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KARST HYDROGEOLOGY AND SPELEOGENESIS OF SISTEMA ZACATÓN, TAMAULIPAS, MEXICO

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KARST HYDROGEOLOGY AND SPELEOGENESIS OF SISTEMA ZACATÓN, TAMAULIPAS, MEXICO

by

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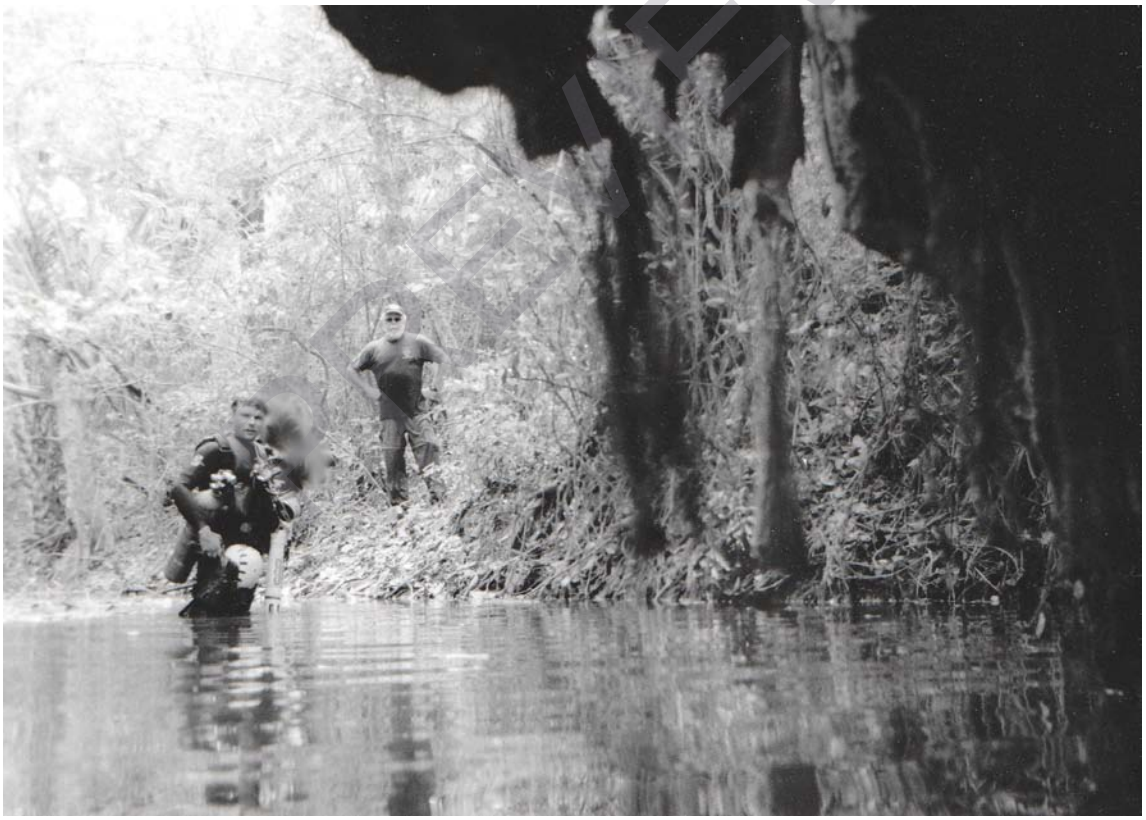
Dedication

In 1990, I took a spring break adventure travel trip to Mexico; my first venture outside of the country and a defining point in my life. As a freshmen accounting major at The University of Texas, I had recently taken up SCUBA diving, becoming intrigued by the opportunity to experience a totally new environment. I joined Jim Bowden, Dr. Ann Kristovich, Karen Hohle, and a half dozen or so eager college students south of the border to camp, learn cavern diving, and experience a new culture. After returning from that trip, I realized there was much more to life than earning a respectable income and living the standard professional life with all the accompanying material objects. A whole new world was opened to my eyes; one with adventure, the joy of discovering untouched places, and ultimately the curiosity to gain scientific skills needed to understand the unknown.

In the years following this initial venture into the underwater world of caves, I learned full cave-diving techniques from Jim and Ann, then moved on to develop hands-on, blue-collar experience as a commercial diver at the College of Oceaneering in Los Angeles, California. Once I completed an Associate Degree in Marine Technology, I returned to Mexico with Jim, Ann, Karen, and joined by the legendary Sheck Exley and Mary Ellen Eckhoff. Jim and Sheck were making an attempt to reach the bottom of what was at the time, the deepest underwater cave in the world; *El Zacatón* was known to be over 300 meters deep. The experience of that week will always remain fresh on my mind. There are few times when such emotions are alive, but must be set aside to

continue the task. Once we realized Sheck was gone, it became increasingly important to ensure Jim returned from his dive to 284 meters alive.

The mystery and allure of El Zacatón eventually inspired my curiosity enough to lead me into an undergraduate program in hydrogeology at The University of Texas at Austin. After pestering a number of professors (many of whom are on this committee) about this amazing underwater cave system in Mexico time after time, I eventually nudged my way into a Ph. D. degree program to satisfy the quest sparked following that 1990 spring break trip. The information compiled within this dissertation ultimately is owed to the explorers who opened those doors to my life. Thanks.



Acknowledgments

The list of individuals and organizations that have contributed to research presented in this dissertation is extensive. Hopefully, I mention all in these acknowledgements, because there is much deserved merit to give. First and foremost my family has provided patience and support in all my endeavors, and particularly with the "obsession" I developed with these caves in Mexico. My mother, Rebecca Sikes can be proud that finally all of her children have completed doctorates in the natural sciences after raising the family in the small north Texas town of Bowie. All of those "cultural experiences" obviously paid off. My late father, Jake Gary, was always supportive and encouraging in my younger years. Every time I squinted through the hand lens to look at a rock, the same lens he used as a geology student at The University of Texas, I thought of him. My brother, Jim Gary, made several trips down to Sistema Zacatón with our scientific expeditions, earning notorious fame for his socializing skills.

My wife Robin Gary has been a partner in this entire work since the first trip I dragged her to Zacatón in March 2000. If I listed all the things she has added to the research effort, it would exceed the length of the dissertation. For years we chopped through the dense thorn forest looking for caves, or trees, or just chasing our dogs, all in the name of our studies. She completed her master's degree investigating the anthropogenic impacts on Sistema Zacatón and the surrounding area, documenting the

fragile ecosystems that exist here. Her translation skills are unparalleled. Without her communicating with Mexican custom officials, the DEPTHX probe would never have made it to the study site. Her cooking……exceptional.....…all those who joined us on expeditions know what I mean! She fed dozens of hungry scientists, media journalists, cavers, and whoever was lucky enough to join our camp for a meal. It is absolutely true that this dissertation represents as much blood, sweat, and tears from Robin as from me. I can't thank her enough.

John "Jack" Sharp, my Ph.D. advisor, has given a tremendous level of encouragement and support in the formulation of hypotheses presented in this dissertation. Without his patience and willingness to investigate something "off the beaten path" of normal hydrogeology, it is unlikely I would have had the opportunity to explore my dreams. Geology is a science that benefits from creativity and imagination, but the basis lies with fundamental scientific principles. Jack nurtured both.

This investigation couldn't have taken place without access to the study site. A researcher dreams of having full rein to explore and test the natural environment without logistical headaches. The landowners of most karst features in this study, The Dávila family, particularly Alejandro, have been unimaginably gracious hosts. Time after time, trip after trip, our teams were met with hospitality and generosity for the opportunity to study the world-class karst on their property. Hopefully I can repay the Dávilas with an environmental understanding of Sistema Zacatón that they can use to continue conservation and education on Rancho BioVentura.

The faculty and staff at the Department of Geological Sciences have given amazing support for this research. Mark Helper spent a week nailing down the

georeference benchmarks with precision GPS and has always offered a welcome ear of the status of events at Zacatón. His editorial effort of this dissertation greatly improved the writing and figures. Jay Banner's insight and support on all things isotopic has made obvious contributions to the value of this research. Phil Bennett provided assistance with geochemical analysis of the cenote water. Larry Mack has worked diligently in the Banner isotope lab to produce accurate data. Reuben Reyes at the Bureau of Economic Geology has produced some spectacular animations of the karst system from data we collected. Jeff Horowitz always gave a helping hand with illustrations and advice. The late Todd Housh helped with imaging the thin-sections of travertine. Hours spent with Bob Folk on the SEM looking at microscopic "goodies" were always enlightening.

Research at Sistema Zacatón includes numerous individuals and organizations outside of The University of Texas that have contributed to successes, and their help is greatly appreciated. The NASA ASTEP program funded the DEPTHX project led by Bill Stone. In particular, Nathaniel Fairfield, previously with Carnegie Mellon University (CMU), generated some of the 3-dimensional maps used in this and other publications and presentations. Other scientists from CMU, including David Wettergreen, George Kantor, and Dom Jonak along with John Spear and Jason Sahl from the Colorado School of Mines and John Kerr made the DEPTHX project successful. Todd Halihan at Oklahoma State University provided geophysical support to detect the travertine-sealed cenotes. Art and Peggy Palmer contributed fundamental karst insight in early studies used to form our major hypotheses. The Geology Foundation at the Jackson School of Geosciences and the Environmental Science Institute, both at the University of Texas at Austin, also funded aspects of research at Sistema Zacatón. I also thank Serdar Bayari

for usage of the conceptual model figure for the Turkish Obruks and Giorgio Caramana for his contributions on the Merro Well. Alan Riggs at the USGS made several trips, aiding in underwater rock collection.

Many individuals in Mexico played important roles aiding this work. Dr. Alonso Ramirez-Fernandez from the Universidad Autónoma de Nuevo Leon Facultad de Ciencias de la Tierra has become a wonderful correspondant and collaborator. His insights on the igneous rocks of the Sierra de Tamaulipas have played a key role in this investigation, and his department's involvement in the DEPTHX project was critical. Carlos Ortega from Tampico has been a close friend for years. His help with logistics is also greatly appreciated. The ranch hands at Rancho BioVentura (formerly Rancho la Azufrosa) also provided a hand chopping through the brush, clearing out a pad for the crane to launch the DEPTHX vehicle with their handy bulldozer, or any other thing that was needed. Finally, I thank Antonio Fregoso and his wife Nora from Tampico for always aiding in diving and biological support for years. We could not have achieved success without our friends and gracious hosts in Mexico. Saludos to all!

KARST HYDROGEOLOGY AND SPELEOGENESIS OF SISTEMA ZACATÓN, TAMAULIPAS, MEXICO

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Understanding geologic mechanisms that form karst is of global interest. An estimated 25% of the world's population obtains water from karst aquifers and numerous major petroleum reserves are found in paleokarst reservoirs, so characterization and classification of specific types of karst is essential for resource management. Sistema Zacatón, which includes the second deepest underwater cave in the world, is hypothesized to have formed from volcanogenic karstification, defined as a process that relies on four components to initiate and develop deep, subsurface voids: a carbonate matrix, preferential groundwater flowpaths (fractures), volcanic activity that increases groundwater acidity, and groundwater flux through the system. Phases of karstification creating this modern hydrogeological environment are defined using numerous methods: field mapping, 3-D imaging of surface and aqueous environments, geophysical investigations, physical and chemical hydrogeologic characterization, and microbial analysis. Interpretation of the results yields a multi-phased speleogenetic model of the

karst, with most phases occurring in the late Pleistocene. The surface rocks are carbonate travertine with Pleistocene mammoth fossils found within the rock matrix, and are interpreted as a hydrothermal travertine terrace formed as nearby volcanic activity peaked, thus representing the end member of a carbonate mass transfer system originating deep in the subsurface. The modern karst system includes a dynamic set of deep, phreatic sinkholes, also called cenotes, which propagated up through the travertine, eventually exposing hydrothermal water supersaturated with carbon dioxide to the atmosphere. In some cases these cenotes have precipitated seals of a second stage of travertine as CO_2 degassed, capping the sinkhole with a hydrologic barrier of travertine. Evidence of these barriers is observed in aqueous physical and geochemical characteristics of the cenotes, as some have high hydrologic gradients and contrasting geochemistry to those of neighboring cenotes. Investigations of electrical resistivity geophysics and underwater sonar mapping support the hypothesis of the barriers and define the morphology in intermediate and final phases of sinkhole sealing. Volcanogenic karstification is not limited to Sistema Zacatón, although the localized nature coupled with rapid and extreme degrees of karstification makes it an ideal modern analogue for classifying other karst systems as volcanogenic.

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Chapter 1: Introduction

Studies related to speleogenesis and hydrogeology of cave and karst systems are important for understanding crustal diagenesis of the Earth's surface and shallow subsurface and provide unique records of climatic, tectonic, and hydrogeological fluxes in the environment. The term "karst" is the German derivation of the Slovenian term "kras," which relates to a geographic area of northeastern Italy and primarily in Slovenia, east of Trieste (Gams, 1993). Throughout much of the 20th century, North American theories on cave formation were limited to either physical or chemical controls. In more recent literature, the term karst has evolved to define and describe a specific landform characterized by dissolution features in soluble bedrock (Watson and White, 1985; White, 1988; Ford and Williams, 2007; Palmer 2007).

The term karst is used to identify geologic processes that form caves and related features, and is also applied to characterize specific types of modern heterogeneous hydrogeologic systems. Many geological factors influence how karst evolves and exists in present day settings and how it is preserved in the historical rock record. Two primary types of karst (systems and processes) have been identified in the previous decades, *epigenetic* (epigene) and *hypogenetic* (hypogene) (Palmer, 1991). Although specific definitions for these karst types are subjectively interpreted internationally, the basic distinction between epigene and hypogene karst can be distilled into a brief general statement: *Epigene karst forms from the top down, and hypogene karst forms from the*

bottom up. The goal of this dissertation is not to classify the details which distinguish these types of karst features and processes, but rather to document a unique subset of hypogene karst that results from a combination of geological factors, including volcanism.

This dissertation focuses on the karst area of Sistema Zacatón, located in northeastern Mexico (Figure 1.1), and includes a number of extremely deep, phreatic mega-sinkholes. El Zacatón, the primary feature, is the largest cenote (phreatic sinkhole) in the system and may be the deepest such feature on Earth (Gary et al., 2003b). Prior to research presented within this dissertation, no previous scientific studies had documented geology, hydrology, biology, or any other environmental details on this karst system. This research stems directly from underwater cave exploration during the late 1980's and 1990's that discovered many of the unique characteristics of the area, including the extreme depth of El Zacatón (Kristovich, 1994). The hypothesis that volcanic activity affects karst development here is inferred from a number of factors. Thick Cretaceous carbonates were uplifted and fractured during late Laramide deformation (80 to 55 Ma; English and Johnston, 2004), and subsequent igneous events (Pliocene intrusive and Pleistocene extrusive) dramatically altered the local landscape around Sistema Zacatón (Camacho, 1993; Ramirez Fernandez, 1996). In addition to this juxtaposition linking karstification and volcanism, water chemistry and isotopic data also support this theory. Finally, the hydrothermal travertine terrace deposits of Sistema Zacatón are consistent with the volcanogenic karstification hypothesis.

RESEARCH OBJECTIVES

This study relies on observations and data collected from Sistema Zacatón to describe the physical, geomorphological, and chemical characteristics of the karst, present the speleogenetic history, and compare and contrast Sistema Zacatón with other karst geologic systems worldwide. Because no previous studies exist related to Sistema Zacatón, this dissertation is organized to provide a broad background of geologic information using multi-disciplinary methods. The research results provide a foundation for future specialized studies and establish a common context from which many future independent investigations can relate to each other.

Objective 1: Define Physical and Geochemical Characteristics of Sistema Zacatón

Sistema Zacatón is a complex area of karst landforms. Initial exploration during the 1990's determined that numerous, extremely deep cenotes existed with hydrothermal characteristics in southeastern Tamaulipas, Mexico (Gilliam, 1995; Kristovich, 1994; Kristovich and Bowden, 1995). Beginning in 1999, preliminary analysis of the geology, hydrogeology, and geomorphology established baseline information beyond that generated by cave exploration alone (Gary et al., 2003a). Although the system is confined to a relatively small area, the number and diversity of karst features is quite high, and the semi-tropical climate supports dense vegetation, thus making surficial observations difficult. As much of Sistema Zacatón lies within the phreatic zone, access to these zones presents logistical challenges for direct study.

Due to the relative scientific obscurity and difficult access to the study area features, it is critical to include broad physical and geochemical investigation at Sistema