THE CHICXULUB METEOR IMPACT AND ANCIENT LOCATIONAL DECISIONS ON THE YUCATÁN PENINSULA, MEXICO: THE APPLICATION OF REMOTE SENSING, GIS, AND GPS IN SETTLEMENT PATTERN STUDIES

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ABSTRACT

In addition to the visible surface expression of the buried Chicxulub crater, the effect of the meteor impact is discernable in the cultural landscape of northwestern Yucatán, Mexico as a uniquely patterned distribution of archaeological sites and modern towns and villages. The event and subsequent formation of a 180-kilometer wide sedimentary basin ultimately produced favorable conditions for human settlement in a region where surface water is scarce. Of 1,152 known archaeological sites in the region of study, 65.45 percent are located above the buried crater. Modern populated places follow a similar pattern, but evidence the influence of transportation networks and recent economic development. This paper reports of the application of remote sensing data, geographic information systems technology, and spatial statistics to identify relationships between the physical and social environment and settlement decisions. The study revealed that shallow aquifer depths in the Chicxulub basin area enabled the ancient inhabitants of the Yucatán Peninsula to access subsurface water with a stone tool technology thereby influencing locational decisions in the region.

INTRODUCTION

Access to water, both for drinking and agriculture, is widely regarded as a necessary determinant of settlement for ancient civilizations. The ancient Maya were no exception (Carneiro 1970; Dunning 1992; Fedick 1990, 2000; Harrison 1983; Lucero 2006; Matheny 1976; Morley 1946; Scarborough 1998, 2003, 1993; Stephens 1988; Winemiller 2003; Wittfogel 1957). The Maya of the lowlands of Guatemala, Belize, Honduras and the Yucatán Peninsula of Mexico located settlements near rivers, caves, *cenotes* (natural water-filled sinkholes), and modified the landscape by creating wells, *chultunes* (cisterns), *aguadas* (culturally modified lakes), and ditching swamps for agriculture. Due to a scarcity of rivers or other surface water features and greater aridity, adaptive options were limited in the NW Yucatán as compared to southern parts of the peninsula of Mexico, Guatemala and western Honduras. The impact of the Chicxulub meteor in NW Yucatán, Mexico (Figure 1), and subsequent formation of a 180-km. wide sedimentary basin contributed to the development of a desirable environment for ancient Maya settlement in a region where surface water is otherwise scarce (Figure 2).

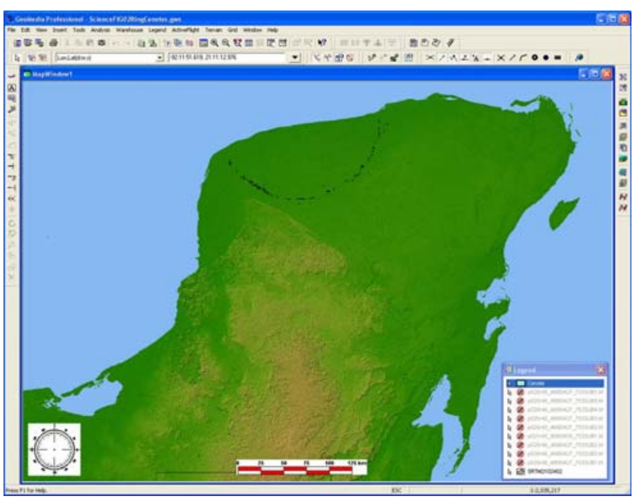

Figure 1. Ring of cenotes**.** High numbers of cenotes (black points) occur along the trough or moat that defines the crater basin area. The trough is visible in Shuttle Radar Topography Mission SRTM image (courtesy of NASA/JPL).

Discussion of the Chicxulub crater has focused on its role in mass extinctions near the end of the Cretaceous. The current study reveals a significant relationship between the unique NW

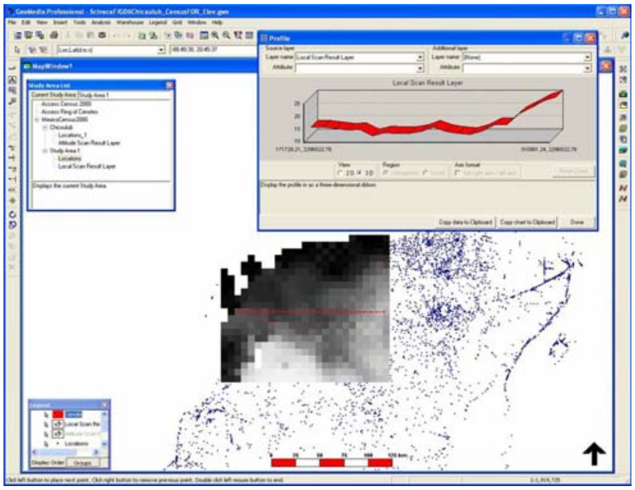

Figure 2. 3D rendering of horizontal transect through the Chicxulub basin area. A horizontal west to east transect reveals the depression formed above the buried Chicxulub crater. Sharp incline on the right portion of the 3D inset indicates the rising eastern rim of the crater. Elevations of point features, modern populated places, were used to derive topography.

Yucatán landscape created by the meteor impact and ancient Maya settlement wherein the Chicxulub sedimentary basin ultimately enhanced access to underground water resources, thereby creating a landscape favorable for settlement. Using geographic information systems (GIS) technology, the study revealed that in addition to the visible surface expression of Chicxulub characterized by a relatively flat zone bounded by concentric crescent-shaped shallow troughs and a ring of cenotes (Pope 1991), the effect of this event is discernable in the cultural landscape as a distinct pattern of ancient settlements associated with the basin area and its shallow water table. The distribution of two different water management strategies and aquifer depth data further indicate that the Chicxulub basin area was a preferential location to establish settlements in ancient times.

ANCIENT MAYA SETTLEMENT CHOICES

The ancient Maya populated the Yucatán Peninsula by applying a range of adaptive strategies to cope with a scarcity of surface water. Reported dates for the principal occupation of settlements in this report range from as early as the Middle to Late Formative Period 400 B.C. to the Early Post Classic, roughly A.D. 1200. The modern Maya continue to construct dwellings above the remains of ancient settlements. The notion that the ancient Maya employed various adaptive strategies to populate the Yucatán Peninsula is not new. Nevertheless, the idea that the Chicxulub event prompted processes that ultimately resulted in a unique milieu for Maya settlement has not been suggested.

Near the middle of the 19th century, Stephens (Stephens 1988) revealed the practically unknown ruins of Maya high-civilization to the academic community and commented on the existence of various water systems. Two centuries before Stephens, Landa (Landa 1941), a Spanish priest, remarked about access to water on the peninsula. In the years since Stephens published descriptions of the archaeological ruins of the Maya, Mayanists have sought to identify causal relationships between settlement location and the physical environment. S. Morley (Morley 1946), a researcher with the Carnegie Institution of Washington, D.C., argued that cenotes were "principal factors" in determining the location of ancient Maya settlements. The idea that the Maya purposely established settlements near sources of water and the significance of cenotes to settlement distribution is widely accepted.

Field survey on the Yucatán Peninsula during 1999 and 2001 (Winemiller 2003) revealed that for each visible *cenote* in or near the ring, many others are either too small to provide a return in remote sensors or concealed by dense vegetation (Figure 3). The walled area at Mayapan, an ancient settlement

Figure 3. Cenotes of the Yucatán Peninsula. Types of cenotes found in the region and ring zone. The vertical-walled *cenote* on the upper left from Chichén Itzá is visible in satellite data and air photos. The feature on the upper right is smaller and concealed by vegetation. The lower two cenote types have small openings and are ubiquitous inside the ring.

located 4.0 km. north of the ring zone, covers approximately 5.5 km^2. Over 30 cenotes of varying size have been reported at Mayapan - none is detectable as a water feature in satellite data. Cenotes or natural wells, like those found at Mayapan, are ubiquitous in portions of the peninsula enclosed by the ring. Today, the indigenous inhabitants often modify cenotes with small openings by constructing well curbs and installing winches to draw water from the vast network of underground water-filled chambers.

PREVIOUS UNDERSTANDING OF THE CHICXULUB METEOR IMPACT

First knowledge of the Chicxulub feature dates to the 1950s when geologists discovered anomalies in gravity surveys which were later interpreted as probable evidence of a buried impact crater (Blum 1993; Hildebrand 1991, 1994; Koeberl 1994; Krogh 1993; Perry 1995; Pope 1991, 1993; Sharpton 1992, 1993; Swisher 1992). The feature was named Chicxulub after Chicxulub Puerto, the location of an exploratory well excavated by *Petróleos Mexicanos*, PEMEX, to investigate the anomaly. After its discovery, researchers focused on characterization of the structure and surface expression of the Chicxulub feature (Collins 2002; Morgan 1997; Pope 1996; Sharpton 1997). In addition, they attempted to define the role the event played in the mass extinction, believed to have taken place at or near the end of the Cretaceous Period (Alvarez 1980; W. Stinnesbeck 2004). Today, the Chicxulub basin is buried beneath 300 to 1,100 meters of sedimentary limestone (Pope 1996; Sharpton 1995).

Although scientists from various disciplines possess a considerable amount of data concerning the physical environment inside the Chicxulub area, no attempt has been made to account for the effect the event had on subsequent geological and hydrological processes as they relate to human locational decisions in the region. In the years since discovery of Chicxulub (Penfield 1981), researchers have studied and characterized the surface expression of the impact crater, buried beneath a portion of the Yucatán Peninsula (Hildebrand 1994; Perry 1995; Pope 1991). Pope et al. (Pope 1991) identified a ring-shaped zone of cenotes, that marks the location of the crater in Landsat imagery. The ring of cenotes spans approximately 244 km. along an arc projecting roughly 82 km. inland at its southernmost apex. In addition to its role in the formation of the ring of cenotes, the Chicxulub impact appears to have influenced subsequent carbonate deposition and development of the basin area (Lefticariu 2004; Pope 1996). See Morgan (Morgan 2000) and Collins (Collins 2002) for discussions of peak ring formation, collapse, and basin development.

CHICXULUB CRATER AND ANCIENT MAYA SETTLEMENT LOCATION

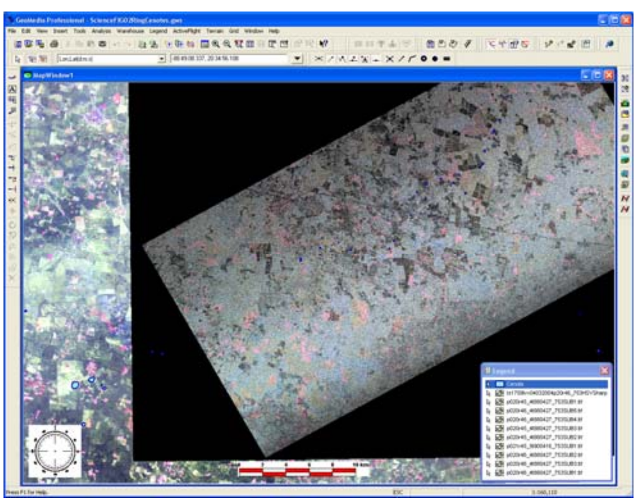

Figure 4. Classification. Fused AIRSAR and Landsat TM, and Landsat TM. (Data courtesy of NASA/JPL).

The dataset for this research contains the geographic locations for 1,694 known archaeological sites and 7,430 modern populated places located on the Yucatán Peninsula. A region of interest (ROI) was defined that contains 1,152 ancient settlements and 1,458 modern populated places distributed among 588 – 39.7km^2 quadrats in a graticule created to accomplish point pattern analyses. The region of study covering most of NW Yucatán, Mexico has been intensively surveyed over the past 150 years. Although undiscovered settlements remain to be found, their number and size is in all probability small. Therefore, the sample reported in this paper is representative for archaeological sites located on the NW peninsula. Population estimates for archaeological sites, recorded census figures for modern populated places, and site rank, a hierarchical classification system based upon architecttural development and population estimates (Garza Tarazona de Gonzales 1980), were not considered as variants for statistical analysis.

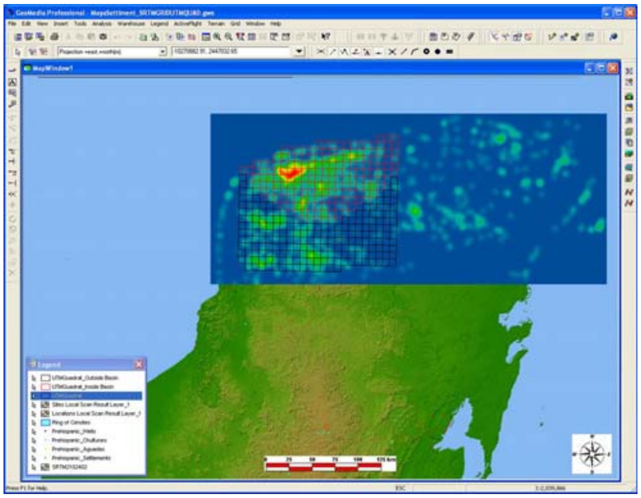

Figure 5. Grid surface analyses in the GIS, ancient site locations. The grid shown demarcates the region of interest. Points represent ancient site locations and numbers frequency per quadrat. Red, green, blue RGB values indicate high density (red) to no recorded sites blue) respectively.

Using visual and computer-aided classification techniques and remote sensing data, 211 cenotes were identified along the trough that defines the ring of cenotes (Figure 4). In the absence of intensive systematic foot survey, it is safe to assume that a number remain undetected. Cenotes are abundant outside the ring zone as well, but the large vertical-walled variants, Type 1 variety as defined by Roys (Roys 1939), are with few exceptions, more randomly distributed. Spatial queries indicate that significant numbers of known archaeological sites in the database do not occur adjacent to or near the large cenotes that form the ring zone. In effect, the ring of cenotes is a narrow crescent-shaped strip of land containing relatively few known sites that bisects the NW peninsula into two sub-regions with proportionally different settlement densities, one inside the Chicxulub area and the other south of the ring in a hilly area known as the *Puuc* as well as further to the south and west. See Dunning (Dunning 1992) for a detailed discussion of settlement in the *Puuc* region. Of the 211 cenotes identified in remote sensing data within the ring zone, five (2.4 percent) have documented sites within one-half km. That number increases to 12 (5.7 percent) when the distance is increased to 1.0 km. An undetermined but in all probability small number of cenotes known to exist today were almost certainly not fully developed 1,000 to 2,000 years ago. Additional potential causal factors are discussed below. Nevertheless, the findings suggest that large cenotes located in or near the trough marking the ring feature itself were not overly attractive sites for settlement.

A total of 754 settlements representing 65.45 percent of the known archaeological sites in the ROI are located within the 294 - 39.7km^2 quadrats falling inside the Chicxulub basin area (Figure 5). The remaining 398 (34.55 percent) are situated in the 294 quadrats outside the area. Variance-mean ratios (VMR) were calculated to determine if observed spatial patterns of locations in the ROI are statistically significant. The VMR of 3.359, corresponding *t*-statistic of 57.545, and *p*-value of less than 0.0001 for ancient settlements indicates a significant non-random pattern exists in the distribution. Based on a larger 56.1 km^2 quadrat size, the VMR for ancient sites is 4.425 with a *t*-statistic of 62.977 and *p*-value of less than 0.0001. The distribution favors the Chicxulub basin area and argues for the presence of an underlying benefit the ancient Maya derived by establishing settlements there. Nearest neighbor analysis conducted in the GIS for site locations in the ROI returned an observed mean distance of 0.0168, an expected mean distance of 0.0210 with an R-statistic of -0.8014. The statistic indicates a low probability that the pattern is random.

Further analyses in the GIS, suggested that no overriding causal relationship existed between any single factor such as rainfall, climate, or soil type and ancient settlement location. Unlike variation in soils, where the ability to secure essential subsistence goods from Puuc sites (Dunning 1992) would have counteracted population pressures on carrying capacity or extended periods of environmental stress, the availability of water was a major consideration in the selection of a place to occupy. Although the region appears to have witnessed periodic severe droughts in the past(Gill 2000), there is no reason to suspect that the monsoonal pattern of rains lasting from May or June to November or December followed by six months of little or no rainfall typical throughout the region today (INEGI 2001) differs greatly from the climate early settlers would have experienced. Procuring water in any location during the period of rains was most likely not a major problem. The dry season would have presented inhabitants living in certain sections of the ROI with unique challenges. The relatively higher site density inside the Chicxulub area suggests that access to water was less problematic in that location. Shallow aquifer depths, normally found along the peninsular littoral, extend inland across a major portion of the Chicxulub area. The 10 -15 meter zone skirts the NW section of the Ticul fault then tracks inland along the crescent-shaped ring of cenotes, creating an anomalous inland area of locally shallow readings covering nearly 1,700 km^2. Widespread access the shallow aquifer is a major environmental feature that distinguished NW Yucatán from other physical zones in the Maya Lowlands and attracted humans to the area.

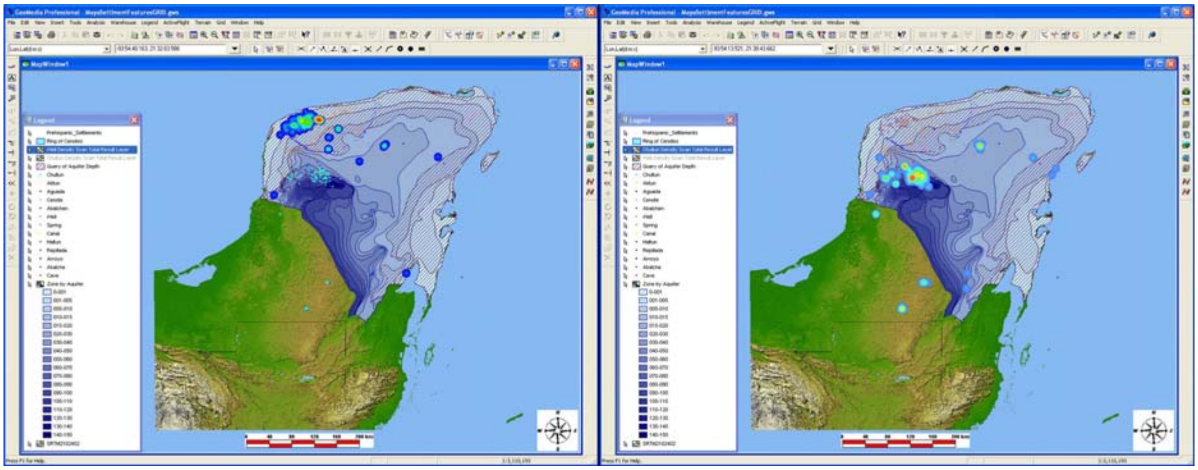

Figure 6. Grid surface analyses in the GIS, well and *chultun* frequencies. Frequencies of wells (left), chultunes (right), with aquifer depth zones. RGB indicates high density (red) to no recorded features (light blue) respectively. Aquifer depth zones light blue – shallow to dark blue – deep, shaded to 10 - 15 m. depth.

Natural or artificially excavated ancient wells and chultunes, bell-shaped cisterns constructed by the Maya to capture and store rainwater, occur in dissimilar patterns that correspond to variations in aquifer depths throughout the ROI. Higher frequencies of naturally occurring small cenotes and artificially constructed shallow wells are found at archaeological sites inside than outside the basin area (Figure 6). Grid surface analyses reveal hot spots where the highest frequencies of both features occur. The number of shallow wells at archaeological sites inside the basin area totals 195 at 80 sites. Only two wells have been reported for locations outside the area but in the ROI. Ancient wells do occur outside the ROI, but typically are located at the bottom of dry sinkholes or depressions where the aquifer is a few meters below the surface. No chultunes were documented for basin area settlements, whereas 707 were found at 63 non-basin area sites in the ROI. An abrupt falloff in the presence of wells takes place within the 15 - 20 meter aquifer depth zone. Chultunes begin to appear where depths range from 20 - 30 meters. The absence of wells in this section of the ROI and the apparent 20-meter threshold suggest that the Maya were limited by their technology to a maximum depth at or near 20 meters, a notion suggested by other Maya researchers as well. To achieve a more representative summary of feature distribution, counts from Dzibilchaltún, Sayil, and Uxmal, sites where extremely high numbers of wells or chultunes occur, were removed from the dataset prior to calculation of average frequencies per site. Adjusted ratios of 1.05 wells per site and 4.53 chultunes per site indicate that where water storage was essential, a higher investment in chultunes was necessary to insure a year-round water supply.

Although site rank was not considered as a factor in the statistical analyses presented above, it is instructive at this point to consider settlement location and size. There are two first-ranked (large) sites and five second-ranked sites located inside the Chicxulub basin area. One first-ranked site, Uxmal, and six second-ranked sites including Sayil are located outside the basin area but within the ROI. Uxmal (H.E.D. Pollock 1980a) and Sayil (Sabloff 1991a, b) are higher order sites that relied heavily on chultunes and possibly to a lesser extent on aguadas. Six first-ranked and 18 second-ranked sites are located beyond the ROI. These communities depended on aguadas, chultunes, cenotes, canals, wells, and a variety of naturally occurring water resources. No evidence was discovered to suggest an overarching correlation exists between a particular adaptive strategy and site rank.

WATER RESOURCES AND ANCIENT MAYA SETTLEMENT

The results of this study reveal the nature of the relationship between water resources and ancient Maya settlements on the peninsula and support the generally accepted assumption that the presence of water resources influenced locational decisions. However, the small number of archaeological sites found in association with the large vertical-walled cenotes scattered along the ring that defines the Chicxulub basin area today suggests that bigger was not always better. The number of known archaeological sites situated above the buried Chicxulub crater is statistically at variance with distributions outside the sedimentary basin area. Markedly higher numbers of the archaeological remains of Maya settlements exist inside the Chicxulub basin.

The Chicxulub basin area is a setting where, over time, karstic processes produced abundant small cenotes that intersected the shallow aquifer and served as natural wells. Two conditions, high frequencies of natural wells or cenotes and shallow aquifer depths inside the basin area, provided a highly desirable locality for human occupation.

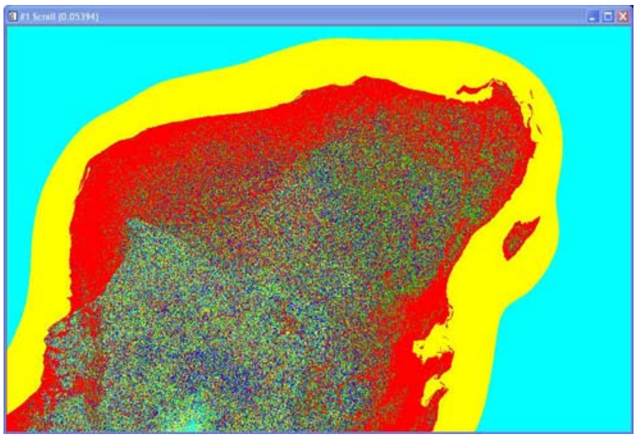

Figure 7. K-Means – SRTM 1-arcsecond (Feb 2000). K-Means classification in ENVI 4.3. Change threshold = 15 percent. Chicxulub basin, crescent-shaped red to green area, is clearly visible in northwest. Similar values elsewhere on the peninsula predict comparable settlement frequencies. (Data courtesy of NASA/JPL).

The ancient Maya were acutely aware of this unique setting as evidenced by the preferential location of their settlements inside the basin. There, they took advantage of cenotes or shallow wells as reliable and constant sources of water. In many instances, the natural wells would have required little or no functional modifications. In areas where no cenotes existed, the Maya could employ available technology to intercept water flowing through the aquifer by excavating shallow wells. Where static levels exceeded the Maya's technical capabilities, they employed a less desirable but effective alternative, excavating chultunes to capture and store rainwater for use during the dry season or transported water drawn from sources assessable by foot such as caves or open cenotes in the area. The model proposed in this paper, wherein as aquifer depth increases, frequency of natural or artificial wells decreases and alternative hydrological strategies increase in the archaeological record, further predicts that settlement densities similar to those documented inside the Chicxulub basin area will occur in areas outside the ROI with shallow subsurface water resources. A classification of SRTM 1-arcsecond elevation data reveals areas on the peninsula where comparable settlement densities are expected to occur (Figure 7). Moreover, the results help researchers understand settlement distribution on the peninsula as well as predict the location of unknown sites. Initial data collected during recent investigations in other parts of the peninsula confirm this relationship. The ancient Maya possessed sufficient skills and technology for hydrological management and were adept in the application of a variety of adaptive strategies to cope with the environmental diversity of the peninsula (Figure 8). It is quite likely that low densities of known settlements in some portions of the peninsula east and south of the ROI might indicate physical conditions such as the absence of a shallow aquifer or unfavorable soils or rock formations for the construction of chultunes. The ancient inhabitants of those areas would have been compelled to rely on naturally occurring water features that were accessible from the surface.

Figure 8. Uxmal, Yucatán, Mexico**.** The site of Uxmal located outside the Chicxulub sedimentary basin area. A total of 72 chultunes have been found inside the 0.50 km^2 walled area of the settlement. An additional 20 chultunes were recorded outside the wall.

For various reasons, the utility of remote sensing data covering the northern Yucatán Peninsula has not been effectively tested. This research demonstrates that classification and interpretation of remote sensing imagery and data is a viable means for archaeologists to detect one type of natural water feature. Furthermore, the link between the location of natural water features and ancient settlement has been established. Future research is planned to assess the value of Landsat TM, radar, and other data products such as ASTER to identify concealed sources of water and determine likely areas where the undiscovered remains of ancient settlements might exist. Much of the success depends on whether a sufficient number of signature keys can be developed to predict the particular environmental factors that would have influenced settlement decisions in ancient times. Clearly, there are problems associated with characterization of modern landscapes to predict ancient environments.

METHODS

Several analytical computer programs were employed in this study. The core GIS for housing, mapping, and spatial analysis of project data was designed in GeoMedia Professional 6.0. Supervised and unsupervised classifications of remote sensing data were accomplished in ENVI 4.2. The nearest neighbor analysis and statistic was prepared in ArcMap 9.0. Conversions of map entities from vector to raster format and grid surface analyses were completed in GeoMedia Grid 6.0.

The geographic coordinates for archaeological sites were derived from field reconnaissance, existing monographs, unpublished site reports, and publications (Andrews 2002; Dunning 1992; Garza Tarazona de Gonzales 1980; Piña-Chan 1959; Harry E.D. Pollock 1980a,b; Ruppert 1943; Velazquez Morlet 1988; Williams-Beck 1998; Winemiller 2003). The locations of modern populated places were collected from Mexico’s 2000 census report (INEGI 2000). Archaeological data were published or provided in a variety of formats that are incompatible with GIS and computer aided statistical analyses. A spreadsheet was designed to standardize data entry in a single format. Site locations published in latitude and longitude were converted to Universal Transverse Mercator, WGS84 geodetic datum. All locational data were merged and geo-coded as point features in the GIS, and exported to a feature table in an Access database. Data layers for climate, evapotranspiration, land use, rainfall, soil type, and surface and subsurface geology and hydrology were created using published thematic maps (INEGI 2001) and measurements collected in the field. An aquifer depth layer was created using recent well depth-to-surface measurements and static-level readings for the states of Campeche, Quintana Roo, and Yucatán (Direccion General de Administracion y Control de Sistemas Hidrologicos Direccion de Aguas Subterraneas 1989). High-resolution air photos, Landsat Thematic Mapper subsets, and AIRSAR radar data were classified using computer-aided supervised and unsupervised techniques as well as visually interpreted to pinpoint the location of cenotes in the ring zone and elsewhere throughout the ROI (Figure 9).

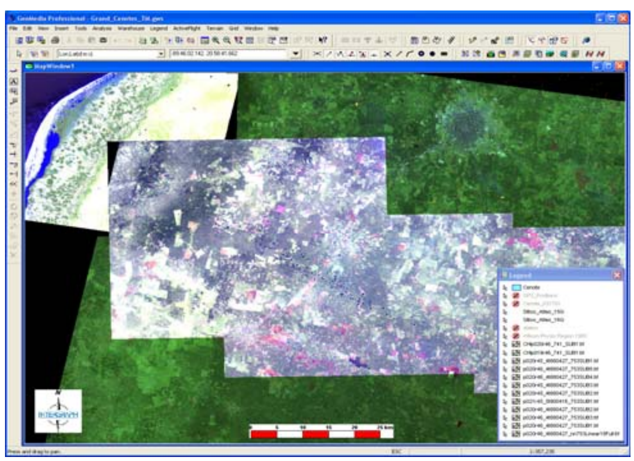

Figure 9. Interpretation of Landsat TM Images. Cenotes identified in the ring zone. (Data courtesy of NASA/JPL).

To carry out point pattern and surface analysis, a grid containing 588 quadrats, each covering approximately 39.7 km^2 of land surface, was defined, see figure 5, and plotted over site locations in the GIS. Optimal quadrat size was determined according to Wong and Lee (Wong 2005). Using the ring of cenotes as a natural boundary, equal numbers of quadrats were classified as lying inside or outside the Chicxulub basin area. Grid surface analyses were performed in the GIS environment using a second grid containing 406 - 56.1 km^2 quadrats as well as the optimal grid. Point features for each site were converted to raster format. Location frequencies were averaged by quadrat and displayed as variable RGB (red, green, blue) values to pinpoint areas of highest density. Surface density layers were constructed for natural and artificial wells and chultunes as well. The distributions were subsequently compared to environmental layers by constructing spatial queries of topological layers in the GIS.

Descriptive and spatial statistics were used to evaluate the significance of the patterned distribution of settlements in the ROI. Where applicable, an alpha level of .05 was used for statistical tests. Quadrat analysis (VMR) tests a point distribution using a total-points-per-area (density) concept whereas Nearest Neighbor Analysis tests a distribution using an area-per-location (spacing) concept. Both tests were used to confirm an apparent non-random pattern in the location of settlements in the ROI. To calculate VMR, formulae were written in a summary table containing the inventory of archaeological sites per quadrat in the ROI. A difference test was applied to establish the statistical significance of the VMR. The null hypothesis assumed randomness thus no difference between observed and expected frequencies by quadrat. For testing purposes, no major physical evidence was present to suggest the remains of ancient settlements should be clustered. Consequently, a non-directional two-tailed test using the chi-square of the VMR was selected. Chi-square and corresponding *p*-values were determined for ancient and modern settlement distributions. The nearest neighbor or *R*-statistic for settlements in the ROI was calculated in ArcMap. Like VMR, a returned value for the R-statistic of 1.0 indicates a random distribution.

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