

The Sac Actun System, Quintana Roo, Mexico

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ABSTRACT

The Sac Actun system, located in northeast Quintana Roo, Mexico, is among the most extensive underwater cave systems located along the Caribbean coast of the Yucatan Peninsula. The cave is composed of linear phreatic conduits that have two forms. The coastal sections of the Sac Actun system are characterized by low horizontal tunnels that form mazes paralleling the coast and rudimentary conduits broken by fracture-controlled rooms. Inland passages are fault/fracture controlled, have a linear, anastomotic configuration, and align perpendicular to the coast. Access to the cave system is gained through cenotes which are the portals into the Yucatan underwater cave systems. The occurrence of drowned speleothems in many parts of the cave system, and sections of air-filled upper level passages are indicative of major fluctuations in sea level. The Sac Actun system is part of one of the most extensive and significant eogenetic karst aquifers in the world. The development of the Sac Actun system, as well as the many other caves systems along the Yucatan Caribbean Coast is controlled by the coastal hydrologic regime, driven by glacio-eustatics, and influenced by stratigraphic and structural controls. The karstic permeability of the aquifer makes it and the Sac Actun system vulnerable to the anthropogenic impacts of increased population growth, quarries, and infrastructure development associated with the burgeoning tourist industry that dominates land use in the region.

Keywords: anchialine cave, caleta, cenote, eogenetic karst, mixing-zone corrosion

Sistema Sac Actun, Quintana Roo, México

RESUMEN

El sistema Sac Actun, situado en el noreste de Quintana Roo, México, es uno de los más extensos sistemas de cuevas submarinas ubicadas a lo largo de la costa caribeña de la Península de Yucatán. La cueva se compone de conductos freáticos lineales que tienen dos formas. Las secciones costeras del Sistema Sac Actun se caracterizan por túneles bajos horizontales que forman laberintos paralelos a la costa y conductos rudimentarios rotos por salas controladas por la fracturación. Los pasajes tierra adentro están controlados por fallas/fracturas y tienen una configuración lineal y anastomosada y se alinean perpendiculares a la costa. El acceso al sistema de cuevas se hace a través de cenotes que son los portales hacia el sistema de cuevas subacuáticas de Yucatán. La presencia de espeleotemas sumergidos en muchas partes del sistema de cuevas, y las secciones de pasajes del nivel superior llenos de aire son indicativos de grandes fluctuaciones en el nivel del mar. El sistema de Sac Actun es parte de uno de los más extensos e importantes acuíferos kársticos eogenéticos en el mundo. El desarrollo del Sistema Sac Actun, así como los muchos otros sistemas de cuevas a lo largo de la costa caribeña de Yucatán está controlado por el régimen hidrológico costero, controlado por procesos glacio-eustáticos, e influenciado por los controles estratigráficos y estructurales. La permeabilidad kárstica del acuífero hace del Sistema Sac Actun un medio vulnerable a los impactos antropogénicos por mayor crecimiento de la población, canteras, y el desarrollo de infraestructura asociados con la industria de un turismo floreciente que domina el uso del suelo en la región.

Palabras clave: caleta, cueva, cueva anchialina, cenote, karst eogenético, corrosión, zona de mezcla.

VERSIÓN ABREVIADA EN CASTELLANO

Introducción

El Sistema de Sac Actun es un extenso sistema de cuevas anquihalinas situado en el municipio de Tulum en la costa del Caribe, Quintana Roo en la península de Yucatán, México (Figura 1). Las secciones submarinas (312.6 km) del sistema de cuevas y los pasajes de la zona vadosa (5.8 km) tienen actualmente una longitud total de 318.5 km y una extensión vertical de 127 metros (diciembre de 2013, QRSS). El Sistema de Sac Actun se divide geográficamente en distintas secciones que incluyen la región de Sac Actun, la región de Nohoch Nah Chich, la región de Aktun Hu y la región de Dos Ojos (Figure 2).

Exploración del sistema de Sac Actun

La exploración sistemática submarina de cuevas costeras de Quintana Roo comenzó alrededor de la zona de Tulum a mediados de los años ochenta. Diferentes equipos de buzos comenzaron a explorar y cartografiar los numerosos cenotes en la región y encontraron en la cueva extensos pasajes asociados entre ellos. Conforme continuaban las exploraciones independientes, la longitud de cada sistema de cuevas creció a medida que los exploradores unían diversas cuevas. Las cuatro regiones del Sistema Sac Actun fueron exploradas como secciones separadas y eventualmente conectadas para formar la red actual.

Hidrogeología

El Sistema Sac Actun es parte de uno de los más extensos e importante acuíferos kársticos eogenéticos, y estratificados por densidad, del mundo. La capa superior de aguas subterráneas en el acuífero es una lente delgada de agua dulce que se recarga por agua de lluvia y fluye hacia la costa. La capa más baja se compone de agua salada y se origina por la entrada de agua de mar desde la costa. Intercalada entre el agua dulce y el agua salada se ubica la haloclina que es una capa salobre que se ha formado como resultado de la mezcla y arrastre por flujo de agua dulce por encima de la interfaz de la haloclina (Beddows, 2004b). La haloclina está disociada de la capa salina que está por debajo y sirve como una zona de mezcla dinámica. La profundidad de la haloclina aumenta con la distancia de la costa. Las bahías costeras, llamadas calas, son entradas estrechas que se extienden hacia el interior varios cientos de metros y se asocian con grandes aberturas costeras (Back et al., 1979). Asociado a las calas están las playas en forma de media luna que aparecen cuando la abertura de la cala se ensancha por la acción litoral y eventualmente es erosionada para formar la estructura de la playa (Back et al., 1979).

Distribución de la cueva y morfología

La morfología general del Sistema Sac Actun tiene dos formas distintas que son característicos de todos los extensos sistemas de cuevas a lo largo de la costa caribeña de Quintana Roo. Las secciones más cercanas a la costa muestran una alta densidad de laberintos rectilíneos paralelos a la costa, con una tendencia noreste-suroeste. Los laberintos están asociados con los conductos que transportan agua dulce a la costa (Coke, 2009). Las secciones de la cueva situada a más de un kilómetro desde la costa presentan una forma controlada por fallas. Estas secciones de la cueva son anastomosadas y perpendiculares a la costa en una dirección noroeste-sureste. Los pasajes de la cueva tienen forma elíptica, son más estables que muchos de los segmentos de pasajes costeros y vadosos, y los espeleotemas son comunes.

Desarrollo vertical del Sistema de Sac Actun

La profundidad del sistema de Sac Actun, que se mide con respecto a la superficie, oscila de menos de 2 metros a 20 metros; la profundidad en la región de Nohoch Nah Chich abarcan desde 2-6 m, 8-15 m y 16-20 m; en la región de Actun Hu de 5-10 m; y la región de Dos Ojos de 5-10 m y de 14-20 m. Sin embargo, existen tres excepciones notables que no ocurren dentro de la región Nohoch Nah Chich, Aktun Hu y Dos Ojos del Sistema Sac Actun. El Blue Abyss (Figura 7) es un pozo submarino vertical con una profundidad de 71 metros y ha sido explorado un laberinto en la base del pozo. "The Pit" en Dos Ojos (Figura 8) es un pasaje descendente escarpado de suelos en descomposición que comienza en la entrada de un cenote y conduce a una serie de grandes cámaras con un suelo desglosado, alcanzando esa sección de la cueva 119 metros

de profundidad. El Hoyo Negro (Figura 9) es un pozo dentro de la región de Actun Hu con una profundidad de 60 metros. Se han encontrado importantes restos arqueológicos y paleontológicos en este área (Nava Blank, 2011) (Figura 10).

Factores de control en el desarrollo del sistema de Sac Actun

1. **Control hidrogeológico.** El Sistema Sac Actun se compone de conductos freáticos lineales que se formaron como resultado de la interacción de agua meteórica, roca y agua salina subterránea. La corrosión de la zona de mezcla es aceptada como el principal mecanismo para el desarrollo de los conductos en el acuífero del Caribe Yucatán (Beddows 2004a, Smart et al. 2006). Aunque para la génesis del Sistema Sac Actun, así como para muchos de los otros sistemas de cuevas submarinas extensas de la región, se cree que es predominante la corrosión por la mezcla de aguas (Beddows 2004b), las reacciones de microbios asociadas a procesos redox de sulfatos y reoxidación de sulfuro para producir ácido sulfúrico que también pueden provocar la disolución (Stoessel et al., 1993).

2. **Control sedimentario.** El sistema de Sac Actun está formado por sedimentos costeros que consisten en una secuencia marina y continental que se acumularon en el margen de plataforma, arrecife y "lagoon". Las unidades están separadas por discordancias, indicativos de la exposición y la erosión de la superficie de la plataforma cuando el nivel del mar descendió (Perry et al., 1995).

3. **Control estructural.** El sistema Sac Actun está situado en el distrito de Eastern Block-Fault de la península de Yucatán que se extiende desde la punta de la costa noreste, hasta la frontera de la península de Yucatán con Belice. Las dos principales fallas/lineamientos en Quintana Roo son la zona de lineamiento de Holbox y la zona de la falla del Río Hondo (Kambesis y Coke 2013). Las orientaciones direccionales del Sistema Sac Actun, así como otras cuevas a lo largo de la costa parecen estar controladas por estas estructuras regionales dominantes. Las características costeras incluyendo calas y playas en forma de media luna que parecen estar influenciadas por una fractura con dirección noroeste bien definida que controla su desarrollo interior, y un conjunto de orientaciones noreste paralelas a la costa que influye en la extensión lateral de estas características (Gondwe et al., 2010). Wedie (1978) basándose en los cambios en las orientaciones de fractura a lo largo de la costa, especuló sobre la existencia de un sistema conjugado. Esto puede explicar las tendencias paralelas y perpendiculares del desarrollo de la cueva y la alta densidad de pasajes de la cueva en el área de Tulum.

Desarrollo polifásico de la cueva

El marcado bajo gradiente hidráulico de la península de Yucatán significa que los niveles de agua en las cuevas de Quintana Roo son el nivel del mar (Mosley et al 2013). La ubicación actual de la haloclina y la distribución vertical de los pasajes de la cueva indican que el Sistema Sac Actun ha sufrido múltiples fases de desarrollo. Los espeleotemas aparecen en todas las secciones interiores de la cueva como balsas de calcita. Estas formas características se suelen formar en condiciones vadosas donde los pasajes de la cueva estarían llenos de aire, lo que permite la desgasificación del CO_2 tras infiltrarse las aguas y depositarse la calcita. Las balsas de calcita, que son comunes en todo el sistema de cuevas, especialmente cerca de los cenotes, precipitan en agua estancada que permite la desgasificación del CO_2 . Cuando el nivel del mar sube, estas características típicamente vadosas son inundadas. Prístinos espeleotemas son característicos de los pasajes interiores en la región de Sac Actun e indican al menos una fase de desarrollo. Sin embargo las áreas cerca de la costa muestran espeleotemas corroídos, un indicador de la inundación que pudo existir en los pasajes de la cueva; así se sucedieron múltiples fases de desarrollo de la cueva (Smart et al. 2006).

Impactos ambientales del desarrollo humano

El Sistema Sac Actun es parte de uno de los más extensos e importantes acuíferos kársticos en el mundo. La hidrodinámica del acuífero expone el sistema de cuevas a la extensa intrusión salina que restringe el espesor de la lente de agua dulce. La permeabilidad del acuífero kárstico lo hace vulnerable a los impactos antropogénicos de la agricultura, las minas y el desarrollo turístico (Kambesis y CoKe 2013). La protección del Sistema Sac Actun de los impactos del desarrollo humano requerirá la regulación integral de tratamiento de aguas residuales, la continuada investigación científica de los acuíferos y sus características afines, programas espacio-temporales de monitoreo hidrológico y elaboración de políticas regionales eficientes (Gotwein et al., 2011).

Introduction

The Sac Actun system is an extensive anchialine cave system located in the municipality of Tulum on the Caribbean coast of Quintana Roo on Mexico's Yucatan peninsula (Fig. 1). The name translated from the Maya language means White Cave. The vadose-zone passages (5.8 km) and underwater sections (312.6 km) of the cave system currently have a total surveyed length of 331 km and vertical extent of 127 metres (as of January 2016 QRSS 2016) making the *Sac Actun* system the longest cave in Mexico, and the second longest cave in the world. The *Sac Actun* system is geographically divided into distinct sections that include the Sac Actun region, Nohoch Nah Chich region, Aktun Hu region, and Dos Ojos region (Fig. 2).

The lateral extent of the Sac Actun system, from the extremes of its southwestern to northeastern reaches, spans more than 12 kilometres in a straight-line distance along the east coast of Quintana Roo from Tulum to just south of Xel Ha. The maximum inland extent of the cave system is 9.2 km to the coast from the Aktun Hu region. The currently-known entirety of the Sac Actun system underlies a land surface of 96 km², though the full extent of the area that it actually drains is currently unknown. Three of the deepest sections of the underwater cave in the area occur between the Aktun Hu, Nohoch Nah Chich and Dos Ojos regions of the cave.

From the coast inland, the cave extends under dense coastal mangrove that transitions to scrub jungle (Coke 2009). Numerous collapse cenotes serve

as portals to the cave system and 170 cenotes have been documented so far. Collapse cenotes are extremely common in Quintana Roo and are formed by mechanical failure of the ceilings of shallow phreatic cave systems when buoyant support is lost as a result of a drop in sea level (Beddows *et al.*, 2007). The cave system is drained by coastal springs that resurge into the Caribbean Sea.

Though there appears to be a zone of no cave development between the inland areas of the Sac Actun and Nohoch Nah Chich regions (Fig. 2), this is just an artifact of the map which shows only the passages of the *Sac Actun* system. Other cave systems are currently being explored within this region (and are not shown on the map), and have the potential to connect to the main system.

Exploration of the *Sac Actun* system

Systematic underwater exploration of caves in coastal Quintana Roo began around the Tulum area in the mid 1980s. Different teams of cave divers began exploring and mapping the many cenotes in the region and found extensive cave passages associated with them. As independent explorations continued, the length of individual cave systems grew as explorers linked together different caves. The four regions of the Sac Actun system were explored as separate sections and eventually connected into the current network.

The exploration of the Sac Actun Region of the system began in 1987 via Grande Cenote located 4

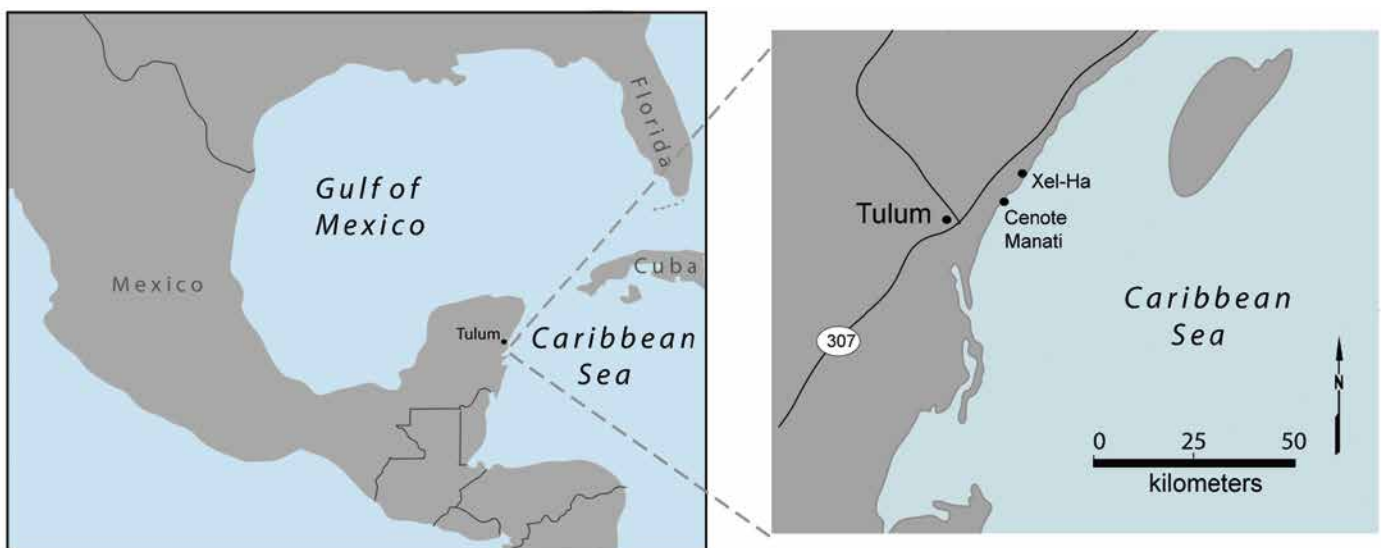


Figure 1: Location map for the *Sac Actun* system.
Figura 1. Mapa de localización del Sistema de Sac Actun.

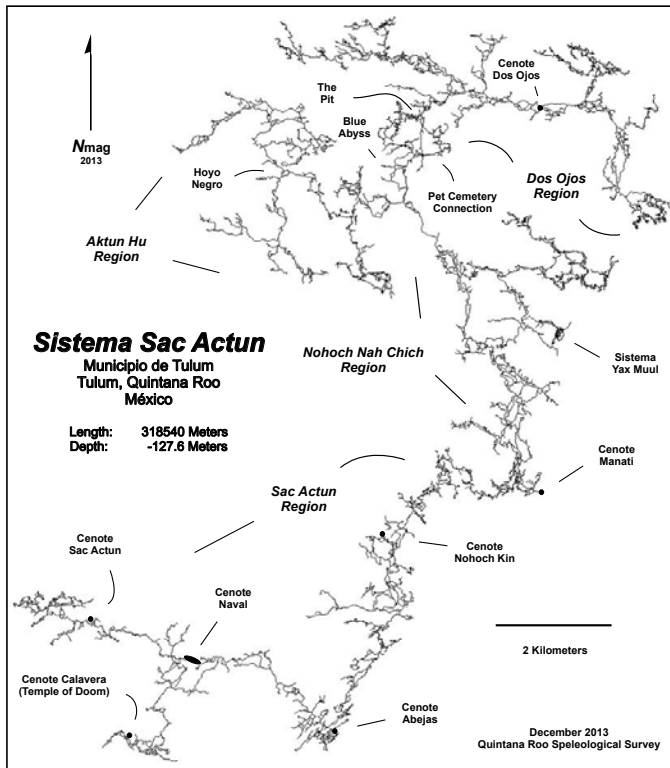


Figure 2: Map of the Sac Actun system showing geographic regions. Cartography by the Quintana Roo Cave Survey.
Figura 2 Mapa del Sistema de Sac Actun mostrando las regiones geográficas. Cartografía de Quintana Roo Cave Survey.

km west of Tulum (Coke 2007). Upstream explorations found an extensive cave that was beautifully decorated and filled with crystal clear blue waters. Passages were typically up to five metres wide with a depth of 10 metres or less. Downstream explorations beyond a major paleo-beach ridge were complicated by size-restrictive, low visibility passages that were at times unstable.

The Nohoch Nah Chich (Big Bird House) region, in the central part of the system was initially discovered in 1986 and explored from the Nohoch Nah Chich cenote located 4 km inland (Fig. 3). Explorers were able to traverse downstream to the coastal spring at Cenote Manati and through to the Caribbean Sea. In 1993, a 71-metre deep cylindrical shaft floored with large breakdown blocks was discovered in the Nohoch Nah Chich region and named Blue Abyss (Gerrard 1993).

Exploration and documentation of a significant air-filled section of the Nohoch Nah Chich region began in 2006 at Yax Muul and several kilometres of air-filled cave are now part of the system (Coke 2007). The Nohoch Nah Chich region was connected to the Sac Actun in 2007 (QRSS 2013).



Figure 3: Mapping in Nohoch Nah Chich region of the the Sac Actun system. Photo by Simon Richards.
Figura 3. Cartografía de la región Nohoch Nah Chich del Sistema Sac Actun. Foto por Simon Richards.

The northwestern-most region of the cave is the Aktun Hu (Iguana Cave) which was discovered in 1992. During explorations in 2007 a 60-metre deep pit named Hoyo Negro was discovered within that section of cave (Attolini 2010), as were significant archaeological and paleontological remains (Nava Blank 2011). A connection to the Sac Actun system was accomplished in 2011.

Exploration of the Dos Ojos (Two Eyes) region, the northeastern-most extent of the system began in 1987. In 1994 the discovery was made of a cenote that led to what is now the deepest cave segment in the system called "The Pit" and gives this section of cave a depth of 119 metres (Barton 2001). "The Pit" is also the deepest section of cave passage of all of the cave systems in the coastal zone of Quintana Roo. The Dos Ojo was linked via dry connection to the Sac Actun system in 2012 making it the longest cave in Mexico and second longest cave in the world (Heyer and Sprouse 2012) (Fig. 4). Cave divers still consider the Sac Actun system to be the second longest underwater cave, behind the Ox Bel Ha system, because the connection to the Dos Ojos was in an air-filled passage. Exploration continues in all sections of the Sac Actun system and it is likely that more connections will be made with satellite cave systems.

Hydrogeology

Groundwater movement through the cave systems of the Yucatan has been portrayed as flowing in underground rivers. It is more accurate to describe it as

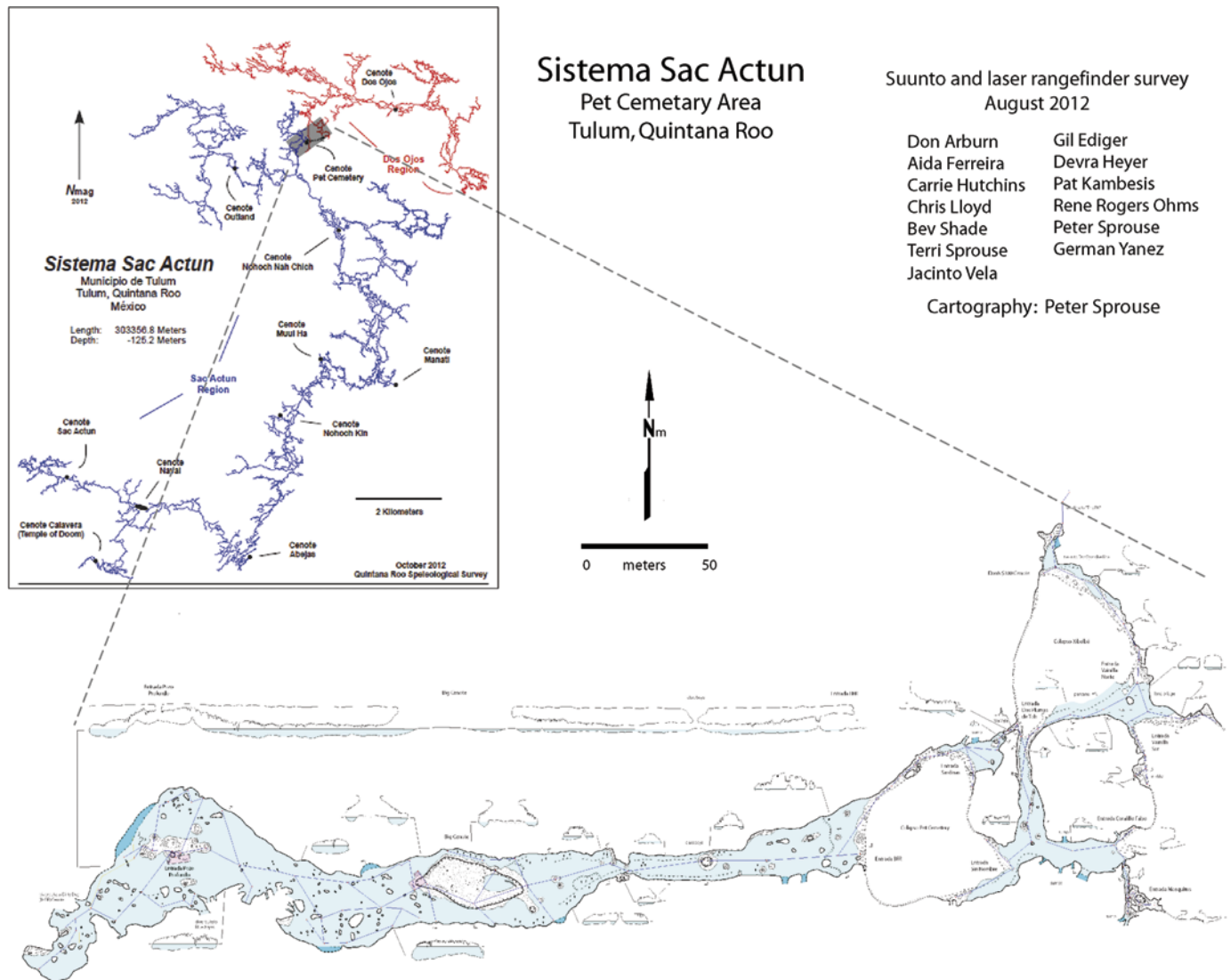


Figure 4: Map of the connection area between *Nohoch Nah Chich* and *Dos Ojos* regions. Cartography by Peter Sprouse.
Figure 4. Mapa de la zona de conexión entre las regiones de *Nohoch Nah Chich* y *Dos Ojos*. Cartografía de Peter Sprouse.

a combination of turbulent and laminar flow through underground estuaries because the groundwater chemistry contains a mix of fresh and saline water. Some cave passages display turbulent water flow but many others do not.

The Sac Actun system is part of one of the most extensive and significant eogenetic, density-stratified karst aquifers in the world. The upper-most layer of groundwater within the aquifer is a thin lens of fresh water that is meteorically recharged and flows toward the coast. The lowest layer consists of saline water and originates from the influx of sea water from the coast. Sandwiched between the fresh and saline water is the halocline which is a brackish layer that has formed as a result of mixing and entrainment

by freshwater outflow above the halocline interface (Beddows 2004b). This zone is also a thermocline as evidenced by cooler temperatures in the freshwater lens and warmer temperatures in the underlying saline water (Beddows 2004b). The halocline is decoupled from the saline layer below it and serves as a dynamic mixing zone. Halocline depth increases with distance from the coast. Fluctuations in the halocline result from periods of sustained precipitation, ocean tides, and the pervasiveness of exposed mixing zones in cave passages (Coke 2012).

Though there is an absence of flow indicators (scallops) in the underwater portions of the Sac Actun system, cave divers report strong water flow within many of the passages in all regions of the cave system and

the observed occurrence of dunes of white silt along the perimeter of cave passages, indicating turbulent flow (Fig. 5). Hydrologically active passages are influenced by proximal Pleistocene ridges or through young Holocene deposits that are located between the coastline and the Pleistocene ridge (Coke 2009).

Dye tracing conducted in the Nohoch Nah Chich region indicated that significant fresh water flow does occur in many cave passages (Worthington *et al.*, 2000). Because of the inherent cavern porosity of the aquifer it is highly transmissive and the tidal signal has been documented in cenotes up to five km inland from the coast (Beddows 2004b).

The water makes it way to the coast where it drains through coastal discharge vents to the Caribbean Sea. Coastal embayments called "caletas" are narrow inlets that extend inland for several hundred meters or more and are associated with large coastal vents (Back *et al.* 1979). "Caletas" form where discharging freshwater from submerged cave passages mix with saltwater at their seaward margins causing an increase in local dissolution and inducing cave

passage collapse that migrates inland to form a cove (Beddows 2004a). Cenote Manati is one of the major discharge points of the Nohoch Nah Chich region and is located at the downstream end of a "caleta". The upstream end of the caleta is where spring vents debouche and flow almost 200 meters before sinking underground at a large cave entrance at the downstream end of the "caleta". The water resurges again in a series of vents located within 50 meters from the coast. In the Dos Ojos region of the system, dye tracing demonstrated that large volumes of water flow to the northeast toward Caleta Xel-Ha (Beddows 2004b). This "caleta" is the largest in the region with an inland extent of 600 metres.

Associated with the "caletas" are crescent-shaped beaches that occur when the "caleta" openings are widened by littoral action and eventually eroded to form the beach structure (Back *et al.*, 1979). There are many crescent-shaped beaches, more "caletas" and many discharge vents with a frequency of every 2-3 km along the coastal stretch that is hydrologically associated with the Sac Actun system.

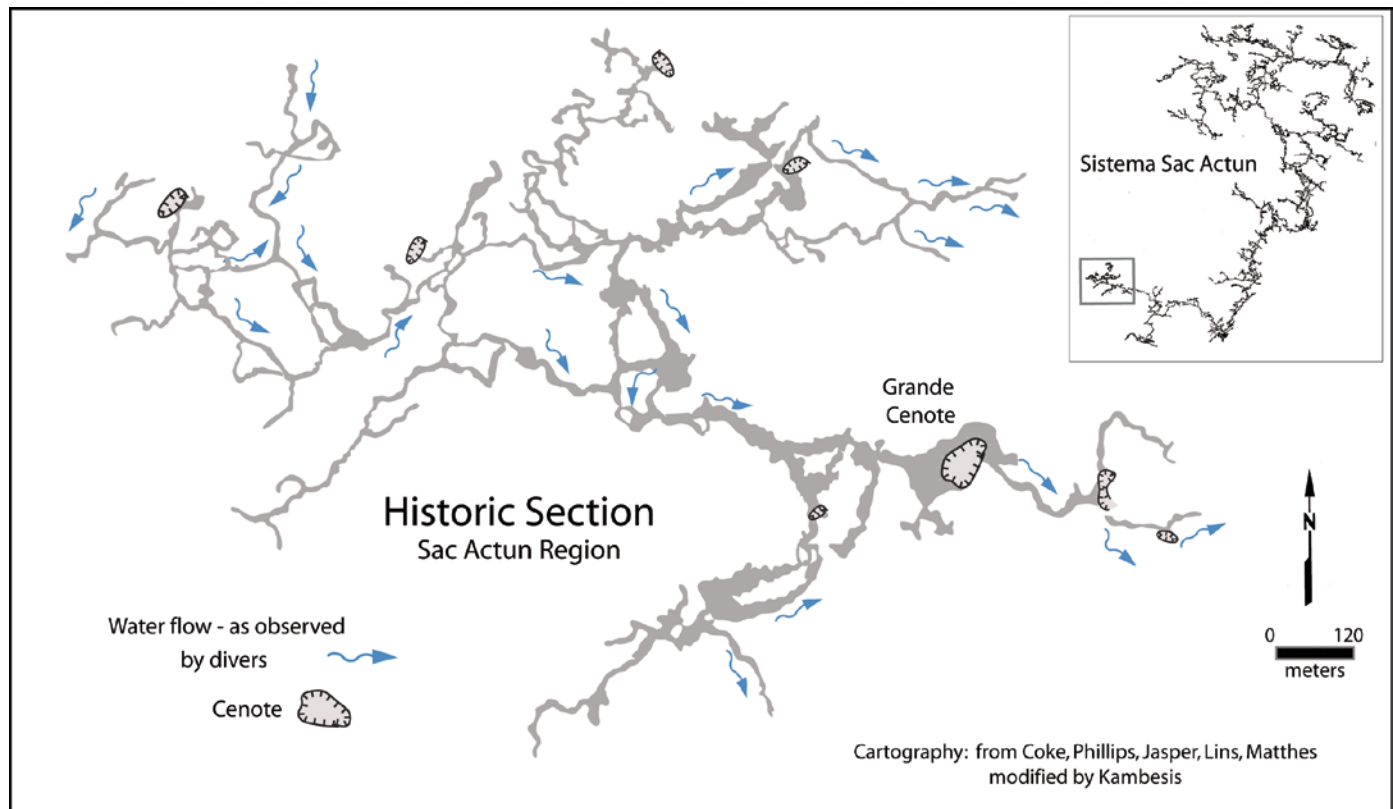


Figure 5. Map of historic *Sac Actun* showing the water flow as observed by divers. Cartography by Coke, Phillips, Jasper, Lins and Matthes, modified by P. Kambesis.

Figura 5. Mapa histórico del flujo de agua de *Sac Actun* según lo observado por los buceadores. Cartografía por Coke, Phillips, Jasper, Lins and Matthes, modified by P. Kambesis.

Cave distribution and morphology

The overall morphology of the *Sac Actun* system has two distinct forms that are characteristic of all of the extensive cave systems along the Caribbean coast of Quintana Roo. Sections that are closest to the coast display high-density rectilinear mazes that parallel the coast on a northeast-southwest trend. The mazes are associated with conduits that carry fresh water to the coast (Coke 2009). The cave passages that make up these mazes are low and horizontal and are interspersed with fracture-controlled chambers. They are characteristically devoid of speleothems, and coated with clay-like silt (Coke 2012). The limestone in this section is very friable and in places can be unstable. Passages in the Cenote Abejas section of the Sac Actun region exemplify this morphology.

Sections of the cave located greater than a kilometre from the coast display a distinct fracture and fault morphology. These sections of cave are anastomotic in configuration and run perpendicular to the coast on a northwest-southeast trend. Cave passages have an elliptical shape, are more stable than many of the coastal passage segments, and vadose speleothems are common. The northern sections of the Sac Actun region exemplify this type of passage development. The anastomosing configuration may be in part be influenced by regional structure though local conditions can also be important. Extensional fractures associated with mechanical ceiling collapse and the formation of cenotes may result in collapse zones that host an anastomosing pattern of passages The Balancanche. Cenote (Fig. 6), located in the Nohoch Nah Chich region has 10 collapse cenotes located within a 0.6 km² zone of anastomosing passages. The cross section in Figure 6 displays a 600-metre wide collapse zone that strongly influences the morphological pattern of the cave passage. Other factors that influence cave patterns include sediment and speleothem occlusion and hydrologic piracy.

The morphological difference from coastal to inland configuration may in part be caused by changes in lithology where Pleistocene to Holocene age carbonates transition to older, more consolidated ones and cave passages are contained within more massive and stable bedrock (Kambesis and Coke 2013).

At distances of 3 to 6 km from the coast the southern and northern arms of the system (Sac Actun-Naval and Nohoch Nah Chich respectively) there are Neogene rocks. Lateral branching of passages still occurs but the number of passages is limited to just one or two primary discharge tunnels; secondary passages are small in dimension and length and typically end in impassible tubes or cracks that discharge fresh water (Coke 2009).

As with any extensive cave system, individual cave passage morphologies within Sac Actun system range from the simple canyon-type and elliptical shapes to more complex morphologies that indicate the overprinting of processes. Ceiling collapse, sediment fills, speleothem deposition and undercutting of passage walls have modified the original cross section of many cave passages within the system.

Vertical development of the *Sac Actun* System:

The submerged passages of the Sac Actun system are fairly shallow in terms of world depth standards. Depths, which are measured below the surface in the Sac Actun region, have ranges that span from < 2 m to 20 metres; the Nohoch Nah Chich region depth ranges span from 2-6 m and 8-15 m and 16-20 m; the Actun Hu region from 5-10 m; and the Dos Ojos region at 5-10 m and 14-20 m. However, there are three notable exceptions that all occur within the Nohoch Nah Chich-Aktun Hu-Dos Ojos regions of the Sac Actun system. These areas require advanced cave diving techniques and equipment, mixed gases, and experience. The Blue Abyss (Fig.7) is an underwater vertical shaft with a depth of 71 metres and has been explored to a breakdown maze at the base of the shaft. "The Pit" in the Dos Ojos (Fig. 8) is a steeply descending breakdown-floored passage that begins at a cenote entrance and leads to a series of large breakdown-floored chambers, giving that section of cave a depth of 119 metres. The largest chamber in

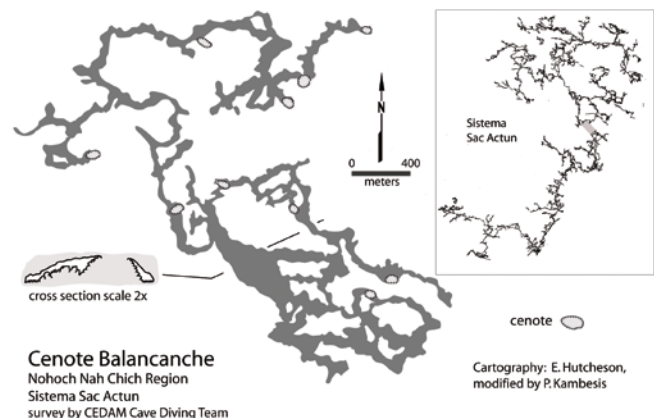


Figure 6: The influence of cenote collapse on cave configuration, Balancanche Cenote (Nohoch Nah Chich region). Cartography by E. Hutcheson and modified by P. Kambesis.

Figura 6. Influencia del cenote de colapso en la configuración de la cueva Cenote Balancanche (región de Nohoch nah Chich). Cartografía por E. Hutcheson y modificada por P. Kambesis

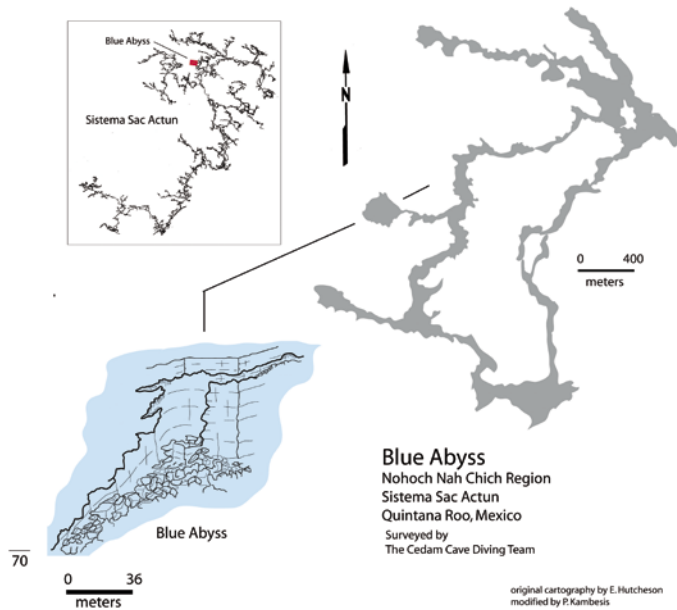


Figure 7: Blue Abyss in the Nohoch Nah Chich Region. Cartography by E. Hutcheson and modified by P. Kambesis.
Figura 7. Región de Blue Abyss Nohoch Nah Chich. Cartografía por E. Hutcheson y modificado por P. Kambesis.

this section is the Wakulla Room, 150 m long and 30 m wide. The Hoyo Negro (Fig. 9) is a breakdown-floored pit within the Actun Hu region with a depth of 60 metres. Significant archeological and paleontological remains have been found in this area (Nava Blank 2011) (Fig. 10).

The deep sections of the Sac Actun system are in salt water and hint at the existence of deeper levels of cave development which are mostly unknown. Water samples collected in The Pit were analyzed to be chemically identical to nearby marine water (Barton 2001). There are reports of large holes along the walls of the modern barrier reef at depths of 100 metres that could potentially lead to deep levels of cave development formed when sea level was over a hundred metres lower than it is today (Barton 2001).

The Yax Muul section (Figs. 11 and 12) of the *Nohoch Nah Chich* region is an air-filled segment of cave that exists above underwater passages. This section probably formed when sea level was 6 metres higher, associated with the last interglacial that took place 125000ka.

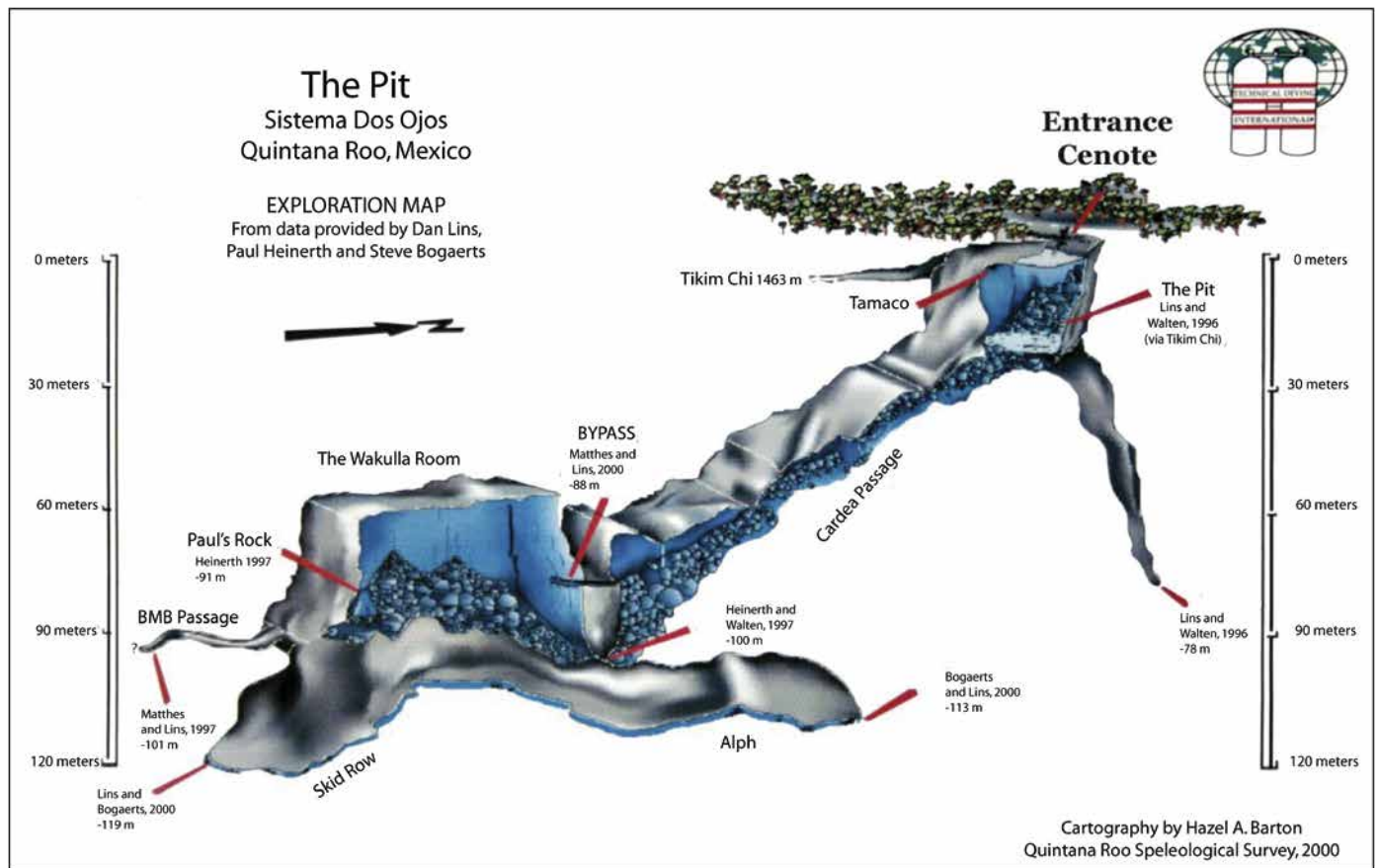


Figure 8: The Pit in the *Dos Ojos* Region. Cartography by Hazel Barton.
Figura 8. El Pit en la región de *Dos Ojos*. Cartografía por Hazel Barton.

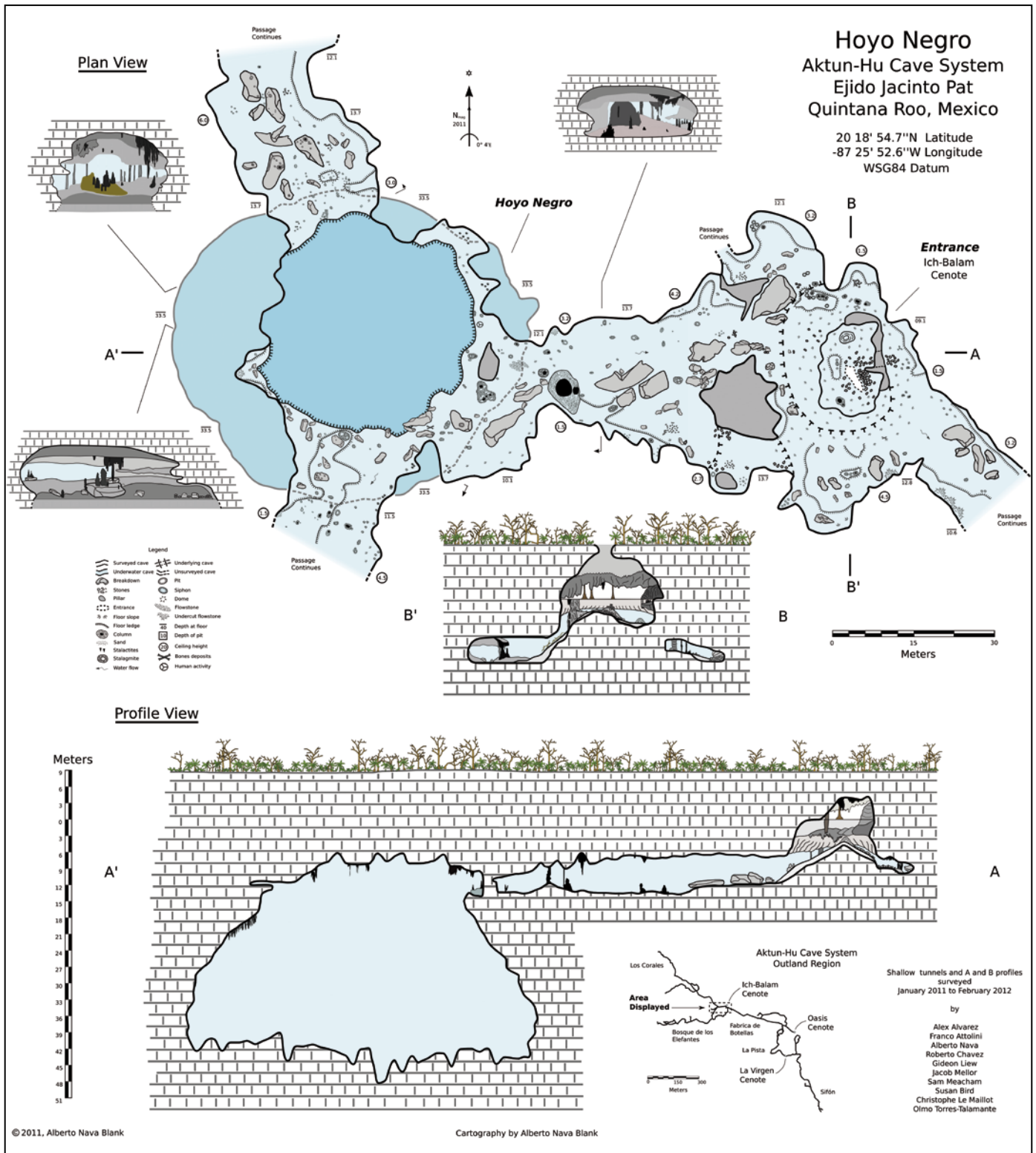


Figure 9. Map of Hoyo Negro in Aktun Hu region. Cartography by Alberto Nava Blank.

Figura 9. Mapa de Hoyo Negro en la región de Aktun Hu. Cartografía de Alberto Nava en blanco.



Figure 10: Divers documenting human remains in the Aktun-Hu region. Photo by Daniel Riordan.

Figura 10. Buceadores documentando los restos humanos en la región de Aktun-Hu. Foto de Daniel Riordan.

Controls on cave development of Sistema Sac Actun

Hydrogeologic controls

The development of the Sac Actun system, as well as the many other caves systems along the Yucatan Caribbean coast is controlled by the coastal hydrology, driven by major fluctuations in sea level, and influenced by stratigraphy and geological structure.

The Sac Actun system is composed of linear phreatic conduits that formed as a result of the rock/water interaction between meteoric and saline groundwater. As meteoric water infiltrates the bedrock it attains chemical equilibrium with respect to carbonate and loses much of its dissolutional capability. Saline groundwater is also typically saturated with respect to carbonate and has very little dissolutional capacity. At the halocline the two end members mix and form a brackish water zone that is undersaturated with

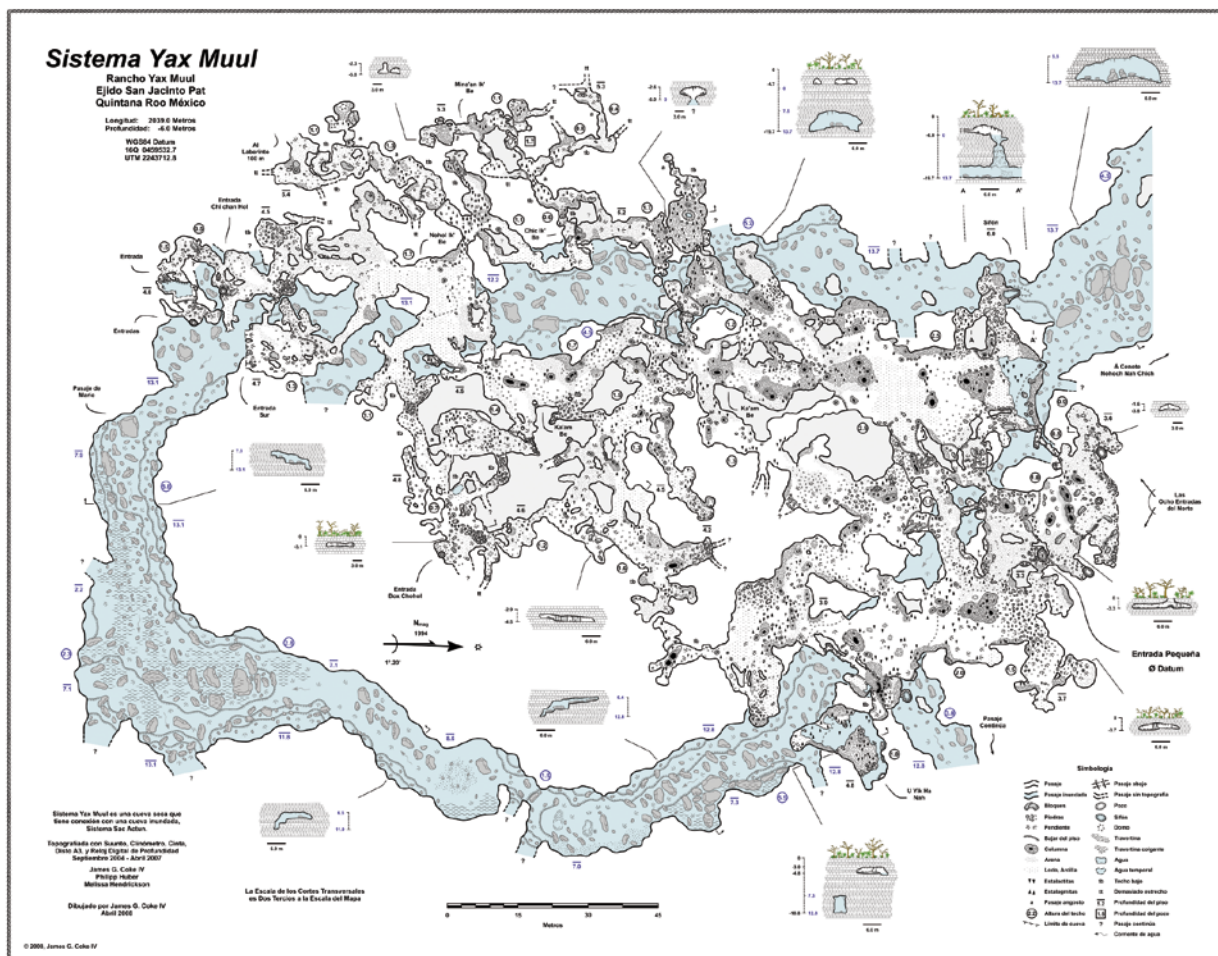


Figure 11: Map of the Yax Muul section in the Nohoch Nah Chich region. Cartography by Jim Coke

Figura 11. Mapa de la sección de la región de Yax Muul Nohoch Nah Chich. Cartografía de Jim Coke



Figure 12: A sump in the dry Yax Muul section of Nohoch Nah Chich region. Photo by Simon Richards.

Figura 12. Un sumidero en la sección seca de Yax Muul de la región Nohoch Nah Chich. Foto por Simon Richards.

respect to carbonate (Wigley and Plummer 1976). Dissolution of limestone occurs at the mixing zone along the path of discharge of the undersaturated brackish water (Beddows 2003). Mixing zone corrosion is accepted as the main mechanism for conduit development in the eogenetic aquifer of the Yucatan Caribbean (Beddows 2004a, Smart *et al.*, 2006). This idea is supported by the observation that the vertical location of caves in the region is either directly associated with the position of the halocline or is above it -between 10 to 25 meters below current sea level (Beddows 2004a, Smart *et al.* 2006). Though genesis of the Sac Actun system as well as many of the other extensive underwater cave systems of the region is thought to be predominantly from mixing corrosion (Beddows 2004b), microbially mediated reactions associated with redox processes involving sulfates and reoxidation of sulfide to produce sulfuric acid may also drive dissolution (Stoessel *et al.*, 1993). These processes can also occur in sediments derived from surface runoff via cenotes (Smart *et al.*, 2006).

Gulley *et al.* (2013) put forth an alternate model for cave formation in eogenetic karst aquifers. They hypothesize dissolution occurs when water flows from aquifer regions with low p_{CO_2} into regions with higher p_{CO_2} . The increase in p_{CO_2} comes from fractures connecting the soil zone to water tables and water flowing from regions of low p_{CO_2} into regions of high p_{CO_2} . This condition dissolves CO_2 from the atmosphere, reduces pH, and dissolves limestone. They posit that simple geochemical models demonstrate small gradients in p_{CO_2} along flow paths are an order of magnitude more efficient at dissolving limestone than mixing of vadose and phreatic water.

Smart *et al.* 2006 suggested that dissolution could occur in the salt-water-occupied deeper zones of the cave. Beddows (2004a) documented an increase in temperature with depth in The Pit and Blue Abyss (approximately $2^\circ\text{C}/100\text{m}$). Though these waters are typically saturated with respect to carbonate, forced advection could cool the water and result in undersaturated water that could dissolve limestone in the deep saline zone (Smart *et al.*, 2006).

Stratigraphic Controls

The Sac Actun system is formed in eogenetic coastal strata that consist of marine and non-marine sequences accumulated in shelf margin, reef, and back reef environments facies. The units are separated by unconformities indicative of exposure and erosion of the platform surface when sea level retreated (Perry *et al.*, 1995). The marine strata include beach, near shore and lagoonal types, and coral-reef limestone; non-marine strata consist of eolianites, freshwater lacustrine carbonate mudstone, and caliche (Ward 2003).

The coastal strata have been chronologically divided by Back *et al.* (1979), into Upper (125000 ybp), Middle (174000 ybp), and Lower Pleistocene (200000-800000 ybp) units. The Upper Pleistocene unit was deposited when sea level was 6-meters above current levels and cave passages have developed at this level. Cueva Yax Muul, located in the Nohoch Nah Chich region is an example of vadose-zone cave passage formed when sea level was highest 125000 years ago (M15e). Miocene-Pliocene rocks underlie the Quaternary-age strata (Ward 2003, Richards and Richards 2009) and contain the region's deepest cave passages.

An important local feature in the Tulum area is a Pleistocene ridge whose location ranges from 200 m to a kilometre inland from the coast and displays a 10-metre increase in elevation. This area may mark a change in lithology where Pleistocene to Holocene age carbonates transition to older, more consolidated ones and cave passages are contained within more massive and stable bedrock. Analogous to this would be Vallgornera Cave of the Migjorn karst on the island of Mallorca, Spain. Though that region is more structurally complex than the Yucatan peninsula, bedrock lithology strongly influences cave passage density and shape (Ginés *et al.* 2009a, Ginés *et al.*, 2009b).

Structural Controls

Sistema Sac Actun is located within the Yucatan peninsula's Eastern Block-Fault district that extends

from the tip of the northeast coast, to the Yucatan's border with Belize. The two main faults/lineaments in Quintana Roo are the Holbox Lineament Zone and the Rio Hondo Fault Zone (Kambesis and Coke 2013). The directional trends of Sistema Sac Actun, as well as other caves along the coast appear to be controlled by these dominant regional structures.

The Holbox Lineament Zone (HLZ) is a northeast trending feature that starts at the northeastern coast of the peninsula and continues south to within 10 km of the coast inland from Tulum (Bauer-Gottwein et al. 2012). HLZ is evident on the surface by the alignment of polje-like features (Weidie 1978). The extensive cave systems that characterize the northeast coast of Quintana Roo all appear to terminate at HLZ and there are no known extensive cave systems formed beyond HLZ.

The Rio Hondo Fault Zone (RHFZ) is an extensional feature composed of northeast trending normal faults and is the on-shore continuation of an extensive horst and graben system located off the southern Caribbean coast of Quintana Roo (Weidie 1985). Remote sensing analysis suggests that RHFZ extends northwards and intersects with the HFZ in the vicinity

of Tulum (Gondwe *et al.*, 2010). This intersection of structural features could account for the density of cave passages that have been documented in this area.

Coastal features, including "caletas" and crescent-shaped beaches, appear to be influenced by a well-defined northwest trending fracture that controls their inland development and a northeast trending set that parallels the coast and influences the lateral extent of these features (Gondwe *et al.*, 2010). Based on changes in fracture trends along the coast, Wedie (1978) speculated the existence of a conjugate fracture system. This may explain the parallel and perpendicular trends of cave development and the high density of cave passages in the Tulum area.

The orientation of "caletas" and crescent-shaped beaches correlate with areas of maximal fracturing. The existence of extensive underwater conduits with trends that appear to match those of the regional structures strongly suggest that linear dissolution corridors are developed along the extensive fracture and lineament zones that occur in northeastern Quintana Roo (Tułaczyk *et al.*, 1993).

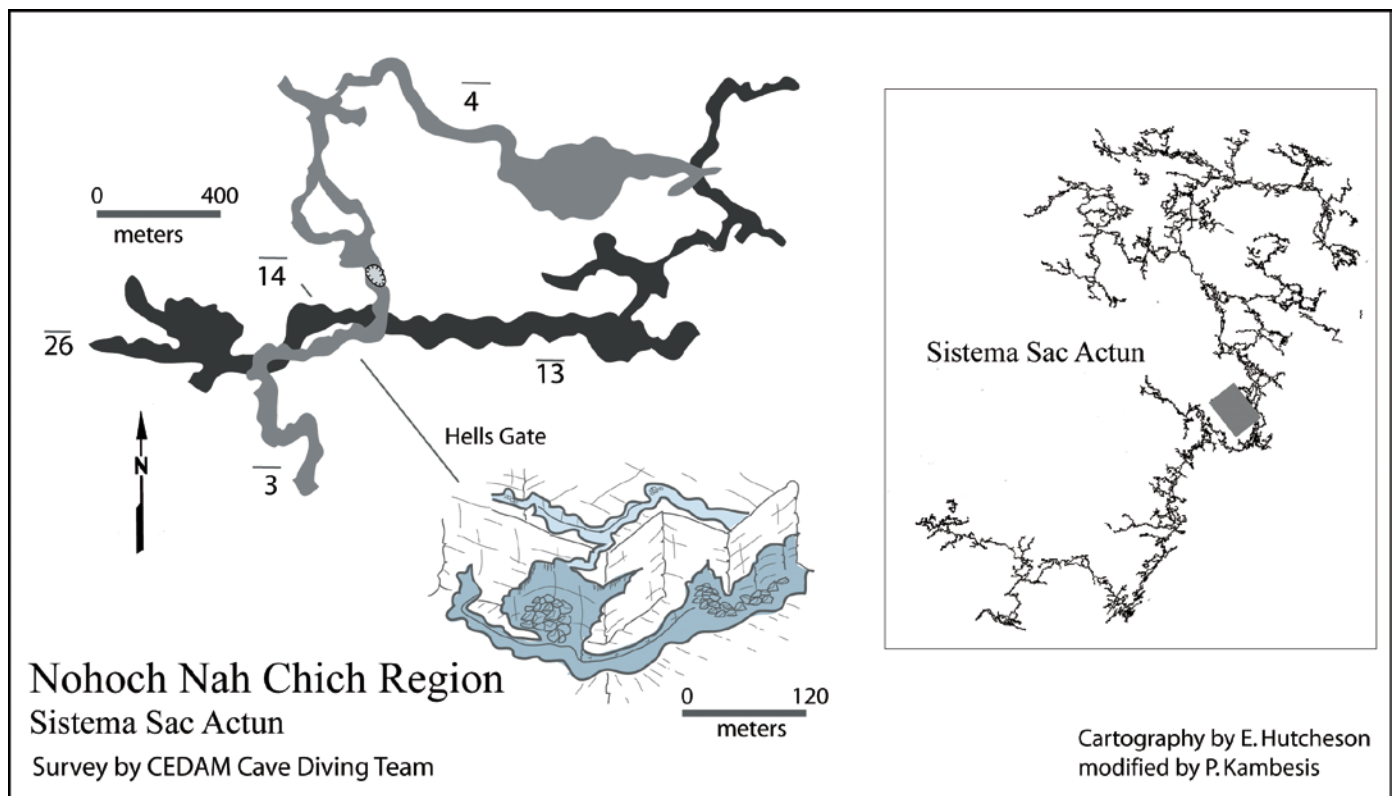


Figure 13: Multi-level passages in Hells Gate section of Nohoch Nah Chich. Cartography by E. Hutcheson and modified by P. Kambesis.

Figura 13. Pasajes multiniveles en la sección Hells Gate de Nohoch Nah Chich. Cartografía por E. Hutcheson y modificado por P. Kambesis.

Multiphase cave development

The low hydraulic gradient of the Yucatan peninsula means that water levels within Quintana Roo cave systems track sea level (Mosley *et al.*, 2013). The current location of the halocline and the vertical distribution of cave passages indicate that the Sac Actun system has undergone multiple phases of development. The existence of air-filled cave passages such as Yax Muul and multilevel areas such Hells Gate, both in the Nohoch Nah Chich region (Fig.13) attest to the relationship of sea level to cave passage development.

Speleothems are prevalent at all of the inland sections of cave as are calcite rafts. These features typically form under vadose conditions where cave passages would be air-filled allowing the degassing of CO₂ from infiltrating waters, and the deposition of calcite. Calcite rafts, which are common throughout the cave system especially near cenotes, precipitate from pooled water that is degassing CO₂. When sea level rises, these typically vadose-zone features become inundated.

Pristine speleothems are characteristic of the inland passages in the Sac Actun region and indicate at least one phase of development. However, areas near the coast such as the *Abejas* area of the Sac Actun region and the Balancanche Cenote area in the Nohoch Nah Chich region display speleothems that are corroded; an indication of re-inundation of existing cave passages and thus multiple phases of cave development (Smart *et al.*, 2006). Preliminary work on the correlation of U-series dates of corals on Quintana Roo with speleothems from various caves in the region (Mosley *et al.*, 2013) is beginning to relate age-dates of the different elevations of cave passage development to the stadial and interstadial of MIS5 series.

Environmental impact of human development

The Sac Actun system is part of one of the most extensive and significant eogenetic karst aquifers in the world. The hydrodynamics of the aquifer expose the cave system to extensive saline intrusion that restricts the thickness of the freshwater lens. The karstic permeability of the aquifer makes it vulnerable to the anthropogenic impacts of agriculture, quarries, and touristic development (Kambesis and Coke 2013).

The coastal district in Quintana Roo, called the Mayan Riviera, is undergoing large-scale development for tourism that poses significant threats to the groundwater resources. The many cenotes and

“caletas” that occur along the coast are used for nature parks and other touristic developments. The most spectacular of the “caletas”, including Xel Ha and Yalk Hu are used for recreational water activities as are the numerous cenotes that dot the coastal zone.

Population growth that is associated with touristic development is impacting the aquifer with increasing amounts of wastewater and solid waste as are the growing number of landfills (Bauer-Gotwein *et al.*, 2011). These land uses impact not only the groundwater resources of the region but also the anchialine cave habitants that are associated with the cave systems. Subterranean waters move quickly through karst conduits that drain the aquifer, at times as much as kilometers per day (Beddows 2004a). The thin soil cover characteristic of the peninsula, and fast groundwater flow do not provide the natural filtration and holding time necessary for the natural breakdown of pollutants. All groundwater that flows through the extensive conduit systems of Quintana Roo is eventually discharged onto the barrier reef system that fringes the modern coast.

Injection of effluents into deep saline water zones near the coast and pumping fresh water from wells 10 km inland may not be environmentally sustainable due to the hydrodynamics of the density-stratified, de-coupled fresh and saline waters of the aquifer (Beddows 2003, 2004a). Effluent is similar in density to fresh water so it tends to rise up either into the fresh water lens or to the fresh water-saline water mixing zone (Richards and Richards 2007). The flow of saline water between cenotes and beaches, and the coastward flow of freshwater can bring effluent to beaches and reefs (Beddows 2004a).

The flow dynamics of the fresh water lens is impacted by construction of waterfronts and marinas for hotels, resorts, and housing developments. Man-made trenches that cut inland from the coast and the removal of shallow bedrock increases the flow of freshwater to the coast and can potentially cause the loss of the freshwater lens (Richards and Richards 2007).

The number of cenotes and their density are a threat to the construction of tourist facilities and housing developments as is the existence of extensive dry sections of thin-roofed cave passages in the area.

Protection of the Sac Actun system from the impact of human development will require comprehensive regulation of wastewater treatment, continued scientific research of the aquifer and its related features, space-temporally resolved hydrological monitoring programs and efficient regional policy making (Gotwein *et al.*, 2011).

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References

- Attolini, F., 2010, 2007, First years of Actun Hu Exploration, *AMCS Activities Newsletter*, 33, 95-98.
- Back W, Hanshaw B.B., Pyle TE, Plummer L.N. and Weidie A.E. (1979) Geochemical significance of groundwater discharge and carbonate solution to the formation of Caleta Xel Ha, Quintana Roo, Mexico. *Water Resources Research* 15:1521-1535.
- Barton, H. 2001, The Pit in Dos Ojos, *AMCS Activities Newsletter* Number 24, p. 84-91.
- Bauer-Gottwein P, Gondwe B.N.R., Charvet G, Marin LE, Robellodo-Vieyra M and Meresiz-Alonso G (2011) Review: The Yucatan Peninsula karst aquifer, Mexico, *Hydrology Journal*, 19:507-524.
- Beddows P.A. (2003) Cave hydrology of the Caribbean Yucatan coast: *Association of Mexican Cave Studies Bulletin* 11, 96 p.
- Beddows P.A. (2004a) *Groundwater hydrology of a coastal Conduit carbonate aquifer: Caribbean Coast of the Yucatán Peninsula, México*, PhD Thesis, University of Bristol, UK.
- Beddows, P.A., 2004b, Yucatan Phreas, Mexico, in the *Encyclopedia of Cave and Karst Science*, Ed. John Gunn, Fitzroy-Dearborn, New York. p. 786-88.
- Beddows P.A., Smart P.L., Whitaker F.L. and Smith .SL. (2007) Decoupled fresh-saline groundwater circulation of a coastal carbonate aquifer: Spatial patterns of temperature and specific electrical conductivity, *Journal of Hydrology*, 346: 28-42.
- Coke, J. G. (IV), 2007, The Exploration of Sistema Sac Actun 1987-2007, *AMCS Activities Newsletter*, Vol 30 p. 39-42
- Coke, J. G. IV, 2007, Sistema Yax Muul, *AMCS Activities Newsletter*, 30, 43-49.
- Coke J. G., IV. 2009, Yucatan Peninsula, (Campeche, Yucatán, Quintana Roo), *Caves and Karst of the USA*, eds. A. Palmer and M. Palmer, National Speleological Society, Huntsville, AL. p. 388-390.
- Coke, J.G. (IV), 2012, Underwater Caves of the Yucatán Peninsula, in *Encyclopedia of Caves*, second edition, eds. White, W.B., and Culver, D. p. 833-838.
- Gerrard, S., 1993, Diving in Quintana Roo, Yucatan Peninsula Three Reports, *AMCS Activities Newsletter Number* 20, 84-87.
- Ginés A, Ginés J, Gràcia F and Fornós JJ (2009a) Cave surveying and cave patterns in the southeastern coastal karst of Mallorca Island (Spain). In: White, W.B. (ed.) *Proc. 15th Int. Congress Speleology*. 1: 488-495. Kerrville, U.S.A.
- Ginés J, Ginés A, Fornós JJ, Merino A and Gràcia F (2009b) About the genesis of an exceptional coastal cave from Mallorca Island (Western Mediterranean). The lithological control over the pattern and morphology of Cova des Pas de Vallgornera. In: White, W.B. (ed.) *Proc. 15th Int. Congress Speleol.*, 1: 481-487. Kerrville, U.S.A.
- Gondwe B.R.N, Lerer S, Stisen S., Marín L., Rebolledo-Vieyra M., Merediz-Alonso G. and Bauer-Gottwein P., 2010, Hydrogeology of the south-eastern Yucatan Peninsula: new insights from water level measurements, geochemistry, geophysics and remote sensing. *Journal of Hydrology*. doi:10.1016/j.jhydrol.2010.04.044.
- Gulley, J. D., Martin, J. B., Moore, P. J. and Murphy, J. (2013), Formation of phreatic caves in an eogenetic karst aquifer by CO₂ enrichment at lower water tables and subsequent flooding by sea level rise. *Earth Surf. Process. Landforms*, 38: 1210-1224. doi: 10.1002/esp.3358.
- Heyer D. and Sprouse, P., (2012) The Sac Actun Connection. *National Speleological Society News*, 70(12): 12-17.
- Kambesis, P.N., and Coke, J.G. IV, 2013, *Overview on the controls on eogenetic karst development in Quintana Roo, Mexico, Coastal Karst Landforms*, Springer, New York, ed. M.J. Lace and J.E. Mylroie, p.347-374.
- Moseley, G., Smart, P.L., Richards, D.A., Hoffmann, D.L., 2013, Speleothem constraints on marine isotope stage (MIS) 5 relative sea levels, Yucatan Peninsula, Mexico, *Journal of Quaternary Science*, ISSN 0267-8179. DOI: 10.1002/jqs.2613.
- Nava Blank, A., 2011, Hoyo Negro, *AMCS Activities Newsletter* Number 34 p. 53-58.
- Perry E., Marin L., McClain J. and Velazquez G., 1995 Ring of cenotes (sinkholes), Northwest Yucatan Peninsula, Mexico: Its hydrogeologic characteristics and possible association with the Chicxulub impact crater. *Geology* 23(1): 17-20.
- Quintana Roo Speleological Survey website (accessed December 2013): <http://www.caves.org/project/qrss/qrss.htm>.
- Richards D. and Richards S., (2007) Overview of the Geology and Hydrology of Coastal Quintana Roo, *AMCS Activities Newsletter*, No. 30:104-109.
- Smart P. L., Beddows P.A., Coke J., Doerr S., Smith A. and Whitaker F., 2006, Cave Development on the Caribbean coast of the Yucatan Peninsula, Quintana Roo, Mexico. In: Harmon RS and Wicks C (eds.) *Perspectives on karst geomorphology, hydrology, and geochemistry - A*

- Tribute volume to Derek C. Ford and William B. Whiter: Geological Society of America Special paper 404:105-128.
- Stoessell, R. K., Moore, Y.H. & Coke, J. G., 1993, The occurrence and effect of sulfate reduction and sulfide oxidation on coastal limestone dissolution in Yucatan cenotes, *Ground Water*, 31(4) p. 566-75.
- Tułańczyk, SM., Perry E.C., Duller C.E. and Villasuso M. (1993) Influence of the Holbox fracture zone on the karst geomorphology and hydrogeology of northern Quintana Roo, Yucatan Peninsula, Mexico. In: Beck B (ed.) *Applied Karst Geology*: Rotterdam, Balkema: 181-188.
- Ward W.C. (2003) Salt Water Intrusion & Coastal Aquifer Conference (SWICA) Field Trip to the Caribbean Coast of the Yucatan Peninsula (April):13-22.
- Weidie A.E., (1978) Lineaments of the Yucatan Peninsula and Fractures of the Central Quintana Roo Coast. In: Field Trip No. 10 – Yucatan, Road Log and Supplement to 1978 Guidebook, 1982 GSA Annual Meeting, New Orleans, Louisiana: 21-25.
- Wigley T.M.L. and Plummer L.N. (1976), Mixing of carbonate waters, *Geochimica Cosmochimica Acta*, 40(9): 989.
- Worthington, S.R.H, Ford, D.C. & Beddows, P.A., 2000, Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution. In *Speleogenesis: Evolution of Karst Aquifers*, edited by A. B. Klimchouk, D. C. Ford and A.N. Palmer and W. Dreybrodt, Huntsville, Alabama: National Speleological Society pp. 463-472.

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