by collapse and sediment infill.

Keywords: Yucatan, cave development, cave pattern, mixing-zone dissolution, collapse, sea-level change, eogenetic karst.

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INTRODUCTION

Our understanding of the development of karst landforms and caves is dominated by studies of continental carbonate terrains (“telogenetic karst” of Vacher and Mylroie, 2002). However, there is a growing realization that the continental karst model may be inappropriate when the time elapsed between deposition of the host carbonate and exposure is quite short (“eogenetic karst”). Under such conditions, the limestones may still be diagenetically immature, with a high primary porosity and presence of metastable carbonates, while the ubiquitous fracture sets of telogenetic karst are generally absent. Mylroie and Carew (1990) presented a general model for eogenetic cave development: the flank-margin model. Isolated ramiform chambers form along the seaward margin of the exposed carbonates and extend into the island interior, where blind passages are fed by diffuse flow through intergranular porosity. These caves are localized where undersaturation results from mixing of fresh and saline water, and are much more similar to hypogene continental caves formed by acidity generated at depth (Palmer, 1991) than the more common (90%) epigene caves, which have informed much of our understanding of the karstification process. Epigene caves are formed by acidity generated at the surface and develop as a tributary network from recharge points toward the lowest hydrological outlet from the carbonates, with individual passage directions determined by the host fractures. Progressive elimination of relief and the resulting isostatic compensation cause lowering of base level and abandonment of the initial network, with development of newer systems at depth. In contrast, eogenetic caves are abandoned downward by progressive rise in relative sea level as basin subsidence occurs, and the host carbonates move below the interface zone of enhanced dissolution.

While the flank-margin model is useful, its general utility is limited in several respects. First, it is based almost wholly on observations in caves developed during the last interglacial highstand, and which are now subaerial (Mylroie and Carew, 1990; Mylroie et al., 1991). Second, the flank-margin model is based on observations from small isolated islands, such as San Salvador in the Bahamas. While more recent studies have extended this work to larger islands (Mylroie et al., 2001), there has been limited examination of cave development in very large carbonate islands or attached carbonate platforms (i.e., those that have a noncarbonated hinterland). In such situations, the extensive interior catchment area may generate a very substantial discharge of meteoric water at the coast, resulting in high rates of dissolution (see numerical simulations of mixing-zone dissolution rates of Sanford and Konikow, 1989). Thus, in such situations, very large caves would be expected to form. This paper describes the cave systems that have developed in the attached, distally steepened carbonate platform of the Yucatan Peninsula, Quintana Roo, Mexico, which are recognized as representing an important intermediate type between flank-margin and epigenetic continental caves.

FIELD AREA

The eastern shelf margin of the 300,000 km^2 Yucatan Platform (Fig. 1), which is the focus of this study, is rimmed and developed along a normal fault complex running southwest from the island of Cancun. The present coast is incised into Pleistocene shelf margin, reef, and back-reef limestones, which were deposited during the last highstand of glacial sea level (marine isotope stage [MIS] 5). The Pleistocene deposits extend inland for some 10 km and form the most recent of a sequence of accreted carbonate units at least 12 m thick (Ward et al., 1985). The depositional porosity of the carbonates ranges from 29% to 50%, but this has generally been reduced to 14%–23% by cementation (Harris, 1984). Further inland, off-lapping Pliocene to Upper Miocene limestones of the Carillo Puerto Formation (>300 m thick) are present, overlying >300 m of carbonate-rich impact breccias associated with the Chicxulub meteorite impact (Ward et al., 1995; Morgan et al., 1997). The porosity of the limestones sampled in core from boreholes in Merida is highly variable, ranging from <5% to >40% (mean 22, ±10%, n = 71; Gonzalez Herrera, 1984). Evaporites are present at depth (>1500–2000 m) below Jurassic and Cretaceous carbonates. Where these are much shallower to the north and west of the study area, Perry et al. (2002) suggested that their dissolution may be reflected in the highly karstified “pockmarked” surface terrain. The Cenozoic limestones remain subhorizontal, indicating little Tertiary or recent deformation. However, a series of NNE-SSW–trending lineaments (the Holbox fracture zone) form a zone that runs from Isla de Holbox on the north coast to within 10 km of the coast inland from Tulum in the south of the study area.

Along the northern part of the Caribbean coast, a series of ridges and swales form a prominent topographic feature (Ward and Brady, 1979), but these narrow to a single ridge south of Akumal (Fig. 1). A particular feature of the coast is the presence of caletas, narrow inlets that extend inland several hundred meters from the coast, such as that at Xel Ha. Back et al. (1979) argued that these features result from dissolution due to the mixing of seawater and fresh water discharging from springs. Inland from the coastal ridge and swale area, elevations rise gradually to >20 m, and small-scale dissolution depressions are present, but local relief is generally less than 5 m. This pattern is interrupted by development of large (maximum of 10 km long and several hundred meters wide), flat-bottomed linear depressions (solution corridors; Tulaczyk et al., 1993), associated with the eastern elements of the Holbox fracture zone (Fig. 1). The linear depressions define the inland margin of a broad low ridge, which narrows and becomes more pronounced in the south of the study area inland from Tulum. South of Tulum, linear depressions are absent, but the continuation of the zone is marked by large shallow alluviated lakes, such as Laguna Chumkopo. West of the depressions, the topography is much more subdued.

The local climate is tropical (average annual temperature 26 °C, range in monthly average 23–29 °C), with a subhumid

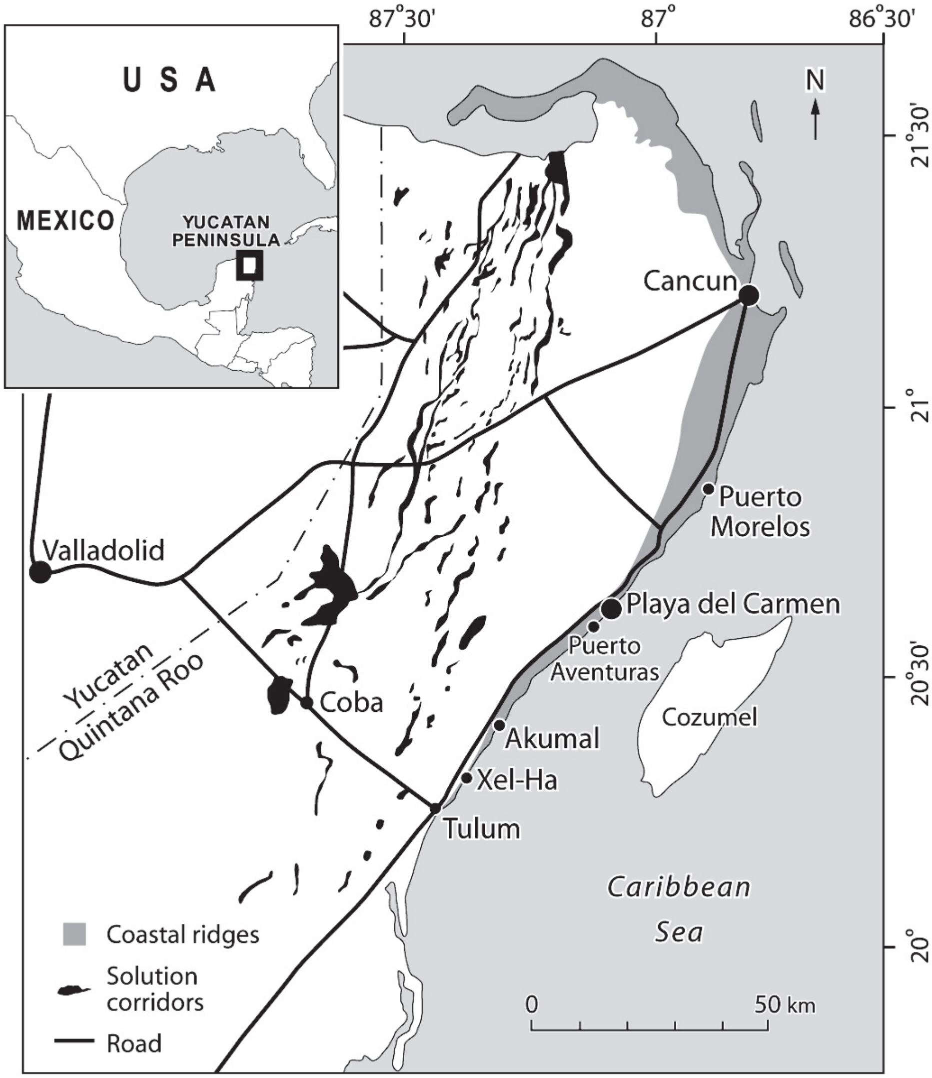

Figure 1. Location of study area on the east coast of the Yucatan Peninsula, Mexico.

moisture regime and summer precipitation maximum. There is an east to west precipitation gradient across the peninsula, with the Caribbean coast receiving in excess of 1500 mm per year, 80% of which falls in the summer wet season (May to September). The effective precipitation is not well known, but potential evapotranspiration exceeds precipitation in all but the months of September and October. Tropical storms move from east to west onto the Caribbean coast and average 0.6 storms per year (Merino Ibarra and Otero Dávalos, 1991). Over much of the limestone, soils are limited to skeletal organic material, but inorganic terra rossa soils are locally present in fissures and in closed depressions. Natural vegetation is a relatively open perennial tropical forest with a thick understorey of palms, succulents, and immature trees. In many areas, the forest has been cleared by slash and burn agriculture, with dense scrub on regeneration.

In excess of 500 km of caves have been explored and mapped up to 15 km inland along ~100 km of the Caribbean coast of Quintana Roo (www.caves.org/project/qrss/qrlong.htm). The caves include Sistema (abbreviated to S. below) Ox Bel Ha south of Tulum, which is currently (January 2005) over 133 km long and ninth on the list of the world's longest caves (www.pipeline.com/~caverbob/wlong.htm). There are also three systems (S. Sac Actun, Nohoch Nah Chich, and S. Dos Ojos) that have in excess of 55 km of passage each, and a further five cave systems over 9 km long. All of these systems are underwater and have been explored by cave divers. By contrast, the 18 or so dry caves that have been surveyed in the area together total less than 7 km in length.

METHODS

Scientific study of the caves is hindered by two related problems, the caves are very extensive, and they require diving for access, which limits the time available for observation.

Underwater observations of cave morphology are only easier than those in subaerial caves in two respects: in the ease of inspection of the passage morphology over the full range of heights, and in determination of their elevations using a depth gauge. For this study, we selectively visited readily accessible parts of the cave systems on a transect from the coast to the interior, and targeted characteristic sites based on the suggestions of local divers familiar with the systems. We also used available cave surveys published by the Quintana Roo Cave Survey (QRSS), both to inform our choice of "characteristic" sites, and to set our localized observations into the wider context of the whole system.

In the text below, "depth" denotes depth below water surface, which is essentially sea level, as the gradient of the water table is very low (~6×10^{-5}). The depth of the fresh water/saline water mixing zone, where present, was also observed using the sharp light-reflective density interface (halocline), which approximates the top of the mixing zone. In addition, detailed in situ salinity profiles were obtained at selected sites using a YSI XLM600 probe.

RESULTS

Cave Distribution and Pattern

Figure 2 is a compilation of available survey information for the 25 km segment of the Caribbean coast in the vicinity of Tulum. This area contains several of the most extensively explored cave systems in the study area, and thus yields values for passage density and extent that may be biased toward high values, but the general pattern is probably representative of much of the ~100 km of the Caribbean coast, from just south of Tulum to Puerto Morelos. The caves form subparallel anastomosing systems running inland, roughly perpendicular to the coast. These systems feed to point discharges, which are spaced on average every 2–3 km along the coast and are often associated with caletas or bays. Although there appear to be noncavernous zones separating the individual systems (for instance between S. Sac Actun and Nohoch Nah Chich), this may be an artifact of incomplete exploration. Certainly, lateral hydrological links exist between systems not yet seen to be connected by divers. In some areas, single trunk passages connect more complex upstream and downstream parts of the systems, for instance the Strangler Roots link in S. Sac Actun and Heaven's Gate in Nohoch Nah Chich (HG in Fig. 2). However, additional exploration often proves that such passages are in fact part of the larger-scale anastomosing network, for instance, the recently explored Cenote Verde extension, S. Sac Actun (CV in Fig. 2). The general passage distribution may therefore be better represented by that seen in Ox Bel Ha, where numerous cross links occur between the major NW-SE–trending passages. Despite intensive exploration, and the good accessibility of the most-inland parts of the systems at upstream sites such as Actun Ha and Cenote Cristal in S. Naranjal, the extensive cave systems mapped in Figure 2 are known to extend no further inland than 8–9 km. This inland limit is coincident with the rise in terrain elevation inland of the Holbox fracture zone, weakly defined in this area as a subdued east-facing crenulated escarpment (Fig. 2B). Only pit cenotes such as Cenote Angelita (11 km inland; Fig. 2) are known further inland. These are predominantly vertical pits floored by debris and lack substantial horizontal passage development. They are therefore very different from the laterally extensive caves in the coastal zone. Further north, some laterally extensive systems, such as Cenote Baab Zotz (1241 m) and Chan-hol (3938 m), are known to extend up to 12 km inland, but systems such as Nohoch Nah Chich are limited to the broad coast ridge east of the linear solution-corridor depressions associated with the Holbox fracture zone.

The passage density for Ox Bel Ha and associated caves is 4.3 km/km^2, falling to 1.8 km/km^2 for the total 8–9 km cavernous zone mapped in Figure 2. These values are somewhat lower than comparable regional estimates for some of the world's most-cavernous continental karst areas, but are significantly less than for hypogene systems and gypsum karst (Table 1). Definition of the extent of cavernous areas is difficult for the latter types, however, because they tend to be relatively compact. Therefore, system estimates were also calculated by sampling the breadth of the area occupied by passage along the length of the system to compute area for cave systems of comparable length to those in the study area (Table 1). Surprisingly, this gave only a marginal increase in estimates of cave density for the larger Quintana Roo caves, whereas densities for continental cave systems in carbonates increased significantly. This demonstrates that the Quintana Roo caves tend to be relatively uniform in distribution, whereas epigenetic continental caves tend to be focused in preferred areas, for instance along contacts with noncarbonate strata. Many of the carbonate continental caves, both epigene and hypogene, span a considerable depth range (Table 1), allowing superimposition of passages at several different depths, which increases passage density. In contrast, Quintana Roo caves are more comparable to gypsum caves and shallow hypogene systems, in that most passages lie within a limited depth range.

At the passage scale, the pattern of Quintana Roo caves is more complex than is apparent at the regional scale (compare Figures 2 and 3). In S. Aak Kimin (0.15 km from the coast), the cave pattern is markedly linear (Fig. 3A), because the passages have formed predominantly along joint sets subparallel to the coast. Other coastal sites, including S. Abejas (0.4 km inland; Fig. 2) and S. Xel Ha, exhibit a network of passages developed on joints subparallel and subperpendicular to the coast; at Xel Ha, a partial collapse has formed a remarkably rectilinear caleta (Back et al., 1979; Thomas, 1999). However, other coastal outlets have a more anastomosing pattern, for example, Casa Cenote (an outlet for Nohoch Nah Chich) and Chuchen at Tres Rios. Although some joint-guided passages are found further inland (for instance at the start of River Run in S. Ponderosa, 1.8 km from the coast), unlike those at the coast, they are gen-

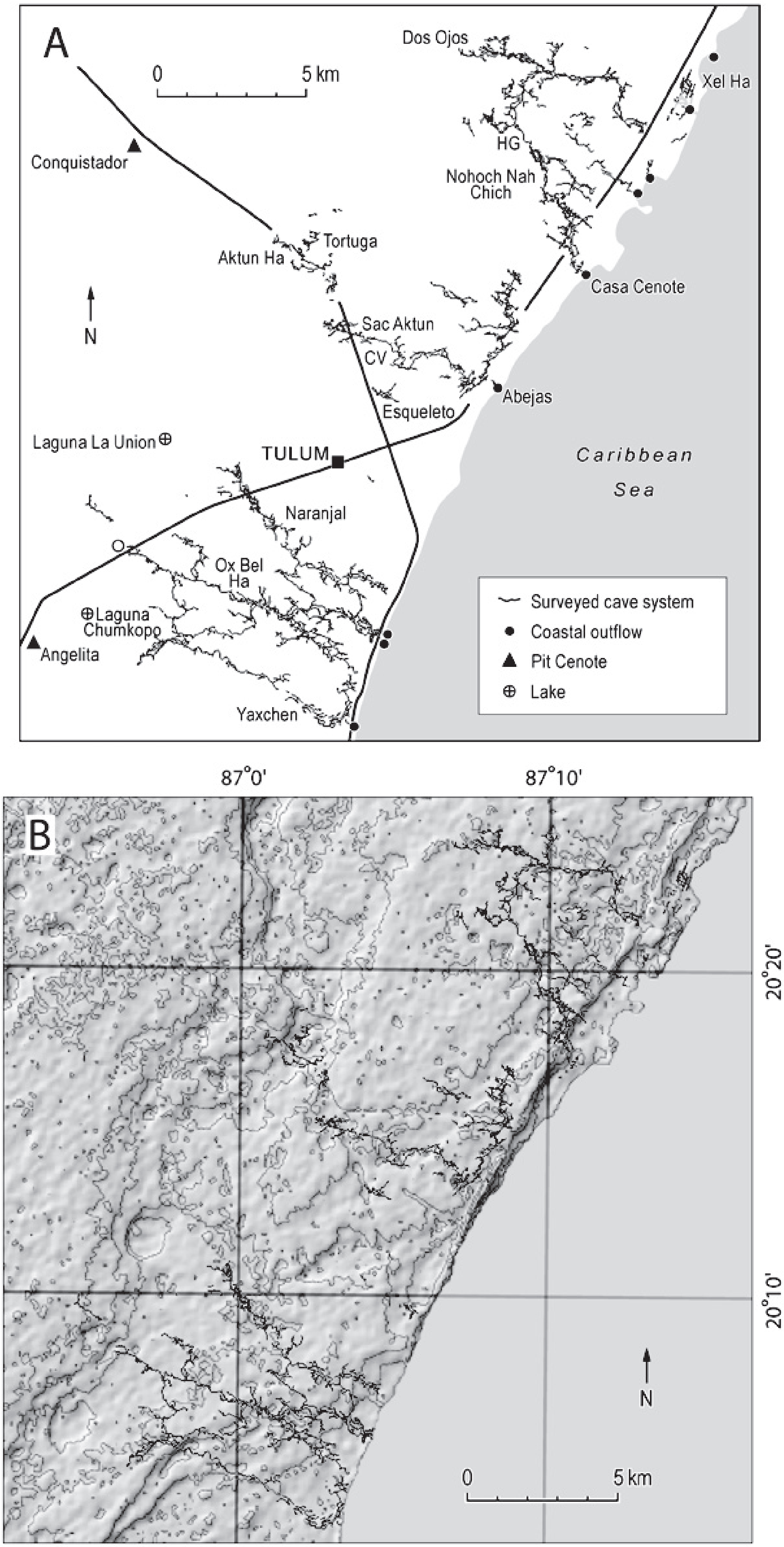

Figure 2. (A) Compilation of underwater cave surveys for the area near Tulum. Line survey data and cave entrance locations were determined by global positioning system data (Coke, 2004) provided by the Quintana Roo Cave Survey (QRSS), with permission from the original surveyors (see acknowledgments). Four additional systems with a total length of 17 km are not shown. Letter codes are for specific passages mentioned in text; HG—Heaven's Gate, Nohoch Nah Chich; CV—Cenote Verde Bypass, Sistema Sac Actun. (B) Cave surveys for the Tulum area (as in A), superimposed on a rectified shaded-relief contour map based on satellite altimeter data. Contour interval is 10 m; illumination is from northwest. No correction has been made for effect of tree cover.

TABLE 1. DENSITY OF CAVE PASSAGES IN QUINTANA ROO COMPARED TO THOSE OF OTHER LONG CAVE SYSTEMS

Cave	Cave type†	Cave length (km)	Maximum cave depth (m)	Sample area (km^2)	Passage density (km/km^2)
Regional Estimates					
Tulum Area, Mexico	QR	380	34.7	213	1.8
Ox Bel Ha/Naranjal/Yaxchen, Mexico	QR	171	35	40	4.3
Podol'sky Great Cave Area, Ukraine	CG	377	30	309	1.2
Optimisticheskaja, Ukraine	CG	208	15	3.5	59
Mammoth / Flint Ridge, USA	CE	579	116	90	6.4
Sieben Hengste/Hohgant, Switzerland	CE	250	1340	39	6.4
Gunung Api, Sarawak	CE	157	355	45 (31)	3.5 (5.1)
Jewel, USA	CH	208	193	11	19
Wind, USA	CH	178	202	2.6	68
System Estimates					
Ox Bel Ha, Mexico	QR	115	34	17.8	6.5
Nohoch Nah Chich, Mexico	QR	61	72	8.9	6.8
Naranjal, Mexico	QR	22	35	1.3	17
Abejas, Mexico	QR	9.7	13	0.53	19
Ozernaja, Ukraine	CG	122	8	0.43	287
Zolushka, Ukraine	CG	90	30	0.51	176
Kristalnaja, Ukraine	CG	22	20	0.14	154
Clearwater, Sarawak	CE	114	355	7.2	16
Ojo Guarena, Spain	CE	89	163	5.8	15
Easegill, England	CE	71	211	2.7	26
Purificacion, Mexico	CE	68	895	2.8	24
Ogof Draenen, Wales	CE	66	98	2.1	32
Ogof Ffynnon Ddu, Wales	CE	50	308	0.82	61
Kingsdale, England	CE	24	131	1.8	13
Castleguard, Canada	CE	20	390	2.7	7.5
Lechuguilla, USA	CH	181	489	0.55	330
Wind, USA	CH	178	202	1.6	113
Toca da Boa Vista, Brazil	CH	102	50	1.9	53

Note: Regional estimates determine density over the whole of the cavernous limestone area, including intersystem areas. System estimates focus on the cavernous areas only, which is determined by sampling the breadth of the cave zone 10 times along the long axis of the system. Length and areas for Ojo Guarena and S. Purificacion are based on older surveys—the cave lengths are now 100.4 and 93.8 km, respectively. Bracketed figure for Gunung Api is for main cavernous area only.

†QR—Quintana Roo caves, CG—continental gypsum caves, CE—continental epigene caves, CH—continental hypogene caves.

erally isolated and never in sufficient density to develop a network cave pattern. Some inland fracture-guided passages are also clearly related to local extension associated with extensive collapse adjacent to cenotes, for instance, the subparallel passages of the Dead Zone in Mayan Blue, S. Naranjal (5.6 km from the coast; Fig. 4).

While an anastomosing pattern is predominant in inland caves, there are considerable differences in local patterns. Spongework can sometimes form the predominant passage pattern at the local scale, as, for instance, in parts of River Run, S. Ponderosa (1.8 km from the coast), but is often incompletely represented by line survey. Some systems, such as S. Chac Mol (2.5 km from the coast), appear at the area scale to be composed predominantly of linear passage segments with a consistent orientation. On closer inspection, a highly irregular ramifying pattern is apparent in plan form, with passage margins sometimes including areas of spongework (Fig. 3B). In some places, the anastomosing pattern is partly caused by passage occlusion and diversion associated with roof collapse and breakdown piles, for instance, further downstream in Chac Mol around Cenotes Pakal and Mojarra (Fig. 3C). In other caves, the anastomosing pattern is made up of clearly defined separate passages. In S. Esqueleto (3.4 km from the coast), the individual passages are of comparable size (Fig. 3D). By contrast, in Nohoch Nah Chich (4 km from the coast), the pattern is formed by a complex of smaller (5–10 m) tubes that run subparallel to the much larger Heaven's Gate trunk passage, upstream of the major collapse at the Nohoch Cenote (Fig. 3E). In other caves, such as S. Naranjal (Fig. 4 and the following section on Phases of Cave Development), the anastomosing pattern results from the complex superposition of several different styles and sizes of passages, which today function as a single hydrological entity. Finally, although retaining an anastomosing element, some systems have a more dendritic pattern, as is typical of many continental cave systems. This is displayed well in the upstream parts of S. Sac Actun, 5 km inland, where a large number of smaller passages lead water toward a trunk conduit that feeds to Grand Cenote (Fig. 3F). Note, however, that the system is incompletely mapped, and distributaries are present, which indicates a continuing anastomosing circulation. Similar dendritic elements are also known from the most-inland segments of other systems, including Nohoch Nah Chich upstream of Heaven's Gate (6 km from the coast; Fig. 2), and upstream of Cenote Cristal in the S. Naranjal (6.5 km from the coast).

In addition to the tendency for cave patterns to be more complex near cenotes, major changes in passage pattern, density, and character sometimes occur downstream of cenotes. Examples include Nohoch Nah Chich, where the large conduit and diversion maze upstream of the Nohoch Cenote gives way downstream to relatively small and very shallow passages in the Main Line Downstream; S. Sac Actun, where dendritic feeders and a large trunk passage upstream of Grand Cenote feed downstream into a single, very restricted passage with only limited junctions (Fig. 3F); and the downstream end of S. Naranjal, where a large passage gives way to the ludicrously small and much shallower Snakeman's Revenge (Fig. 3G).

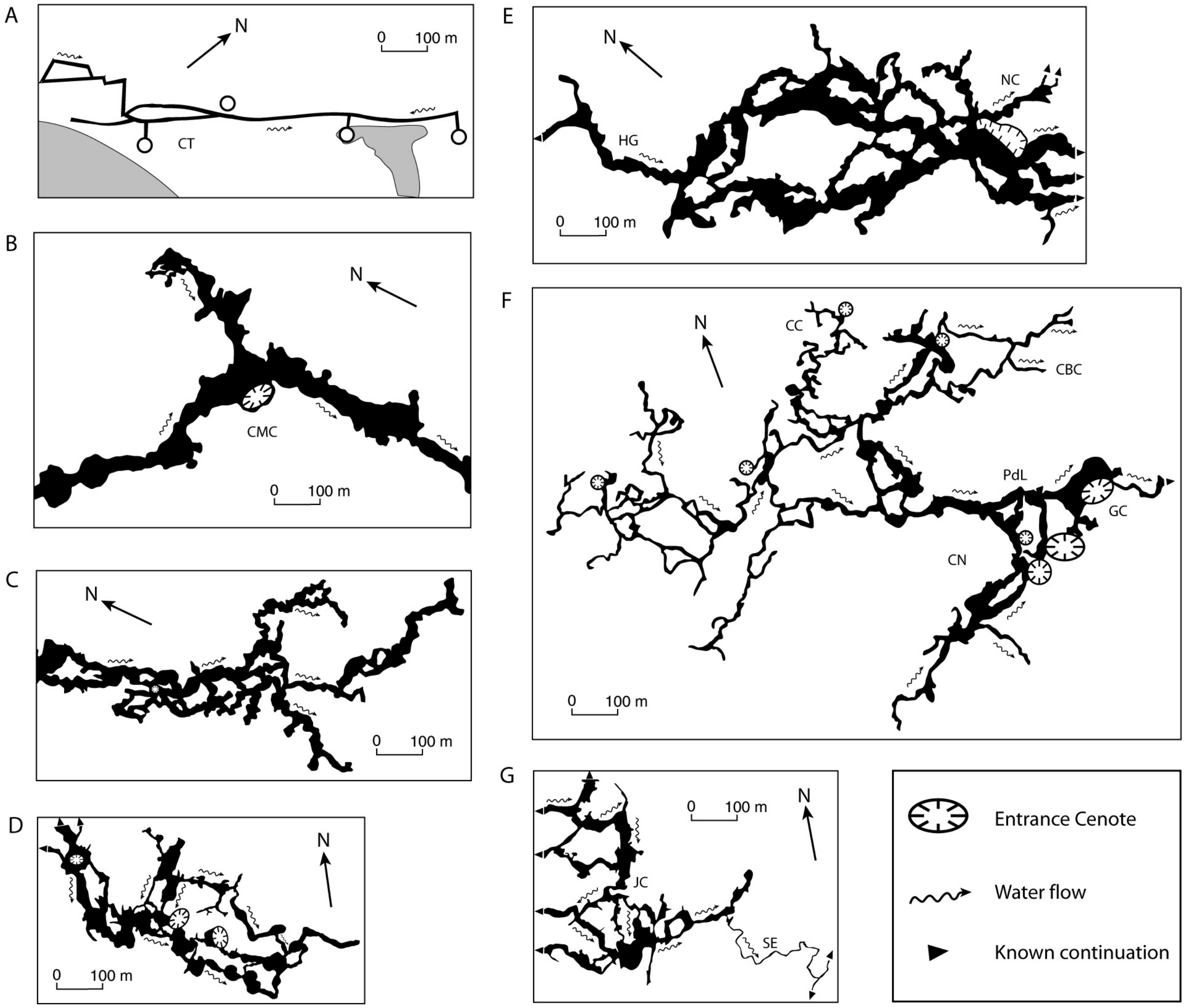

Figure 3. Plan surveys of selected cave passage patterns for Quintana Roo cave systems based on Quintana Roo Cave Survey (QRSS) and other surveys. (A) Sistema (S.) Aak Kimin, Akumal, unpublished line survey courtesy of Gregg Brown. Circles are entrances; CT—Cenote Tortuga. (B) S. Chac Mol near Chac Mol Cenote (CMC) and (C) S. Chac Mol near Mojarra Cenote, Puerto Aventuras, from QRSS survey by Andreas Matthes. (D) S. Esqueleto east of Hall of Giants, Tulum, from QRSS survey by J.G. Coke and C. Sutton. (E) Nohoch Nah Chich, Tulum, from Cedam Cave Diving Team Survey by Mike Madden, Chuck Stevens, and Eric Hutcheson. HG—Heaven's Gate; NC—Nohoch Cenote. (F) S. Sac Actun upstream of Grand Cenote (GC), Tulum, from QRSS survey by Jim Coke, Bil Phillips, Marike Jasper, Dan Lins, and Andreas Matthes. CBC—Cenote Bosh Chen; CC—Cenote Calimba; CN—Cuzan Nah; PdL—Paso do Lagarto. (G) Muknal Remote Siphon area, S. Naranjal, Tulum, from QRSS survey by Jim Coke and Bil Phillips. JC—Jailhouse Cenote; SE—Snakeman's Escape. Black triangles indicate known continuation of passage; arrows show flow direction.

In summary, Quintana Roo caves comprise cross-linked anastomosing systems running from the coast to a maximum distance of ~12 km inland. Beyond this limit, laterally continuous caves are absent, although pit cenotes are present. The anastomosing pattern results from several different causes, including separation of penetrable passage by breakdown, development of separate subparallel passages, and superimposition of passages, which may be from different phases of development. Near the coast, rectilinear fracture-guided caves are present, but are not found further inland. Anastomosing cave patterns are relatively rare in continental caves, comprising only 10% of the several thousand caves sampled by Palmer (1991), and rarely constituting the whole cave. Thus, the pattern of Quintana Roo caves appears to be very different from that of both the majority of continental caves, which are made up of branching networks (65% by length, Palmer, 1991), and typical ramiform flank-margin caves, which are composed of mixing chambers with short blind passages (Mylroie and Carew, 1990).

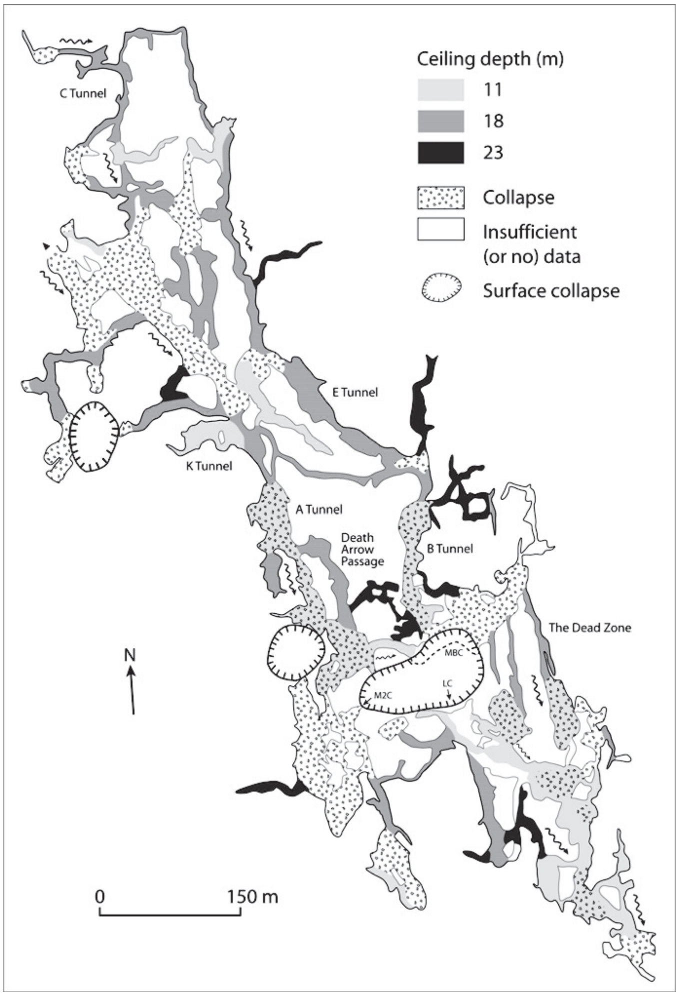

Figure 4. Plan survey of Mayan Blue area, Sistema Naranjal, Tulum, from Quintana Roo Cave Survey (QRSS) survey by Jim Coke, Lorie Conlin, and Tomas Young, showing laterally continuous passages, with corresponding ceiling depths, and areas affected by breakdown. M2C—Maya's Two Cenote; MBC—Mayan Blue Cenote; LC—Lost Cenote.

Cave Passage Morphology

There are two basic passage morphologies in the Quintana Roo caves; fissure passages and elliptical tubular passages. Fissure passages are much higher (5–10 m) than they are wide (0.5–2 m), and typically are guided by a vertical to subvertical fracture (Fig. 5A). In general, their lateral continuity is limited to tens of meters. The walls are often pocketed or fretted, and may have planes of repose on upward-facing wall facets, most commonly near the floor. There is a general absence of flow indicators such as scallops. Sediment frequently mantles the passage floor. Fissure passages are generally most common near the coast.

Elliptical tubular passages typically are somewhat wider (1.1–5 times) than they are high (Fig. 5B). They range widely in size, from 1 to 2 m wide, as in the understorey tubes in S. Tortuga, to >30 m. The larger sizes are confined predominantly to the interior. Lateral continuity is high (100 m to 1 km), although junctions are common due to the anastomotic passage pattern. Despite their shape, elliptical tubes generally lack evidence of any guiding bedding plane. Rather, the modern mixing zone is often coincident with the widest part of the passage, and the walls often are composed of soft weathered bedrock, fragments of which may become detached by diver's exhaust bubbles, forming a fine white gritty snow. The walls and roof range from smoothly rounded to pocketed and sometimes highly fretted, but there is a general absence of flow indicators such as scallops. The passage floor is nearly always mantled in sediment. This may be composed of weathering debris ranging from fine limestone particles to large irregular interlocking fragments of fretted wall rock (known locally as "boneyard"); this is well illustrated in River Run, S. Ponderosa. More commonly, the sediments are composed of fine-grained silts and clays, presumably washed in from the surface. In some passages, prominent planes of repose are present on the lower passage walls (Fig. 5C), indicating retardation of bedrock dissolution by the veneer of accumulating insoluble sediment.

In addition to these simple passage forms, several more complex morphologies are commonly observed. Fissure passages may sometimes be modified by the presence of an undercut or notch, typically 1–3 m high, that is often at the elevation of the present mixing zone (Figs. 5D and 5E). Where the mixing zone is near the base of the passage, undercutting can result in extensive foundering of the upper parts of the passage wall, and may give rise to a more canyon-like passage cross section (Fig. 5F). In some cases, the notch may lead into a separate passage that leaves and re-enters the main passage, generating a small-scale anastomosis. In many passages, undercuts and notches are not at the present position of the halocline and may indicate a previous mixing-zone stillstand of sufficient duration to leave a morphological record (Fig. 5G). However, not all undercuts appear to be associated with mixing-zone dissolution. Along 1.6 km of Heaven's Gate (Nohoch Nah Chich), undercuts range in depth from 4.0 to 8.7 m and occur at or just above the level of the floor sediments, which are composed of organic-rich silts and clays washed in from cenotes upstream. This suggests formation from enhanced dissolution at or below the sediment surface, rather than dissolution at a past position of the mixing zone. Thus, the lateral continuity in elevation of any undercut or notch is a critical indicator of its probable association with a former position of the halocline.

Many passages exhibit overall morphologies comparable to the tube and incised canyon form typically seen in continental caves (Fig. 5E, 5G, 5H, and 5I). However, while some vadose modification of the previously submerged passages is a possibility as the water table falls following a glacio-eustatic lowering of sea level, it is difficult to confirm this origin from morphological evidence. Despite careful searching, there appears to be a total absence of small-scale (vadose) scallops.

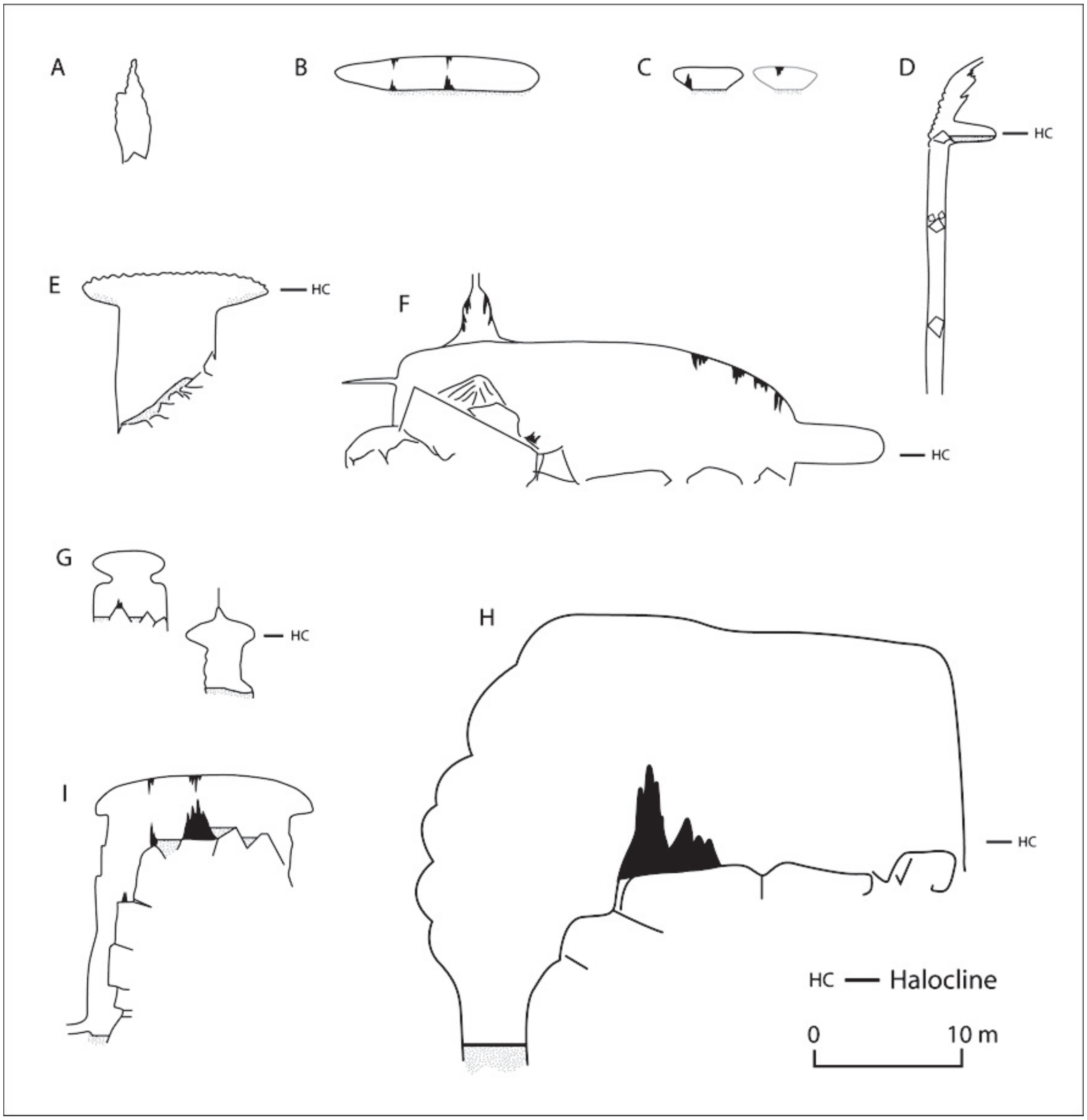

Figure 5. Passage cross sections for selected Quintana Roo caves based on field sketches. (A) Entrance passage, Sistema (S.) Abejas, Tulum. (B) Death Arrow Passage, Cenote Mayan Blue, S. Naranjal, Tulum. (C) Unnamed passages Nohoch Proper area, Nohoch Nah Chich, Tulum. (D) Cenote Tortugas passage, S. Aak Kimin, Akumal. (E) River Run, Cenote Eden, S. Ponderosa, X'pu Ha. (F) Cavern line Cenote Eden to Cenote Coral, S. Ponderosa, X'pu Ha. (G) The Canyons, S. Esqueleto, Tulum. (H) A Tunnel, Cenote Mayan Blue, S. Naranjal, Tulum. (I) Main passage, S. Tortuga, Tulum. HC is modern halocline.

This could be due to masking of the cave floor by sediments introduced during subsequent highstands, but more likely it is due to overprinting upon return to water-filled conditions. Even fresh surfaces revealed by breakdown exhibit the general rounded phreatic dissolution morphology, suggesting that vadose scallops would be short-lived in these young limestones. Some canyon-shaped passages show basal undercutting sometimes characteristic of vadose erosion by freely meandering streams (Fig. 5H). However, in the absence of vadose scallops, this is difficult to differentiate from undercutting associated with floor sediments or a past position of the halocline. In such large canyons (up to 30 m wide and 10 m high), the downstream propagation of meander bends with progressive vadose incision (Lauritzen and Lundberg, 2000) is difficult to determine, but this criterion for a vadose origin may be more reliable in smaller canyon-shaped passages. In S. Tortuga (7.8 km from the coast), there is a progressive deepening of a small canyon incised into the floor of an understorey of small tubular passages at 22–24 m depth (Fig. 6). This strongly suggests a vadose origin for the canyon, with flow downstream in the direction of penetration from the entrance cenote. However, the floors of most canyon-shaped passages are masked in breakdown and sediment, and so it is rarely possible to define the slope of the passage floor.

Collapse is ubiquitous in the Quintana Roo cave systems. The resultant breakout domes produce passages with stepped cantilevered ceilings above a breakdown floor similar to those seen in continental caves (Fig. 7A), although the roof is generally modified by subsequent dissolution. In some cases, breakdown fills the passage almost to roof level, and a square cut passage section is observed (Fig. 7B); in others, the open passage skirts around the breakdown in an undercut associated with the present mixing zone (Fig. 7C). Lateral undercutting at the elevation of the mixing zone can give rise to very wide passages, such as that which generated a collapse zone more than 500 m wide in Balam Can Chee (Nohoch Nah Chich, 2 km from the coast; Fig. 8). Here, much of the central part of the passage is occupied by an extensive breakdown pile, which reaches to the roof. The surface may also be intersected, forming an open cenote floored by breakdown (which may rapidly become masked in material washed in from the surface), often with undercut walls. As at Balam Can Chee, many individual cenote entrances may be part of a single, much more extensive area of collapse. Such extensive zones of collapse substantially modify the present-day hydrology. At Mayan Blue, S. Naranjal, the three entrance cenotes and associated breakdown-choked passages define a major collapse zone some 150 m wide, which prevents direct flow from the two large feeder passages upstream to their continuations to the south (Fig. 4).

Many passages associated with collapse have walls that are smooth and pass without break into a sloping ceiling (Fig. 7D). Generally, the breakdown pile reaches the cave roof, but in some cases an intact horizontal rock roof is present. Such passages are often linear over distances of tens of meters, as if fracture controlled. Good examples are seen in the entrance part of S. Abejas, in Balam Can Chee in Nohoch Nah Chich, and coastward of the Cenote of the Sun entrance to S. Naranjal. At other sites, similar wall to ceiling curvature is associated not with breakdown, but with an opposing rock wall, as can be seen in the Tortugas entrance of S. Aak Kimin, a coastal fracture-controlled cave (Fig. 5D).

In summary, the predominant simple passage type is the horizontal elliptical tube, which is often associated with the position of the present halocline. Vertical fissure passages are more common near the coast and developed on fractures. However, many passages are compound, and include horizontal notches, which form in the mixing zone. Canyon-shaped passages, which are similar in morphology to vadose canyons found in continental caves, are also common, although evidence for a vadose origin is inconclusive. All passages are extensively modified by collapse, but many retain a dissolutional wall morphology.

Vertical Distribution of Caves

The association between the position of the present mixing zone and morphological evidence for active wall-rock dissolution (horizontal enlargement of the passage, fretted and friable wall rock, and speleothem dissolution) strongly suggests that the mixing zone is the most favored location for cave formation. The depth of the middle of the mixing zone (50% differ-

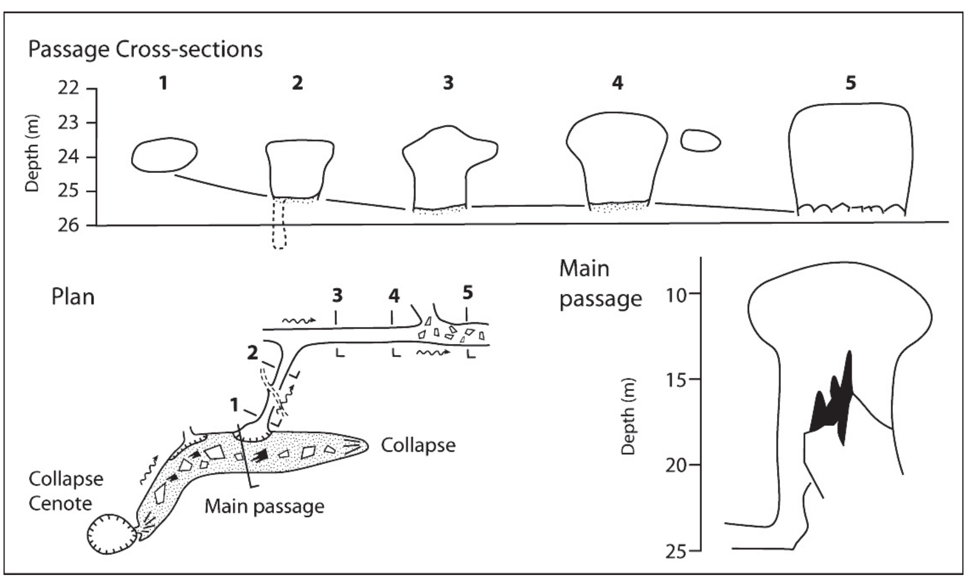

Figure 6. Passage cross sections, Sistema Tortuga, Tulum. Locations are shown on the sketch plan, which is not to scale.

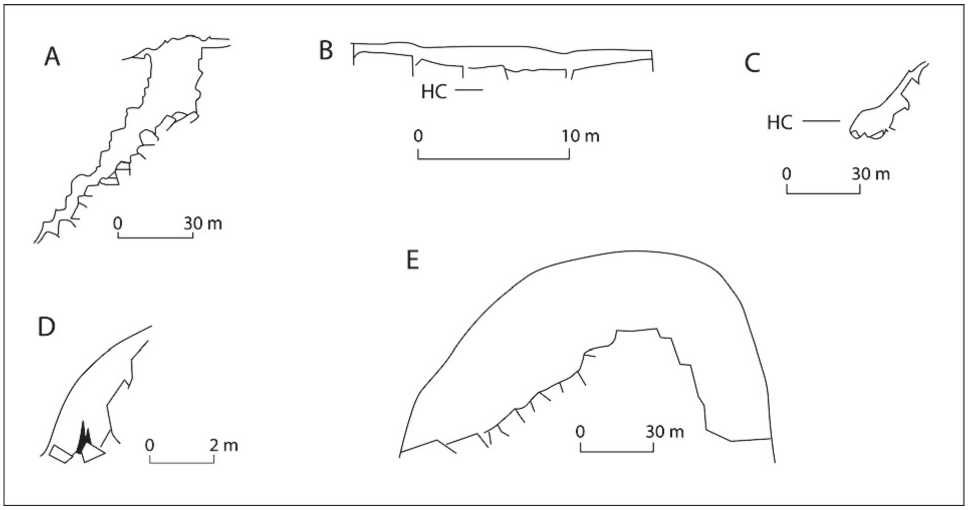

Figure 7. Passage cross sections for selected Quintana Roo caves based on field sketches and from surveys. (A) Blue Abyss, Nohoch Nah Chich, Tulum, from Cedam Cave Diving Team Survey by Mike Madden, Chuck Stevens, and Eric Hutcheson. (B) Casa Cenote, Nohoch Nah Chich, Tulum. (C) Balam Can Chee, Nohoch Nah Chich, Tulum. (D) Main passage, Sistema (S.) Abejas, Tulum. (E) Spring Tunnel, S. Chac Mol, Puerto Aventuras. HC—modern halocline.

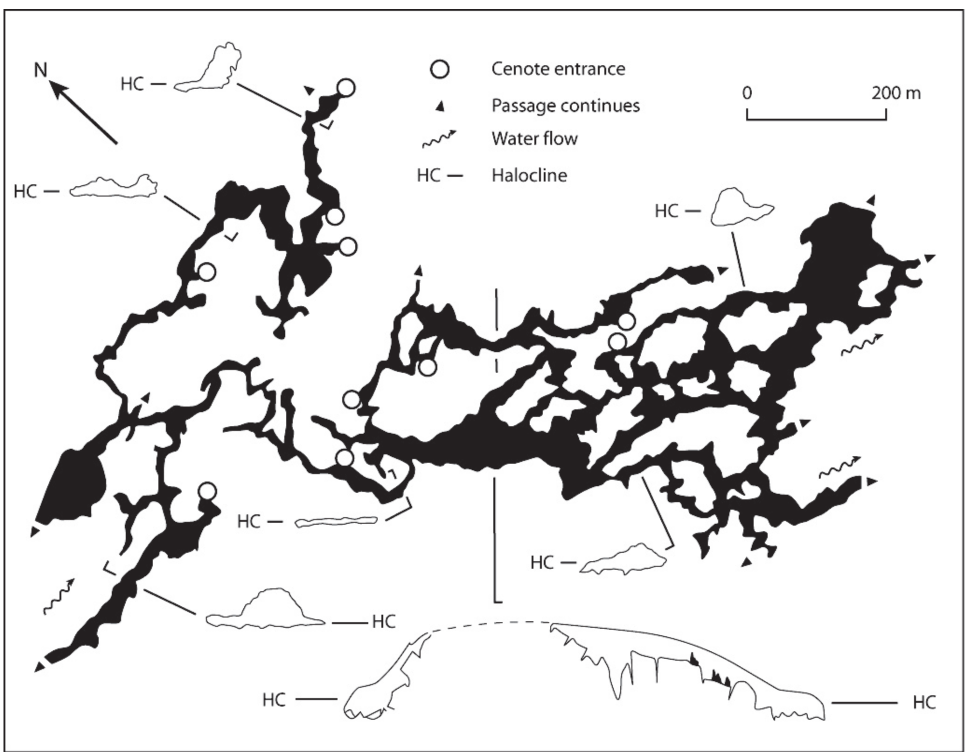

Figure 8. Plan and passage cross sections of Balam Can Chee, Nohoch Nah Chich, Tulum, from field observations and Cedam Cave Diving Team Survey by Mike Madden, Chuck Stevens, and Eric Hutcheson. Passage cross sections are four times plan scale.

ence between fresh water and saline water salinities) increases inland (Fig. 9A), although the data are best fitted by a linear relationship with a nonzero intercept at the coast ($R^2 = 0.88$, $n = 33$), rather than the parabolic form expected from the Dupuit-Ghyben-Herzberg relationship (Beddows, 2004). Figure 9B shows the observed general depth range for passage floors and ceilings recorded on survey dives and derived from surveys against distance inland (depths adjacent to cenotes are excluded, because they are often associated with stoping of the passage ceiling). The range is used despite its strong bias to often atypical localities, because insufficient information is available to compute a reliable representative mean and standard deviation where survey data are not available. Note also that the survey data often record points of maximum depth, giving a bias toward a larger range. There is a general trend for mean passage depth to increase progressively inland from the coast. This relationship parallels the increase in the depth of the mixing zone with distance inland. Note also that most of the caves in our data set include passages that extend at least as deep as the present mixing zone. The available data suggest that caves in the interior have a greater depth range than those at the coast, although this trend breaks down beyond 5 km inland, and is less apparent in the QRSS maximum depth data set, which includes more sites. The obvious exception to this pattern is the very deep (68.6 m) fracture-controlled S. Aak Kimin system close to the coast at Akumal.

Many cave systems have passages at depths both above and below that of the present mixing zone (Fig. 9B). The sub–mixing-zone cave is often represented by downward extension of the main passage network in canyon-shaped passages, e.g., in the Madonna Passage, S. Esqueleto (3.4 km from the coast). At some sites, there is access into a separate understorey of passages. For instance, in S. Tortuga (7.8 km inland; Fig. 6), the main passage is composed of a trunk conduit with a large tube in the roof of a deep canyon extensively filled by breakdown, abundant speleothem, and sediments that mask its true depth along much of the passage. At a number of points, access down the side of the breakdown and through the halocline leads to a separate network of much smaller tubes at 22–23 m depth. A similar understorey of small tubes at 23–24 m is also present in Mayan Blue, S. Naranjal (5.5 km inland; Fig. 4). Extensive sediment infill greatly reduces the apparent depth of canyon passages, and may prevent access to the deepest parts of the system. The full extent of cave development at depth is, therefore, only revealed at one or two sites, and involves logistically complex and sustained technical diving. The best example is The Pit in Dos Ojos (5.6 km from the coast), which reaches a maximum depth of 119 m. From the cenote, an extensive collapse cone leads down to a very large and extensive lower level composed of a series of chambers, the largest of which is the Wakulla Room, which is 150 m long and 30 m wide with the roof at a depth of ~60 m.

Maximum cave depths are, without exception, equal to or greater than the depth to the mixing zone to a distance of 3.5 km from the coast (Fig. 9B). Further inland, many of the systems have extensive segments of passage at depths shallower than the present mixing zone. In Nohoch Nah Chich, all of the passage upstream of the Nohoch Cenote (except the short passage segment in the Blue Abyss) has floor depths between 5 and 9 m, significantly shallower than the present mixing zone at 10.7–12.0 m. This passage continues downstream of Nohoch Cenote, becoming even shallower (Fig. 10B), and links to an underlying passage via a constricted vertical shaft at Hell's Gate. Downstream of this point, much of the cave developed at the depth of the present mixing zone, with a modal floor depth of 12–13 m.

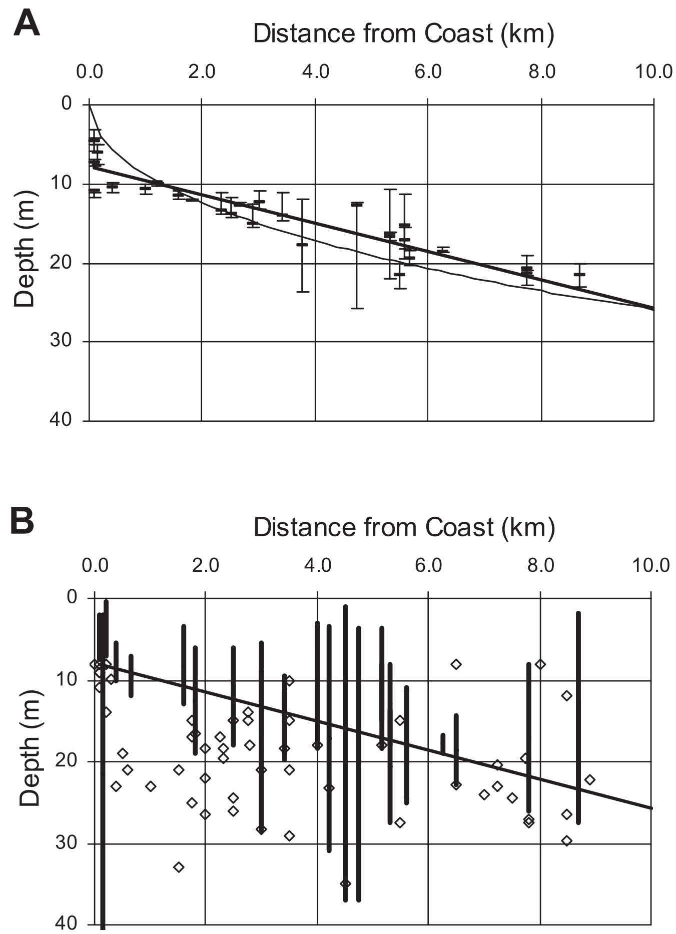

Figure 9. (A) Variation of depth of mixing zone with distance inland for Quintana Roo cave sites based on vertical salinity profiles. Bars show top, middle, and base of the mixing zone. Bold line is linear fit to mid-mixing zone; thin line is Dupuit-Ghyben-Herzberg relationship for a strip island (Vacher, 1988) for recharge of 590 mm/yr, hydraulic conductivity of 6×10^4 m/d, and an island width of 70 km, chosen to give a reasonable fit to the data (see Beddows, 2004). (B) Variation of depth of cave development with distance inland compared with linear trend for present mid-mixing zone (from A). Vertical bars are depth range for caves derived from surveys and field observations; open diamonds are maximum depth of caves from Quintana Roo Cave Survey (QRSS) list (www.caves.org/project/qrss/qrdeep.htm).

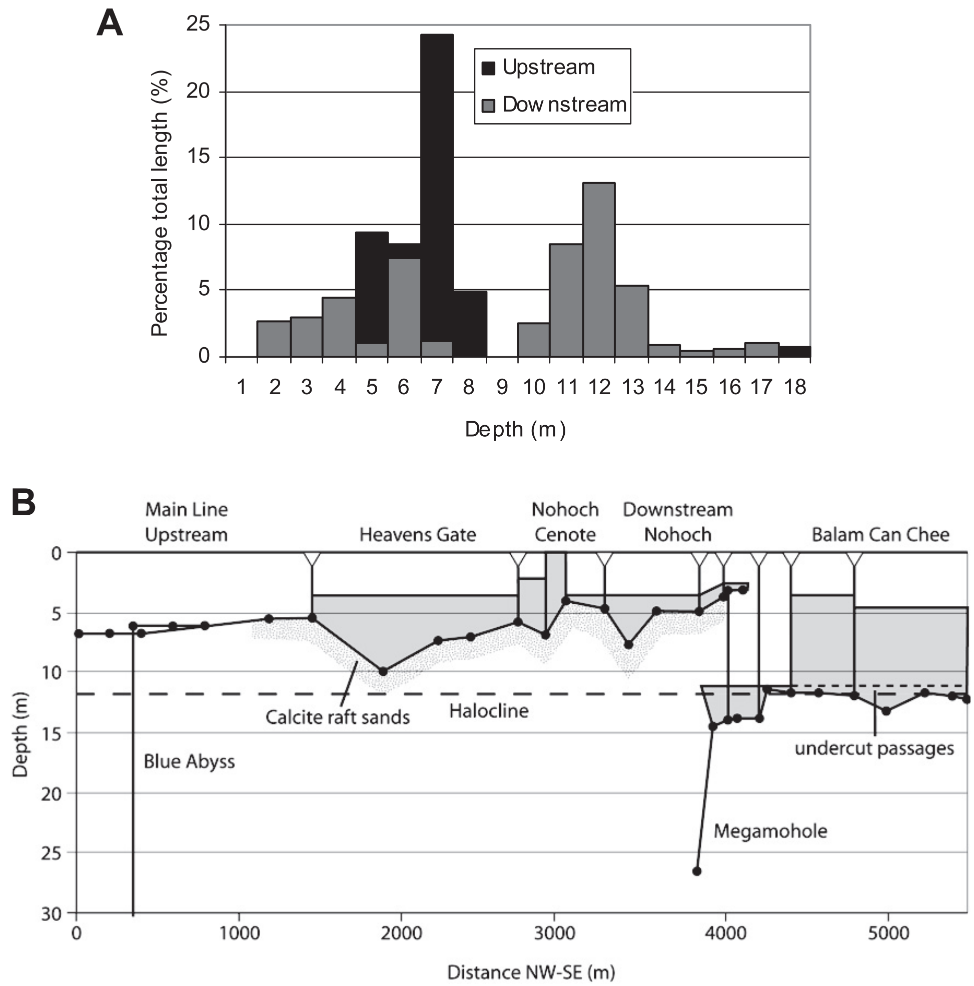

Figure 10. (A) Frequency distribution of floor depths for Nohoch Nah Chich upstream and downstream of Nohoch Cenote (data from Cedam Cave Diving Team survey by Mike Madden, Chuck Stevens, and Eric Hutcheson). Passage depth is the average for two adjacent recorded values and is weighted by the intervening passage length. Halocline center in downstream section is at a depth of 11.6 m. (B) Schematic northwest-southeast projected elevation of Nohoch Nah Chich Main Line upstream and downstream of Nohoch Cenote. Floor elevations (black circles) are from Cedam Cave Diving Team survey by Mike Madden, Chuck Stevens, and Eric Hutcheson, and ceiling elevations (horizontal lines), floor sediments (stipple), and depth of halocline (long dashed line) and undercut passages (short dashed line) are from field observations. Inverted triangles represent cenote entrances.

The inland supra–mixing-zone passages are filled by fresh water and are very different in character to those associated with the halocline. The bedrock exposed in the roof and walls is generally smooth rather than fretted and friable. Indeed, much of the ceiling may be adorned in pristine speleothem. Massive speleothem also accumulates on the passage walls and floor, significantly occluding the open passage. Further speleothem, disrupted by collapse, can be seen preserved in the extensive floor sediments. As noted by Thomas (1999), there are also often copious volumes of sands derived from disarticulation and sedimentation of calcite rafts. These deposits are generally associated with open cenotes, and result from degassing of CO_2 from the fresh waters at the cenote surface. At Cenote Ho Tul (S. Sac Actun), the volume of these sediments is sufficient to infill a passage that is 8 m deep and 20 m wide to the roof (Fig. 11). Downstream of the cenote entrances, cross-bedded sands extend along the passage and are capped by subaerial speleothem, but a vadose trench has been cut into the fill downstream of a small tributary passage. Some dry caves, such as Actun Chen (3 km from the coast), retain a similar morphology to the subaqueous caves; indeed subaqueous wall features can be observed at least 3 m above the present water table. The cave passages have extensive pools, some of which may connect to underlying submerged passages. Calcite raft sands and speleo-

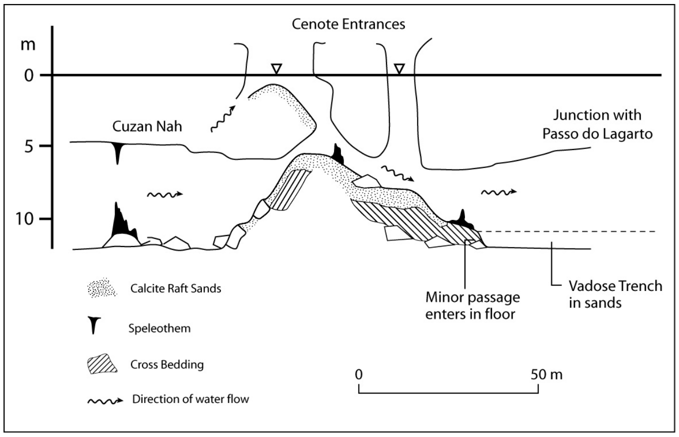

Figure 11. Extended elevation from Cuzan Nah to Paso do Lagarto, Sistema Sac Actun showing distribution of calcite raft sands derived from Cenote Ho Tul and an unnamed cenote immediately upstream.

them deposits are again abundant, and in places fill the passage to the roof. Because they lie only just below the surface, these caves are also frequently interrupted by roof collapse, where enhanced degassing and evaporation often cause copious speleothem deposition.

In summary, although many of the caves are associated with the position of the present mixing zone, cave levels both above and below this horizon are also present. Those at depth are found throughout the area, but those at shallower depth are concentrated predominantly in the interior. Such shallow caves are generally infilled with extensive sediments, including breakdown, surface-derived clays, speleothem, and sands derived from calcite rafts, and are morphologically very different from passages at the halocline, which are still actively enlarging.

Phases of Cave Development

The pervasive subaerial speleothem in most caves in the interior indicates at least one phase of development preceding the present highstand flooding. In some of the coastal caves, such as Casa Cenote, speleothem is sparse or absent, but speleothem is present at others, indicating that they have not simply developed during the present highstand. At many sites a short distance inland, such as S. Abejas (~0.5 km from coast) and Balam Can Chee in Nohoch Nah Chich (1.6 km from the coast), speleothem is extensively corroded, indicating renewed enlargement of the pre-existing cave by dissolution. At other sites somewhat further inland, such as S. Ponderosa (1.8 km from the coast), two phases of speleothem may be recognized, one extensively corroded and often brown in surface patination, and the other less dissolved and much whiter. These sites contrast markedly with those in the interior, such as those accessed from Grand Cenote (S. Sac Actun), where all the speleothem remains pristine, suggesting that active enlargement of the cave by dissolution has ceased. In many inland sites, such as Heaven's Gate, Nohoch Nah Chich, more than two phases of speleothem deposition can be recognized, sometimes separated by subaqueous overgrowths, but also indicated by collapse and regrowth. We plan to carry out U-series dating of the various phases of speleothem deposition, which in the longer term will constrain the antiquity of the caves and their phases of development.

Although the speleothem indicates at least two phases of cave development in inland systems, the difficulty in recognizing vadose passage morphologies makes traditional approaches to separation of phases of cave development problematic. This is exacerbated by the present highstand state of the systems, because modern sedimentation occludes lower passages and masks evidence for earlier sediment fill and re-excavation phases. Nevertheless, as suggested above, there is clear evidence of passages that are not associated with the present phase of active cave enlargement (Figs. 9B and 10). Furthermore, some of these passages are of the elliptical tube type, possibly indicative of past positions of the mixing zone. If so, the elevation of the passage ceiling may provide evidence for the different phases of development, because dissolution rates will be much lower in the fresh water above the top of the mixing zone. In Mayan Blue, S. Naranjal, the passage ceiling elevations fall into five distinct groups (Fig. 12). The deepest group is composed of the understorey of tubes present beneath the main passages, while the next deepest and most frequent group includes the ceilings of many of the main passages (Fig. 4). The three shallower groups are less well represented by a laterally continuous passage and have an increasing proportion of sites where breakdown is evident on the survey. Nevertheless, there is some evidence that at least the two deeper modes represent a distinctive passage grouping. At present, the mixing zone in Mayan Blue is rather diffuse and lies between 15–18 m, possibly corresponding to the 14.5 m ceiling level. Similarly, as the last interglacial sea level is generally recognized as reaching some 6 m higher than at present, the 11 to11.5 m level could derive

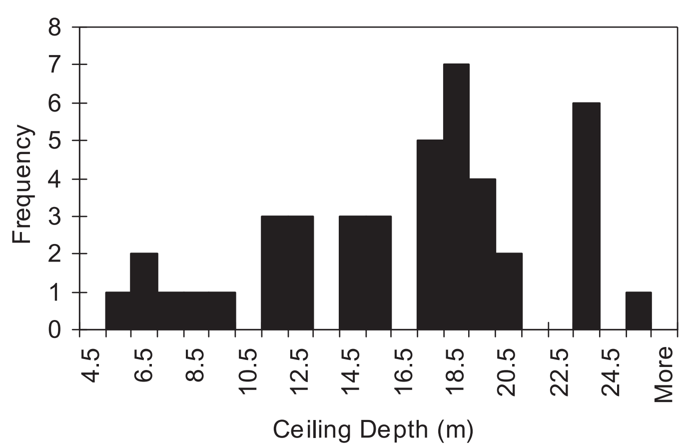

Figure 12. Frequency distribution of ceiling elevations Mayan Blue area, Sistema Naranjal, Tulum (see also Fig. 5). Data are from a Quintana Roo Cave Survey (QRSS) survey by Jim Coke, Lorie Conlin, and Tomas Young.

from this time. The two deeper levels may therefore represent cave development during other lower highstands.

In summary, cave sediment fill, speleothem characteristics, and passage ceiling elevation data provide evidence suggesting multiple phases of cave development. Careful field observations will, however, be needed to confirm the possible concordant ceiling levels suggested here, to map them in the cave, and to test their concordance with elevations of wall notches and undercuts, which may also record past positions of the halocline. Evidence from speleothem distribution and preservation suggests that caves in the interior have more phases of development than those closer to the coast.

KEY PROCESSES AFFECTING CAVE DEVELOPMENT

Dissolution in the Mixing Zone

Previous geochemical studies (Stoessell et al., 1989; Back et al., 1979; and Perry et al., 2002), together with our more recent work (Smith, 2004), indicate that fresh water in the vadose zone sampled in cave drips is saturated with respect to calcite, as are lens waters sampled from wells and conduits in the interior (>2 km from the coast) of the peninsula. Therefore, these waters are not capable of explaining the dissolution of extensive cave systems in the coastal zone. However, the progressive mixing of fresh and saline water results in undersaturation in the zone of mixing between these two waters and dissolution of additional carbonate (Plummer, 1975; Smart et al., 1988; Stoessell et al., 1989; Back et al., 1979; Smith, 2004). Where the mixing zone is diffuse and mixing results from turbulent processes in the conduit, dissolution may affect passage walls and carbonates in any sediment fill, but may not result in a specific morphological overprint. This may be the current situation in Mayan Blue, S. Naranjal, where most surfaces, even those affected by breakdown, exhibit a dissolutional morphology. However, almost universally in the Quintana Roo caves, the saline waters are warmer than the overlying fresh water (Beddows et al., 2002; Beddows, 2004), resulting in a sharp mixing zone due to enhanced removal of salt from the boundary zone by thermally driven double-diffuse convection (Kantha and Clayson, 2000). This is often marked by a visible halocline at the base of the freshwater lens. In such situations, dissolution is focused in the vicinity of the halocline and may lead to development of an elliptical tube or a marked undercut or notch in the side of an existing passage. In both cases, active dissolution is often indicated by solution fretting and a general weakening of the rock by dissolution of the binding carbonate cement, which may result in disaggregation or mass failure. Such features are characteristic of many passages in Quintana Roo caves, and it is clear that throughout the area, active development of the caves is occurring in passages that host the present mixing zone. So, the increasing depth of the freshwater lens into the interior is a primary control on the depth distribution of caves (Fig. 13A).

The extent of mixing, as indicated by the salinity of the freshwater lens, is limited inland of the most-upstream conduit sampling site (8.7 km from the coast). Mixing increases downstream, particularly within 3.5 km from the coast, where the salinity is six times that in the upstream parts of the conduit network, probably due to tidal forcing (Beddows, 2004). The additional volumes of salt water incorporated into the system by mixing and tidal forcing contribute to the increase in discharge toward the coast. Thus overall, cave dissolution rates would be expected to be higher nearer the coast than inland. As argued by Back et al. (1979), this may explain the headward enlargement of caletas by collapse of the rapidly enlarging outlet caves. The high rates of dissolution downstream may also explain the tendency for all possible openings to develop equally, giving rectilinear maze systems where coastal fractures are present.

While we believe that dissolution resulting from mixing is the most important process driving carbonate dissolution in Quintana Roo caves, several other processes may also be occurring. A number of studies (Bottrell et al., 1991; Stoessell et al., 1993; Socki et al., 2002) have shown that redox processes involving sulfate are important for carbonate dissolution in pit cenotes. Oxidation of organic carbon exhausts dissolved oxygen, but continued oxidation is possible by reduction of sulfate derived from mixing with underlying saline groundwater. Reoxidation of sulfide in the overlying oxygenated waters will also drive dissolution by formation of sulfuric acid. It is probable that these and other microbially mediated processes may also occur within cave sediments derived from surface runoff via open cenotes. Unlike recharge entering the caves by diffuse seepage, such runoff may also be somewhat undersaturated, and thus some dissolution may occur with the parts of the cave occupied by fresh water during the rainy season. Furthermore, Beddows (2004) reported a progressive increase in salinity of fresh water toward the coast, and this mixing may drive dissolution in the bulk of the freshwater lens as well as in the mixing zone. Finally, temperature profiles from deep boreholes and The Pit and Blue Abyss both show an increase in temperature with depth (~2 °C/100 m; Beddows 2004). While these waters also increase in salinity with depth, and thus are hydrodynamically stable, forced advection could result in cooling and undersaturation of previously carbonate-equilibrated waters, allowing dissolution of bedrock to occur in the saline zone. These additional dissolution processes may explain the ubiquity of dissolved bedrock surfaces seen in the Quintana Roo caves, irrespective of present hydrological zone.

Contemporaneous Carbonate Sedimentation

Modern carbonate sediments are accumulating onshore and offshore of the present fringing reef, in the back-reef lagoon, and along active beach ridges (Ward and Brady, 1979). With a fall in sea level and subaerial exposure, these accumulations will be augmented and modified by aeolian activity. At least three such units were recognized in the subsurface by Ward et al. (1985),

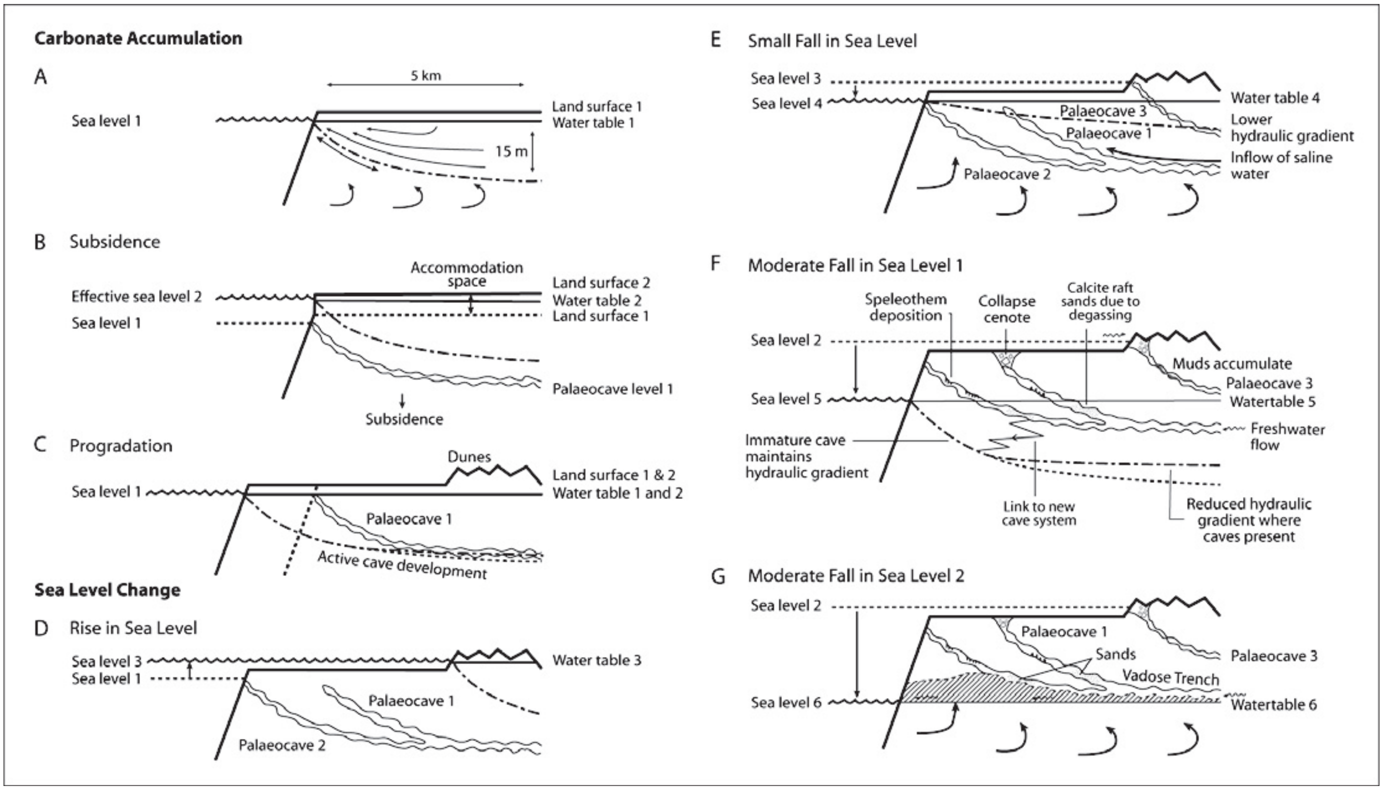

Figure 13. Response of Quintana Roo cave development to carbonate deposition and changes in sea level. Note that the cartoons have a large (~120×) vertical exaggeration, and for simplicity, the theoretical parabolic relationship between depth of mixing zone (shown as a sharp interface approximation) and distance from the coast for a porous media is used (but see Fig. 9). Chained line indicates locus of active carbonate dissolution in the mixing zone. (A) Groundwater flow and active cave development by mixing-zone dissolution. (B) Subsidence with constant sea level generates accommodation space, and carbonate sediment accumulates on the platform top. Earlier caves are abandoned (paleocave 1) as cave development occurs in a new shallower mixing zone. (C) Progradation of carbonate sediments with a constant sea level causes seaward extension of the cave system from A into the newly deposited carbonates, but within the platform, interior cave development continues in the existing caves. (D). A small rise in sea level may have a dramatic impact on position of the coast in the low-relief carbonates, shifting the locus of cave development. (E) A subsequent small fall in sea level exposes a large area of carbonates. Previous caves substantially increase the transmissivity of the platform, which results in a much lower gradient for the mixing zone. Consequently, the zone of active carbonate dissolution crosscuts earlier cavernous zones, only some of which are reactivated. (F) Further fall in sea level causes vadose conditions in the earlier caves with speleothem deposition, collapse, and accumulation of calcite raft sands and surface-derived sediments. A new, deeper level of cave development is initiated, and may link to existing passages, which continue to discharge fresh water from inland. (G) A similar moderate sea-level fall occurs, but input of saline water is sufficient to make the freshwater flow aggressive, developing a canyon passage, the gradient of which determines both the water table and mixing-zone position. Note: for B and C, cartoon A is the prior stage, but for D to G cartoon C is the prior stage.

the most recent of which dates from marine isotope stage 5e. The outlets of the cave systems that transect this unit must have developed either during the present highstand, or very soon after carbonate deposition. This limited time for development may explain why the coastal outlet caves are relatively restricted in size and in some cases lack speleothem deposits. Conversely, caves at depth and in the interior have had a longer and more complex history, as indicated by the extensive nature and large size of many of the passages. Thus, individual cave systems may be highly diachronous. There also appears to be a substantial contrast in fracture frequency between the limestones presently on the coast, within which fracture-guided rectilinear systems develop, and the anastomosing systems predominant in the interior. This may reflect a recent phase of neotectonic activity, perhaps due to movement on the offshore faults. Alternatively, reorientation of the systems may have occurred with time from an initial hydraulically indirect fracture-guided maze to efficient downgradient trunk conduits.

Continuing deposition of host carbonates also affects the position of the mixing zone. Accommodation for newly deposited sediments is generated by subsidence and also dissolution during subaerial exposure. Thus, accommodation may be generated some distance into the interior, e.g., younger limestones can be seen to unconformably overly karstified limestones in the walls of the Mayan Blue Cenote (5.6 km inland). Subsidence (but not surface dissolution) will cause a relative lowering of the limestones hosting the caves. However, rates of subsidence are quite low (typically <1 cm/k.y.) and are comparable to probable rates of wall-rock dissolution. Therefore, subsidence would result in progressive vertical enlargement of the passage by mixing-zone dissolution at the passage roof, rather than formation of a new cave level (Fig. 13B). This could lead to development of passages that have canyon morphologies and are genetically comparable to paragenetic canyons in continental karst. Precisely this process can be seen at present in the River Run, S. Ponderosa, where the visible halocline is coincident with low points in the passage roof that control discharge of fresh water.

Carbonate sedimentation may also result in progradation of the platform edge, which will result in a deepening of the position of the interface for a given highstand elevation. Because of the decreasing gradient of the fresh water/saline interface curve with distance inland, increases in the depth of the mixing zone will be significant for sites near the coast, but more minor for those inland (Fig. 13C).

Changes in Highstand Sea Level

Because of the low surface gradient of the marine carbonate deposits, the effects of carbonate sedimentation in controlling the position of the mixing zone will be small compared with the effects of differing highstand elevation (Fig. 13D). During the last interglacial, sea level was sufficiently high (~6 m above present sea level) that some of the previous littoral marine deposits were inundated, and the coast was probably several kilometers inland, where higher aeolian ridges are present. Such displacement of the coastline will change the local gradient of the mixing zone and, therefore, the zone of cave development. In addition, flank-margin type cave systems can develop in such ridges isolated from the inland meteoric catchment (Kelley et al., 2006). Subsequently, these may become incorporated as elements into the coastal-margin cave systems.

Reactivation of older shallow passages will also occur when sea level rises to a new highstand. Thus, the different levels of cave development, seen for instance at Mayan Blue, S. Naranjal, may be associated with different highstands. However, even during the last interglacial highstand, quite complex small-scale changes in sea level occurred (Chen et al., 1991), which would have resulted in multiple or dispersed overprinting by dissolution at a sharp halocline. A more realistic model of past sea levels is that over much of the last glacial and the later part of the last interglacial, it has varied continuously between some 20 and 120 m below present sea level, with stillstands a minor feature (Siddall et al., 2003). Thus, continued shifts in the depth of dissolution would be the norm, rather than the formation of a series of distinctive horizons tied to particular sea-level stillstands. This may explain the remarkably pervasive evidence for dissolution sculpting on submerged bedrock walls and ceilings in the caves.

Hydrodynamically, it is also clear that the position of the mixing zone is modified by the distribution of pre-existing transmissive conduits. In many carbonate islands, the thickness of the freshwater lens is limited by the presence of more transmissive limestones at depth (Vacher and Wallis, 1992). The effects of cavernous porosity can be seen at a local scale in passages such as River Run in the Ponderosa system. Similarly, the position of the mixing zone may be affected by head differences generated by constrictions in the conduit network. For instance, in Nohoch Nah Chich, coastward flow is limited by constrictions below the Natural Bridge Entrance, and is forced through a restricted passage (Hell's Gate), where it attains such high velocities that divers can only pass this link in a downstream direction. Overall, a complex relationship is expected between the elevation of any highstand and the position of the mixing zone. Continued reoccupation, and thus dissolutional overprinting, may occur in a particular passage despite varying sea-stand elevation, and the depth of the zone of active formation will tend to decrease with time (Fig. 13E).

Low Sea-Level Stands

The extensive subaerial speleothem, which is a spectacular feature of many of the inland underwater caves, is a clear indication of the effect of changes in sea level on cave development. During lowstand conditions, the presently accessible caves would be air-filled, and degassing of vadose percolation waters would result in speleothem deposition (Fig. 13F). Previous highstand sediments would also be entrained and transported to deeper levels in the vadose zone by mechanical processes and by percolation water running in the pre-existing cave void. In contrast to extensive evidence of these porosity occlusion processes, there is little direct evidence for vadose cave enlargement during lowstands. In S. Esqueleto, subaerial karren forms are incised into a bench on the wall of Madonna Passage at a depth of 14 m, some 17 m below the surface. Some caves must also have hosted free-air surface streams, as indicated by the clear vadose trench in the lower levels of S. Tortuga described previously. These may have resulted either from concentrated recharge via open cenotes and other surface openings into existing open passages, or vadose entrenchment of the main regional cave streams during times of lowered sea level (Fig. 13G). The former are indicated by misfit canyons, such as that which traverses the Desconocido Dome passage, S. Naranjal, although these are surprisingly infrequent. There is more evidence for incision by the main cave streams in the form of large canyon-shaped passages and meandering undercuts. Vadose scallops have not, however, been observed, either because of overprinting during subsequent reflooding or because flow velocities were too low.

While glacio-eustatic sea-level fall resulted in a cessation of cave development and accumulation of fill in the higher cave levels that are readily accessible to divers, cave development must have continued at depth. Because of technical limitations to diving at depth and a general paucity of access into the deeper levels, we know much less about the nature of these systems. Those that have been entered appear to be extensive and very large, with massive breakdown chambers over 30 m high interconnected by smaller restricted passages. Speleothem is absent. Saline water continues to circulate in these voids under the present highstand conditions, but rates of dissolution are very low. More rapid dissolution will occur during lowstands, when the mixing zone reoccupies these levels, and may result in foundering of cavern roofs. At The Pit in S. Dos Ojos, such a collapse has allowed access to these lower systems, but elsewhere, as in the Blue Abyss (Nohoch Nah Chich), the breakdown has closed such routes. Access may also be precluded in the shallow caves, because they have been sealed by sedimentation.

Collapse

Probably the most characteristic feature of Quintana Roo caves is the almost universal mechanical failure of the passage roofs. Roof domes and associated block breakdown piles are common throughout the caves, the latter reaching heights >20 m and forming major barriers to diving access. Even in passages that appear to retain original dissolution features on the walls, some breakdown is commonly present on the floor, and ceiling steps attest to local loss of roof strata. Only the smallest passages do not exhibit this block breakdown process, although there are remnants of fretted wall and roof rock on the passage floor that attest to smaller-scale mechanical failure. Extensive roof failure has also been reported for other caves in Pleistocene and Tertiary limestones (Palmer, 1984; White, 1994; Webb, 2002). The high frequency of mechanical failure is due primarily to the low strength of the young limestones, which lack the more extensive cementation found in older Mesozoic and Paleozoic limestones that host continental karst caves. On Barbados, Burton et al. (2001) demonstrated a linear dependence of compressive strength of corals and coral-derived carbonate sediments on dry density, where the latter reflected the extent of secondary cementation (increasing density) and dissolution (decreasing density).

Roof failure is augmented by the very significant loss of buoyant support, which occurs during lowstands. According to the Archimedes principle, the upward buoyant force is proportional to the ratio of the density of the water to the density of the rock. Thus, for calcitic carbonates, some 38.5% of the ceiling support is lost when the cave becomes air-filled. The effect is slightly larger when seawater is considered (39.4%), but somewhat less for aragonitic carbonates, which have a higher mineral density (35.7% for fresh water and 36.6% for sea water). Thus, extensive modification of the cave voids by collapse would be expected to occur as sea level falls.

However, dissolutional weakening of the limestone is most rapid when the caves are flooded, and active collapse is graphically demonstrated by wardrobe-sized blocks that have fallen on diving lines inserted only a few years ago. In weak limestones, roof failure occurs by tensile fracture nucleation and propagation in the roof. Therefore, collapse is an inevitable consequence of the excessive tensile stresses set up by the increased roof span caused by lateral passage enlargement within the mixing zone. The generation of a roof dome and associated breakdown pile forces water flow to be diverted over and around the collapse. In the center of the dome, the breakdown pile may be high enough to decouple the freshwater flow from the underlying saline water. As a consequence, dissolution is focused around the margins of the collapse where geochemical gradients are still present. This leads to progressive subsidence of the breakdown pile and widening of the passage, further roof failure, and inexorable enlargement of the area of collapse. These active dissolution and collapse processes are well demonstrated in Balam Can Chee (Nohoch Nah Chich), discussed previously (Figs. 8 and 10). Although in places failure of bedding-defined beams may occur as in continental caves (White and White, 2000), this is relatively uncommon, because well-developed bedding planes are infrequent since the limestones have not been subject to burial and unloading processes. Failure therefore often occurs along lines of weakness defined at the grain-to-grain scale, and the roof shape closely approximates the stress field, forming a dome with a progressive reduction in gradient toward the center of the span. This form is characteristic of many passages where collapse has occurred (Fig. 7E). Where passage widening leads to a break-out dome reaching the surface, a water-filled cenote often results. The size of the surface opening may be limited by the increased strength of the surficial limestones due to evaporative precipitation of cements (case hardening). This is demonstrated in numerous shallow quarries, where this mechanically resistant layer must be removed to enable access to the softer, more easily crushed limestones below. A similar depth dependence of cave roof stability was reported by White (1994) for caves in Pleistocene dune limestones.

Once collapse extends to the surface, enhanced sedimentation of the underlying breakdown pile and cave passages can occur. Two processes are important: precipitation of calcite rafts following degassing of fresh water exposed in cenotes, and ingress of organic matter and soil by surface runoff. Oxidation of organic matter in these sediments may increase the dissolution by generation of additional carbonic acid. Together with continued dissolution of breakdown in the mixing zone, this may result in dissolution of the breakdown pile, as at Cenote Uchil Ha (S. Ponderosa), where low cliffs ring a central depression with an underwater passage leading off on one side. Where the water table is high, lakes or marshy areas may form in these subsided areas, as can be seen northeast of Cenote Tortuga. Collapse and subsequent sedimentation result in blockage of trunk conduits, and the reduced cross-sectional area for flow results in increased head differences. This can result in higher flow velocity and entrainment of sediment infill (Fig. 11). It also causes development of diversion passages, a feature of the area around many cenotes (e.g., Fig. 4). This process may also be augmented by fracturing of the limestone adjacent to the collapse. The high frequency of passage collapses and cenotes, and the development of diversion routes, may be key to development of the anastomosing cave pattern typical of the area. Certainly, the sharp contrasts in cave patterns that typify some systems are most readily explained by blockage of large but unstable pre-existing routes and the development of small and immature systems to discharge water toward the coast.

A MODEL FOR DEVELOPMENT OF QUINTANA ROO CAVES

We believe that the Quintana Roo caves represent an important new cave type intermediate between flank-margin and epigene continental systems. In the interior, they may display elements of a dendritic tributary pattern, typical of epigene continental caves. Downstream this passes into an extended zone characterized by a cross-linked anastomosing passage pattern, with local areas of spongework and ramiform passage patterns. Anastomosing patterns are relatively rare in continental cave systems, especially when they are the predominant type over much of the system. Large isolated mixing chambers characteristic of flank-margin–type caves are absent, rather large chambers occur as an element in the anastomosing zone and are generally associated with collapse. Rectilinear maze patterns are generally absent from the interior caves, but do appear to be characteristic of some of the coastal caves where fractures have developed parallel to the bank margin.

The Quintana Roo caves have many features more diagnostic of hypogene than epigene caves. Specifically, these include the lack of relationship to surface topography, a nondendritic pattern, abrupt variation in passage size, abrupt passage terminations, lack of fluvial sediments, lack of scallops, and evidence of bacterial activity (Auler and Smart, 2003). They do not, however, display the specific mineralogical artifacts of hypogene development, such as extensive gypsum deposits, acidophilic clay minerals and uranium-rich minerals, indicating that deep-seated hypogenic fluids are not primarily responsible for their development. This similarity arises because both hypogene and coastal mixing-zone epigene caves are formed primarily by dissolution at or very close to the point of generation of aggressiveness (Palmer, 1991).

In Quintana Roo, dissolution is driven by mixing of fresh water and saline water, but this occurs over a much wider zone (8–12 km) than has been reported previously for flank-margin–type coastal mixing-zone caves (~100 m; Mylroie and Carew, 2000). The inland limit of the cavernous zone can be determined by the specific discharge (discharge per unit area of aquifer), which controls the rate of mixing of saline water and fresh water. The specific discharge is much greater at the coast, where the freshwater lens is thinnest and the total contributing area is greatest, than in the interior, where the rate of mixing-driven dissolution may be below the critical limit for cave formation. Support is provided for this suggestion by the coupled geochemical and hydrological modeling study of Sanford and Konikow (1989), which demonstrated that rates of dissolution are directly proportional to specific discharge. More recently, Kaufmann (2003) demonstrated that matrix permeability critically determines the time scale for conduit development via the supply of reactants to the evolving conduit, although the simulations were of continental epigene systems rather than coastal mixing caves.

Therefore, there may be a continuum between classic flank-margin caves that develop on small islands, where the internal catchment area and thus coastal freshwater discharge are small, and Quintana Roo–type caves that develop on the continental margin of attached carbonate platforms. In the former, the limited discharge of fresh water results in critical rates of mixing-driven dissolution occurring only adjacent to the coast, and dissolution potential is consumed over a short distance due to the low groundwater velocity resulting in a large chamber. By contrast, in Quintana Roo, the greater discharges associated with a large interior catchment cause higher velocities, enhancing mixing inland from the coast, distributing the dissolution potential along the flow path toward the coast, and generating much longer cave passages. Unfortunately, there are relatively few extant large carbonate islands or attached platforms with which to test this hypothesis. On Grand Bahama Island, Lucayan Caverns exhibits a similar general pattern to the Quintana Roo caves, with an anastomosing system extending ~1 km inland, as predicted from the much smaller catchment area of the ~10-km-wide island. Underwater caves beneath the very extensive (300 km) Tertiary limestones of the arid Nullarbor Plain, Australia (Webb, 2002), extend inland some 60 km from the coast. These may be largely inherited from a previously much wetter climate, however.

In practice, such a static model seems unlikely. Rather than the cavernous zone being fixed for a given freshwater discharge, it is more probable that it extends progressively inland with time, such that mixing is enhanced in the open cave passage compared to the diffuse flow zone, which delivers fresh water and saline water to the head of the conduit. The extent of the coastal cavernous zone is, therefore, probably both a function of the net freshwater discharge at the coast (the product of catchment area and effective recharge) and the total time over which it has developed. Thus, while many (small) flank-margin caves have only developed over a single and relatively short highstand, evidence suggests that the extensive Quintana Roo caves developed over a much longer time frame. Indeed, in the case of the Nullarbor systems, this could be as long as 14 million years (Webb, 2002).

Alternative explanations for the inland extent of cavernous development on the Caribbean coast have also been considered. One possibility is that, because of the very low relief, surface lowering may reduce the unsaturated zone to such an extent that the conduits become unroofed in the interior. However, available topographic information does not support such a contention—upstream passage terminations in Dos Ojos and Nohoch Nah Chich terminate in breakdown, despite a reasonable depth of overlying limestone (Fig. 2). Thomas (2002) suggested that the caves formed initially as a link between an interior lagoon and the coast, and drew parallels with similar systems in Cuba and Isle de Lifou, New Caledonia. While a present-day topographic low has developed in the interior along the Holbox fracture zone, there is no evidence to support a depositional rather than erosional origin. Furthermore, the geochemical processes responsible for such focused dissolution coastward of such a lagoon are not entirely clear. Unlike groundwater, lagoon water is typically highly supersaturated due to degassing of fresh water, which discharges into the lagoon, and to subsequent evaporation. Geochemical modeling suggests that mixing of such waters with seawater would be unlikely to generate calcite undersaturation. Some other explanation is needed for the required undersaturation to make this suggestion tenable.

In continental caves, joint-bedding plane interceptions form particularly favorable locations for development of cave passages and give a structurally determined cave pattern. The anastomosing pattern typical of Quintana Roo caves, therefore, may partly result from the lack of structural control of cave passages away from the coast. However, a more probable explanation is that, because of the high permeability and consequent low hydraulic gradients, the head differentials critical in driving the linking of individual joint- or bedding-guided protocaves to form a dendritic tributary system are inoperative. Thus, in Quintana Roo, separate subparallel passages, which have developed in response to the coastward hydraulic gradient, intersect due to random encounters rather than local redirection of the hydraulic gradient. However, the high susceptibility of the weak limestones to failure results in extensive collapse, which may both subdivide an existing large passage, and more importantly result in development of diversion conduits, as described by Palmer (1991) in continental caves.

Overall, the Quintana Roo cave pattern bears a remarkable similarity to cave networks simulated by Kaufmann and Braun (2000) for porous limestones with a random network of fractures, although there is several orders of magnitude difference in the diameter of the conduits formed. The simulated conduits develop progressively from the outlet to the interior, perpendicular to the pre-existing hydraulic gradient, and the degree of cross linking is determined by the initial fracture density. Of particular note is the importance of porous matrix flow (which occurs in the Quintana Roo study area) in developing the structured downgradient conduit network, rather than the maze-like cave patterns that occur in simulations with a nonporous matrix (Kaufmann and Braun, 1999). There are, however, significant differences between Quintana Roo and the conditions specified in the simulations. The simulations employ a random fracture field, whereas in Quintana Roo, fractures are largely limited to the coastal zone and have a structured permeability field. However, across most of the study area, the preferred cave inception flow pathways are probably associated with linked vug porosity and developed by random linkages between dissolution-susceptible fragments and existing voids. Thus, the random fracture specification in the model may well reproduce the pattern of secondary openings in Quintana Roo, if not the magnitude of the enhanced permeability. Nevertheless, there are more substantive differences in the dissolution processes in the simulations and those in Quintana Roo. Dissolution in the Kaufmann and Braun (1999) simulations is driven by progressive consumption of surface-derived dissolution potential under closed-system conditions. Thus, the shortest dissolution pathways (those nearest the coast) have much higher dissolution rates than those in the interior. This gives rise to the initiation of conduit systems in the coastal zone. In contrast, in Quintana Roo dissolution is driven by mixing of fresh water and saline water, which is greater in coastal areas than inland due to the greater net discharge of both fresh and salt water. As a result, the geometrically similar cave patterns arise by rather different dissolution processes.

Of specific interest is the case simulated for a permeable fracture parallel to the linear outlet from the limestones (Kaufmann and Braun, 2000, their Figure 12). Despite the no-flow lateral boundaries specified, there was rapid development of an outlet-parallel conduit system along the fracture prior to the development inland of the down–hydraulic gradient cave systems. In Quintana Roo, this simulation may be in accord with preferred cave development along the Holbox fracture zone to the north coast, with subsequent capture into the east-coast caves as headward development occurs. In the simulation, only one route was linked to the fault-guided conduit, and this enlarged more rapidly than all others. In Quintana Roo, there seems to be no evidence for such preferred drainage; rather many caves have extended headward toward the Holbox fracture zone, each capturing a comparable volume of discharge from it and consequently having broadly comparable dimensions. By inference from the model study, the earlier development, and thus larger size of the Holbox conduits compared to the outlet systems would cause early extensive collapse and unroofing. This would explain the development of the solution corridor features marking this zone.

The Quintana Roo caves are also very different from most continental caves, because they do not evolve along a simple linear pathway through time. Continental caves accord well with a general Davisian model, where the passage of time is the major control on cave development, and it acts essentially through the progressive reduction of base level and surface relief. Thus, cave passages evolve from protocaves to phreatic and then vadose caves, before they are abandoned by their formative streams, infilled by sediment and collapse, and finally destroyed by surface lowering. While temporary reversals in this sequence may occur, most notably by aggradation of surface rivers, such events are only minor hiccups in the otherwise linear progression.

In the Quintana Roo caves, repeated phases of active cave development associated with interglacial highstands are the norm. These are separated by phases of vadose conditions during the intervening glacial periods, with corresponding collapse, speleothem deposition, and in some cases, development of vadose canyons. Because of the slow rate of subsidence, these separate phases of development are largely superimposed. However, quite minor differences between boundary conditions (e.g., position of the coastline) at each highstand may cause subtle differences in the depth to the mixing zone and thus the locus of active dissolution. More importantly, because of the very large glacio-eustatic sea-level fluctuations that characterize the Pleistocene, more than 130–140 m of subsidence is required before individual passages are below the lowstand mixing zone. Thus, the time span available for cave development is extended, and in all probability, it exceeds the lifetime of any individual cave passage due to collapse. The pattern of cave development and morphology of cave passages is controlled by this complex superimposition of different phases of activity. The vadose deposits, and in particular the speleothem that accumulate between phases, may enable some separation of these many individual phases of development.

For the Quintana Roo caves, there appear to be two critical bifurcations in the path of cave development. These are demonstrated by the remarkable contrast in the nature of many of the inland caves, which are above the present mixing zone, and the more coastward passages, which are coincident with the present mixing zone. These bifurcations are dependent on the continued inflow of first saline and second fresh water to an individual passage (Fig. 14). When there is a fall in sea level, collapse due to reduction of buoyant support, sedimentation, and speleothem accumulation may all occur, occluding the passage void. When the passage refloods, if there is still a link to the underlying network of openings that supply saline water, then mixing-driven dissolution can occur, and the predominantly carbonate fill will either be removed or a new bypass passage will form. Passage enlargement therefore continues, and there is widespread evidence of corrosion of passage walls and more obviously speleothem. Many downstream passages in the study area are of this type.

In the case of Balam Can Chee (Nohoch Nah Chich), saline water is input to the system from the deep conduit segment the Megamohole and results in extensive dissolution in the passages downstream of this within the modern mixing zone (Fig. 10B). However, where such inputs are sealed by lowstand sedimentation, or the position of the mixing zone is significantly below the level of the passage floor, influx of saline water can no longer occur, and consequently the dissolution rate is greatly reduced. Should parts of the passage be air-filled, or collapse cenotes open to the surface, degassing of the circulating fresh water will occur, and the passage may become further infilled by calcite raft sands. In Heaven's Gate (Nohoch Nah Chich), there are extensive and thick floor sediments that choke openings down to lower levels. Saline water is present upstream in the 72-m-deep Blue Abyss, but the mixing zone is some 5 m below the passage floor (at a depth of ~11 m, Fig. 10B). Thus, in contrast to the very fretted passages downstream in Balam Can Chee, speleothem is pristine in Heaven's Gate, and there is only limited and localized corrosion associated with the organic-rich floor sediments.

However, Heaven's Gate has a very significant discharge of fresh water supplied by upstream tributary passages.

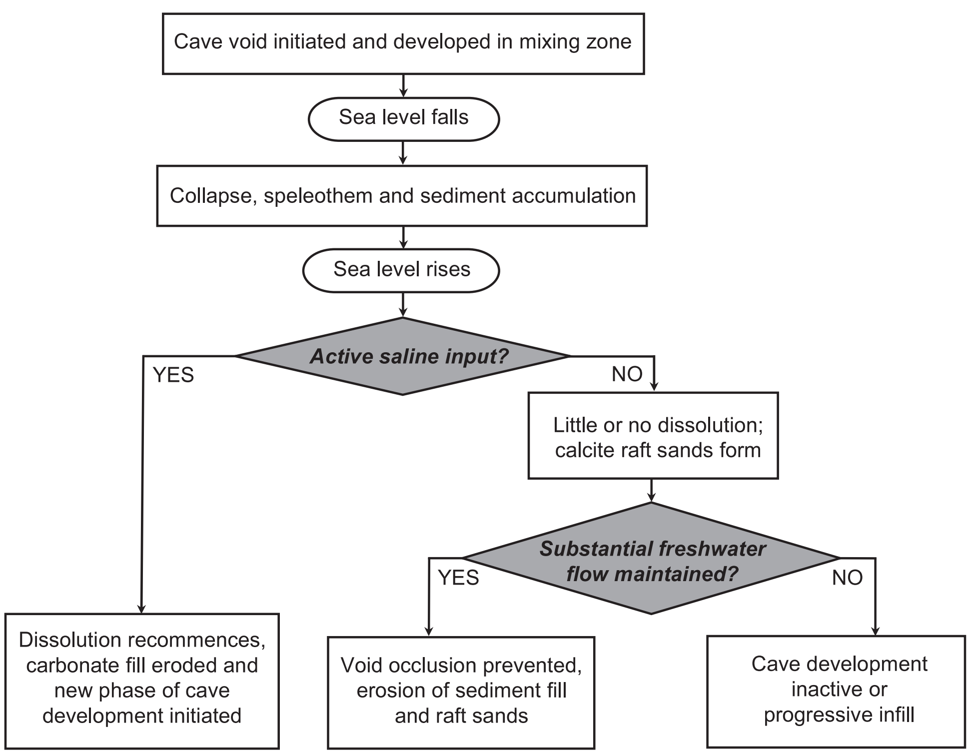

Figure 14. Critical bifurcations in the evolution of a Quintana Roo cave passage segment following a rise in sea level.

Although this water is saturated and incapable of significant carbonate dissolution, it can physically entrain sediments, and there is extensive evidence for erosion and transport of sediments in the passage at present. Indeed, during the early stages of flooding, enhanced erosion of the sediment infill may have occurred by vadose (high-velocity) flows, as is evidenced by extensive collapse of massive speleothem deposits. The passage size is thus maintained, although dissolution is largely inactive.

By contrast, where collapse has severed the link to a passage from the tributaries, or the passage is in the upstream parts of the tributary system, mechanical erosion of the floor sediments by freshwater flows will not occur. Thus, the passage void is neither actively enlarged by dissolution, nor is it maintained by mechanical erosion. It's total occlusion is therefore inevitable (Fig. 14).

CONCLUSIONS

1. Very extensive (133 km maximum length) cave systems have been explored by cave divers in Quintana Roo on the east coast of the Yucatan Peninsula, Mexico. Cross-linked anastomosing systems run inland from the coast for maximum distances of 8 to 12 km. The anastomosing passage patterns differ both from those of other eogenic caves, which are composed of mixing chambers with short blind passages, and telogenetic continental caves, which are predominantly dendritic and rectilinear maze systems.

2. The predominant passage types in Quintana Roo caves are horizontal elliptical tubes, which are often associated with the position of the present halocline, and canyon-shaped passages, which have morphologies similar to vadose canyons found in continental caves, although evidence of a vadose origin is inconclusive. All passages are extensively modified by collapse, but many retain a dissolutional wall morphology.

3. Many of the Quintana Roo caves are associated with the position of the present mixing zone, and are actively enlarging as a result of undersaturation resulting from the mixing of fresh and saline water. However, many caves in the interior are above the present mixing zone and are characterized by breakdown and infill with surface-derived clays, speleothem deposits, and calcite raft sands. Finally, a few systems penetrate to depths well below the present mixing zone, and attest to an extensive network of deeper cavernous openings, which are as yet mostly unknown.

4. Cave sediment fill, speleothem, and ceiling-level data indicate multiple phases of cave development. These multiple phases are associated with glacio-eustatic changes in sea level, which alternate individual passages between active phreatic enlargement and vadose incision and sedimentation. Caves in the interior have more phases of development than those closer to the coast because of continued coastal accretion of the host carbonates during sea-level highstands.

5. In Quintana Roo caves, collapse of the cave roofs is extensive and ubiquitous, resulting in widespread breakdown and the development of crown-collapse surface cenotes. Collapse is a result of the large roof spans caused by lateral expansion of passages at the level of the mixing zone, the low strength of the poorly cemented Pleistocene limestones, and the withdrawal of buoyant support at sea-level lowstands.

6. Two critical conditions control the development of multiphase Quintana Roo caves following glacio-eustatic variations in sea level. Where passages segments remain connected to the underlying deep cave systems and are occupied by the present mixing zone, substantial inflow of saline water maintains the rate of mixing-driven carbonate dissolution, and the predominantly carbonate lowstand fill may be removed, and active passage enlargement continues. Where such links are absent, rates of dissolution are low, and passage enlargement will cease. However, if the flow of fresh water through the passage is maintained by tributaries, the velocities may be sufficient to prevent accumulation of further sediments or even to flush uncemented sediments from the passage, and the cave void will remain open. If such freshwater flows are limited or absent due to blockage of the feeders, the passage segment will gradually become occluded by infill and roof collapse.

7. There may be a continuum between flank-margin and Quintana Roo–type caves, which is determined by the magnitude of the specific discharge at the coast. Where, as in the Yucatan, there is a substantial inland catchment, the high specific discharge generates high rates of mixing dissolution. Dissolution is distributed along the downstream flow path by the high groundwater velocities in the evolving conduit system, generating extensive anastomosing cave systems. By contrast, in small islands or under arid conditions, rates of dissolution are much lower and are exhausted largely in the vicinity of initial mixing, generating coast-margin chambers. It is also likely that headward extension of the cavernous zone will occur with time in response to the greater rates of mixing occurring in the conduit system than the diffuse-flow feeder zone.

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