AN INCONCLUSIVE TRUTH:
AN EVALUATION OF SPELEOTHEM EVIDENCE FOR CLIMATE CHANGE AS A DRIVER OF ANCIENT MAYA CULTURE CHANGE

by

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ABSTRACT

As anthropologists who focus their scholarly attention on the past, archaeologists are interested in examining past changes in human cultures, which can include investigating the role(s) of climatic conditions in shaping them. Paleoclimatology offers the possibility of reconstructing past climates and demonstrating their variability over time, potentially contributing a great deal to archaeology. However, while paleoclimatology may lead to new discoveries about the human past, it may also lead to new errors in interpreting it. Cave speleothems are sources of paleoclimatic data that have recently attracted attention in Mesoamerican archaeology, particularly in studies of the Maya region. In order to evaluate past uses of speleothem paleoclimatic records to support archaeological hypotheses, I will describe the strengths and weaknesses of particular datasets, evaluate the arguments that have been advanced for their broad spatial applicability, examine the science behind the spatial variability of precipitation patterns, and consider how the application of speleothem paleoclimatology to Maya archaeology might be improved upon. I hope to make clear that speleothem paleoclimatic records can potentially yield insights into the relationship(s) between Precolumbian climate change and ancient Maya culture change, but must be interpreted with the utmost caution.

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CHAPTER ONE: INTRODUCTION

Maya Geography

The Maya region, which represents but one segment of the broader archaeological region of Mesoamerica, is located in southeastern Mexico and northern Central America (Demarest 2004:10-11; Sharer and Traxler 2006:26, 28). More specifically, the Mexican portion of the Maya region is comprised of the Yucatecan states of Campeche, Quintana Roo, and Yucatán, and parts of the states of Chiapas and Tabasco; its Central American portion consists of Belize, Guatemala (which includes the Petén, its largest and northernmost department), a small part of Honduras, and an even smaller part of El Salvador (Demarest 2004:1, 3; Sharer and Traxler 2006:24, 28). The modern-day political boundaries, however, primarily reflect the colonial and neocolonial actions of Europeans and their descendants, and did not exist in Precolumbian times. Therefore, while an awareness of the locations of contemporary political (and especially national) borders is essential to the actual practice of archaeology, archaeologists often divide the Maya homeland into an alternate set of subregions (that cross-cut these borders) in their discussions of the Maya past (Demarest 2004:11-12; Sharer and Traxler 2006:30-31; J. Webster 2000:3).

A common scheme, and the one of which I will make use in this thesis, subdivides the Maya region into three zones (listed here in north-to-south order): the Northern (Maya) Lowlands, the Southern (Maya) Lowlands, and the (Maya) Highlands (e.g., D. Chase and A. Chase 1988:3; Iannone et al. 2016:9; McKillop 2004:29-30). It bears mention that the phrase “Central (Maya) Lowlands” has been applied by some to a northeastern section of the Southern Maya Lowlands, the term “Eastern (Maya) Lowlands” has been used by others to refer to the subregion’s Belizean portion, and both alternative schemes call only the remainder of the subregion the “Southern (Maya) Lowlands” (Houk 2015:xviii; Sharer and Traxler 2006:24; J. Webster 2000:4; J. Webster et al. 2007:2). Similarly, the Maya Highlands subregion has been divided by some into areas termed the “Northern (Maya) Highlands”, the “Southern (Maya) Highlands”, and the “Coastal Zone and Piedmont” (Sharer and Traxler 2006:24; J. Webster 2000:4; J. Webster et al. 2007:2). However, for the sake of uniformity, the simpler three-subregion scheme (which is used by most Mayanists) will be employed throughout the thesis. And, since the drawing of boundaries between subregions of the Maya homeland is neither standardized nor consistent (e.g., A. Chase et al. 2014:15; Iannone et al. 2016:9; Kennett and Beach 2013:90), I will now explain the delineation of the borders that will be applied in this thesis.

I define the boundary between the Northern and Southern Maya Lowlands as an imaginary line running from the Laguna de Términos (Campeche) in the west to Chetumal Bay (Quintana Roo and Belize) in the east. I draw the boundary between the Southern Maya Lowlands and the Maya Highlands in such a way as to include Palenque, the Petexbatún, and Copán in the Southern Maya Lowlands, but to place the high-elevation areas to their west, south, and east in the Maya Highlands. In other words, I am defining the Northern Maya Lowlands (See Figure 1) to include three Mexican states: Yucatán, and all but the southernmost portions of Campeche and Quintana Roo. It therefore includes the Maya sites of Chichén Itzá (Yucatán), Edzná (Campeche), and Tulum (Quintana Roo), as well as the Puuc (See Figure 2), a hilly area that includes the Maya sites of Oxkintok and Uxmal (Yucatán) (Medina-Elizalde et al. 2010:256; Sharer and Traxler 2006:24, 533-534; J. Webster 2000:4) (See Table 1). I am defining the

Southern Maya Lowlands to include Belize and the Guatemalan departments of Petén and Izabal (in their entireties), as well as parts of Honduras and the Mexican states of Campeche, Chiapas, Quintana Roo, and Tabasco (D. Chase and A. Chase 1988:3; Iannone et al. 2016:9). It therefore includes the Maya sites of Calakmul (Campeche), Cerros (Belize), Copán (Honduras), Palenque (Chiapas), and Tikal (Petén), as well as the Mirador Basin, a geological depression (in northern Petén) that includes the Maya sites of El Mirador and Nakbé, and the Petexbatún, a lake-rich area (in southern Petén) that includes the Maya sites of Dos Pilas and Punta de Chimino (Hansen et al. 2002:273-275; Medina-Elizalde et al. 2010:256, 2016:94; Sharer and Traxler 2006:24, 383, 386) (See Table 1). The geographical designation “Southern (Maya) Lowlands” is arguably misleading, since the subregion is also home to the Vaca Plateau, a zone of limestone hills (with elevations of from 300 to 560 meters above sea level, in east-central Petén and west-central Belize) that includes the Maya sites of Caracol and Minanha (Belize), and the Maya Mountains, a bona-fide mountain range (with elevations of over 1000 meters above sea level, south of the Vaca Plateau) that separates the southern Belizean sites of Lubaantun, Nim Li Punit, Pusilhá, and Uxbenká from the majority of Maya sites in Belize (Iannone et al. 2013:271-273, 2014:160; Kennett et al. 2012:S17; Sharer and Traxler 2006:24, 26; J. Webster 2000:24) (See Table 1).

I am defining the Maya Highlands to include the highland and coastal portions of Chiapas, Guatemala, Honduras, and El Salvador that lie within the Maya region but outside the Maya Lowlands (A. Chase et al. 2014:15; Iannone et al. 2016:9). This subregion therefore includes the Salvadoran sites of Cerén and Chalchuapa and the Guatemalan sites of Nebaj and Takalik Abaj (Sharer and Traxler 2006:24), but does not figure prominently in this thesis, the focus of which is on the (Northern and Southern) Maya Lowlands.

While most of the maps that illustrate ancient-Maya-themed publications divide the region into either the subregions used by archaeologists (e.g., Sharer and Traxler 2006:24; J. Webster et al. 2007:2), or its modern-day political divisions (e.g., Ebert et al. 2014:339; Hansen et al. 2002:274), others (e.g., Hoggarth et al. 2016:27) ignore both and instead use a scheme based entirely on nature. In 1980, geographer Eugene Wilson filled a perceived gap in the literature of his science by offering a detailed examination of the geographical diversity of the Yucatán Peninsula (Dunning et al. 1998:91). Since the peninsula as defined by Wilson (1980:6, 8) included not only Yucatán, Campeche, and Quintana Roo, but also Belize and the Petén, it was essentially equivalent to the Maya Lowlands (minus a few parts of the Southern Maya Lowlands). In addition to describing and classifying the geology, topography, climatology, vegetation, and soil of the region, he made use of the above lines of information to construct a novel map that divided it into fourteen physiographic districts (Wilson 1980:6-16, 19-35). At the time of publication, Wilson (1980:5) admitted that it was "still true that Yucatan [was] one of the least explored land areas in North America"; still, the author made the most of his expertise as a geographer and the information then available to him.

In the 1990s, fellow geographers Nicholas Dunning and Timothy Beach brought Wilson's physiographic map up to date, and (with the help of two additional authors) not only revised it further, but also expanded its spatial range to include more of the Southern Maya Lowlands (Dunning and Beach 1994:63; Dunning et al. 1998:89, 91). While their work transformed Wilson's (1980:7-9) fourteen physiographic districts into twenty physiographic regions (Dunning and Beach 1994:63) and, subsequently, twenty-seven adaptive regions (Dunning et al. 1998:89), their underlying principle, and basis on fine-grained and up-to-date geographical information, remained the same (Dunning et al. 1998:87-88, 90-91). In fact, the article featuring their 1998 incarnation has continually been cited by scholars writing about the Maya Lowlands up to the present day (e.g., A. Chase et al. 2014:13; Dahlin 2002:333; Ebert et al. 2014:349; Hoggarth et al. 2016:27). Unfortunately, while geographers have long recognized the geographical diversity of the Maya Lowlands, the Maya archaeologists who have explicitly acknowledged their findings and incorporated them into their research (e.g., A. Chase et al. 2014; Garrison and Dunning 2009; Hoggarth et al. 2016; Iannone et al. 2014) appear to be in the minority. I would argue that to ignore the differences in topography, geology, and climatology that are apparent within the Maya region and each of its subregions is to limit one's (and one's readership's) understanding of the physical environments by which Maya societies (and Maya culture) were affected.

Maya Chronology

In a similar vein, Maya archaeologists (and other scholars who have written about the ancient Maya) have found it convenient to divide Precolumbian Maya prehistory and history into a set of somewhat standardized categories (A. Chase et al. 2014:14; Demarest 2004:12-13; Sharer and Traxler 2006:98; J. Webster 2000:7). As with the spatial subregions, the temporal subdivisions are not defined identically by all scholars, but those detailed below are both fairly conventional and employed throughout this thesis. Although some archaeologists have studied the Paleoindian (12,000 to 8000 B.C.) and Archaic (8000 to 2000 B.C.) periods (Sharer and Traxler

2006:98, 153-156), most Mayanists have focused their scholarly attention on the Preclassic, Classic, and Postclassic periods, which also comprise the temporal focus of this thesis.

The longest of the three, the Preclassic period lasted from ca. 2000 B.C. until A.D. 250, and is subdivided into the Early, Middle, Late, and Terminal Preclassic (Sharer and Traxler 2006:98, 155). The Early Preclassic (the second millennium B.C.) saw the dawn of complex societies in the Maya region; these Maya societies increased in socioeconomic complexity during the Middle Preclassic (the tenth through fifth centuries B.C.). The first fully-fledged Maya states arose in the Late Preclassic (the fourth through first centuries B.C. and first century A.D.) (Sharer and Traxler 2006:98), but some of these early states evidently dissolved and were depopulated during the Terminal Preclassic (from A.D. 100 to 250), in a development that affected the Mirador Basin and has been termed the "Preclassic Abandonment" (Medina-Elizalde et al. 2016:94; Sharer and Traxler 2006:98).

It bears mention, however, that the phrase "Preclassic Abandonment" originally referred to a culture-change event that, like the later "Maya Collapse" to which it has been compared, supposedly entailed the abrupt abandonment of sites throughout the Maya Lowlands (Hansen et al. 2002; Medina-Elizalde et al. 2016:93-94; D. Webster 2002:190; J. Webster 2000:9; J. Webster et al. 2007:1-2). Although its use has evidently fallen out of favor in archaeological circles, the two-word phrase has frequently and continually graced the pages of paleoclimatological publications on the Maya region (e.g., Hodell et al. 2007:215; Medina-Elizalde et al. 2016:93-94; Rosenmeier et al. 2002a:183, 189; J. Webster et al. 2007:1-2, 12, 15). Interestingly, it appears to owe its origin (and present-day popularity among paleoclimatologists) to a handful of sources that were authored by a handful of Maya archaeologists. Specifically, these were a published site report by Richard Hansen (1990), and journal articles by Bruce Dahlin (1983) and Ray Matheny (1986). Both articles describe the apparent phenomenon without naming it (Dahlin 1983:245, 251, 257-261; Matheny 1986:352). However, the former appeared in a climate-change-themed journal, and the latter is cited in a book by David Webster that, like the Hansen report, names the phenomenon (Dahlin 1983:245; Hansen 1990:216; D. Webster 2002:190, 357). What is more, a book by Richardson Gill cites the 1983, 1986, and 1990 publications, while the Dahlin article, the Gill book, and the Webster book are widely cited in the literature on Maya paleoclimatology (Gill 2000:401, 410, 420; Hodell et al. 2007:239-240; Medina-Elizalde et al. 2016:102; Rosenmeier et al. 2002a:190; J. Webster 2000:212; J. Webster et al. 2007:16).

A reexamination and reevaluation of the Dahlin (1983), Matheny (1986), and Hansen (1990) sources, however, would reveal a number of issues that have not been noted in the subsequent non-archaeological writings they have influenced. First, the three Mayanists appear to disagree with one another as to at which Maya sites the “Preclassic Abandonment” took place. Although a whopping forty-two sites are named by Hansen, only ten of them are also mentioned by Dahlin, while a mere trio of Maya sites (i.e., Cerros, Edzná, and El Mirador) appear by name in all three Mayanist-authored sources. Second, all three authors include sites that simply underwent (apparent) population declines and/or (apparent) construction hiatuses, alongside those they characterize as having actually been abandoned, in their discussions of the phenomenon. Third, the authors conclusions were all based primarily on the results of archaeological fieldwork that was conducted during, and/or prior to, the early 1980s (Dahlin 1983:251, 257-260, 262; Hansen 1990:216, 218-220; Matheny 1986:351-352). While some radiocarbon dates had evidently been obtained, site chronologies were apparently based largely on the (potentially valuable, but arguably more contentious) identification and dating of ceramic types (Dahlin 1983:253; Hansen 1990:187-189, 216, 218-220; Matheny 1986:334, 336, 339; Matheny et al. 1983:29, 60). In addition, excavations at a number of Preclassic Maya sites had been either very limited or non-existent (D.S. Anderson 2011:301). Although each of the three authors had contributed to the relatively extensive fieldwork at El Mirador, they also all acknowledge the limitations of the (then-accessible) archaeological record of the region (Dahlin 1983:251-253, 261; Hansen 1990:vii, 216, 220-221; Matheny 1986:332, 352). As one bluntly admits: "The demise of this culture [i.e., the so-called Preclassic Abandonment], although unevenly manifest over the Lowlands, is poorly understood" (Matheny 1986:352).

Bearing the above issues in mind, what, if anything, can be said with certainty about the abandonments of Cerros, Edzná, and El Mirador? Archaeologists' understanding of Preclassic Edzná has advanced little in the past quarter-century, and the precise timing of its abandonment is still uncertain (D.S. Anderson 2011:301-302; Faust 2001:156; Hansen 1990:219; Matheny et al. 1983:197-198). Even if it were determined to have been contemporaneous to the abandonments of Cerros and El Mirador, however, I would argue that the Northern Lowland site's abandonment is unlikely to have had the same cause as its Southern Lowland counterparts, due to its distant location (in northern Campeche, or, if one prefers, the northern part of the Edzna-Silvituk Trough adaptive region) (Dahlin 1983:247; Dunning and Beach 2010:370). The Southern Lowland sites of Cerros and El Mirador, on the other hand, are not only nearer to one another than to Edzná, but have also been subjected to more seasons of archaeological excavation (than their Northern Lowland counterpart), the results of which indicate that the pair of Maya cities were abandoned contemporaneously, in the mid-second century A.D. (Hansen et al. 2002:273; Walker 2005:2-3, 6, 15, 25). However, while Cerros and El Mirador are relatively close to one another, they are located in different adaptive regions (the former on the Caribbean Reef & Eastern Coastal Margin; the latter on the Petén Karst Plateau) (Dunning et al. 1998:89; Dunning and Beach 2010:370; Walker 2005:3). Furthermore, each site shares its adaptive region with at least one Maya site that was occupied during the Preclassic but not abandoned at its close (Santa Rita Corozal in the case of Cerros; Tikal in the case of El Mirador) (D. Chase and A. Chase 1986:5-8, 1988:10-11; Dunning and Beach 2010:370; Iannone et al. 2014:163; Martin and Grube 2008:25-27; Walker 2005:3). Given the above considerations, I would argue that, while the El Mirador and Cerros abandonments may have shared a political or economic cause, they are unlikely to have shared a climatic one.

The Terminal Preclassic depopulation of El Mirador and its possible influence on the contemporary abandonment of Cerros and other sites are archaeological topics that are worthy of scholarly consideration. However, given the evidently localized and disjointed nature of the so-called "Preclassic Abandonment", and the broad spatial applicability and apparent causal unity of its original definition, I would consider the term's abandonment by Mayanists to have been wise, and its continual use by non-archaeologists (whether in reference to the Maya Lowlands at large or the Mirador Basin in particular) to be misguided and misleading.

A focus of numerous archaeological research projects, the Classic period lasted from A.D. 250 until 1000, and is subdivided into the Early, Late, and Terminal Classic (Sharer and Traxler 2006:98; J. Webster et al. 2007:7). The Early Classic (from A.D. 250 to 600) saw the rise of additional Maya states and the expansion of state-level civilization throughout the Maya

Lowlands (Sharer and Traxler 2006:98, 371, 374-376). Tikal, Calakmul, Caracol, and Copán were some of the more notable states that rose to prominence. In the last decades of the Early Classic and first decades of the Late Classic, the erection of inscription-bearing monuments and large-scale constructions apparently ceased at once-mighty Tikal; the phenomenon, which has been known by several names and will henceforth be referred to as the "Maya Hiatus", was originally regarded by Mayanists as an enigma (A. Chase and D. Chase 1987:59-60; Moholy-Nagy 2003:77; Thompson 1954:55-56; Willey 1974:417, 423-424). Subsequent archaeological and epigraphic research, however, has revealed that the so-called hiatus was essentially confined to Tikal and possibly due to the Petén polity's military defeat, which may have come at the hands of Caracol (A. Chase 1991:35-36; A. Chase and D. Chase 1987:33, 59-61; Houston 1987:93, 1991:40; but see Martin and Grube 1995:44 and Moholy-Nagy 2003:77, 82 for alternatives). During the Late Classic (the seventh and eighth centuries A.D.), Tikal resumed inscribing hieroglyphs on its monuments and waging war on its neighbors (Sharer and Traxler 2006:300-395, 400), and Maya states throughout the Southern Lowlands reached new heights of civilization (which is to say, power, and the use and display thereof).

The closing chapter of the period, the Terminal Classic (the ninth and tenth centuries A.D.) saw the dissolution of once-powerful polities and the depopulation of once-populous cities throughout the Maya Lowlands in an often-discussed, and even more often debated, phenomenon known as the "Maya Collapse" (Medina-Elizalde et al. 2010:255-260; Sharer and Traxler 2006:98, 499). As was the case with the (so-called) Maya Hiatus, developments at thoroughly-excavated Tikal were once thought to typify those at its contemporary sites (Aimers 2007:331, 351). While the Maya Collapse had much broader spatial applicability than the Maya Hiatus, archaeological and epigraphic research has revealed that its timing was not uniform (Aimers 2007:334-346; Medina-Elizalde et al. 2010:259-261). The dissolution and depopulation of sites in the Petexbatún subregion occurred in the early decades of the ninth century (Medina-Elizalde et al. 2010:259-260) (in a phenomenon to which I will henceforth refer as the “Petexbatún Collapse”); in contrast, analogous developments in the Puuc subregion (to which I will henceforth refer as the “Puuc Collapse”) did not take place until the early tenth century (Medina-Elizalde et al. 2010:260-261). The more “typically” timed collapses and abandonments of such Classic-period powerhouses as Tikal, Caracol, and Calakmul (i.e., the so-called Maya Collapse) evidently occurred after the Petexbatún Collapse but before the Puuc Collapse, and mostly in the latter half of the ninth century (Medina-Elizalde et al. 2010:260; Sharer and Traxler 2006:517-520; J. Webster et al. 2007:2).

Last but not least, the Postclassic period (the eleventh through fifteenth centuries A.D.), which many Mayanists choose not to subdivide (but see A. Chase et al. 2014:14; Dunning et al. 2015:169), saw the rise and/or fall of cities in the northern and eastern parts of the Yucatán Peninsula (Sharer and Traxler 2006:98, 591-613). While some, like the prosperous Belizean site of Santa Rita Corozal, were occupied until the arrival of Europeans (D. Chase and A. Chase 1988:2,7; Iannone et al. 2014:163), others, like the once-mighty Mexican site of Mayapán, dissolved and were depopulated prior to the Spanish Conquest (Hoggarth et al. 2016:39; Sharer and Traxler 2006:603). East of Mayapán, Chichén Itzá, a site that had first risen to prominence in the Terminal Classic, suffered its own collapse in the late eleventh century (Kennett et al. 2012:790-791; Sharer and Traxler 2006:591-593). In the sixteenth and seventeenth centuries, the entire Maya region and the lives of its indigenous people were permanently altered by the

Spanish Conquest, a culture-changing event that was arguably more drastic, and certainly more widespread, than the so-called Maya Collapse. The Spanish Conquest was followed by a period of Spanish and British colonialism, which ended with the independence of Mexico and the modern-day nations that comprise Central America. Today, millions of Maya people continue to inhabit the region of their ancestors, and many of their ancestral languages continue to be spoken (A. Chase et al. 2014:13; Sharer and Traxler 2006:23). However, the Postcolumbian periods of Maya history are beyond the scope of this thesis.

Although much of this thesis stresses taking the finer points of geography and speleothem paleoclimatology into consideration when seeking scientific answers to archaeological questions (about the relationship between climate change and culture change in the case of the ancient Maya), I hope that the facts and comments about Maya chronology I have just presented (and particularly those relevant to the Preclassic Abandonment, the Maya Hiatus, and the Maya Collapse) amount to a compelling argument for the importance of informing one's paleoclimatological research and writings with archaeological data that is fine-grained and up-to-date.

CHAPTER TWO: BACKGROUND

Speleothem Paleoclimatology

"In recent years", according to a recently published textbook on the subject, "speleothems have been established as one of the most valuable resources for understanding… the regional to global patterns of change that characterize former environments and climates" (Fairchild and Baker 2012:3). More specifically, the authors of an even more recently published article on paleoclimatological methodology have identified speleothem analysis as one of "[t]he two most promising approaches for reconstructing past climate in the Maya area" (Douglas et al. 2016:5), the other being paleolimnology. In view of their importance within Maya paleoclimatology and their centrality to my thesis, I will now provide some relevant background information on speleothems and their analyses.

Speleothems are naturally occurring cave deposits, and two of the more visually prominent, and paleoclimatologically relevant, types of speleothems are stalactites and stalagmites (Fairchild and Baker 2012:3). Stalactites grow down from the ceiling of a cave, stalagmites grow up from its floor, and both are sometimes referred to as dripstones, since they are essentially made of stone and created through the dripping of water. As rain falls through Earth's atmosphere, it combines with carbon dioxide and becomes carbonic acid (Douglas et al. 2016:6). As the carbonic acid seeps through limestone, it dissolves some bedrock (with calcium and bicarbonate ions) into underground caves. As a result, stalactites and "soda straws" (hollow, tubular speleothems), both of which are made of calcium carbonate, form on cave ceilings. When water passes through a "soda straw" and hits the cave floor below, carbon dioxide outgasses, and the remaining calcium carbonate lands in a particular spot on the cave floor, where, over time, a stalagmite builds up (Fairchild and Baker 2012:6). Although cave stalactites can be, and have been, used to reconstruct paleoclimate (e.g., Dill et al. 1998), cave stalagmites are considered better-suited to the task; since the internal structures of stalagmites are comparatively simpler, their interpretation is more straightforward (Fairchild and Baker 2012:3-4). Unlike stalactites, a typical stalagmite has "internal layering which tends to be flat on the top of the sample, allowing a set of observations representing different time periods in the past… to be generated along a sub-vertical line" (Fairchild and Baker 2012:4). Additionally, paleoclimatologists have generally avoided the analysis of speleothems that form in or near the entrances of caves, since their formation (and hence their composition) is potentially affected not only by above-cave precipitation (and the aforementioned subsequent geological processes), but also by evaporation (as a result of their exposure to the outside atmosphere). Since speleothems that develop deeper within cave interiors are understood to be immune to the potentially confounding effects of evaporation, their analysis for paleoclimatic purposes is much less controversial, and therefore much more common (Hendy 1971:801, 820-822).

Paleoclimatic Proxies

Oxygen and Carbon Stable-Isotope Analysis

Their structures, compositions, locations, and formation processes enable stalagmites to preserve the isotopic composition of rainwater (which can reflect precipitation amount) from a particular point in the past for posterity (Douglas et al. 2016:6; Fairchild and Baker 2012:3). Uncoincidentally, stable-isotope analysis is a popular proxy for ascertaining patterns in past precipitation (D.E. Anderson et al. 2013:29-30). Basically, isotopes are different nuclides of the same element (Douglas et al. 2016:4); they are similar in terms of proton quantity, electron quantity, atomic number, and electric charge, but different in terms of neutron quantity and mass. Isotopes' mass difference is important, because it is the reason for fractionation, which is when a change like condensation or evaporation causes a change in isotope ratio (D.E. Anderson et al. 2013:30; Douglas et al. 2016:4). After a stalagmite has been removed and halved, it is sent to a laboratory, where scientists extract samples and use a mass spectrometer to measure the isotope ratio of each sample (Douglas et al. 2016:4,6). Of the element oxygen, the ratio of 18O to 16O molecules is measured, while the relevant ratio for carbon is of 13C to 12C molecules (D.E. Anderson et al. 2013:29-30; J. Webster 2000:54). Because the above isotopes never decay, they are called stable isotopes (as opposed to radioactive isotopes like 14C, which decay over time). Whichever the element, each ratio is expressed in delta notation, which entails solving a particular mathematical equation that incorporates the stable-isotope ratio itself and a particular standardized stable-isotope ratio (D.E. Anderson et al. 2013:30; Brenner et al. 2002:144; Douglas et al. 2016:4; J. Webster 2000:54-55).

Although they are not the only stable isotopes in existence, oxygen and carbon isotopes are by far the ones most relevant to Maya paleoclimatology, and oxygen isotopes are considered the more scientifically valuable of the two (Douglas et al. 2016:7-8). Unlike carbon-isotope ratios, which can potentially be influenced by agricultural activities and other anthropogenic factors, oxygen-isotope ratios can serve as reliable records of paleoclimate alone, since they are generally unaffected by possible changes in land use and vegetation. Although temperature and precipitation intensity are also potentially influential factors in regions north and south of the tropics, precipitation amount is considered the only factor that significantly influences oxygen-isotope ratios and their change over time in such tropical areas as the Maya Lowlands (Douglas et al. 2016:5). Despite its evident inferiority to oxygen-isotope analysis (a.k.a. δ18O [J. Webster 2000:178] or O isotope analysis [J. Webster et al. 2007:4]), however, carbon-isotope analysis (a.k.a. δ13C [J. Webster 2000:178] or C isotope analysis [J. Webster et al. 2007:4]) is nevertheless a common feature of Maya paleoclimatic studies, because it can confirm (or refute) the scientific validity of the results of the oxygen-isotope analysis of a speleothem via the Hendy test (Douglas et al. 2016:8; Wong and Breecker 2015:7).

The issue of whether the isotopic data of a given paleorecord faithfully recorded climatic conditions or was potentially compromised by non-climatic factors has, for obvious reasons, been a pressing concern in speleothem paleoclimatology. Besides taking notice of such details as the cave location whence a particular speleothem was extracted, one can potentially ascertain its reliability by subjecting it to one or more of a handful of specialized tests and observing whether it “passes” or “fails”. The specialized tests described below are the Hendy test, the replication test, and the equilibrium test. While each of the three tests has its disadvantages, each is also considered to have scientific merit.

The Hendy Test

The Hendy test entails conducting carbon and oxygen isotope analyses on pairs of samples along, and/or perpendicular to, the growth axis of a speleothem (Douglas et al. 2016:7; Wong and Breecker 2015:7). If the carbon and oxygen isotope ratios do not co-vary, and if the oxygen isotope ratio remains constant along a single growth layer, the relevant speleothem dataset is said to have "passed" the Hendy test and to therefore be a reliable paleorecord (Dorale and Liu 2009:73; Lachniet 2015:1531). The basis of the Hendy test is that speleothems that did not precipitate in isotopic equilibrium with cave drip waters are susceptible to the isotopic effects of kinetic fractionation, which can alter oxygen-isotope ratios and thereby render them unreliable as indicators of paleoclimate. By virtue of being free from the potentially confounding influence of kinetic effects, a speleothem paleorecord that has "passed" the Hendy test (i.e., has yielded oxygen and carbon isotope ratios that do not appear to co-vary) may be interpreted as purely a reflection of past climatic conditions (Douglas et al. 2016:7; Wong and Breecker 2015:7).

While the Hendy test is often employed to assess the validity of speleothem datasets, some scholars have expressed reservations about the validity of the Hendy test itself (Dorale and Liu 2009:73-74, 78; Lachniet 2015:1531; Wong and Breecker 2015:7). Since oxygen-isotope ratios might potentially be constant along a single growth layer even in speleothems that precipitated under non-equilibrium conditions, and since oxygen and carbon isotope ratios might potentially co-vary even in speleothems that precipitated in equilibrium with cave drip water, it has been argued that the possibilities of "false positives" and "false negatives" bear consideration (Dorale and Liu 2009:73,76; Lachniet 2015:1531). In light of the Hendy test's shortcomings, its critics have argued for the implementation of alternative or additional tests to evaluate the reliability of speleothem paleorecords. In particular, such critics have advocated that the datasets be subjected to the replication test (Dorale and Liu 2009:73-74; Lachniet 2015:1521, 1531-1532; Wong and Breecker 2015:7).

The Replication Test

The replication test entails examining multiple contemporaneous stalagmites from the same cave or region and comparing the results of their isotopic analyses. If they significantly resemble one another, their isotopic similarity is interpreted as an indication that they were not compromised by kinetic effects and therefore faithfully recorded (the same) paleoclimate (Dorale and Liu 2009:74, 78; Lachniet 2015:1522). Since the replication tests offers an antidote to the potential errors of the Hendy test, the argument for its implementation is quite strong. However, since political and financial considerations (i.e., the difficulties of securing the necessary permission to extract speleothems and the necessary funding to analyze them) tend to limit the quantity of speleothems that represent a given cave or region, the replication test is not always an option (Dorale and Liu 2009:78; Lachniet 2015:1532). The Hendy test, on the other hand, requires but a single stalagmite, and, unlike the replication test, is often a mandatory prerequisite to the publication of the results of one's paleoclimatic research (Dorale and Liu 2009; Lachniet 2015:1531). As long as the above (political, financial, and academic) circumstances stay the same, it appears likely that the Hendy test, for better or worse, will continue to be a more common means of ascertaining the validity of speleothem paleoclimate records.

The Equilibrium Test

The equilibrium test, which is less commonly mentioned than the replication test but does not require the extraction and analysis of multiple stalagmites, is another potential alternative (or supplement) to the Hendy test (Lachniet 2015:1521-1522). In order to carry out the equilibrium test, one must have access to a few key pieces of information: the oxygen-isotope measurements of the drip waters that have contributed to the growth of a particular speleothem and of modern drip waters, the temperature of the cave during the relevant carbonate precipitation, and the mineralogy of the stalagmite in question (i.e., whether it is composed of calcite, aragonite, or both) (Lachniet 2015:1522). If the (water-calcite or water-aragonite) fractionation factor that is ascertained through the application of the data to a particular mathematical equation is comparable to what one would expect from a speleothem precipitated in equilibrium, the paleorecord is said to have “passed” the equilibrium test and to be a reliable (or, at least, not unreliable) one (Lachniet 2015:1522-1523, 1528). While the equilibrium test is apparently less error-prone than the Hendy test and more economical than the replication test, it involves comparing a stalagmite paleorecord to freshly-gathered data and therefore is not easily applicable to inactive speleothems or older portions of active ones (Lachniet 2015:1531-1532). Since each method of evaluation has its own limitations, it appears that the best solution to the problem of assessing the validity of speleothem datasets would be to follow the expert advice of geoscientist Matthew Lachniet (2015:1521, 1531-1532), who has recommended implementing as many of the above methods as circumstances allow.

Luminescence Analysis

An alternate analysis to which a cave speleothem can be subjected to ascertain paleoclimate is luminescence (Brennan and White 2013:210; Douglas et al. 2016:8; J. Webster 2000:37) (a.k.a. "paleoluminescence" when applied to this purpose [Shopov 2004a:5, 2004b:28]). Luminescence refers to the use of photography or lasers to expose a stalagmite to ultraviolet light, in order to measure its humic substance content (Douglas et al. 2016:8; J. Webster 2000:60, 62-63). Long-term changes in humic concentration are interpreted as reflections of climatic changes (Douglas et al. 2016:8). This interpretation relies upon the assumption that increased rainfall leads to increased plant productivity, which leads to the increased dissolution of organic acids in groundwater, which leads to increased luminescence in speleothems in underground caves (Douglas et al. 2016:8).

Besides depending upon an unconfirmed assumption about an indirect relationship, a number of problems with luminescence analysis have, unfortunately, come to light. For instance, the luminescent banding that appears on a speleothem under ultraviolet light is a potentially accurate rainfall proxy only if it is caused solely by the presence of organic material (Shopov 2004a:7,9, 2004b:28,32). Since the invention of luminescence analysis, however, it has come to light that some inorganic materials can also cause banding in speleothems (Shopov 2004b:28-32). Although inorganic-material-induced luminescent banding resembles organic banding visually, it does not carry the same paleoclimatic implications (Shopov 2004b:28). Basically, if at least some of a stalagmite's luminescent banding is inorganic, the results are scientifically invalid, but determining whether banding is organic, inorganic, or mixed is a challenging task (Shopov 2004a:9, 2004b:28, 32). Another issue that complicates the interpretation of luminescence-analysis results is that of spatial applicability. To wit, scientists have found that even evidently paleoclimatologically valid speleothems from the same cave can have sharply different luminescence records (Brennan and White 2013:216). Because of this, it has been argued that luminescence signals in speleothems reflect the extremely localized conditions above one particular part of a cave, as opposed to the climatic patterns of the surrounding region (or even, for that matter, the entire area above a single cave) (Brennan and White 2013:216-217).

Chronometry

U-Series Dating

Since paleoclimatologists seek to understand climatic changes over time, and Maya archaeologists seek to understand their relationship (or lack thereof) to cultural changes, absolute dating is an essential component of speleothem studies, and especially of those conducted in the Maya region (Douglas et al. 2016:3, 6; McDermott 2004:901-902; Wong and Breecker 2015:1). Just as oxygen stable-isotope analysis has become the preferred means of ascertaining paleoprecipitation, U-series dating has risen to prominence as the preferred means of speleothem chronometry (Douglas et al. 2016:6-7; Fairchild and Baker 2012:7,9). U-series dating (a.k.a. uranium-series [D.E. Anderson et al. 2013:49], uranium-thorium [Douglas et al. 2016:6], U-Th [Medina-Elizalde at al. 2016:93], U/Th [Medina-Elizalde et al. 2010:256], or 234U-230Th [Kennett et al. 2012:788] dating) uses a mass spectrometer to measure the proportions of 238U, 234U, and 230Th in samples (Douglas et al. 2016:6). 238U and 234U are isotopes of uranium, and 230Th is a thorium isotope that is also the daughter isotope of 234U; all three are radioactive (as opposed to stable) isotopes that decay over time (D.E. Anderson et al. 2013:61; Douglas et al. 2016:6). In that it establishes a chronology by measuring radioactive isotopes in a series of samples, it is reminiscent of radiocarbon dating (a.k.a. 14C dating [J. Webster et al. 2007:3]) (D.E. Anderson et al. 2013:61), which is more familiar to most archaeologists.

U-Series Dating vs. Radiocarbon Dating

Although both the U-series and radiocarbon dating methods can be, and have been, successfully applied to speleothems, they differ from one another in significant ways. First, because of the relatively long half-lives of the relevant isotopes, U-series dates that go back literally hundreds of thousands of years are attainable from sufficiently old samples (D.E. Anderson et al. 2013:61, 65; Douglas et al. 2016:6; Fairchild and Baker 2012:7, 291). Radiocarbon dates, in contrast, only go back as far as tens of thousands of years before present (D.E. Anderson et al. 2013:61, 63). Second, the U-series method allows researchers to establish a chronology without having to obtain and apply detailed and accurate information about atmospheric content and its change over time, which is a potential source of dating error in the radiocarbon method (Douglas et al. 2016:7). Third, since uranium and thorium naturally occur in cave deposits, samples from throughout a speleothem can be analyzed to obtain U-series dates; on the other hand, a stalagmite can only be radiocarbon dated through the analysis of terrigenous macrofossils, which are unlikely to be present throughout a given speleothem (if at all) (Douglas et al. 2016:7). Fourth, since U-series dating does not involve the analysis of 14C, it is immune to the uncertainties introduced by the "dead carbon" effect (Fairchild and Baker 2012:294). Because some of the carbon present in speleothems comes from bedrock and is therefore ancient, a speleothem may yield artificially early radiocarbon dates. Even more unfortunately, the proportion of a speleothem's 14C that is "dead carbon" from bedrock is not only potentially high, but unpredictably variable, even within a single stalagmite (Fairchild and Baker 2012:294).

The first comparative advantage of U-series dating is obviously irrelevant to Maya archaeology and its investigation of climate change as a potential driver of culture change. Its second, third, and fourth advantages, however, mean that chronologies can be obtained from speleothems more easily, more often, and more reliably with the U-series method than with the radiocarbon one.

U-Series Dating vs. Lead-Isotope Dating

The lead-isotope analysis (a.k.a. 210Pb [J. Webster et al. 2007:4] or lead-210 [D.E. Anderson et al. 2013:65] analysis) of stalagmites, which obtains dates by measuring the amount of 210Pb in samples, is also possible (D.E. Anderson et al. 2013:65; Fairchild and Baker 2012:299; J. Webster et al. 2007:4); its dates, unfortunately, go back merely decades (D.E. Anderson et al. 2013:65). While 210Pb dating can obviously not be used as an alternative to the U-series method in the analysis of speleothems that would be of interest to Mayanists (D.E. Anderson et al. 2013:65), it can be, and has been, employed as an additional method, in order to maximize the quality and reliability of the most recent portion of a stalagmite-derived chronology (J. Webster et al. 2007:4, 6-7).

The History of Speleothem Paleoclimatology

The paleoclimatic examination of speleothems through the laboratory analysis of their stable isotopes was first developed in the 1960s (McDermott 2004:901). Although the Hendy test was also developed at that time to ensure the validity of isotopic results, the dating methods then available left much to be desired. To wit, scientists were forced to choose between radiocarbon dating, which had its own limitations when applied to speleothems (as delineated above), and an early form of the U-series method known as alpha-spectrometric U-series dating (McDermott 2004:901). Unfortunately, the U-series dating of speleothems by alpha-spectrometry not only required the extraction of very large samples, but also produced dates with a very low degree of precision (McDermott 2004:901-902). Fortunately, the 1980s saw the dawn of thermal ionization mass-spectrometric (a.k.a. TIMS) U-series dating, a superior form of the method that not only could be conducted with samples approximately ten times smaller, but also generated dates roughly ten times more precise (McDermott 2004:901-902). The TIMS technique was itself improved upon in the early 2000s, when plasma-ionization magnetic-sector mass-spectrometric (a.k.a. PIMMS) U-series dating, which raised the bar yet higher with its smaller sample-size requirement and higher analytical-precision potential, was introduced (McDermott 2004:902). In the twenty-first century, the new-and-(twice-)improved U-series dating of speleothems is not only on par with rival forms of paleoclimatic chronometry (e.g., the radiocarbon dating of lake-sediment cores, as will be detailed below), but arguably their superior.

The History of Maya Speleothem Paleoclimatology

At the close of the twentieth century, the results of the analyses of only two speleothems from the Maya region had appeared in print (Dill et al. 1998; J. Webster 2000). One was a stalactite from a cavern on an atoll, off the east coast of Belize (Dill et al. 1998:189); the other, a stalagmite from a chasm on a plateau, in the far west of Belize (J. Webster 2000:ii,76, 79, 85). Both were radiocarbon dated, and both were subjected to oxygen-isotope and carbon-isotope analyses (Dill et al. 1998:193-195; J. Webster 2000:90-91, 101). In addition, U-series dates, and measurements of magnesium, sodium, and strontium content, were taken from the stalactite from Blue Hole, Lighthouse Reef (Dill et al. 1998:193-195) (See Table 2); luminescence and grayscale reflectance analyses were conducted on the stalagmite from Macal Chasm (See Figures 1 and 4), Vaca Plateau (J. Webster 2000:ii, 90, 96, 101). Lighthouse Reef has apparently always been uninhabited by humans, and its stalactite was analyzed to ascertain past changes in sea level (Dill et al. 1998:189-190, 195-196); the Vaca Plateau, while also uninhabited at the time of analysis, was home to a number of Maya archaeological sites (most notably Caracol), and MC-01 (See Table 2), as its stalagmite was named, was analyzed to ascertain past changes in rainfall, and especially during the time of Maya occupation (J. Webster 2000:ii, 1-3, 79-83). Each study, in its own way, foreshadowed the work that would be done on speleothems in the following (now current) century: An early use of the U-series method was made on the Blue Hole stalactite (Dill et al. 1998:194-195), while MC-01 was but the first of several stalagmites that would be studied as archives of paleoprecipitation, and not the last that would be invoked as a data source in hypotheses about Maya droughts and their evident sociocultural effects (Webster 2000:ii-iii, 3). The analyses were similar, however, in having been published by non-archaeologists in non-anthropological venues (Dill et al. 1998:189; J. Webster 2000:i, iv), and having had no apparent effect on Maya archaeology, at least initially.

In Volume 13 of *Ancient Mesoamerica*, an archaeological journal that is widely read by Mayanists, a two-issue special section entitled "Historical Climatology in the Maya Area" appeared. In it, scholars of various stripes, and working in various parts of the Maya region, each enlightened the journal's readership with the fruits of their expertise and research on Precolumbian Maya paleoclimatology (Brenner et al. 2002; Dahlin 2002; Fowler 2002; Fowler and Morgan 2002; Gill and Keating 2002; Gunn et al. 2002a, 2002b; Hansen et al. 2002; Leyden 2002; Messenger 2002; Popenoe de Hatch et al. 2002; Robichaux 2002; Rue et al. 2002; Siemens et al. 2002; Vargas Pacheco 2002). While none of the articles contained therein dealt with speleothems per se, the special section may well have inspired more Maya archaeologists, and perhaps more archaeologically-themed academic journals, to turn their scholarly attention toward the search for conclusive evidence for Precolumbian climate change, as opposed to simply for the Maya cultural developments that may or may not have been responses thereto. Then again, the subsequent novel presence of speleothem-based paleoclimatology within Maya archaeology may have been more (if not entirely) due to the introduction of PIMMS U-series dating (which is alluded to above, and which also took place in 2002) (McDermott 2004:902) than to the publication of the *Ancient Mesoamerica* special section.

In the remainder of the 2000s (i.e., 2002-2009), the results of four Central American speleothem analyses (See Table 2) appeared in print. However, two were analyses of speleothems (V1 and CHIL-1) from south of the Maya region (Venado Cave in Costa Rica, and Chilibrillo Cave in Panama, respectively) (Lachniet et al. 2004a, 2004b), and a third was an analysis of a Belizean speleothem (ATM7, from ATM Cave [a.k.a. Actun Tunichil Muknal, or the Cave of the Stone Sepulchre {Frappier 2008:34}]) whose entire temporal range postdated the end of the Postclassic period (Frappier et al. 2002, 2007). The fourth was actually a reanalysis of MC-01, but one with a new chronology that was primarily based on U-series (as opposed to radiocarbon) dating, and a revised climatology based chiefly on luminescence data (as opposed to an amalgamation of data from four paleoprecipitation proxies) (J. Webster et al. 2007). (See "Findings" for further details on the 2007 reanalysis, and the 2000 initial analysis, of MC-01.)

The 2010s have thus far seen the publication of the results of the analyses of thirteen Mexican and Central American speleothems (See Table 2). However, four of the Mexican speleothems (CBD-2, JX-1, JX-6, and JX-7) were from west of the Maya region (la Cueva del Diablo and Juxtlahuaca Cave [a.k.a. JX Cave {Lachniet 2015:1523}], respectively, both in Guerrero) (Bernal et al. 2011; Dunning et al. 2015:171; Lachniet 2015; Lachniet et al. 2012a, 2012b). Furthermore, while all of the Central American speleothems were from Belize, four (YOK-G, ATM1, CH04-02, and CH04-03; from Yok Balum Cave, ATM Cave, and Chen Ha Cave) had temporal ranges that either postdated the Spanish Conquest or predated the Preclassic Abandonment (Crosby 2010; Pollock 2015; Ridley 2014), and two (VP-10-1 and VP-10-2, both from Vaca Perdida Cave [a.k.a. la Cueva de la Vaca Perdida, or the Cave of the Lost Cow {Smyth et al. 2011:26}]) had yielded dating results so poor that their inadequacy was admitted even by the authors who published them (Smyth et al. 2011:39-41). In fact, since the appearance of the MC-01 studies (J. Webster 2000; J. Webster et al. 2007), only three articles that presented novel, and potentially valid, data from speleothems from the Maya region, and with temporal ranges that coincided with the Preclassic Abandonment and/or the Maya Collapse, have appeared. The relevant speleothems were Chaac, YOK-I, and Itzamna, from Tzabnah Cave (a.k.a. Tecoh Cave [Medina-Elizalde et al. 2010:256]; See Figures 2 and 5), Yok Balum Cave (a.k.a. Jaguar Paw Cave [Kennett et al. 2012:S1]; See Figures 3 and 4), and Río Secreto (See Figure 5), respectively (Kennett et al. 2012; Medina-Elizalde et al. 2010, 2016). (See "Findings" for further details on the analyses of Chaac, YOK-I, and Itzamna.) Each and every one of the Mexican and Central American speleothems whose data has been disseminated in the 2010s has been subjected to oxygen stable-isotope analysis for paleoclimatic purposes, and to the U-series dating method for chronometric ones. Whether the future will see the above modes of analysis improved, replaced, or neither remains to be seen; it would appear, however, that luminescence analysis and radiocarbon dating as means to extract climatologies and chronologies (respectively) from speleothems have become things of the past.

Paleolimnology

The second of the "two paleoclimate archives [that] have been most widely applied in the Maya Lowlands and have the greatest potential to provide insights into climate change impacts on the ancient Maya" (Douglas et al. 2016:3) is paleolimnology, or lake sediment cores. Like cave speleothems, lake cores can be removed, sampled, and analyzed in a laboratory (Brenner et al. 2002:144-145). More specifically, and again as with speleothems, the oxygen and carbon stable-isotope ratios of samples from lake cores can be measured with a mass spectrometer, and inferences regarding paleoprecipitation and paleoenvironment can be drawn from the results (D.E. Anderson et al. 2013:48-49; Douglas et al. 2016:10-13; Leng and Marshall 2004:811-812; Rosenmeier et al. 2002b:120-121). While the results of lake-core carbon-isotope analyses have been interpreted to reflect such anthropogenic paleoenvironmental changes as deforestation, those of oxygen-isotope analyses have been interpreted as records of mostly non-anthropogenic changes in paleoprecipitation, such as droughts (Douglas et al. 2016:10-13; Rosenmeier et al. 2002b:117, 119). Some lakes are inhabited by species of freshwater shellfish and aquatic snails whose carbonate shells record the particular isotope ratios prevalent during their owners' lifetimes, become fossilized in lake sediments, and thereby preserve paleoclimatic data for posterity (Brenner et al. 2002:142; Leng and Marshall 2004:823-824). Although such fossilized shells lack uranium and thorium and therefore cannot be chemically dated via the U-series method, they can, being the remains of carbon-based life forms, yield radiocarbon dates (Brenner et al. 2002:142; Douglas et al. 2016:9; Rosenmeier et al. 2002b:117).

Unfortunately, just as radiocarbon dates from cave speleothems are susceptible to the "dead carbon" effect, those from lake cores are susceptible to hard-water-lake error (Douglas et al. 2016:9). Acidic rain dissolves limestone bedrock (which is, as mentioned above, so ancient as to have become "14C-dead"), and causes its bicarbonate ions to bleed into lakes (through runoff), where it may be used for photosynthesis by algae, which may be consumed by zooplankton, which may themselves be consumed by larger forms of aquatic life, whose fossilized remains may therefore include at least some "dead carbon" from bedrock and appear to scientists as older than its true age (Douglas et al. 2016:9). The fossilized remains of terrestrial plants and other land-based life forms that had fallen into lakes would be immune from the possibility of hard-water-lake error; however, they tend to be found neither abundantly nor consistently-distributed (if at all) in lake-sediment cores. Other potential sources of error include the inherent limitations of the radiocarbon dating process and (as mentioned above) imperfectly understood variations in atmospheric content over time (Douglas et al. 2016:9).

The History of Paleolimnology

The analysis of oxygen stable isotopes for paleoclimatic purposes was first developed in the 1950s; at that time, however, it was primarily seen, and employed, as a means of reconstructing paleotemperature (as opposed to paleoprecipitation) (Leng and Marshall 2004:811; McCrea 1950:849, 857; Urey et al. 1951:399, 414-415). In the 1960s, the effect of precipitation and evaporation on oxygen-isotope ratios in bodies of water was discovered (Covich and Stuiver 1974:682-683), while the ratio of inflow (which includes precipitation) to evaporation was identified as the determining factor in the isotopic compositions of lakes.

The History of Maya Paleolimnology

The 1960s also saw the publication of the results of the first lake-core study to be conducted in the Maya region, by Ursula Cowgill and colleagues (Brenner et al. 2002:142; Douglas et al. 2016:3). Although they analyzed lake-core pollen (rather than faunal material) to investigate the effects of Maya actions on nature (rather than the other way around), it may be considered the dawn of Maya paleolimnology (Brenner et al. 2002:142-144; Douglas et al. 2016:3). Both Maya paleolimnology and the science behind it were taken a step further in the 1970s, when Alan Covich and Minze Stuiver (1974) published the results of their paleoclimatic examination of sediment cores from Lake Chichancanab (a.k.a. Laguna Chichancanab [Covich and Stuiver 1974:682]; See Figures 1, 2, and 5) (Brenner et al. 2002:144). Their pioneering study represented not only a breakthrough in the then-novel science of paleolimnology, but also a transformative moment for Maya paleoclimatology, since it included the first oxygen stable-isotope analysis from the Maya region (Douglas et al. 2016:10). In particular, Covich and Stuiver (1974:682), who had made a point of selecting a closed lake (since such lakes gain water in part through precipitation, but lose water exclusively through evaporation), ascertained a chronology through the radiocarbon method, and analyzed the oxygen-isotope ratios of samples from fossilized shells (Brenner et al. 2002:144; Douglas et al. 2016:10). While their study primarily aimed to discover past changes in lake level (as opposed to rainfall itself) (Covich and Stuiver 1974:682), it paved the way for the many subsequent studies of Maya-region lakes that followed.

Later in the decade, paleolimnologist E.S. Deevey teamed up with Maya archaeologists Don and Prudence Rice (and other co-authors) (1979) to produce a multidisciplinary paper that compared (then-)novel paleolimnological data and (then-)current archaeologically-derived information to investigate the relationship between Precolumbian Maya cultural change (in this case, population increase and decrease) and paleoenvironmental change (namely, deforestation and reforestation). Since the publication of Deevey and colleagues’ 1979 article, so many studies that presented paleolimnological data on climate change and drew conclusions about ancient Maya culture change have appeared in print (Douglas et al. 2016:10-12; Dunning et al. 2015:169-170) that it would be impractical to here offer a detailed overview of post-1979 Maya paleolimnology. After all, cores from Lakes Petenxil, Puerto Arturo, Quexil, Sacnab, Salpetén, and Yaxha, in the Petén (Guatemala); Lakes Cobá, Macanxoc, and Punta Laguna (See Figures 2 and 5), in Quintana Roo (Mexico); and Lakes Chichancanab and Sayaucil, in the Yucatán (Mexico) have all been analyzed to investigate past changes in precipitation, and those are just the studies cited in the publications that presented data from the Chaac, Itzamna, MC-01, and YOK-I speleothems (Kennett et al. 2012:789; Medina-Elizalde et al. 2010:256-261, 2016:93, 95, 97-100; J. Webster 2000:200-204; J. Webster et al. 2007:2, 15). Suffice it to say that, over the past (nearly) four decades, such articles have continually been written, read, and cited, and research methodologies (and thereby the precisions of radiocarbon dates and stable-isotope ratios) have consistently improved (Douglas et al. 2016:4,9-10; Dunning et al. 2015:169-170). Despite the disadvantages of paleolimnology relative to speleothem paleoclimatology (Douglas et al. 2016:7, 9), the analysis of lake cores is less destructive environmentally, and less expensive economically, than that of cave speleothems, and shows no signs of disappearing or being replaced. I would argue, however, that the results of studies of speleothems (that formed within cave interiors, are composed of calcite, and yield highly-resolved paleoprecipitation records) are nevertheless potentially much more valuable in the investigation of non-anthropogenic climate change and its possible effects on ancient cultures, due to the aforementioned challenges inherent in the interpretation of lake-core data.

Dendroclimatology

A third potential source of data on past rainfall patterns in the Maya region is dendroclimatology, or the analysis of tree rings to ascertain paleoclimate (Douglas et al. 2016:16) (as opposed to dendrochronology, which is their analysis for merely chronometric purposes [D.E. Anderson et al. 2013:50; Sharer and Ashmore 2003:326]). Because growth rings whose thickness is determined by precipitation amount form on trees annually, rainfall records that not only have annual resolution but convey chronological and paleoclimatic information in the same dataset (and without the need for isotopic analysis) are preserved for posterity (D.E. Anderson et al. 2013:50; Douglas et al. 2016:16). The methodology generally involves sampling the sequence of rings from each tree by using a coring device to remove a core of wood (that extends from its bark to its center), sanding and polishing the core, and then counting and measuring its rings (D.E. Anderson et al. 2013:50). The resulting dataset is then compared to data from the rings of similar trees that grew in the same general area, and, when possible, to other types of climatic data (D.E. Anderson et al. 2013:50-51).

The History of Dendrochronology and Dendroclimatology

As one might expect, the reconstruction of ancient climates through dendroclimatology was predated by the dating of ancient materials through dendrochronology (Sharer and Ashmore 2003:326-327). In fact, nineteenth-century American archaeologists like E.G. Squier and E.H. Davis would often turn to the method in their attempts to determine the ages of the structures and artifacts they discovered (Sharer and Ashmore 2003:53, 326). However, the modern version of dendrochronology, and its sister science of dendroclimatology, were both pioneered in the very early twentieth century by A.E. Douglass, an astronomer who sought to understand Southwestern US paleoclimate. By crossdating, which entails juxtaposing modern tree rings with rings from increasingly old trees, he demonstrated that one could potentially construct a paleoclimatic history longer than the lifespans of even the oldest and longest-lived trees (D.E. Anderson et al. 2013:50; Sharer and Ashmore 2003:327). In fact, a dendrochronological sequence spanning over ten millennia was derived from the rings of bristlecone pine trees (*Pinus longaeva* [D.E. Anderson et al. 2013:50]) from southeastern California (Sharer and Ashmore 2003:327). Following its successful application to the archaeology of the American Southwest, dendrochronology, which has often been accompanied by (though initially more popular than) dendroclimatology, spread to northern Europe, where the world's longest dendrochronological sequence (the nearly 12,600-year-long Hohenheim oak-pine chronology) was constructed through the analysis of the rings of oak and pine trees from Germany and Switzerland (D.E. Anderson et al. 2013:50; Sharer and Ashmore 2003:327). In addition, the incremental dating method has been introduced to the eastern Mediterranean, northern Mexico, Alaska, and elsewhere (D.E. Anderson et al. 2013:50; Sharer and Ashmore 2003:327; Stahle et al. 2012a:6).

The History of Maya Dendroclimatology

While dendroclimatology, like dendrochronology, is "potentially useful anywhere in the world where trees were used by prehistoric peoples" (Sharer and Ashmore 2003:327), its introduction to the homeland of the ancient Maya, a prehistoric people who most certainly made use of trees, has only taken place quite recently (Anchukaitis et al. 2015:1537-1539; Stahle et al. 2012a:1-2, 4-6). Unfortunately, only a few of the species of trees that have annual growth rings can be found in the Maya region, and those only in a few small parts thereof (Anchukaitis et al. 2013:270-271; Douglas et al. 2016:16; Stahle et al. 2012a:2, 5-6). In particular, there are the Guatemalan fir (*Abies guatemalensis*), which grows in the Sierra de los Cuchumatanes, a mountain range in western Guatemala (Anchukaitis et al. 2013:270-271, 2015:1537-1538); and the Montezuma baldcypress (*Taxodium mucronatum*), which grows along rivers in high-elevation parts of Chiapas and far western Guatemala (Anchukaitis et al. 2013:271; Stahle et al. 2012a:1-2, 5). The habitats of both species are not only quite restricted geographically, but also quite far from the well-excavated Maya sites in Belize, the Petén, and the Yucatán (Anchukaitis et al. 2013:270-271, 2015:1537-1538; Stahle et al. 2012a:1-2, 5). Furthermore, trees only produce rings while alive, and those in the Maya region appear to have lifespans of a few centuries at most (Douglas et al. 2016:16). Additionally, given the poor preservation conditions that prevail in the humid, tropical region, the preserved trunks of trees that died long ago are unlikely to be found. Still, in spite of all of the above factors that make dendroclimatology arguably irrelevant to archaeological investigations into Precolumbian Maya cultural responses to climate change, the botany of northern Central America and southeastern Mexico is still but imperfectly understood, and some have expressed optimism that new discoveries of annual-ring-bearing trees will be made in the Maya region (Anchukaitis et al. 2013:271; Douglas et al. 2016:17).

It bears mention, however, that the sparsity of relevant data from the Maya region (thus far) has not entirely stopped scholars from drawing upon dendroclimatology to make archaeological arguments about the Maya past. In fact, the first such comparison of dendroclimatic and archaeological records was made nearly a century ago, when Ellsworth Huntington examined Maya prehistory (as understood in an era prior to the decipherment of hieroglyphs [Sharer and Traxler 2006:137-141], the invention of radiocarbon dating [Sharer and Ashmore 2003:335-336], and the discovery of Caracol [A. Chase et al. 2011:388]) in light of then-novel dendroclimatic data from centuries- to millennia-old giant sequoia (*Sequoia washingtoniana*) trees from southern California (Huntington 1917:158-161). Interestingly, he hypothesized that the tree-ring data suggesting increased rainfall in southern California were indicative of drought in the Maya region, and vice versa. Even more interestingly (from the perspective of modern-day Maya archaeology and paleoclimatology), since he associated humidity with high levels of malaria and correspondingly low levels of human intelligence and ambition (Huntington 1917:153-154), and dry conditions with “a comparatively stimulating and healthful climate”, he viewed Precolumbian drought as a likely driver of the rise and fluorescence of Maya polities (Huntington 1917:154-159), as opposed to their collapses and abandonments.

Because of the unpopularity of environmental determinism in the early twentieth century, Huntington’s work was not embraced by the Maya archaeologists of his era (Turner 2010:575). Furthermore, since the advances that have been made in Maya archaeology, epigraphy, and paleoclimatology over the past century have essentially rendered his argument obsolete (to say nothing of the implicit racism of much of his prose), it is unsurprising that Huntington’s 1917 paper is seldom cited nowadays, other than as part of cursory overviews of the history of Maya paleoclimatology (e.g., Aimers 2012:27; Dunning et al. 2015:167; Gunn et al. 1995:4). Still, despite his shortcomings, Huntington (1917:158-161) can arguably be considered to have been ahead of his time, for not only considering climate change as a potential factor in Maya culture change, but for even foreshadowing current discussions on the subject with his caveat that "a belief in the potency of climate does not alter our faith in the importance of other factors… Climatic changes, if they have really occurred, merely provide conditions which help or hinder the operation of the other factors" (Huntington 1917:161).

Moving from the 1910s to the 2010s, D.W. Stahle and colleagues (2011) have recently followed in Huntington's footsteps by extracting and examining dendroclimatic data from ancient trees from outside the Maya region and correlating it with droughts and their supposed influence on Maya civilization (Stahle et al. 2011:L05703). In their case, the tree-ring data came from Montezuma baldcypress (*Taxodium mucronatum*) trees from Barranca de Amealco, Queretaro, Mexico, and they correlated the droughts it suggests with cultural decline rather than fluorescence (as is conventional in the current era of Maya paleoclimatology). Although the paper that introduced it focuses primarily on Mesoamerica in general, and especially on central Mexico in particular, its non-archaeologist authors make clear that they consider the Barranca de Amealco paleorecord to be applicable to the Maya region (Stahle et al. 2011:L05703). Furthermore, the 2011 article has already been cited for support by a number of scholars writing about paleoclimate and Maya responses thereto (e.g., Beach et al. 2015:9; Hoggarth et al. 2016:30-31; Kennett et al. 2012:788). However, while the examination of tree-ring data has evidently been valuable to archaeologists working in some locations, I would argue, based on the currently-available information about the geography, botany and climatology of the Maya region, that dendrochronology is unlikely to be a prominent part of future studies of climate change and culture change in the Maya Lowlands. I would add that the attention and resources of those interested in the topic would arguably be better devoted to the advancement of speleothem paleoclimatology.

CHAPTER THREE: FINDINGS

MC-01

In 2000, James Webster (then a graduate student at the University of Georgia) authored a Ph.D. dissertation on the paleoclimatic and chronometric analyses of MC-01 (a.k.a. MC01 [J. Webster et al. 2007:3]; See Table 2), a 92-cm-long calcite stalagmite from the entrance chamber of the Macal Chasm (See Figures 1 and 4), a cave on the Vaca Plateau, Cayo District, Belize, and their implications for Precolumbian Maya history (J. Webster 2000:ii-iv, 85-86, 125; J. Webster et al. 2007:3). The western Belizean speleothem was found approximately eight meters from the cave's entrance, removed by Webster and other members of the Vaca Plateau Geoarchaeological Project (VPGP) in 1996, and subsequently halved, sectioned, and sent to laboratories at the University of Georgia and the University of Arizona for a variety of scientific analyses (Iannone et al. 2013:274; J. Webster 2000:ii, iv, 85, 90-101; J. Webster et al. 2007:3). In terms of paleoclimatology, oxygen and carbon stable-isotope, UV-stimulated and laser-induced luminescence, and grayscale reflectance analyses were carried out (Iannone et al. 2013:274-275; J. Webster 2000:96, 100-101), while radiocarbon dating (including both radiometry and accelerator mass spectrometry) was used for chronometry (J. Webster 2000:90, 96, 100-101).

The results of the aforementioned analyses were combined and interpreted to indicate that four lengthy droughts occurred in the Preclassic through Postclassic periods (J. Webster 2000:194, 196). Specifically, these droughts were posited to have taken place from 735 to 640 (with a peak in 694) B.C., from 275 to 125 (with a peak in 182) B.C., from A.D. 200 to 350 (with a peak in 214), and from A.D. 700 to 1225 (with peaks in 809, 928, 1126, and 1205) (J.

Webster 2000:194, 196-197). As Webster pointed out, the third major drought appeared to have been contemporary with the Preclassic Abandonment, and the fourth (which the author termed "the Late Classic/ Early Post Classic dry phase") with the Maya Collapse (J. Webster 2000:196-198, 200). Furthermore, the data was also interpreted to suggest a minor drought centered in A.D. 611 (between the third and fourth major ones), which appeared to correspond to the Maya Hiatus (J. Webster 2000:197-198, 200). In Webster's view, these results lent strong support to the hypothesis that drought was a key factor in bringing about the Preclassic Abandonment, the Maya Hiatus, and, especially, the Maya Collapse in a large section of the Southern Maya Lowlands (inclusive of Calakmul, Caracol, Tikal, and the Mirador Basin) (J. Webster 2000:ii-iii, 4, 204-205). While Webster's study presented the results of the first paleoclimatic analysis of a cave speleothem from the Maya region, it appeared in the form of a non-anthropological dissertation (J. Webster 2000:ii, iv) and therefore received little attention from Maya archaeologists.

Seven years after his dissertation, Webster (2007) served as the principal author of a similar study that was published as a peer-reviewed academic-journal article. Although the article was based on the same Belizean stalagmite and did not present any new paleoclimatic data per se, it introduced a revised chronology that was based on U-series and lead-isotope dating, and supported by both the radiocarbon dates used in Webster's dissertation and additional ones (Iannone et al. 2013:274; J. Webster et al. 2007:3-7). Furthermore, while data from grayscale reflectance and stable-isotope analyses were again presented, its arguments were based primarily on the luminescence data (J. Webster et al. 2007:9-14). As one might expect, the revised chronology led to a revision of the dates when the Precolumbian droughts were said to have taken place (J. Webster et al. 2007:11-14). Short droughts during the Preclassic through Postclassic droughts were said to have been centered on 1225, 1007, 645, 78, and 5 B.C., and A.D. 141, 517, 871, 1074, 1139, and 1472 (J. Webster et al. 2007:11-14). Multidecadal droughts were posited to have occurred from A.D. 754 to 798 (with a peak in 780), and from A.D. 893 to 922 (with a peak in 910). The reader may notice that, while the multidecadal droughts (and, for that matter, the eighth, ninth, and tenth short droughts) would have taken place within Webster's (2000:196) "Late Classic/ Early Post Classic dry phase", the A.D. 214- and 611-centered Maya droughts of his dissertation do not reappear in the *Palaeogeography, Palaeoclimatology, Palaeoecology* article (J. Webster 2000:194, 197; J. Webster et al. 2007:11, 13). However, since the more recent data results placed droughts in A.D. 141 and 517, he repeated his argument that the MC-01 paleoclimatic record supports the hypothesis that drought was a significant causal factor in the Preclassic Abandonment and the Maya Hiatus, as well as (and again, most importantly) the Maya Collapse (J. Webster et al. 2007:11-15).

Argument for Broad Spatial Applicability

Although the argument advanced in both studies is fundamentally the same, it should be noted that the 2007 article expands its geographical frame of reference to include an even larger portion of the Southern Maya Lowlands (J. Webster et al. 2007:13-15). For example, Webster and his co-authors bolstered their argument for climate change as a driver of ancient Maya culture change with a graph that correlated droughts (as suggested by the Belizean speleothem record) with an archaeological dataset compiled from data drawn from as far afield as the

Chiapan site of Palenque and the Honduran site of Copán (Lowe 1985:20, 213-216; J. Webster 2000:4; J. Webster et al. 2007:13-15). The authors' argument for the broad spatial applicability of the MC-01 data is that, since it appears to correspond to paleoclimatic datasets from even further from the Macal Chasm than any site in the Southern Maya Lowlands (namely, a sediment core from Lake Chichancanab, in the Northern Maya Lowlands [Hodell et al. 1995:391], and a box core from the Bermuda Rise, in the northern Sargasso Sea, which lies well outside the Maya region [Keigwin 1996:1504]), it must surely reflect the paleoclimate of all sites within the subregions (J. Webster et al. 2007:2, 15).

Data and Precision

The temporal resolution of the luminescence record of MC-01 is 0.5 to 3 years (Iannone et al. 2013:276; J. Webster et al. 2007:12). Its stable-isotope record has a temporal resolution of 5 to 30 years (Iannone et al. 2013:275-276; J. Webster et al. 2007:12), and is based on the analysis of 93 samples for paleoclimatic reconstruction (J. Webster 2000:101). An additional 24 carbonate samples were analyzed for the Hendy test, which MC-01 passed (J. Webster 2000:101). The four radiocarbon dates upon which the 2000 study's chronology was based have average attached errors of ±65, while the seven U-series dates upon which the 2007 analysis was primarily based have attached errors of from ±37 to ±44 years (J. Webster et al. 2007:5-7, 125, 129).

Lake Chichancanab Core

The Lake Chichancanab sediment-core stable-isotope analysis (Hodell et al. 1995) that Webster cited in both speleothem studies (2000:200-201, 203; 2007:15) has a temporal resolution of approximately 20 years (Medina-Elizalde et al. 2010:258), and the average attached errors of its radiocarbon dates are roughly ±100 years (Hoggarth et al. 2016:28). Although additional Chichancanab data has subsequently been extracted, analyzed, and published (Hodell et al. 2001, 2005a, 2007), Webster does not acknowledge any of the post-1995 data, even though at least some of it had appeared in print prior to he and his co-authors' 2007 article. The principal author of the aforementioned Northern Maya Lowland lake-core studies has recently advocated geographic caution in the use of paleoclimatology to answer archaeological questions, since, in his well-informed view, "[t]here was undoubtedly considerable regional and local variability in the timing and distribution of droughts in the Maya lowlands" (Aimers and Hodell 2011:45).

HU89038 BC-004

HU89038 BC-004 (a.k.a. HU89-038-BC4), the Bermuda Rise box core that was also mentioned by Webster and colleagues (2007:15), was likewise dated by means of radiocarbon dating, and the attached errors of the dates upon which its chronology was based are from ±20 to ±70 years (Keigwin 1996:1504). It was subjected to both oxygen-isotope and carbonate-percentage paleoclimatic analyses (Keigwin 1996:1504-1505). While the study yielded data relevant to the past three millennia of Sargasso Sea paleoclimate, this information was on paleotemperature, and particularly sea-surface temperature (Keigwin 1996:1504-1507; Webster et al. 2007:15), as opposed to past rainfall patterns. In addition to this issue, geoscientist David Hodell's expert opinion on such non-Mesoamerican paleoclimatic records as HU89038 BC-004 is that "the farther an archive is from the Maya lowlands, the less confident one can be that a rainfall reconstruction applies to the Maya area" (Aimers and Hodell 2011:45).

Application (of MC-01)

Since the publication of the U-series-dating-based study (J. Webster et al. 2007:2-3, 15) that compared it to the Southern Maya Lowlands, in general, and the sites of Caracol, Ix Chel, and Tikal in particular, the MC-01 data has received a fair amount of attention from Mayanists. For example, archaeologists who conduct excavations in Belize have applied the MC-01 paleoclimatic proxy to the archaeological record to investigate the relationship between climate change and culture change at the Vaca Plateau sites of Caracol (D. Chase and A. Chase 2014:145-150; Iannone et al. 2013:284-295), Ix Chel (Iannone et al. 2013:276-279, 287-291), and Minanha (Iannone et al. 2013:281-283, 287-295, 2014:160-163; Schwake and Iannone 2016:152-157). Furthermore, and further afield, other scholars have cited it (alongside other paleoclimatic datasets) as evidence for Preclassic and Classic droughts at the Puuc site of Xcoch (Smyth et al. 2011:1, 2014:45; Zubrow et al. 2010:2). It has also been invoked to support paleoclimatic inferences drawn from the Chaac (Medina-Elizalde et al. 2010:259), YOK-I (Hoggarth et al. 2016; Kennett et al. 2012:789), and Itzamna (Medina-Elizalde et al. 2016:93) speleothems.

Of the above studies, those authored by Diane and Arlen Chase (2014), and Gyles Iannone and colleagues (2013, 2014) are of special significance, as they have repeated Webster and colleagues' (2007) assertions about the timing of climate-change events while challenging their assumptions about the relationship between droughts and episodes of culture change. By juxtaposing the MC-01-derived paleoclimatic chronology and the archaeologically (and epigraphically) derived cultural histories of Caracol and Minanha, they demonstrate that increases in population, construction activity, and sociopolitical power can potentially coincide with (or follow) periods of reduced rainfall (as appears to have been the case at the Vaca Plateau sites). However, although the authors suggest the possibility that droughts stimulated the construction and expansion of agricultural terracing, which led to population booms, their findings do not lend support to conclusions of environmental determinism. As they also point out that droughts appear to have corresponded to episodes of collapse and abandonment at the pair of sites, and suggest the possibility that earlier adaptations to climatic adversity ultimately led to inflexibility in the face of later climate change, they make clear that the relationship between environmental conditions and human actions is potentially complex. And, since they apply the Macal Chasm paleorainfall record only to Maya sites in the same adaptive region (i.e., the Vaca Plateau), their analyses not only draw upon data from archaeology, epigraphy, and speleothem paleoclimatology, but consider details of geography as well (D. Chase and A. Chase 2014:145-150; Iannone et al. 2013:281-295, 2014:160-163).

Chaac

In 2010, Martín Medina-Elizalde (a geoscientist who was then affiliated with the University of Massachusetts) and seven co-authors published an academic-journal article that presented data from the paleoclimatic and chronometric analyses of Chaac (a.k.a. Chaak [Dunning et al. 2015:170]; See Table 2), a 45-cm-long calcite stalagmite from Tzabnah Cave (a.k.a. Tzab Na Cave [Dunning et al. 2015:170], or Tecoh Cave [Medina-Elizalde et al. 2010:258-259; Smyth et al. 2011:42]; See Figures 2 and 5), in Tecoh, Yucatán, Mexico, and an explanation of its hypothesized relevance to the Terminal Classic period of Maya history (Lachniet 2015:1527; Medina-Elizalde et al. 2010:255-256). The Yucatecan speleothem was removed in 2004 and then sent to a laboratory at the University of New Mexico for scientific analysis. The dating method employed was U-series dating; oxygen and carbon stable-isotope analyses were also undertaken, the former to reconstruct paleoclimate, and the latter to test the fidelity of the former (Medina-Elizalde et al. 2010:256-257). Since Chaac was determined to date only as far back as to the late fifth century A.D. (Medina-Elizalde et al. 2010:256, S2-S9), its data was not applied to the Preclassic Abandonment. It was, however, applied to the Maya Collapse, as well as both the Petexbatún Collapse that preceded it and the Puuc Collapse that postdated it (Medina-Elizalde et al. 2010:259-261).

The Chaac data was interpreted to indicate that the Classic period saw the occurrence of three droughts in the sixth and seventh centuries (A.D.) and a prolonged dry period in the ninth and early tenth centuries (A.D.), during which eight severe droughts struck the Maya region. The three earlier droughts were posited to have taken place from 501 to 518, from 527 to 539, and from 658 to 668 (Medina-Elizalde et al. 2010:257). The later dry period was said to have lasted from 804 to 938, and its eight droughts were said to have peaked in 806, 829, 842, 857, 895, 909, 921, and 935 (Medina-Elizalde et al. 2010:257, 259). A multidecadal "moist interval" was placed between the fourth and fifth ninth-century droughts (Medina-Elizalde et al. 2010:259, 261). Comparing this speleothem-derived paleoclimatic history with the archaeologically-derived sociocultural history of the Petexbatún subregion of the Southern Maya Lowlands, Medina-Elizalde and colleagues (2010:259-260) argued that the Petexbatún Collapse was caused ultimately by warfare, and only proximately by drought. However, they argued that the paleoclimatic and archaeological lines of evidence point to drought as the most important causal factor of the Maya Collapse proper, and in particular the collapses of the Southern Maya Lowland sites of Calakmul and Tikal (Medina-Elizalde et al. 2010:260). In addition, they connected the apparent "revitalization" of the Puuc subregion of the Northern Maya Lowlands with the ninth-century "moist interval", and its collapse with the four severe droughts by which it was followed (Medina-Elizalde et al. 2010:260-261).

Argument for Broad Spatial Applicability

The authors' argument for the spatial applicability of the Chaac dataset to the Southern Maya Lowlands (in addition to the Northern Maya Lowlands, whence it was extracted) was based primarily on the use of a global meteorological database to compare, and apparently correlate, the rainfall regime of Tzabnah Cave with precipitation patterns at points elsewhere in the region. In their view, "a significant correlation between the precipitation history at this location and the southern Maya lowlands including the Yucatán Peninsula, Chiapas and Guatemala" indicates that "the Chaac δ18O record is expected to reflect climate variability of a broad region of the Maya lowlands" (Medina-Elizalde et al. 2010:257).

Data and Precision

The oxygen-isotope rainfall-proxy data of Chaac is based on 709 samples (S2-S9), and has an average temporal resolution of 2.3 years overall (from A.D. 478 to 2004), but is of annual resolution for the Terminal-Classic-period (from A.D. 800 to 940) portion of the record (Hoggarth et al. 2016:28; Medina-Elizalde et al. 2010:257). The dozen U-series dates upon which its chronology is based (Medina-Elizalde et al. 2010:256) have attached errors of ±7 to ±60 years (Hoggarth et al. 2016:28, 30).

CRU TS 2.1

CRU TS 2.1, the meteorological database of global precipitation with which Medina-Elizalde and colleagues (2010:257-258) supported their argument for broad spatial applicability, purports to be comprised of data spanning the Earth's six inhabited continents and the time period from A.D. 1901 to 2002 (Mitchell and Jones 2005:693); however, its geographical regions and chronological eras are not all equally well-represented. In particular, many of the Maya-region weather stations recorded precipitation figures for only a few years, while only a few stations recorded such data for many years (Mitchell and Jones 2005:694; Vose et al. 1992:C-134-C-140). In fact, if one excludes a handful of stations in Chiapas, the Maya region is represented by only five meteorological stations (three in Mexico, and two in Belize) that recorded rainfall amounts for at least fifty years, all of which are in lowland locations (Mitchell and Jones 2005:694: Vose et al. 1992:C-130-C-136, C-138-C-140). Of these, only one station (Belize City) recorded such data for at least a century, and even this figure is only reached by including nineteenth-century data that was not incorporated into the database (Mitchell and Jones 2005:693-694; Vose et al. 1992:C-139).

Application (of Chaac)

Since the publication of the study (Medina-Elizalde et al. 2010:255-260) that interpreted Chaac as a record of the paleoclimate of the (Northern and Southern) Maya Lowlands in general, and the sites of Calakmul, Dos Pilas, Oxkintok, Punta de Chimino, Tikal, and Uxmal in particular, the Chaac dataset has been invoked (alongside several other paleorecords) in support of the veracity of the dataset from the Itzamna speleothem (Medina-Elizalde et al. 2016:99-100). More recently, it has been compared to YOK-I, and the results of the comparison have been used to challenge the validity of the latter stalagmite (Lachniet 2015:1527-1528, 1530).

YOK-I

In 2012, Douglas Kennett (an archaeologist at the Pennsylvania State University) and seventeen co-authors published an academic-journal article on the results of the paleoclimatic and chronometric analyses of YOK-I (See Table 2), a 56-cm-long aragonite stalagmite from Yok Balum Cave (a.k.a. Jaguar Paw Cave [S1]; See Figures 3 and 4), near Santa Cruz, Toledo District, Belize, and their implications for Precolumbian Maya history (Kennett et al. 2012:788-

789, S1-S2, S17; Lachniet 2015:1521, 1527). The southern Belizean speleothem was extracted in 2006, and then sectioned and sent to laboratories at the University of New Mexico, the University of Oregon, and the Swiss Federal Institute of Technology Zurich. Dating was done via the U-series method, and oxygen and carbon stable-isotope analyses were carried out to reconstruct paleoclimate (Kennett et al. 2012:S2-S6). The paleoclimatic record of YOK-I was determined to cover a timespan of over two millennia, from 40 B.C. to A.D. 2006. However, while the majority of the stalagmite's data passed the Hendy test, that pertaining to the most recent century and a half did not (Kennett et al. 2012:789, S5, S12). Still, the Preclassic Abandonment, the Petexbatún Collapse, the Maya Collapse, and the collapse of Chichén Itzá lie well within the period for which evidently valid paleoprecipitation data was thought to exist (Kennett et al. 2012:789-791).

According to Kennett and colleagues, multidecadal droughts in the Maya region lasted from A.D. 200 to 300 in the Preclassic period, from 820 to 870 in the Classic period, and from 1020 to 1100 in the Postclassic period (all dates approximate), while shorter droughts peaked in A.D. 420 and 930. Based on the YOK-I-derived timing of droughts, and the archaeologically-ascertained histories of sites, the authors concluded that drought was a major causal factor in the collapses and abandonments that occurred in the Mirador Basin, the Petexbatún region, the elsewhere in the Southern Maya Lowlands, and Chichén Itzá (Kennett et al. 2012:790-791). More specifically, they argued that the periods of relatively high rainfall that preceded droughts led to sociopolitical fluorescence and population increase, which, in turn, made the relevant societies so vulnerable and path-dependent that they were unable to successfully adapt to the subsequent droughts (Kennett et al. 2012:791).

Argument for Broad Spatial Applicability

In terms of an argument for broad spatial applicability, the authors stated that “Tikal and other major Classic Period population centers (such as Caracol, Copan, and Calakmul) are within 200 km and are influenced by the same climate systems” as Yok Balum Cave, and supported this assertion by presenting the results of their application of a diagnostic model for calculating precipitation sources to meteorological data from Belize and adjoining areas (Kennett et al. 2012:788-789, S6-S9, S24). They offered no explicit explanation in defense of their application of the YOK-I data to Chichén Itzá, which is over 200 km from southern Belize.

Data and Precision

The stable-isotope rainfall-proxy data of YOK-I is based on over 4200 samples that have temporal resolutions of 0.01 to 3.68 years (with an average of 0.49 years) (Kennett et al. 2012:789, S4). Its chronometry is based on 40 U-series dates that have attached errors of ±1 to ±17 years, but only ±5 to ±10 years on average (Hoggarth et al. 2016:30). The authors made use of four metrics to synthesize, simplify, and quantify the Maya archaeological record, so as to better illustrate (both literally and figuratively) their hypothesis for climate change as a driver of culture change (Kennett et al. 2012:790-791). Namely, they tabulated the total number of dated monuments, the number of cities with dated monuments, the number of war-related events on dated monuments, and the Inter-Polity War Index, over time (Kennett et al. 2012:790). All four measures were based on the epigraphic data recorded in the Maya Hieroglyphic Database, which incorporated recently-published data and included hieroglyphic inscriptions from throughout the

Northern and Southern Maya Lowlands. The Inter-Polity War Index for each time period was a figure the authors derived by calculating war-related events as a proportion of the total number of events commemorated on dated monuments (Kennett et al. 2012:790, S16).

Lagrangian Moisture Source Diagnostic

Regarding the unnamed “Lagrangian moisture source diagnostic” (Sodemann et al. 2008:D03107) to which Kennett and colleagues (2012) subjected a set of modern Maya-region meteorological measurements (S6-S9, S24), and thereby supported their argument for the broad spatial applicability of the YOK-I dataset (788-789), a number of points bear mention. First, the diagnostic was originally formulated to make sense of precipitation sources in circumpolar regions (Sodemann et al. 2008:D03107). In fact, its creators cautioned would-be emulators that applications of their “Lagrangian analysis of precipitation origin for the Greenland plateau” to “further remote source areas, such as the Pacific and the Gulf of Mexico, are strongly discounted” (Sodemann et al. 2008:D03107). For their part, Kennett and his co-authors (2012:S6) admitted that “[t]he convective aspect of most tropical weather systems is a challenge to Lagrangian calculations”. Second, since applications of the diagnostic model only yield information on precipitation sources (Sodemann et al. 2008:D03107), the relevance of Kennett and colleagues’ (2012:788-789, S6-S9, S24) results to their argument depends upon the validity of the assumption that areas with similar sources would also have had climatic systems similar in every other respect. Finally, the archaeologist and his collaborators only subjected a mere five years of precipitation data to the diagnostic (Kennett et al. 2012:S6), an amount of data so small that it can hardly be said to reflect modern-day climate, let alone paleoclimate.

Application (of YOK-I)

In the few years since the publication of the article (Kennett et al. 2012:788-791) that applied it to the (Northern and Southern) Maya Lowlands in general, and Calakmul, Caracol, Chichén Itzá, Copán, El Mirador, Lubaantun, Naranjo, Nim Li Punit, the Petexbatún region, Pusilhá, Tikal, and Uxbenká in particular, the YOK-I dataset has been used in additional archaeological discussions of the sociocultural trajectories of Maya sites. Examples include the nearby site of Uxbenká (Iannone et al. 2014:157-160), the western Belizean site of Caracol (D. Chase and A. Chase 2014:147), and even the Yucatecan site of Chichén Itzá (Hoggarth et al. 2016:25-31).

However, a recent non-archaeological reexamination of the YOK-I data has called the validity of the stalagmite paleorecord itself into question (Lachniet 2015:1530). In addition to pointing out that aragonite speleothems (e.g., YOK-I [Kennett et al. 2012:S2]) are generally less well-understood and arguably more error-prone than their calcite counterparts (e.g., Chaac, Itzamna, and MC-01 [Medina-Elizalde et al. 2010:256, 2016:94; Webster 2000:125]), its geoscientist author subjected data from YOK-I to the equilibrium test and the replication test, both of which it "failed" (Lachniet 2015:1521-1522, 1527-1528). To be fair, its replication test entailed its comparison to Chaac, which was extracted from a different cave, and one far enough away that the stalagmites may have recorded different climatic conditions (Lachniet 2015:1527-1528, 1530). Still, this consideration has no bearing on the results of YOK-I's equilibrium test, and it cannot be assumed that it would have “passed” a replication test that compared it to a contemporaneous stalagmite from the same cave (or a geographically closer one) (Lachniet 2015:1528, 1530). In the absence of such a replication test, the validity of the YOK-I dataset cannot be said to have been completely discredited; however, in light of the results of its reexamination (i.e., the equilibrium and replication tests to which it has been subjected), it appears that its reliability as a record of paleoprecipitation can no longer be safely assumed (Lachniet 2015:1530).

Itzamna

Early this year, Martín Medina-Elizalde (now a geologist at Amherst College, in Massachusetts) and six co-authors (2016:93) published the most recent (to date) article to present the results of chronometric and paleoclimatic analyses of a speleothem and connect them to the episodes of Maya culture change. Itzamna (See Table 2) is an 87-cm-long calcite stalagmite that was extracted from the Laberinto del Fauno cave chamber, in the Río Secreto Natural Reserve (See Figure 5), Playa del Carmen, Quintana Roo, Mexico, in 2012 (Medina-Elizalde et al. 2016:94). It was sent to laboratories at the University of Massachusetts and National Taiwan University, for oxygen-isotope analysis to ascertain paleoclimate, and U-series dating to determine chronology. It was learned that Itzamna had been inactive for some time, but that it had been an active recorder of climatic conditions from 1037 B.C. to A.D. 397 (Medina-Elizalde et al. 2016:93). While the speleothem was silent on the subjects of droughts and collapses in the

Classic and Postclassic periods, it had a great deal to say (so to speak) regarding climate change and culture change during the Preclassic, according to the authors. Medina-Elizalde and colleagues (2016:97,101) identified six droughts that took place during the Middle Preclassic period, and another half dozen that occurred in the Late Preclassic.

Middle Preclassic Drought Events 1 through 6 (as the authors so dubbed them [Medina-Elizalde et al. 2016:101]) happened from 961 to 947, from 923 to 913 and 902 to 898, from 791 to 782, from 691 to 686 and 670 to 660, from 531 to 516, and from 470 to 464, B.C. Late Preclassic Drought Events 1 through 4 were said to have lasted from 163 until 139, from 108 until 98, from 73 until 62, and from 13 until 3, B.C. Finally, Late Preclassic Drought Events 5 and 6 were placed in the second and third centuries A.D., from 178 through 209 (with a peak in 186), and from 229 through 251 (with a peak in 234). In fact, the apparent timing of the latter two droughts is key to the authors' argument. Since the dry periods appear to have coincided with the Preclassic Abandonment, Medina-Elizalde and colleagues (2016:99, 101) suggested that drought was most likely the main causal factor of the culture-change event.

Argument for Broad Spatial Applicability

Regarding the spatial applicability of the speleothem evidence, they argued that the data from the Quintana Roo speleothem is certainly relevant to paleoclimate in the Mirador Basin and throughout the Maya Lowlands (Medina-Elizalde et al. 2016:99-101). Since, as they pointed out, the Itzamna precipitation-proxy record appears to agree (in part) with similar data from a marine-sediment core from the Cariaco Basin, off the coast of Venezuela, rainfall patterns among sites closer to home (i.e., within the Maya Lowlands) must have been similarly homogenous (Medina-Elizalde et al. 2016:99). Regarding Late Preclassic Drought Events 5 and 6, they boldly stated their conclusion that "[c]learly, these two Late Preclassic droughts affected the entire Y[ucatan] P[eninsula] and likely large portions of Central America… were widespread and affected the entire North American tropics, and may have had significant impacts on the development of ancient cultural centers in Mesoamerica at the time" (Medina-Elizalde et al. 2016:99).

Data and Precision

The chronology of Itzamna is based on 6 U-series dates with attached errors of from ±12 to ±20 years, and its paleoclimatic data is based on 181 oxygen-isotope measurements with temporal resolutions of from 6 to 10 years (Medina-Elizalde et al. 2016:95); the latter dataset was subjected to the Hendy test, which it passed.

Cariaco Basin Cores

The Cariaco Basin marine-core data is based on paleoclimatic and chronometric analyses of sediment cores from Ocean Drilling Program holes 1002C and 1002D (Haug et al. 2001, 2003; Medina-Elizalde et al. 2016:99). The cores of 1002C were dated via accelerator-mass-spectrometry radiocarbon dating (Haug et al. 2001:1304, 2003:1732), and those of 1002D were dated through the visual counting of varves and comparison to data from the former hole (Haug et al. 2003:1734). Cores from both Cariaco Basin ODP holes were subjected to laboratory analysis to determine the titanium content of each (Haug et al. 2001:1304-1305, 2003:1731-1732). Veteran geoscientist David Hodell (who, as mentioned earlier, has himself analyzed sediment-core data and used it to draw inferences about the relationship between climate change and culture change in the Maya region [Hodell et al. 1995, 2001, 2005a, 2005b, 2007]) has mentioned Cariaco Basin by name as a location so far removed from the Yucatán Peninsula and northern Central America that its paleoclimatic data should not be assumed to pertain to Maya sites (Aimers and Hodell 2011:45). In fact, Hodell has advocated that "palaeoclimate records must be evaluated with respect to their location," and made his point by posing the rhetorical question "[D]oes the rainfall record from the Cariaco Basin really inform us about past precipitation at the Maya site at Tikal, Guatemala… some 2,700 kilometres away?" (Aimers and Hodell 2011:45).

Application (of Itzamna)

Medina-Elizalde and colleagues (2016:94-101) would evidently answer Hodell in the affirmative, since they apparently consider their argument for broad spatial applicability sufficiently strong to justify their application of the Itzamna data to the Maya Lowlands in general, and the sites of Cerros, El Mirador, El Palmar, Komchén, Nakbé, and Xcoch in particular.

CHAPTER FOUR: CONCLUSIONS

The Speleothem Datasets

Which, if any, of the aforementioned Maya-region speleothems have yielded data precise enough, and therefore clear enough, to potentially shed light on ancient Maya cultural responses to climate change? Before answering this question, I will first recount the relevant figures. The temporal resolutions of the oxygen-isotope-based paleoclimatic records of the MC-01 and Itzamna speleothems are, respectively and approximately, 5 to 30 years (Iannone et al. 2013:275-276; J. Webster et al. 2007:12) and 6 to 10 years (Medina-Elizalde et al. 2016:95), while that of MC-01's luminescence-based record is 0.5 to 3 years (Iannone et al. 2013:276; J. Webster et al. 2007:12). The respective oxygen-isotope-based records of Chaac and YOK-I have average temporal resolutions of 2.3 years (Hoggarth et al. 2016:28; Medina-Elizalde et al. 2010:257) and 0.49 years (Kennett at al. 2012:789, S4). The respective attached errors of the U-series dates from MC-01, Chaac, Itzamna, and YOK-I are: ±37 to ±440 years (J. Webster et al. 2007:5-7), ±7 to ±60 years (Hoggarth et al. 2016:28, 30), ±12 to ±20 years (Medina-Elizalde et al. 2016:SA1, SD1), and ±1 to ±17 years (Kennett at al. 2012:789) (with average errors of between ±5 and ±10 years [Hoggarth et al. 2016:30]). The AMS radiocarbon dates from the 2000 analysis of MC-01 each have an attached error of ±80 years, while its non-AMS radiocarbon dates each have an error of ±50 years (J. Webster 2000:125, 128).

Given their relatively low attached errors and comparatively high temporal resolutions, MC-01's original radiocarbon dates and luminescence measurements may appear preferable to its U-series dates and oxygen-isotope measurements (Iannone et al. 2013:275-276; J. Webster

2000:125, 129; Webster et al. 2007:5-7, 12). However, applications of the radiocarbon dating method and the luminescence paleoclimatological method to speleothems have been found to yield ambiguous results, and both methods have essentially been replaced (by U-series dating and oxygen-isotope analysis, respectively) in speleothem-based paleoclimatic studies. The Chaac oxygen-isotope data is, like the MC-01 luminescence data, quite precise; unfortunately, its U-series dates are, like those of MC-01, extremely imprecise (Hoggarth et al. 2016:28, 30; Iannone et al. 2013:276; Medina-Elizalde et al. 2010:257; Webster et al. 2007:5-7, 12). Conversely, while the attached errors of Itzamna's U-series dates are much slighter than those of Chaac and MC-01, the temporal resolutions of its oxygen-isotope samples are much worse than those of Chaac and YOK-I (Hoggarth et al. 2016:28, 30; Kennett et al. 2012:789, S4; Medina-Elizalde et al. 2010:256-257, 2016:95, SA1, SD1; Webster et al. 2007:5-7). YOK-I has both the oxygen-isotope data with the greatest temporal resolution and the U-series dates with the slightest attached errors (Hoggarth et al. 2016:28, 30; Iannone et al. 2013:275-276; Kennett et al. 2012:789, S4; Medina-Elizalde et al. 2010:257, 2016:95, SA1, SD1; Webster et al. 2007:5-7, 12).

All four speleothem datasets indicate the occurrence of droughts in (at least some locations in) the Maya Lowlands between the dawn of the Preclassic period and the Spanish Conquest (Kennett et al. 2012:789; Medina-Elizalde et al. 2010:255, 257, 259, 2016:97, 99, 101; Webster 2000:194, 196-198, 200; Webster et al. 2007:11-14). However, since Maya archaeologists are (or, at least, should be) primarily concerned not with proving or disproving that droughts struck the Precolumbian Maya, but with investigating the relationship of ancient Maya culture change (including the dissolution of polities and the abandonment of sites) to climate change (which is to say, primarily non-anthropogenic changes in rainfall patterns), ascertaining the timing of droughts is obviously key to determining how influential they were (or were not) in Maya history. After all, whether a climatic event preceded, coincided with, or followed a cultural development is of obviously great importance when a potential cause-and-effect relationship is being investigated. While researchers must be careful to avoid confusing correlation with causality and consider the possibility of coincidence, a fine-grained understanding of chronology can be valuable in determining which hypotheses to discard and which to continue pursuing. In view of the relative degrees of precision of their chronometries and paleoclimatic proxies, it would appear that Chaac, Itzamna, and MC-01 are inadequate, and that YOK-I alone has yielded data that can potentially answer the anthropological questions of Maya archaeologists. On the other hand, its apparent unreliability as revealed by the results of its recent reexamination by Lachniet (2015:1527-1528, 1530) suggest that even the YOK-I dataset may not be equal to the task.

And, in addition to the aforementioned shortcomings of MC-01, it bears mention that many in the paleoclimatological community would presumably dismiss any conclusions drawn from its data out of hand, because of its entrance-adjacent provenience. To quote the respected author of a seminal publication on the science of speleothem analysis: “[T]he evaporation of water, well within caves, is negligible. However, evaporation of water may be significant in the formation of speleothems in cave entrances” (Hendy 1971:820-821). “Speleothems deposited under conditions of… evaporation of water cannot be used to give palaeoclimate data” (Hendy 1971:801). The perceived unsuitability of MC-01 as a record of past climate is also suggested by the omission of its data from the NOAA (National Oceanic and Atmospheric Administration)

Paleoclimate Database, an American archive of paleoclimatic information drawn from sources that span the globe, including the Chaac and YOK-I stalagmites (Wong and Breecker 2015:2, S1-S17).

The Arguments for Broad Spatial Applicability

Which, if any, of the aforementioned arguments for the broad spatial applicability of the results of Maya-region speleothem studies are based upon evidence relevant enough, and therefore conclusive enough, to scientifically validate the hypothesized paleoclimatic uniformity throughout (at least a large portion of) the Maya Lowlands? Before answering this question, I will first recount the datasets that have been cited as evidence.

To support their assertion that “the dry periods in the Macal Chasm record [i.e., MC-01] were widespread events that would have affected the entire Mayan civilization”, Webster and colleagues (2007:15) cited two sediment-core-based paleoclimatic studies from the mid-1990s: an analysis of a Bermuda Rise box core that yielded information on sea-surface temperatures (as opposed to rainfall patterns) in the Sargasso Sea (as opposed to the Caribbean Sea) (Keigwin 1996); and an analysis of a Lake Chichancanab lake core that yielded data that not only had low temporal resolution and high attached dating errors, but was also no longer current at the time of (Webster and co-authors’) publication (Hodell et al. 1995). To support their assertion that “Tikal and other major Classic Period population centers… within 200 km [of Yok Balum Cave, the source of YOK-I]… are influenced by the same climate systems”, Kennett and colleagues (2012:788-789) cited their application of a model that was intended to shed light on circumpolar (as opposed to tropical) climate to five years of weather data from the Maya region, and the information it ostensibly yielded on rainfall sources (as opposed to distribution) (Kennett et al. 2012:788-789, S6-S9, S24; Sodemann et al. 2008).

To support their assertion that "the Chaac δ18O record [from Tzabnah Cave] is expected to reflect climate variability of a broad region of the Maya lowlands", which they specified as "including the Yucatán Peninsula, Chiapas and Guatemala", Medina-Elizalde and co-authors (2010:257) cited a correlation field analysis based on a global precipitation database that only appears to suggest Maya-Lowland regional climatic uniformity because of the absence of relevant data from most of the relevant parts of Mexico and Central America, for most of the twentieth century (Medina-Elizalde et al. 2010:257-258; Mitchell and Jones 2005). They supported their assertion that droughts recorded by the "stalagmite oxygen isotope record (δ18O) from Río Secreto [i.e., Itzamna]" affected "major centers in the Mirador Basin and others around the Maya Lowlands" (Medina-Elizalde et al. 2016:93) by citing a paleoclimatic analysis of sediment cores from the Cariaco Basin, a part of the Caribbean Sea located literally thousands of kilometers away from the Maya region (Haug et al. 2001, 2003; Medina-Elizalde et al. 2016:99).

In support of the broad spatial applicability of their paleoclimatic data, Medina-Elizalde and colleagues (2016:99) compared Itzamna to South American marine cores, just as Webster and co-authors (2007:15) had compared MC-01 to a North American one; in each case, the argument was made that, if particular droughts affected a location distant from a speleothem's source cave, they must surely have affected locations (and in particular, Maya sites) that lay relatively closer. Obviously, however, the degree to which the climates of two places resemble one another is not determined solely by geographical distance, since additional factors are influential in determining each place’s particular climatic conditions. In the case of long-term precipitation patterns, elevation and topography are especially significant. However, since each of the four article-length speleothem studies has either been illustrated with a map that omitted topographical features (Medina-Elizalde et al. 2010:256, 2016:95), specified Maya sites’ locations relative to a source cave’s location without specifying their elevations (or, for that matter, their locations relative to the nearest mountain range or coast) (Kennett et al. 2012:788-789), or both (J. Webster et al. 2007:2, 3), a reader might be excused for concluding that such details are irrelevant to long-term precipitation patterns (or, at least, are believed to be so by each speleothem study’s authors).

The Spatial Variability of Precipitation Patterns

As climatologists and geographers have long recognized, local topography can be hugely influential over long-term rainfall patterns, which, as a result, are not necessarily shared by locations that might happen to be close to one another “as the crow flies” (Hastenrath 1967:201, 203; Portig 1965:68; Turner and Sabloff 2012:13909, 13913; Whiteside 1985:1, 2). For instance, mountain ranges (e.g., the Maya Mountains) have been known to create what are termed orographic “rain shadows”: due to the elevation gradients created by the presence of mountains, precipitation patterns on opposite sides of a given range may differ starkly from one another (Dunning et al. 2015:168; Hastenrath 1967:201, 203). Generally speaking, areas on the leeward side of a mountain range (or, in other words, in its “rain shadow”) are liable to have especially dry climates; those on its windward side are likely to have wet ones; and, those sufficiently distant may not be subject to either orographic effect (Portig 1965:73; Whiteside 1985:2, 8). However, while the science behind topography and its potential influence over precipitation and its variability is well-understood, the climatology of the Maya region is imperfectly understood, to say the least (Anchukaitis et al. 2013:270, 2015:1537-1538; Sáenz and Durán-Quesada 2015:3, 16). With dendroclimatic records confined to tiny areas in the highlands of Chiapas and Guatemala (Anchukaitis et al. 2013:271; Stahle et al. 2012a:2, 2012b:1443-1444), and long-term weather-station precipitation records confined to a mere handful of Mexican and Belizean (modern) population centers (Vose et al. 1992:13, 15, C-130-C-136, C-138-C-140), the contemporary climatology of the region, much like its paleoclimatology, suffers from a sparsity of relevant data.

Considering the inadequacy of available information on ancient and modern rainfall in the Maya Lowlands (Anchukaitis et al. 2013:270-271, 2015:1537-1538; Sáenz and Durán-Quesada 2015:3, 16; Stahle et al. 2012a:2, 2012b:1443-1444; Vose et al. 1992:13, 15, C-130-C-136, C-138-C-140), and the inconclusiveness of the arguments advanced by Webster (2007:15), Medina-Elizalde (2010:257-258, 2016:93, 99), Kennett (2012:788-789, S6-S9, S24), and their respective co-authors, what, if anything, can be said regarding the spatial applicability of the speleothem datasets? Should one ignore the obvious differences in elevation, topography, and geology (that separate sites within the Maya Lowlands from one another) (Dunning et al. 1998:87-91, 2013:172, 176-179, 2015:171; Turner and Sabloff 2012:13909, 13913; Wilson 1980:6-16, 19-35), and infer the past rainfall patterns of a given Maya site by simply applying the data from the nearest contemporaneous stalagmite (Medina-Elizalde et al. 2010:255-256, 260, 2016:94-95, 100; J. Webster et al. 2007:3)? Or, should one ignore distance and latitude as well, regard the Maya speleothems as climatic archives of the region at large, and apply the dataset with the highest temporal resolution, the slightest attached errors, or the best combination thereof (Hoggarth et al. 2016:25-31)? Alternatively, should one ignore the stalagmites themselves, and refrain from assuming that their proxy records reflect the paleoclimates of any locations but the caves whence they were extracted? As tempting as the first two options might be for Mayanists seeking to bolster their arguments about droughts as drivers for collapses and abandonments, and as tempting as the third choice might be for scholars more interested in avoiding criticism than in potentially advancing their science, I will argue in favor of a fourth option.

Adaptive Regions as Zones of (Speleothem) Spatial Applicability

Since their application would group Maya sites and stalagmites according to multiple, and highly relevant, geographical variables (Dunning et al. 1998:87-91; Wilson 1980:6-16,19-35), as opposed to simply spatial proximity, I advocate using Dunning and colleagues' (1998:89) Maya Lowland adaptive regions as zones of speleothem spatial applicability. Which is to say, I argue that a scientifically valid paleoclimatic dataset from a cave speleothem can safely be presumed to apply to all of the (contemporaneously-occupied) Maya archaeological sites that lie within its adaptive region (or spatial-applicability zone, to coin a phrase). Given the multiple geographical similarities that locations within each region evidently have, I consider the deduction that they would also have had the same climates and been struck (or avoided) by the same droughts (as one another in the past) a reasonable one. To be fair, a given drought recorded by a given stalagmite may well have affected locations outside its adaptive region, or, for that matter, the Maya Lowlands at large. My argument is not that a given drought should be assumed *not* to have affected a given Maya site outside the adaptive region of the cave whence the speleothem that recorded it was extracted; I am simply asserting that it should not be *assumed* to have struck the site.

If one is to apply the adaptive regions (Dunning et al. 1998:89) as spatial-applicability zones, what can be said about the applications of paleoprecipitation records from particular Maya speleothems to archaeological records of particular Maya sites that have already been made (D. Chase and A. Chase 2014:147, 149-150; Hoggarth et al. 2016:25-31; Iannone et al. 2013:276-279, 281-295, 2014:157-163; Kennett et al. 2012:788-791; Medina-Elizalde et al. 2010:255-256, 260, 2016:94-95, 100; Smyth et al. 2011:1, 2014:45; J. Webster et al. 2007: 3, 12-15; Zubrow et al. 2010:2)?

As it happens, the Karstic Piedmont adaptive region contains both Yok Balum Cave, which is the source of YOK-I, and Uxbenká, a Maya site (Dunning et al. 1998:89; Hoggarth et al. 2016:27; Kennett et al. 2012:788-789) to which its data has been applied (Iannone et al. 2014:157-160; Kennett et al. 2012:788-791). Unfortunately, while Yok Balum Cave and Uxbenká can be assumed to have experienced the same climate and thus the same Precolumbian droughts (Dunning et al. 1998:89,95; Hoggarth et al. 2016:27), the comparisons of the paleoclimatic and archaeological records to investigate the relationship between climate change (in the Karstic Piedmont adaptive region) and culture change (at Uxbenká) (Iannone et al. 2014:157-160; Kennett et al. 2012:788-791) cannot be assumed to be scientifically valid, due to the legitimate questions that have been raised about the reliability of YOK-I itself (Lachniet

2015:1527-1528, 1530). Futhermore, both speleological and geographical considerations mean that the applications of the YOK-I dataset that have been made to the archaeological records of Caracol (D. Chase and A. Chase 2014:147; Kennett et al. 2012:788-789, 791) and Chichén Itzá (Hoggarth et al. 2016:25-31; Kennett et al. 2012:790), both of which lie outside the Karstic Piedmont region (Dunning and Beach 2010:370; Hoggarth et al. 2016:27), can be said to lack scientific merit with even greater certainty. In a similar vein, the juxtaposition of the Yok Balum paleorainfall record with epigraphic datasets compiled from throughout the Maya region (most of which also lie outside the Karstic Piedmont) (Kennett et al. 2012:790, S14-S16, S89-S121) is of questionable value. Should Yok Balum Cave eventually yield a stalagmite paleorecord with the precision of YOK-I, but without the shortcomings that caused it to “fail” the equilibrium and replication tests (Lachniet 2015:1527-1528), its data would certainly shed light on the site history of Uxbenká, but not necessarily those of Caracol or Chichén Itzá.

Chichén Itzá is located on the Northeast Karst Plain (Dunning and Beach 2010:370; Dunning et al. 1998:89; Hoggarth et al. 2016:27), an adaptive region from which no cave speleothems have yet been removed for analysis. Caracol, on the other hand, shares the Vaca Plateau (which lends its name to its adaptive region) with the Macal Chasm, the source of MC-01 (Dunning and Beach 2010:370; Dunning et al. 1998:89; Hoggarth et al. 2016:27; J. Webster 2000:85; J. Webster et al. 2007:1). The lesser-known Maya sites of Minanha, Ix Chel, Caballo, Caledonia, and Camp 6 are located on the Vaca Plateau as well (Iannone et al. 2013:272-273, 2014:160). Unfortunately, since the MC-01 data (J. Webster 2000:128; J. Webster et al. 2007:5, 7, 12) is arguably unreliable and insufficiently precise to yield insights into cultural responses to climatic conditions, its applications to the archaeological records of Caracol (D. Chase and A. Chase

2014:145-150; Iannone et al. 2013:287-295; J. Webster et al. 2007:3, 12-15), Minanha (Iannone et al. 2013:287-294, 2014:160-163; Schwake and Iannone 2016:152-157), and Ix Chel (Iannone et al. 2013:287-293; J. Webster et al. 2007:3, 12-15) have been flawed. Should a new, and improved, speleothem dataset be extracted from the Macal Chasm in the future, however, it will presumably be highly relevant, and therefore highly valuable, to the investigation of droughts and their effects (or lack thereof) on the sociocultural trajectories of Maya sites on the Vaca Plateau (Dunning and Beach 2010:370; Hoggarth et al. 2016:27; Iannone et al. 2013:272-273).

The Northwest Karst Plain includes Tzabnah Cave, source of the Chaac speleothem, but neither the (relatively close) Puuc sites of Uxmal and Oxkintok, nor the (relatively far) Petexbatún sites of Dos Pilas and Punta de Chimino (Dunning and Beach 2010:370; Dunning et al. 1998:89; Hoggarth et al. 2016:27), to which its data has been applied (Medina-Elizalde et al. 2010:255-256, 259-261), belong to the adaptive region. Although Mayapán lies within the adaptive region, its (twelfth-century) founding and (fifteenth-century) abandonment both postdate the (ninth- and tenth-century) series of severe droughts (ostensibly) recorded by Chaac and (tentatively) correlated with the collapses and abandonments of sites (Hoggarth et al. 2016:27, 36-37; Medina-Elizalde et al. 2010:259-261). Thus, even if the Chaac paleorecord (Medina-Elizalde et al. 2010:256-257, S1-S9) had greater temporal precision, it would not yield valuable insights into the histories of the above-named sites.

The Coba-Okop adaptive region includes the Río Secreto, source of the Itzamna stalagmite, but none of the Maya sites to which its data have been applied (El Mirador, Nakbé, and El Palmar, Guatemala; Komchén and Xcoch, Mexico; and Cerros, Belize) (A. Chase et al. 2014:15; Hoggarth et al. 2016:27; Medina-Elizalde et al. 2016:93-95, 100; Smyth et al. 2011:40). In fact, the situation of the Coba-Okop region is similar to that of the Northwest Karst Plain: it contains a speleothem, but none of the sites to which its dataset has been compared, as well as a well-known site, but one whose history took place well after the droughts recorded by the speleothem's data. In this case, the Maya site in question is Tulum, whose (twelfth- or thirteenth-century) founding occurred centuries after the (fourth-century) ending of the Itzamna paleorecord, which (again, as with Chaac) lacks the temporal precision necessary for answering the archaeological questions posed by Mayanists (Medina-Elizalde et al. 2016:95, SA1, SD1; Sharer and Traxler 2006:609).

The Disadvantages of YOK-I and Uxbenká

The Disadvantages of YOK-I

Granted that the use of YOK-I to answer archaeological questions about Uxbenká (Iannone et al. 2014:157-160; Kennett et al. 2012:788, 790-791) may (because of the temporal precision of the former and the location of the latter [Hoggarth et al. 2016:27, 30; Kennett et al. 2012:788-789, S4]) be considered by some to have been the most scientifically valid application of a stalagmite paleorecord to a Maya archaeological record that has been made (thus far), do the relevant datasets have any disadvantages that Mayanists seeking to do so should bear in mind? As mentioned earlier, the portion of the YOK-I dataset pertaining to the rainfall of the past century and a half was (by means of the Hendy test) determined to have been compromised (Douglas et al. 2016:8; Kennett et al. 2012:789, S5, S23). And, although the extraction and analysis of multiple speleothems from a single cave (to maximize the reliability of the data recorded by each) has been advocated (Dunning et al. 2015:170; McDermott 2004:915), the only other stalagmite from Yok Balum Cave to have been extracted and analyzed (YOK-G) did not yield any data on Precolumbian rainfall (Ridley 2014:v). However, I would argue that the only disadvantage significant enough to disqualify YOK-I as a source of data on Precolumbian Uxbenká is the dubiousness of its reliability as revealed by its recent reexamination and its subjection to (and "failure" of) the replication and equilibrium tests (Lachniet 2015:1521, 1527-1528, 1530).

The Disadvantages of Uxbenká

While Uxbenká has been subjected to multiple seasons of archaeological fieldwork, its archaeological record is not especially robust (Prufer 2005:4-5; Prufer et al. 2011:202, 216, 218). In fact, the Karstic Piedmont sites of Pusilhá and Lubaantun have both been more thoroughly excavated and are therefore better understood by Mayanists (Prufer et al. 2011:204). However, while the former site has yielded a greater quantity of dated monuments than Uxbenká, these cover a narrower timeframe, and the latter site has an epigraphic record that is inferior to those of both Uxbenká and Pusilhá, and in terms of both quantity and temporal range (Kennett et al. 2012:S100, S105, S110; Prufer et al. 2011:204) (See Table 1). Although Uxbenká has yielded the longest epigraphic history, and the most radiocarbon dates, of the southern Belizean sites, intensive excavations have only been conducted there since 2005, and its hieroglyphic record is comprised of a mere seven dated stelae (Kennett et al. 2012:S100, S102, S105, S110; Prufer

2005:4; Prufer et al. 2011:206-207). In contrast, Caracol, a Maya site which is also located in Belize, has been subjected to over three decades of intensive excavations, has been surveyed by two campaigns of LiDAR, and has yielded at least 43 dated monuments (See Table 1) (A. Chase and D. Chase 2015:47; D. Chase and A. Chase 2015:3, 7-9; Kennett et al. 2012:S92-S93; Martin and Grube 2008:85). As interesting and informative as a comparison between a superior source of paleoclimatic data from Yok Balum Cave and Uxbenká's archaeological data would be, an analogous comparison between a superior paleorainfall record from the Macal Chasm and Caracol's developmental trajectory would be informed by a body of data on culture change that is fairly robust and already accessible (A. Chase and D. Chase 2015:47; D. Chase and A. Chase 2015:3, 7-9; Dunning and Beach 2010:370; Martin and Grube 2008:85).

Suggested Future Directions for Maya Paleoclimatology

Moving forward, how can the application of speleothem-derived paleoprecipitation records to the investigation of Precolumbian climate change and its relationship to ancient Maya culture change best be furthered? In the case of the Karstic Piedmont adaptive region (Dunning et al. 1998:89, 95), the extraction and analysis of an additional stalagmite from Yok Balum Cave, or a different Karstic Piedmont cave, would either confirm or refute the archaeological arguments about southern Belize that have invoked YOK-I (Iannone et al. 2014:157-160; Kennett et al. 2012:788-791). Similarly, the extraction and analysis of multiple speleothems from multiple Karstic Piedmont caves could lend credence to the hypothesis of adaptive regions as (speleothem) spatial-applicability zones I have laid out in this thesis (assuming that it is confirmed by the novel data). And, in the long term, continued and intensified archaeological (and epigraphic) research at Karstic Piedmont sites would also lead to increased insight into Maya cultural responses to climatic conditions.

As mentioned earlier, Caracol (in the Vaca Plateau adaptive region [Dunning and Beach 2010:370; Dunning et al. 1998:89, 94]) is a Maya site in Belize with numerous dated and inscribed historical monuments (A. Chase and D. Chase 2015:47; Kennett et al. 2012:S89-S113). The analogous sites in Guatemala and Honduras would be Tikal and Copán (Kennett et al. 2012:S89-S113) (in the Petén Karst Plateau and Motagua and Copán Valleys adaptive regions, respectively [Dunning and Beach 2010:370; Dunning et al. 1998:89, 93, 95]). Each of the two sites has not only yielded more dated monuments than Caracol (Kennett et al. 2012:S92-S97, S107-S110) (See Table 1), but both have been excavated for longer than the Vaca Plateau site (Martin and Grube 2008:25, 85, 191). Furthermore, the Petén Karst Plateau region includes not only Tikal, but also the Petén site of Naranjo, the Mirador Basin sites of El Mirador and Nakbé, and even the Mexican site of Calakmul (Dunning and Beach 2010:370; Dunning et al. 1998:89, 93). Naranjo and Calakmul (See Table 1) both have archaeological and hieroglyphic records that are rich and well-documented (Kennett et al. 2012:S90-S92, S101-S102; Martin and Grube 2008:69, 101) (as do Tikal and Copán [Kennett et al. 2012:S94-S97, S107-S110; Martin and Grube 2008:25, 191]), and all six of the above-named sites have already been mentioned in Maya-region speleothem studies (Kennett et al. 2012:788-791; Medina-Elizalde et al. 2010:256, 260, 2016:94-95, 100; J. Webster et al. 2007:3) (which presumably indicates great interest on the part of Mayanists in investigating droughts and their roles [or lack thereof] in the collapses and abandonments of the six sites).

Although the Lacandon Fold adaptive region includes both the Maya site in Mexico with the greatest quantity of dated monuments (Yaxchilan) and its likewise epigraphically robust cross-border neighbor (Piedras Negras [Guatemala]; See Table 1) (Dunning et al. 1998:89, 94; Kennett et al. 2012:S89-S113), it is an area which has not been thoroughly excavated, and whose archaeological record is thus much poorer than its hieroglyphic one (Martin and Grube 2008:117-118, 139). While the Yucatecan sites of Chichén Itzá (in the Northeast Karst Plain adaptive region), Uxmal, and Oxkintok (both in the Puuc-Santa Elena adaptive region) have yielded fewer dated monuments (even when combined) than Yaxchilan See Table 1), they are nevertheless more easily accessible and (in the case of the first two) better-understood archaeologically than the borderland site (Cobos et al. 2014:56, 59-65; Dunning et al. 1998:89, 92; Hoggarth et al. 2016:27; Kennett et al. 2012:S93, S102, S110-S113). Furthermore, all three have already been mentioned in Maya-region speleothem studies and represent sites whose collapses and abandonments occurred well after those of the Petén and adjacent areas (Hoggarth et al. 2016:25-31; Kennett et al. 790-791; Medina-Elizalde et al. 2010:255-256, 259-261).

Therefore, in addition to the continuation and intensification of archaeological work in, and the extraction and analysis of additional high-quality cave stalagmites from, the Karstic Piedmont (i.e., non-coastal southern Belize), I argue that the extraction and analysis of high-quality cave stalagmites from other adaptive regions of the Maya Lowlands would further Mayanists' understanding of climate change and its relationship to culture change, and that priority should be given to speleothems from the Vaca Plateau, Petén Karst Plateau, Motagua and Copán Valleys, Northeast Karst Plain, and Puuc-Santa Elena adaptive regions (Dunning et al. 1998:89, 92, 94-95).

In Conclusion

In conclusion, four stalagmites from Belize and southeastern Mexico have been extracted, analyzed, and used to make arguments about climate change as a driver of culture change at sites throughout the Maya Lowlands (D. Chase and A. Chase 2014:147, 149-150; Hoggarth et al. 2016:25-31; Iannone et al. 2013:276-279, 281-295, 2014:157-163; Kennett et al. 2012:788-791; Medina-Elizalde et al. 2010:255-261, 2016:93-101; Smyth et al. 2011:1, 2014:45; J. Webster et al. 2007:1-15; Zubrow et al. 2010:2). On the basis of the temporal resolutions (of oxygen-isotope measurements) and attached errors (of Uranium-series dates) of each of the speleothem datasets (Hoggarth et al. 2016:28,30; Iannone et al. 2013:275-276; Kennett et al. 2012:789,S4; Medina-Elizalde et al. 2010:256-257,S2-S9, 2016:95,SA1,SD1; J. Webster et al. 2007:5-7), I have argued that only the YOK-I dataset (Hoggarth et al. 2016:30; Kennett et al. 2012:789,S4) is of sufficiently high precision to potentially answer the archaeological questions posed by Mayanists. The discouraging results of its recent reanalysis by Lachniet (2015:1527-1528, 1530), however, have led me to conclude that a stalagmite paleorecord that is both highly precise and highly reliable must be sought. After evaluating the arguments that have been advanced for the broad spatial applicability of speleothem datasets (Kennett et al. 2012:788-791; Medina-Elizalde et al. 2010:257-258, 2016:99-101; J. Webster et al. 2007:2-15), examining the science behind the spatial variability of precipitation patterns (Dunning et al. 2015:168; Hastenrath 1967:201, 203; Portig 1965:68, 73; Turner and Sabloff 2012:13909, 13913; Whiteside 1985:1-2, 8), and considering the geophysically-based adaptive regions devised by Wilson (1980:8) and revised by Dunning, Beach, and others (Dunning and Beach 1994:63, 2010:370; Dunning et al. 1998:89), I have argued against applying stalagmite paleorecords to sites that lie outside the adaptive regions within which their source caves are located. Finally, I have expressed my hope and conviction that the continuation and expansion of the archaeological excavation of Maya sites and the paleoclimatic analysis of Maya-region speleothems will yield insights into Precolumbian climate change, ancient Maya culture change, and the relationship(s) between them.

As Ellsworth Huntington (1917:150) began “Maya Civilization and Climatic Changes”, and thereby Maya paleoclimatology, nearly a century ago: “The world’s greatest problems almost invariably belong to more than one science. The search for the ultimate causes and conditions of the rise and fall of nations presents such a problem, for it belongs to every branch of knowledge that deals with man. Therefore each branch must present its conclusions to others for criticism and revision.” Archaeologists and other scientists have come far in their pursuit of knowledge about Maya cultural responses to climatic change over the past hundred years; I am certain that, if Mayanists can continue to collaborate, cordially and constructively, with their colleagues in other disciplines, and with one another, they will come much further in the years to come.

APPENDIX: TABLES AND FIGURES

Table 1: Epigraphic records of (dated-monument-bearing) Maya sites mentioned in thesis.

(D/D/S = Department [Guatemala/Honduras]/District [Belize]/State [Mexico]; MONUMENTS = Total Number of Dated Monuments; EARLIEST = Earliest [Historical] Date on a Dated Monument; LATEST = Latest [Historical] Date on a Dated Monument. All years A.D., Gregorian calendar, GMT correlation.)

SITE	D/D/S	COUNTRY	MONUMENTS	EARLIEST	LATEST
Calakmul	Campeche	Mexico	51	431	810
Caracol	Cayo	Belize	43	400	884
Chichén Itzá	Yucatán	Mexico	18	832	997
Copán	Copán	Honduras	92	435	821
Dos Pilas	Petén	Guatemala	16	682	790
El Palmar	Petén	Guatemala	1	884	884
Lubaantun	Toledo	Belize	1	790	790
Naranjo	Petén	Guatemala	36	593	820
Nim Li Punit	Toledo	Belize	6	721	810
Oxkintok	Yucatán	Mexico	9	475	859
Palenque	Chiapas	Mexico	41	646	790
Piedras Negras	Petén	Guatemala	48	518	795
Pusilhá	Toledo	Belize	10	574	731
Tikal	Petén	Guatemala	55	292	869
Uxbenká	Toledo	Belize	7	437	781
Uxmal	Yucatán	Mexico	5	895	904
Yaxchilan	Chiapas	Mexico	81	435	807

Sources: A. Chase and D. Chase 2015 (Caracol); Kennett et al. 2012 (all).

Table 2: Paleorecords of speleothems mentioned in thesis.

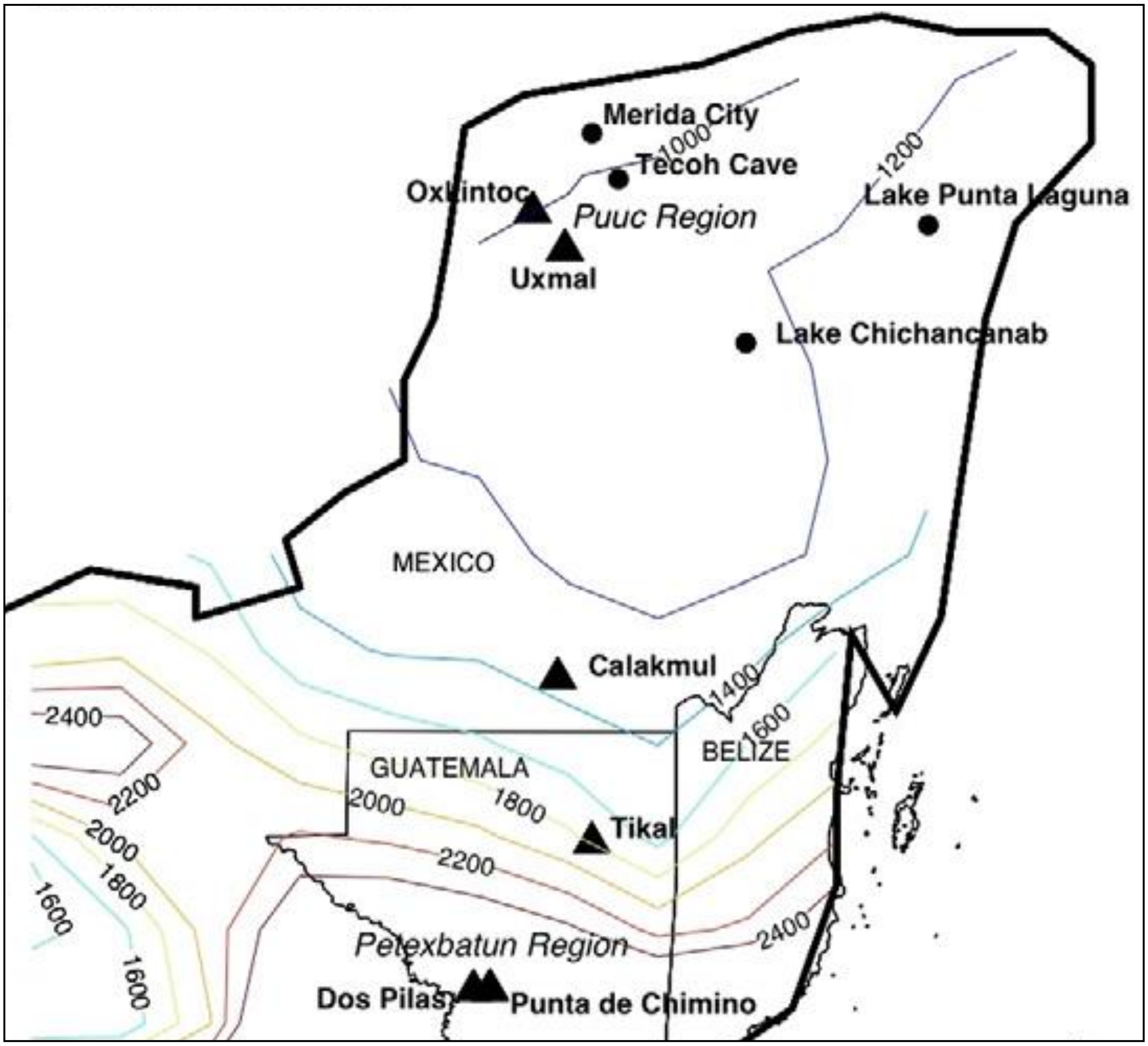
(SPEL = Speleothem; D/P/S = District [Belize]/Province [Costa Rica/Panama]/State [Mexico]; EARLIEST = Earliest year of speleothem paleorecord; LATEST = Latest year of speleothem paleorecord.)

SPEL	CAVE	D/P/S	COUNTRY	EARLIEST	LATEST
ATM1	ATM Cave	Cayo	Belize	~10598 BC	~3554 BC
ATM7	ATM Cave	Cayo	Belize	AD 1973	AD 2000
CBD-2	Cueva del Diablo	Guerrero	Mexico	5960 BC	AD 770
CH04-02	Chen Ha Cave	Cayo	Belize	~4900 BC	~2700 BC
CH04-03	Chen Ha Cave	Cayo	Belize	~4900 BC	~2700 BC
Chaac	Tzabnah Cave	Yucatán	Mexico	AD 478	AD 2004
CHIL-1	Chilibrillo Cave	Panamá	Panama	180 BC	AD 1310
Itzamna	Río Secreto	Quintana Roo	Mexico	1037 BC	AD 397
JX-1	Juxtlahuaca Cave	Guerrero	Mexico	2275 BC	AD 1907
JX-6	Juxtlahuaca Cave	Guerrero	Mexico	390 BC	AD 2010
JX-7	Juxtlahuaca Cave	Guerrero	Mexico	AD 598	AD 1954
MC-01	Macal Chasm	Cayo	Belize	1225 BC	AD 1995
V1	Venado Cave	Alajuela	Costa Rica	6840 BC	2920 BC
VP-10-1	Vaca Perdida Cave	Yucatán	Mexico	~16 BC	AD 1421
VP-10-2	Vaca Perdida Cave	Yucatán	Mexico	?	AD 1421
YOK-G	Yok Balum Cave	Toledo	Belize	AD 1560	AD 2006
YOK-I	Yok Balum Cave	Toledo	Belize	40 BC	AD 2006
(unnamed)	Blue Hole	Belize	Belize	~9542 BC	~912 BC

Sources: Bernal et al. 2011 (CBD-2); Crosby 2010 (ATM1); Dill et al. 1998 (Blue Hole speleothem); Frappier et al. 2002 (ATM7); Kennett et al. 2012 (YOK-I); Lachniet 2015 (JX-7); Lachniet et al. 2004a (V1), 2004b (CHIL-1), 2012a (JX-1), 2012b (JX-6); Medina-Elizalde et al. 2010 (Chaac), 2016 (Itzamna); Pollock 2015 (CH04-02, CH04-03); Ridley 2014 (YOK-G); Smyth et al. 2011 (VP-10-1, VP-10-2); J. Webster et al. 2007 (MC-01).

Figure 1: Map with locations of the Macal Chasm, Lake Chichancanab, and selected Maya sites.

(Note that the map's "Central Lowlands" area is commonly considered part of the Southern Lowlands. Lines represent international boundaries.) After J. Webster et al. 2007:Figure 1.



:

Figure 2: Map with locations of Tecoh Cave (a.k.a. Tzabnah Cave), Lakes Chichancanab and Punta Laguna, and selected Maya sites and subregions in Mexico and Guatemala.

(Black lines represent international boundaries; colored lines represent precipitation gradients.) After Medina-Elizalde et al. 2010:Figure 1.

Figure 3: Map with location of Yok Balum Cave.

(Thick lines represent international boundaries; thin lines represent boundaries between Belizean administrative districts.) After Ridley 2014:Figure 2.1a.

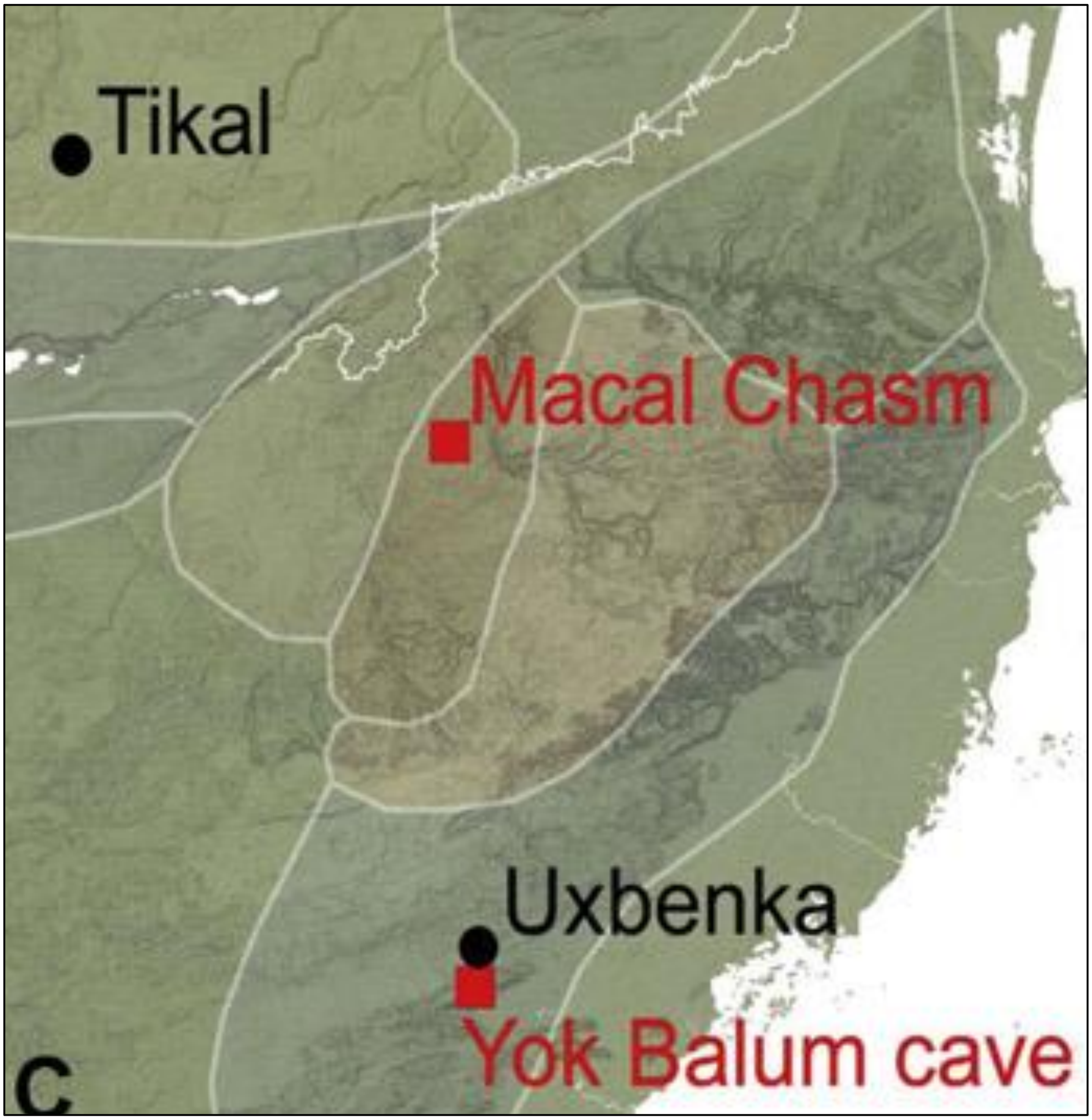


Figure 4: Map with relative locations of the Macal Chasm, Yok Balum Cave, Tikal, and Uxbenká.

(Lines represent boundaries between adaptive regions.) After Hoggarth 2016: Figure 1C.

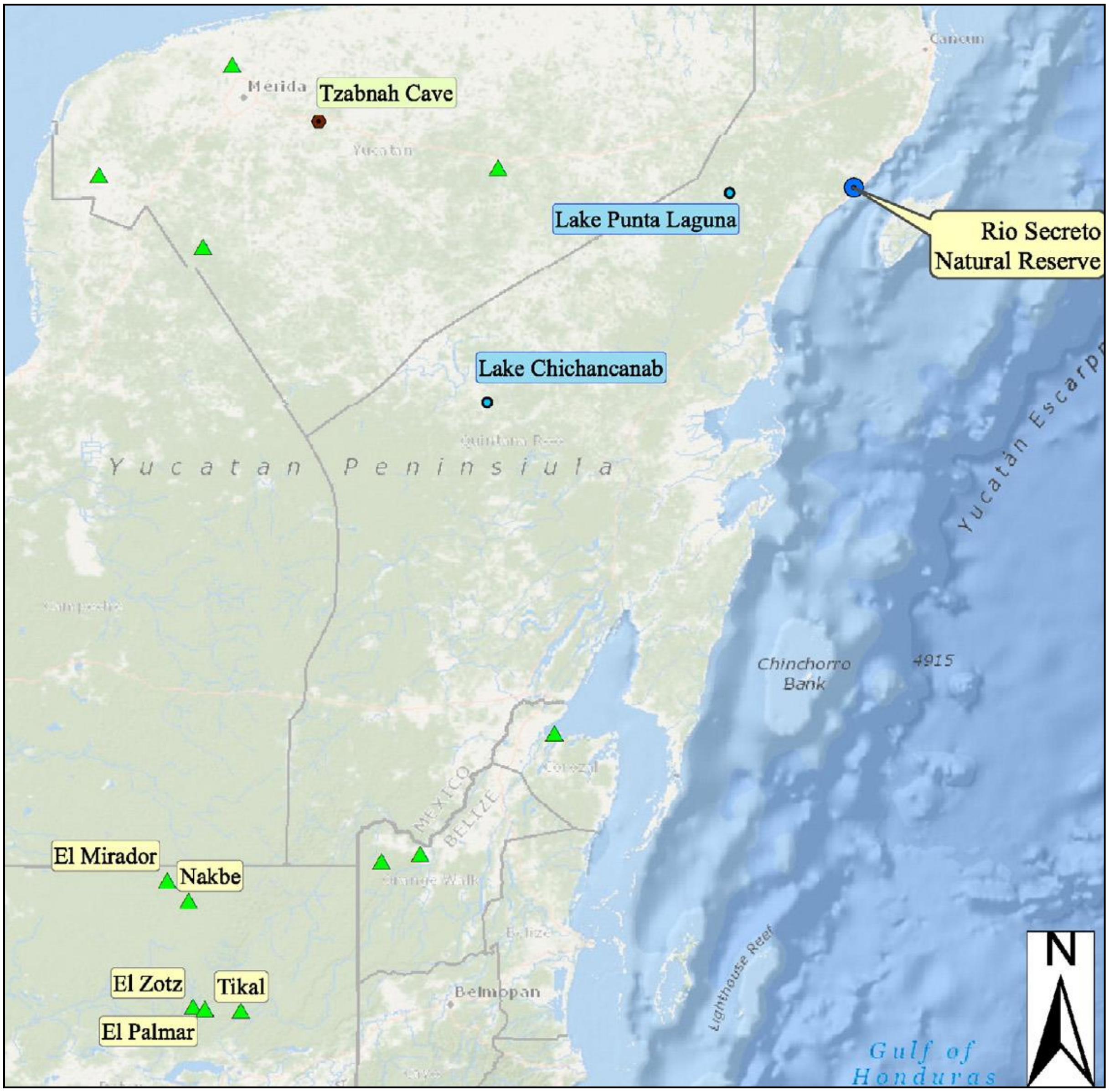


Figure 5: Map with locations of Río Secreto, Tzabnah Cave (a.k.a. Tecoh Cave), Lakes Chichancanab and Punta Laguna, and selected Maya sites in Guatemala.

(Lines represent boundaries between nations, Mexican states, and Belizean administrative districts.) After Medina-Elizalde et al. 2016:Figure 1.

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