

the multi-tapered Method (MTM). No filters were applied. This produced a continuous, millimeter-scale record. The resulting power spectra frequency peaks were converted to calendar years based on the age-depth model. Because of variations in the microfabric record (density of laminations, microburrows, flood layers), spectral peaks were calculated separately for three cores and for selected intervals within the cores. The results were the same for all cores.

Strong peaks of variability were found with periodicities at about 150 yrs (144 ± 18 yrs), 200 yrs (192 ± 20 yrs) and 300 yrs (300 ± 20 yrs) (Table 1). These are associated with productivity/dissolution cycles in the carbonate record. All these periodicities are present prior to 3200 yBP but the 300-year cycle dominates in the latest Holocene. Similar productivity pulses have been identified by Gladys Bernal-Franco (2001) in the biogenic record in La Paz Basin on a 330-year period. We suspect that the centennial variability is related to variations in solar radiation identified in radiocarbon fluctuations

in tree rings and ^{10}Be records. Millennial scale variations at 900 yrs (898 ± 82 yrs) and 1500 yrs (1480 ± 100 yrs) are strong in both the carbonate and sediment lamination records.

Stable isotopes measured on the benthic foraminifera *Bolivina subadvena* in Alfonso Basin (core BAP96-CP) exhibit small variation through the 7700 yBP record, except in the ^{18}O record. Beginning about 6ka, the record is punctuated with a series of short-term excursions or events of 0.5 to 0.9‰, the largest of which occurs between 5200 and 1400 yBP (Fig. 2). The events signal a turnover in the water-mass in the basin and replacement by either much colder or higher salinity water. The basin sill is located at ca. 250 m depth, near the present-day lower boundary of Central Gulf Water—a high salinity water-mass produced by evaporation in the northern Gulf of California during winter months—and is advected at shallow depths along the western margin depth of the Gulf towards the mouth. We believe the most likely explanation for the isotopic excursions is basin turnover, when increased production

of Central Gulf Water flooded the basin (Douglas and Staines-Urias, in press). If this interpretation is correct, the isotopic excursions record periods of intensified NW winds in the mid and late Holocene.

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Climate and the Maya

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The relative stability of Holocene climate, at least when compared to the rapid, large-amplitude climate excursions of the last ice age, has contributed to a view that the road to modern human civilization has been little affected by climate road-bumps. However, significant variations in regional Holocene climate have now been recognized, with some having had clear societal impacts. Here we summarize recently reported new data from the annually laminated sediment record of the anoxic Cariaco Basin off northern Venezuela, a now well-known paleoclimate archive. Using a new method for the measurement of bulk sediment chemistry, we have been able to develop a record of varying river-

derived inputs to Cariaco Basin with roughly bimonthly resolution (50 μm sample spacing) for the period AD 700 to 950 (Haug et al., 2003). Terminal Collapse of the Classic Maya civilization in the lowlands of the Yucatan Peninsula in Mesoamerica occurred during this time, one of the most dramatic events in human history (Fig. 1). Our new record of riverine input to Ocean Drilling Program (ODP) Site 1002 shows in unprecedented detail evidence of a link between regional drought and the demise of the Maya culture.

Paired light-dark laminations preserved in the anoxic, non-bioturbated sediments of Cariaco Basin are the direct result of large regional changes in rainfall and trade wind

strength, driven by seasonal shifts in the position of the Intertropical Convergence Zone (ITCZ; Fig. 1) and its associated convection (Peterson et al., 2000; Haug et al., 2001). Light-colored laminae consist mostly of biogenic components deposited during the dry winter-spring upwelling season when the ITCZ is located at its southernmost position and trade winds along the Venezuelan coast are strong. In contrast, dark laminae are deposited during the summer-fall rainy season when the ITCZ migrates to its most northerly position, nearly above Cariaco Basin. Individual dark laminae are rich in terrigenous grains and contain higher quantities of titanium (Ti) and other lithophilic elements. Our interpretation of bulk

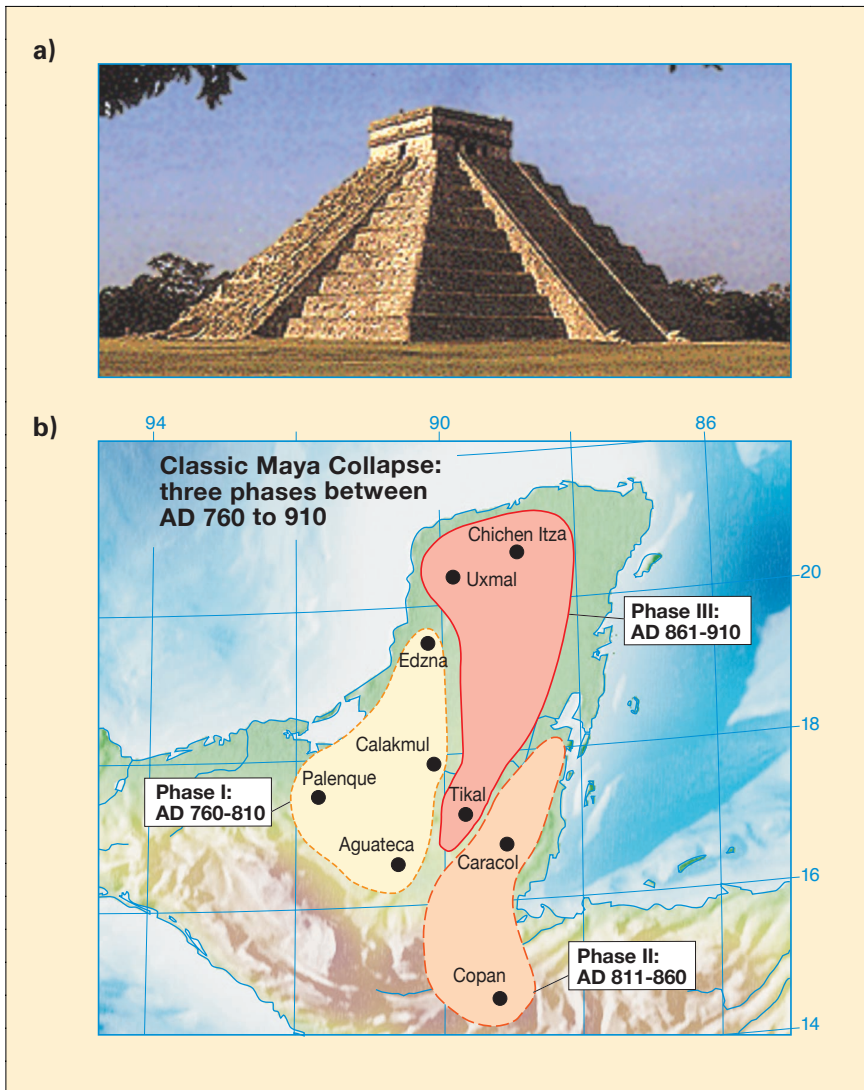


Figure 1: (a) The Pyramid of Chichen Itza in the Yucatan peninsula lowlands. (b) Three phases of Terminal Classic Collapse (~AD 760 to 910). Phase I: Initial abandonment of the western lowlands where rainfall was the primary source of water. Phase II: Abandonment of the southeastern lowlands where freshwater lagoons provided at least some surface water. Phase III: Large-scale abandonment of remaining cities in the central lowlands and the north. (Modified from Gill, 2000).

Ti content as an index of regional hydrologic change, reflecting variations in the mean ITCZ position with time, is supported by comparison of the Holocene Cariaco record with independent paleoclimatic data from the region.

It has been suggested that recurrent patterns of drought played an important role in the complex history of the Maya (Hodell et al., 2001; Gill, 2000). Maya civilization developed in a seasonal desert and was highly dependent on a consistent cycle of rainfall to support agricultural production. Most of the rain available to the Maya fell during the summer, when the ITCZ sits at its northernmost position over the Yucatan. During the winter, the ITCZ is located south of the lowlands and

the climate is dry. Hence, the center of Maya civilization was located in the same climatic regime as Cariaco Basin, with both areas near the northern limit of seasonal ITCZ movement.

In order to inhabit the Yucatan lowlands and to deal with normal seasonal variations in rainfall, the Maya developed elaborate strategies to accumulate and store water. Cities were designed to catch rainfall and quarries were converted into water reservoirs. The Maya also built on topographic highs in order to use the hydraulic gradient to distribute water from canals into complex irrigation systems. Nevertheless, despite its sophistication, the human-engineered system ultimately depended on seasonal rainfall since

natural groundwater resources were restricted over much of the lowlands.

During the Pre-Classic Period prior to about AD 150, Maya culture flourished and the first major cities were built. Between ~AD 150 and 250, the first documented historical crisis hit the lowlands and led to the Pre-Classic Abandonment of major cities (Fig. 2). However, populations recovered, cities were reoccupied and Maya culture blossomed in the following centuries. Around AD 750, at the peak of this Classic Period, the best estimates for the population of the Maya lowlands range from 3 to 13 million inhabitants.

Between about AD 750 and 950, the Maya experienced a demographic disaster as profound as any in human history. During this Terminal Classic Collapse, many of the densely populated urban centers were permanently abandoned and Classic Maya civilization came to an end. What caused this to happen? While the Cariaco Basin record cannot provide a complete explanation, it supports the view that changes in rainfall patterns played a critical role.

Using a Micro-XRF technique not previously applied to sediments, we measured the Ti content (at 50µm spacing) of a slab sample from ODP Hole 1002D taken from the stratigraphic interval known to encompass the period of the Terminal Classic Collapse. Further methodological and chronological details can be found in Haug et al. (2003). Within the Hole 1002D slab sample, we observed distinct Ti minima at depths of ~12 mm, 38 mm, 58 mm and 78 mm (Fig. 2) which we interpret as marking multi-year drought events that began in about AD 910, 860, 810 and 760, respectively. These are superimposed on a period of generally lower Ti content. Not counting the duration of the more severe multi-year droughts, the number of varves between drought events indicates a spacing of ~40 to 47 years (± 5), a number that agrees remarkably well with the observation of subpeaks at about 50-year intervals in the well-known Lake Chichancanab sediment density record (Hodell et al., 2001).

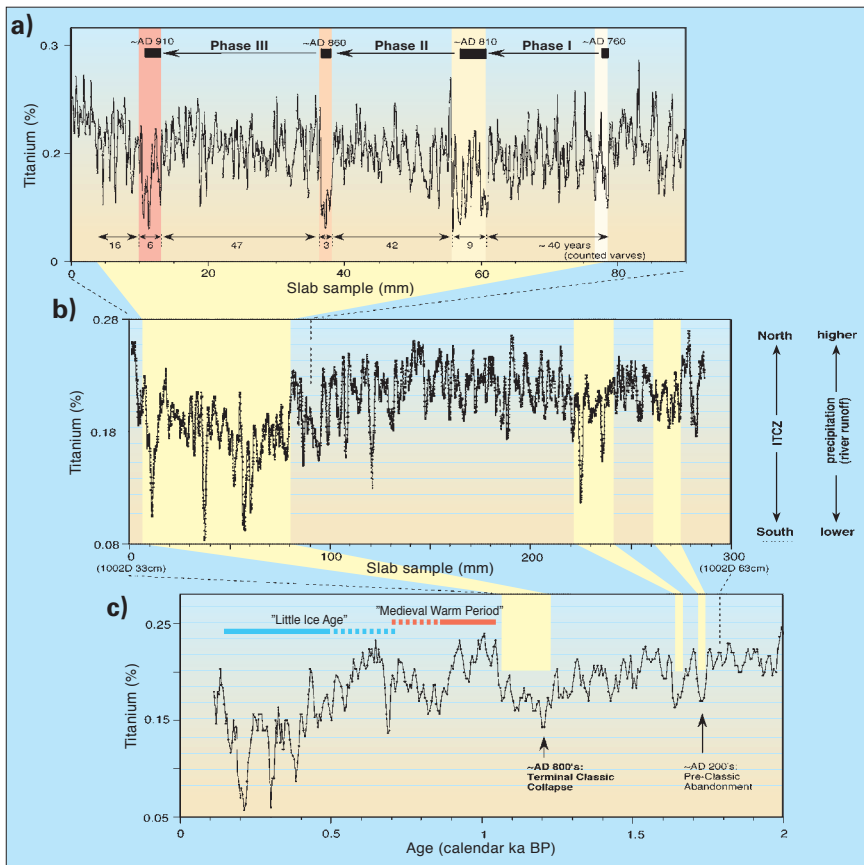


Figure 2: (c) Bulk Ti content (3-point running mean of 2-mm-resolution measurements; Haug et al., 2001) of sediments from ODP Hole 1002C, Cariaco Basin during the last 2000 years. Well-known climate events and major events in Maya civilization history are shown. (b) Bulk Ti content (30-point running mean of 50- μ m-resolution analyses) of a 30-cm-long slab sample from companion ODP Hole 1002D in the time interval ~1.8 to 1.0 ka. (a) Bulk Ti content (3-point running mean of 50- μ m-resolution analyses) of the slab sample during Terminal Classic Collapse. Gill's three phases of Maya Collapse are shown.

Mayanists generally agree that there is strong evidence in the archeological record for regional variability in the Terminal Classic Collapse. Most would also concur that the collapse occurred first in the southern and central Yucatan lowlands, and that many areas of the northern lowlands underwent similar decline a century or so later. A more controversial tripartite pattern of city abandonment (Fig. 1) was proposed by Gill (2000) based on analysis of the last dates carved into local monuments (stelae). On this basis, Gill argues for three separate phases of collapse that terminated respectively in ~AD 810, 860, and 910. He further speculates that periods of drought triggered the Maya demise. Within the limits of chronological uncertainty, the proposed end dates for each phase of abandonment match the three most severe drought events inferred from the Cariaco Basin record. Considerable variability exists in the distribution and

quality of natural water sources in the Yucatan lowlands, a factor that would clearly come into play during periods of drought. While the northern lowlands have the lowest annual average rainfall, collapsed cenotes (water-filled limestone sinkholes) in this region provide the most direct access to groundwater in the Yucatan. In the central lowlands, some freshwater is available in and around the Petén Lake district. Towards the west and south, access to groundwater is scarce and rainfall was almost certainly the primary source of water for Maya cities. During sustained drought, access to groundwater was likely an important factor in determining which large population centers could survive.

No one archeological model is likely to completely capture a phenomenon as complex as the Maya decline. Nevertheless, the Cariaco Basin sediment record provides support for the hypothesis that regional drought played an important

role in the collapse of Classic Maya civilization, and provides a temporal template for comparison of archeological data.

Drought conditions may also have been responsible for the earlier Pre-Classic abandonment of Maya cities that occurred between ~AD 150 and 250, intervals similarly marked by low sediment Ti. These periods of drought are all most probably the result of climatic conditions that prevented the ITCZ and its associated rainfall from penetrating as far north as usual. A southward displacement of the ITCZ, as indicated by low Ti in Cariaco sediments, would be expected to lead to similar rainfall reductions in the Maya lowlands.

We suggest that the rapid expansion of Maya civilization from AD 550 to 750 during climatically favorable (i.e., relatively wet) times resulted in a population operating at the limits of the environment's carrying capacity, leaving Maya society especially vulnerable to multi-year droughts. Given the perspective of our long, sediment time-series, it would appear that the droughts we have highlighted were the most severe to affect this region in the first millennium AD. The intervals of peak drought were brief, each lasting between ~3 and 9 years. However, they occurred during an extended period of reduced overall precipitation that may have already pushed the Maya system to the verge of collapse.

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