

INVESTIGATING ANCIENT MAYA AGRICULTURAL ADAPTATION THROUGH GROUND PENETRATING RADAR (GPR) ANALYSIS OF KARST TERRAIN, NORTHERN YUCATÁN, MEXICO

UPORABA GEORADARJA PRI RAZISKAVAH PRILAGODITEV MAJEVSKEGA KMETIJSTVA NA KRAŠKEM POVRŠJU SEVERNEGA JUKATANA, MEHIKA

Mandy J. MUNRO-STASIUK¹ & T. Kam MANAHAN²

Abstracts

UDC 930.85(726.6)
551.435.8:528.9

Mandy J. Munro-Stasiuk & T. Kam Manahan: Investigating Ancient Maya Agricultural Adaptation through Ground Penetrating Radar (GPR) Analysis of Karst Terrain, Northern Yucatán, Mexico

Landscape adaptation on the Northern Yucatán Peninsula, Mexico, is particularly difficult, as soils are thin and the terrain is devoid of any surface water other than the occasional sinkhole (cenote) that connects directly to the groundwater system. Despite this, ancient Maya cities, including Xuenkal, emerged and thrived, likely because of their proximity to natural sinkholes. In the case of Xuenkal, these sinkholes, known locally as *rejolladas*, have bases above the local water table and, as such, do not provide direct access to the underlying water, but they provide closer access. Recognizing that the presence of *rejolladas* was likely important to the ancient Maya the purpose of this study is to characterize the *rejolladas* in terms of their subsurface characteristics, specifically bedrock configuration and soil. Ground penetrating radar analysis, as well as the results of a test pit excavation, confirm the presence of deep soils in the *rejollada* bases. It seems that the smaller deeper *rejolladas* have the thickest soils and sediment. The ancient city of Xuenkal is constructed amidst a particularly dense cluster of *rejolladas* which may have contributed to its location. *Rejolladas*, containing significantly thicker soils than the surrounding karst surface, and the ability to sustain dense healthy vegetation would have been particularly desirable for the Maya to capitalize on.

Keywords: *rejollada*, sinkhole, archaeology, satellite imagery, ground penetrating radar.

Izvleček

UDK 930.85(726.6)
551.435.8:528.9

Mandy J. Munro-Stasiuk & T. Kam Manahan: Uporaba georadarja pri raziskavah prilagoditev majevskega kmetijstva na kraškem površju severnega Jukatana, Mehika

Prilagoditev življenja na kraškem površju severnega dela polotoka Jukatan v Mehiki, je bilo izjemno težko. Prsti je malo, voda pa je dostopna edino v udornicah (cenotah), ki so neposredno povezane s kraško podtalnico. Razvoj in obstoj starih naselbin Majeve, vključno z mestom Xuenkal, povezuje z bližino kraških depresij. V primeru mesta Xuenkal, so dna vrtač, ki jih lokalno imenujejo *rejolladas*, nad nivojem podzemne vode in ne nudijo neposrednega dostopa do vode. Ker je bila prisotnost teh vrtač za Maje očitno pomembna, smo izvedli študijo teh objektov s posebnim ozirom na kamninsko podlago in prst. Podatki georadarja (GPR) in poskusnih izkopov, so pokazali veliko debelino prsti v dnu vrtač. Kaže, da je prst najdebelejša v manjših, a globokih vrtačah. Xuenkal je zgrajen sredi goste mreže vrtač, kar je bilo verjetno pomembno pri umestitvi mesta. Maji so očitno s pridom izkoriščali prisotnost vrtač z debelim slojem prsti, kjer se je lahko obdržal gost in zdrav vegetacijski pokrov.

Ključne besede: vrtače (*rejollada*), arheologija, satelitsko snemanje, georadar

¹ Department of Geography, Kent State University, Kent OH, 44242, e-mail: mmunrost@kent.edu

² Department of Anthropology, Kent State University, Kent OH, 44242, e-mail: tmanahan@kent.edu

INTRODUCTION

The northern plains of the Yucatán peninsula (Fig. 1) are dominated by a harsh, semi-arid karst plateau that is largely devoid of both thick soils and surface water, thus making modern and ancient landscape adaptation and agricultural practices particularly challenging. In this landscape are *rejolladas*, distinctive sinkholes that are usually round and shallow, are typified by bases that sit above the regional water table, and tend to have thicker soils than the surrounding areas (e.g. Kepecs & Boucher 1996; Fedick & Morrison 2004; Lopez 2008). The distribution of these sinkholes is particularly dense at the ancient Maya center of Xuenkal, lending support to the argument that *rejolladas* were likely important to ancient populations. The Proyecto Arqueológico Xuenkal (PAX) was initiated in 2004 to investigate the relationship between Xuenkal and the Terminal Classic (A.D. 900 – 1100) Maya center of Chichen Itza and to understand the political and economic underpinnings of the Terminal Classic transformation. Xuenkal is the largest urban center between Chichen Itza and the coast and a major component of PAX is to investigate the use of *rejolladas* by the ancient inhabitants of the region. *Rejolladas* as landforms, however, are poorly understood both in terms of their overall characteristics and their specific genesis. As such, this paper reports the results of non-invasive ground penetrating radar

strategies to terrains typically not conducive to intensive methods.

As well as a harsh physical environment, the climate in Yucatán is also relatively harsh with a long dry season dominated by subtropical high pressure, punctuated by a short wet season between July and October when moisture laden air masses from the Gulf of Mexico are forced to move ashore bringing large volumes of rain in a short period of time. Modern precipitation averages about 1,100 mm a year (SARH 1989), with the majority falling in the wet season. Due to the local geology and climate, the natural vegetation is thorny tropical scrub forest, an environment that should provide major environmental challenges to supporting human populations. Despite all these limitations, large urbanized Maya centers flourished across the Yucatán Peninsula for hundreds of years. In fact, the region in and around Xuenkal and the nearby colonial city of Espita has always been a breadbasket of the Yucatán, supplying corn, beans, and cotton since the 16th century (Andrews 1990; Patch 1993). Archaeological investigations at Xuenkal, Yucatán, Mexico, have demonstrated that ancient residential settlement tends to cluster around, or near, *rejolladas*, suggesting that the utilization of these natural features has a long history. The unique karst geology and geomorphology of the



Fig. 1: A. Location of the Yucatán Peninsula in Mexico; B. Location of Xuenkal relative to contemporary pre-Columbian sites.

(GPR) surveys of 3 *rejolladas* in Xuenkal. Specifically, bedrock configuration, and soil and sediment characteristics are documented. GPR was chosen as the tool of study as it is a well documented non-invasive geophysical method for imaging natural geologic materials or archaeological features near the ground surface (e.g. Leckebusch 2003; Froese *et al.* 2005). This geomorphic study has broader relevance to understanding how past and present populations have adapted their cultivation

region, specifically that of *rejolladas*, likely held greater agricultural potential, and as such may have drawn ancient settlers to the study area.

GEOLOGY AND GEOMORPHOLOGY OF THE NORTHERN YUCATÁN PENINSULA

The Ticul Fault crosses the Yucatán Peninsula trending roughly WNW to ESE separating two very different terrains (Fig. 2): the Sierrita de Ticul sitting approximately 150 m above sea level (asl) to the south of the fault; and the lower karstic plains sitting to the north at no greater than 40 m asl (González-Herrera *et al.* 2002). The entire region is composed of thick deposits of uplifted Tertiary limestone bounded by a thin band of Quaternary lagoon and beach deposits at the coast (Pope *et al.* 1993). Because of the dominance of limestone, groundwater flow is through dissolution fractures, channels, and caverns, rather than above ground (e.g. Springfield & LeGrand 1976; Gordon 1986). As a result, in the plains the water table sits at between 1 and 4 m above sea level (Weidie 1985; González-Herrera *et al.* 2002), i.e., no more than 36 m below the modern land surface, making karstification a prominent ongoing process near the ground surface in the modern environment.

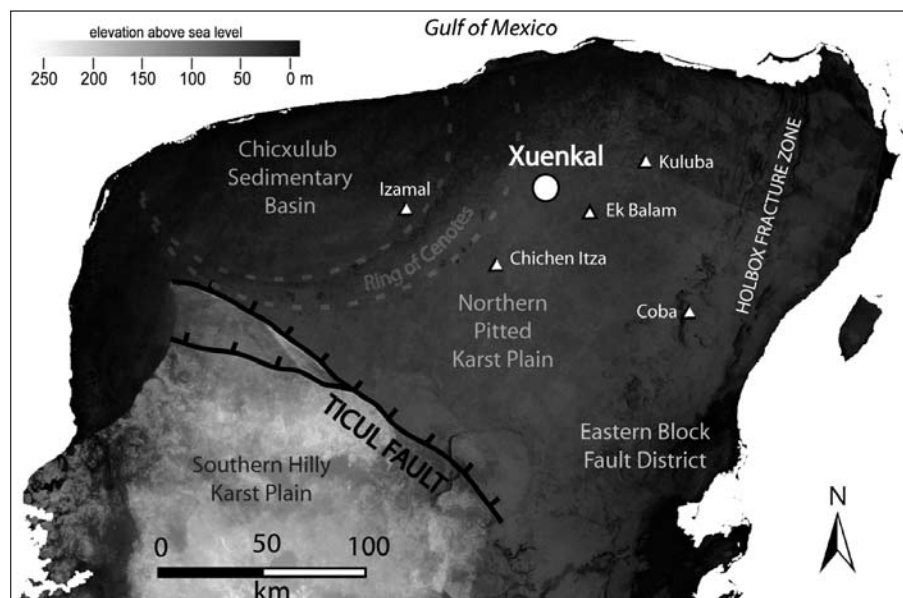


Fig. 2. Simplified geology map superimposed on a digital elevation model (DEM) of the Yucatán Peninsula. Major physiographic regions are noted, as well as the positions of ancient Maya sites. The DEM is composed of 4 SRTM (Shuttle Radar Topography Mission) tiles. Geology and Physiography is modified from Lesser and Weidie (1988) and Pope *et al.* (1993).

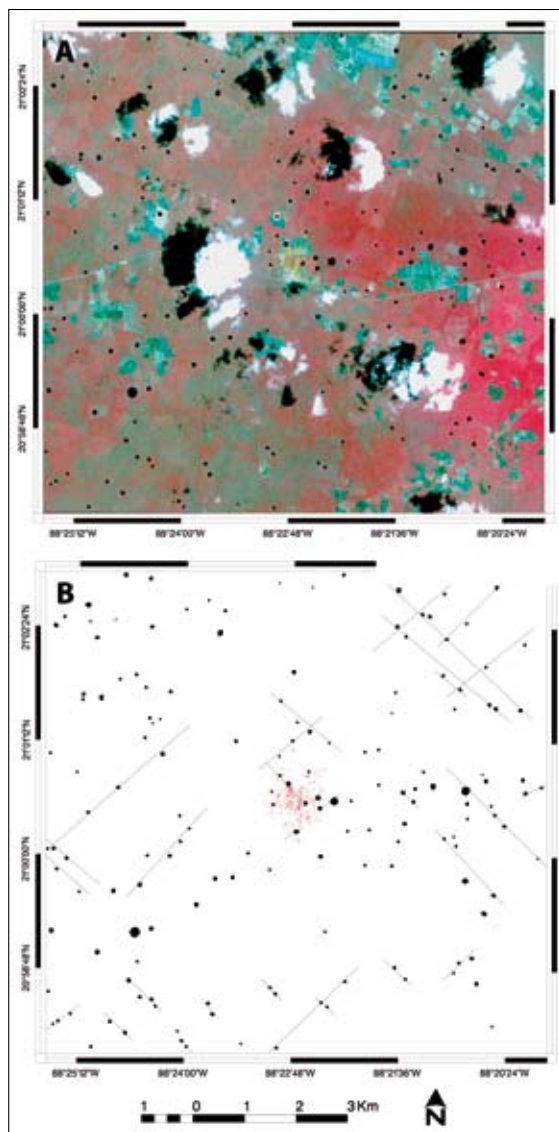
Karstification contributes to the extensive sinkhole development on the northern Yucatán Peninsula. There are several types of sinkholes although the majority of them are of the collapse variety (dolines) and some may have been initiated as solution dolines (cf. Ford & Williams 2007). The indigenous classification system bases typological distinctions not on formation, but rather proximity to the water table. The best known sinkholes are cenotes (derived from the Yucatec Maya name

dzonot, Hall 1935) which have collapsed below the level of the water table and thus have year-round standing water. Technically, an underground cavern with standing water but with an opening to the atmosphere is also considered a *cenote*. *Cenotes* can be the product of surface collapses, subsurface solution, or a combination of the two processes (Lopez 2008). The Yucatec Maya term *dzadz* (plural *dzadzob*) refers to surface collapses that touch the water table but do not significantly penetrate it. They are typically dominated by small swampy areas in their bases. Depending on the depth of the *dzadz* and the amount of silting, some *dzadzob* may be seasonally transformed into wetlands. Finally, *rejolladas* are surface collapses that do not reach the water table and remain dry throughout the year. The study region in and around Xuenkal contains some *cenotes* and *dzadzob*, but *rejolladas* are by far the most common category of sinkhole (Fig. 3). They also tend to line up following the local joint

pattern (Fig. 3). The *rejollada* density is also significantly higher centered on Xuenkal than in the surrounding terrain (Fig. 4).

Also present are fairly large dissolution hollows and channels (grikes and poljes; cf. Ford & Williams 2007) that are at the ground surface and are entirely unrelated to collapse. These remain less well understood but they are now filled with calcareous red soils (Terra Rossas) typical of limestone areas dominated by tropical climates (Ishphording 1976). Although none of these were investigated in this study, they can clearly be seen on the satellite image presented in Fig. 5 especially where vegetation has been cleared.

Interestingly, on the northern plains thick carbonate deposits overlie the Chicxulub impact crater which is believed to have formed by an asteroid impact at the K-T (Cretaceous/Tertiary) boundary resulting in the mass extinction that took place at the end of the Cretaceous period (Hildebrandt *et al.* 1991; Pope *et al.* 1991; 1993). This crater appears to have had an enormous influence on both the location and formation of sinkholes. Verification of the presence of the buried crater comes from



gravity and magnetic anomalies, breccias that show evidence of shock metamorphism and high iridium content (Hildebrandt *et al.* 1991) and surficially, from the presence of the well-known Ring of Cenotes (Pope *et al.* 1991; 1993), a semi-circular ring of sinkholes that lies at or near the edge of the crater (Fig. 2). Here, the abrupt thinning of the limestone relative to the thicker beds in the center of the crater increased bedrock fracturing resulting in higher dissolution and collapse rates in the region of the Ring of Cenotes (Pope *et al.* 1993). There is debate as to whether the cenotes represent the edge of the impact (Pope *et al.* 1991; 1993) or the crater rim (Hildebrandt *et al.* 1991). This interpretation is important as it affects the overall size of the crater, which is estimated to range in diameter from 180 km (Hildebrandt *et al.* 1991) to 240 km (Pope *et al.* 1993). The study area in and around Xuenkal is dominated by the pervasively fractured Northern Pitted Karst Plain (Lesser & Weidie 1988; Fig. 2) and lies about 30 km immediately outside the Ring of Cenotes. While inside the ring there is a lack of significant sinkhole development, outside the ring, especially in the eastern Yucatán, cenotes and other sinkhole types dominate the landscape (Pope *et al.* 1991). Based on Pope *et al.*'s (1991) research, the sinkholes in and around Xuenkal may still represent part of the rim of the Chicxulub impact crater.

Fig. 3: A. False color infrared Quickbird satellite image of a 10 x 10 km region centered on Xuenkal (structures shown in yellow). Rejolladas are mapped in black. B. Map of study area showing only rejollada distribution with superimposed trends of rejolladas associated with the regional joint system.

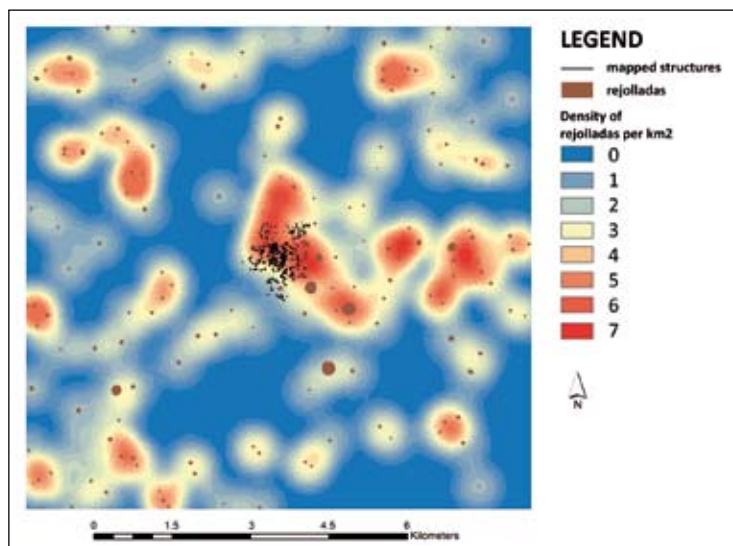


Fig. 4: Map showing the density distribution of rejolladas centered on Xuenkal. Structures are shown in the center of the map and the densest distribution of rejolladas coincides with the position of Xuenkal.

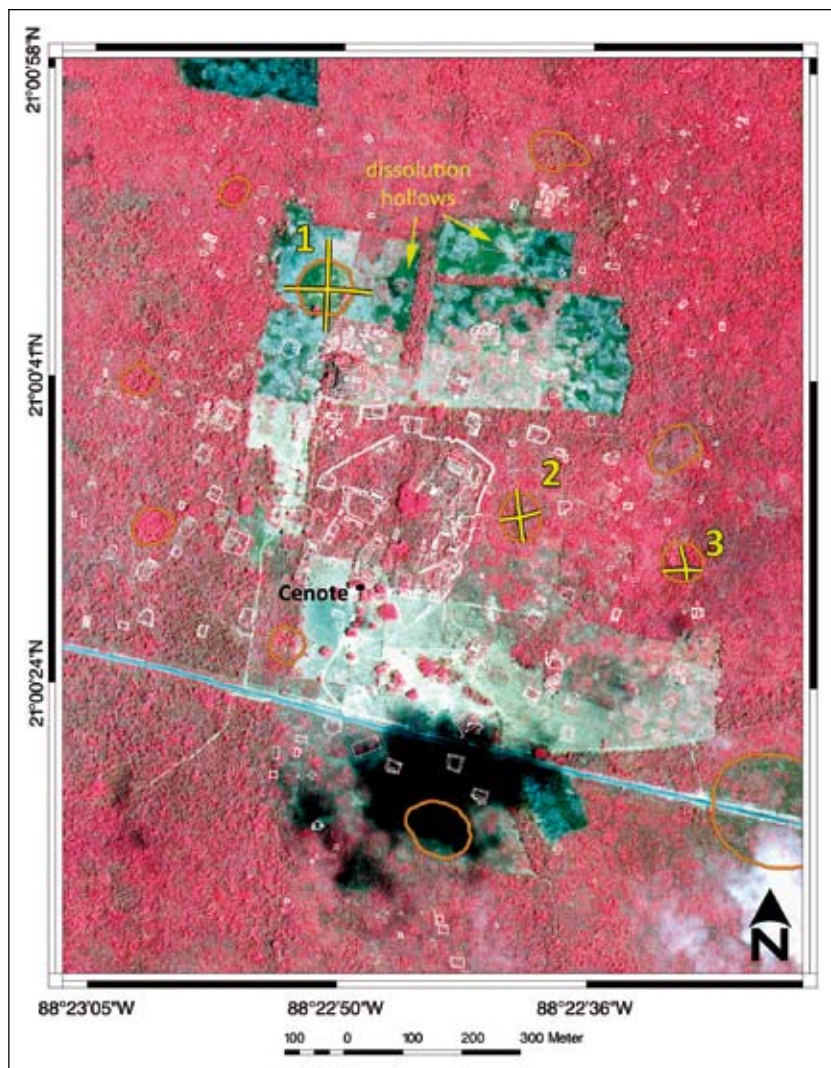


Fig. 5: True color Quickbird satellite image of the terrain in the urban core of Xuenkal. Superimposed are the mapped structures (in white) and *rejolladas* (in yellow). Studied *rejolladas* are numbered and transects are shown as intersecting lines.

THE SIGNIFICANCE OF KARST TERRAIN TO THE ANCIENT MAYA

Archaeologists have documented a rich history of indigenous settlement that spanned from the Middle Preclassic (c.a. 1200 B.C.) through the time of Spanish contact (A.D. 1519). The populations of the Yucatán Peninsula likely reached their peak during the Terminal Classic period (A.D. 900 – 1000) when many expansive ancient Maya centers reached their maximum settlement density. This includes the site of Xuenkal, the center of the present study area, and its famous neighbor, the site of Chichén Itzá located 45 km to the southwest (Fig. 1). The unique karst geology and geomorphology of the region likely served as a primary factor in guiding initial settlement across the Yucatán Peninsula since ancient Maya centers cluster near sinkholes and depressions. *Rejolladas* in

particular act as traps for soil and moisture producing patches of ground useful for cultivating more water-sensitive crops including groves of trees such as cacao, whose fruit (chocolate) was highly valued in ancient times (e.g., Kepecs & Boucher 1996). Deep *rejolladas* were likely important natural features to the ancient Maya because of their proximity to the water table thus they present an ideal location for digging wells in a landscape devoid of above-ground sources of water.

Researchers have long recognized that limited access to groundwater meant that ancient Maya settlement in northern Yucatán clustered around sinkholes of various types. Cenotes were considered as sacred portals that allowed communication with deities associated with rain

and fertility (Morley 1946). The most famous *cenote* is the giant *Cenote Sagrado* (Sacred Well of Sacrifice) at the site of Chichén Itzá, measuring 60 m in diameter and 27 m deep to the water surface. The retrieval of thousands of artifacts as well as bones of young men and boys appears to support the use of the cenote as a place to leave offerings to the gods (Tozzer 1957; Proskouriakoff 1974).

In the Yalahau region in the far northeast of the Yucatán Peninsula, Fedick and Morrison (2004) noted that all elite residential centers, or sites with monumental architecture, are associated with large sinkholes (in the form of either cenotes or *dzadzob*) whereas non-elite sites were associated with smaller *cenotes* with surface openings often less than about 4 m in diameter.

Special attention has been paid to *rejolladas* as it is generally thought that they were controlled during the Classic period (A.D. 600–900) by local elites who grew orchards of economically useful trees, especially cacao, the most valuable pre-Columbian crop (Kepecs & Boucher 1996). For instance, the frieze adorning an elite

compound in Chichén Itzá depicts cacao growing in *rejollada*-like depressions accompanied by elites dancing with monkeys in the groves. Gómez-Pompa *et al.* (1990) suggested that the microclimates of *rejolladas* and *cenotes* allowed for prehispanic cacao cultivation and production and for consumption by local elites after identifying rare remnant sub-species of cacao (*Theobroma cacao*) that were descendants from prehispanic species in three *cenotes* near Valladolid, 50 km south of Xuenkal. An inventory of modern plant species was undertaken in 21 *rejolladas* and 3 *cenotes* in an 8 km area surrounding Xuenkal (Triplett *et al.* 2006) on the assumption that some would possess non-modified habitats, with a heavy presence of only native species including feral populations of cacao. This was not the case. Many *rejolladas* are currently heavily planted and contain important fruit crops such as avocado (*Persea Americana*), mango, nance (*Byrsonima crassifolia*), caimito (*Chrysophyllum caimito*), and sapodilla (*Manilkara zapota*), and are clearly evidence of long-standing cultivation.

THE SITE OF XUENKAL

Xuenkal was first recorded in the late 1970s as a Rank II category site in the classification system determined by the Atlas Arqueológico del Estado de Yucatán and is considered to be an urban center (Garza & Basco 1980). The area in and around Xuenkal contains a dense pattern of *rejolladas* (Fig. 4), with the currently mapped 1.2 km² area of site core containing 8 *rejolladas* and one small *cenote* which is a subterranean cavern with a small opening to the ground surface (Fig. 5). The site contains monumental architecture including a series of large pyramidal temples, a large palace structure, a major defensive wall system, and elite and non-elite residential groups. Many of these, especially residential structures, cluster around the *rejolladas*. Of note, the largest pyramid looms over *Rejollada 1*, and the palace structure tops a bedrock rise on the western edge of *Rejollada 2* (Fig. 5).

Average elevations of the karst surface at Xuenkal vary between 26 and 28 m asl with *rejollada* bases below this level as low as 10 m asl (Tab. 1). Bare limestone sur-

face covers much of the area, with pockets of Terra Rosa filling surface hollows. Most ancient Maya structures are built on the bare limestone surfaces. Based on the water level in the *cenote* and in a modern well, the water table appears to sit at about 4–6 m asl. This is about 6 m higher than suggested by Lesser and Weidie (1988) and González-Herrera *et al.* (2002) for the region, and about 6 m below the depth of the deepest *rejollada* studied.

Tab. 1: Average statistics of the three studied *rejolladas*.

	Average basal diameter	Depth	Base elevation above sea level	Average slope angle
<i>Rejollada 1</i>	97 m	4 m	22 m	9.25°
<i>Rejollada 2</i>	68 m	8 m	18 m	14.8°
<i>Rejollada 3</i>	58 m	12 m	10 m	25.3°

GPR DATA AND METHODS

Since the main purpose of this research was to determine the overall configuration of the *rejolladas*, a necessary analytical technique was required to image the subsurface rocks and

sediment. One of the most common shallow geophysical techniques used is seismic reflection and refraction, however the resolution is too coarse to look at submeter resolution

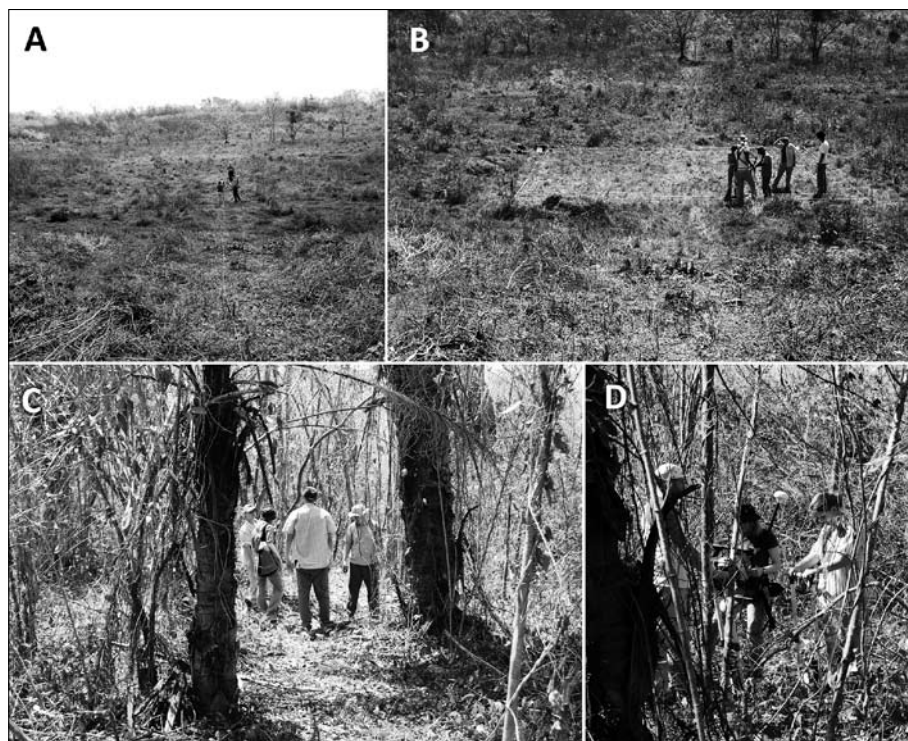


Fig. 6: Photographs of the rejjolladas where GPR work was undertaken. A. running a transect across rejjollada 1. Note there are no trees, simply pasture; B. Collecting GPR grid data in rejjollada 1; C. Collecting a GPR transect in Rejjollada 2. Note that there is significant tree cover; D. Collecting a GPR transect in rejjollada 3. Note that the vegetation is very dense here (Photo: M. Munro-Stasiuk).

layers (Neal 2004) which is required for this study. Consequently, we chose ground penetrating radar (GPR) which is also a non-invasive geophysical method for imaging natural geologic materials or archaeological features near the ground surface (e.g. Jol & Bristow 2003; Leckebusch 2003; Froese *et al.* 2005). This technique is particularly good at imaging limestone (Jol & Bristow 2003). Pulses of high frequency electromagnetic radiation are transmitted into the ground and are absorbed, reflected or attenuated by the subsurface materials. A receiver records the amount, and strength, of the reflected waves, which vary based on sediment and bedrock type, grain size, porosity and compaction (dielectric properties; Jol & Bristow 2003).

The system used for this study was a PulseEkko Pro GPR with interchangeable 100 MHz and 200 MHz anten-

nae. All data were captured in reflection mode using a step size of 25 cm for the 100 MHz antennae and 10 cm for the 200 MHz antennae. Since radar waves move through different materials at different speeds (because of different dielectric properties), all data were calibrated to an average wave velocity of 0.099 m/ns for soil and sediment, and 0.112 m/ns for limestone. Velocities were determined by fitting a hyperbola-response curve to the GPR data. All data have a permanent dewow filter applied, which removes unwanted low frequency interference. In addition an AGC (Automatic Gain Control) was applied to the dataset, which deliberately enhances weak signals at depth (Sensors and Software 2003). All data were georeferenced, topographically corrected, and analyzed in EkkoView, EkkoView Deluxe, EkkoMapper and Voxler 3D.

A 2-phase GPR survey was completed. Phase 1 was a general 2-dimensional overview of each of the three rejjolladas at Xuenkal (Figs. 5 and 6). This consisted of a 2-line 100 MHz survey, and a 2-line 200 MHz survey (Tab. 2), each consisting of an approximate east-west transect and a north-south transect that cross each other in the approximate center of each of the rejjolladas (Fig. 5). Phase 2 consisted of grid surveys, which have a series of x-lines and y-lines that cross each other, allowing 3-D data interpolation and interpretation. This was only completed on Rejjollada 1. Grid surveys were conducted with the higher resolution 200 MHz antennae only, which provides higher resolution data, although the depth of radar penetration is compromised. A standard WAAS enabled handheld GPS was used to tag the ends of every line and the corners of every grid. In addition, GPS integrated with the GPR data collection ensured that all data were tied to the geographic grid. Elevation was derived with a TopCon GTS-226 Total Station and recorded with a Ranger N687 data collector.

Tab. 2: GPR survey parameters.

SURVEY TYPE	Antennae separation	Step size (how far antennae are moved between data points)	Grid line spacing	Approximate maximum depth
100 MHz lines	1 m	25 cm	NA	6.5 m
200 MHz lines	50 cm	10 cm	NA	3.25 m
200 MHz grids	50 cm	10 cm	50 cm	3.25 m

GPR PROFILING

The GPR reflectance patterns in all three *rejolladas* show there to be marginal slopes dominated by bedrock at the surface, some sediment and soil in the *rejollada* bases that mutes the overall signal, evidence of potential man-made structures, and a lack of any distinct GPR reflectors that would indicate the presence of the water table. In terms of the bedrock configuration, all three *rejolladas* represent bedrock ceiling collapse sinkholes. Although the style of collapse may have varied slightly from sinkhole to sinkhole, they all collapsed into underlying caverns.

REJOLLADA 1

In *Rejollada 1*, there are distinct GPR reflectors along the slopes of the *rejollada* and along the base. These are higher amplitude reflectors associated with limestone beds. The reflectance pattern along the walls shows slight slumping and disturbance of the bedrock. Importantly, there is significant reflectance from an uneven distribution of relatively high conductivity material bound laterally by pockets of lower conductivity material. This is interpreted as soil and sediment overlying an uneven distribution of limestone rubble. The limestone rubble is from a ceiling collapse onto an underlying cavern floor (Figs. 7 and 8). A very prominent feature on the GPR profiles of *Rejollada 1* shows a zone of comparatively deeper low conductivity (few reflectors) soil/sediment bounded laterally by the more variable conductivity materials (limestone rubble). No sign of the rubble exists in this zone, which is interpreted as a solution sinkhole, at least 9 x 18 m in size, which has subsequently filled with lower conductivity sediment and soil. The solution hole formed prior to the bedrock collapse when water was still partially flowing at the ground surface. Subsequent infilling represented by undisturbed horizontal layers of sediment and soil attests to collapse followed by soil development. It is even possible that this may have been a small *cenote* connecting to the underground water source but this is difficult to confirm without excavation.

REJOLLADA 2

Rejollada 2 is bound by undisturbed rock walls that appear to have intact bedding (Fig. 9). This *rejollada* represents a major collapse sinkhole into an underlying cavern that left the adjacent bedrock layers untouched. The collapse zone is bounded by steep normal faults. Soil and sediment accumulation seems significant based on very low conductivity reflectors observed on all GPR transects across the bottom of the *rejollada*.

A 2 x 2 m test excavation was placed in the center of *Rejollada 2* (Fig. 10). With the exception of a low historic wall approximately 20 m north of the test pit, no prehis-

toric remains are visible on the surface of the *rejollada*. The excavation was conducted in arbitrary 20 cm levels and reached a total depth of 228 cm, much deeper than any other test pits excavated at Xuenkal. The excavation uncovered three distinct stratigraphic zones although all soil tended towards reddish silt loam with high clay content. Stratigraphic variation consisted principally of changes in soil moisture, compaction, color intensity, and organic content. Generally, soil becomes redder, drier, more compact, and contains decreasing quantities of organic matter with depth. A very thin surface O-horizon (organic layer) exists in the soil profile and grades quickly to a 20-30 cm moist dark red/brown clay silt loam (2.5 YR 2.5/2) representing the A-horizon (the uppermost organic layer below the O-horizon with the greatest amount of biological activity). The A-horizon brightens with depth grading to a semi-moist dark red/brown clay silt loam (2.5 YR 3/6) that reaches a depth of 90–100 cm below surface. A heavily leached, B-horizon of dry, bright red clay silt loam (2.5 YR 4/8) extends to bedrock which has a very uneven, undulating surface and a bright white color at a depth of between 220 and 228 cm. Five flotation samples and five microfloral samples were collected from the unit's profile column. Flotation samples failed to identify any macrobotanical remains. This soil is typical of the Terra Rossas (also locally known as Kancab) found throughout the region (Isphording 1976; Allen & Rincón 2003).

REJOLLADA 3

Like *Rejollada 2*, this *rejollada* is bound by undisturbed rock walls with intact bedding (Fig. 11). Once again, this represents a major collapse sinkhole into an underlying cavern that left the adjacent bedrock layers untouched. Soil development seems significant based on very low conductivity reflectors observed on all GPR transects across the bottom of the *rejollada*. While no test pit was dug here, soil was likely as thick as at *Rejollada 2* based on the homogeneity of the GPR signal in the bottom of the *rejollada*. Several anomalies that were detected in the transects may be anthropogenic in origin. Many of these have the characteristics of walls (cf. Conyers 2004) or stone-lined wells. These need to be ground-checked before further interpretation can be made, however archaeological investigations of other *rejolladas* in northern Yucatán have identified ancient constructions including walls and stone-lined wells (González de la Mata 2006; Houck 2006).

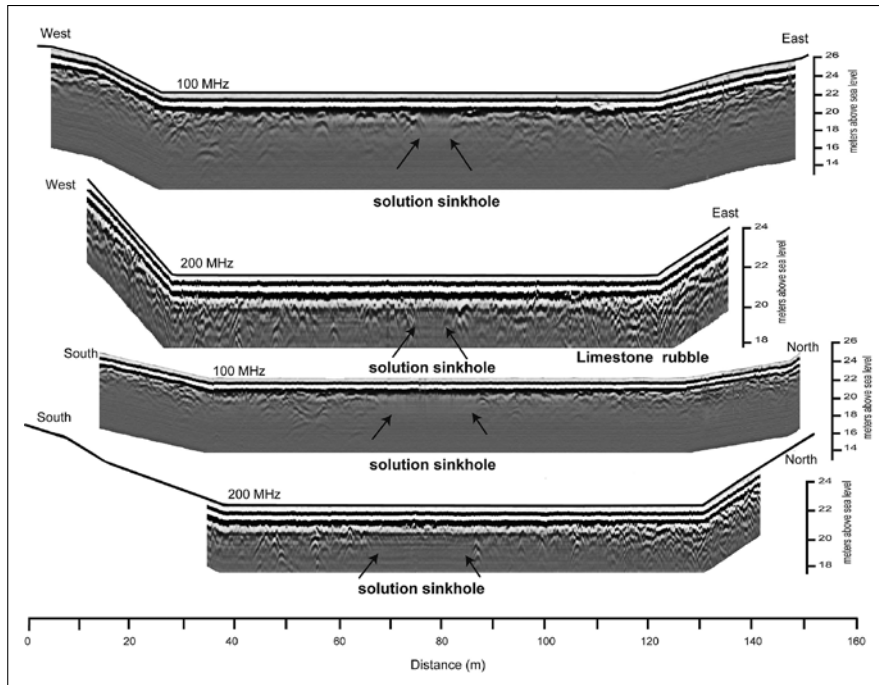


Fig. 7: GPR cross-sections of Rejollada 1 with interpretations.

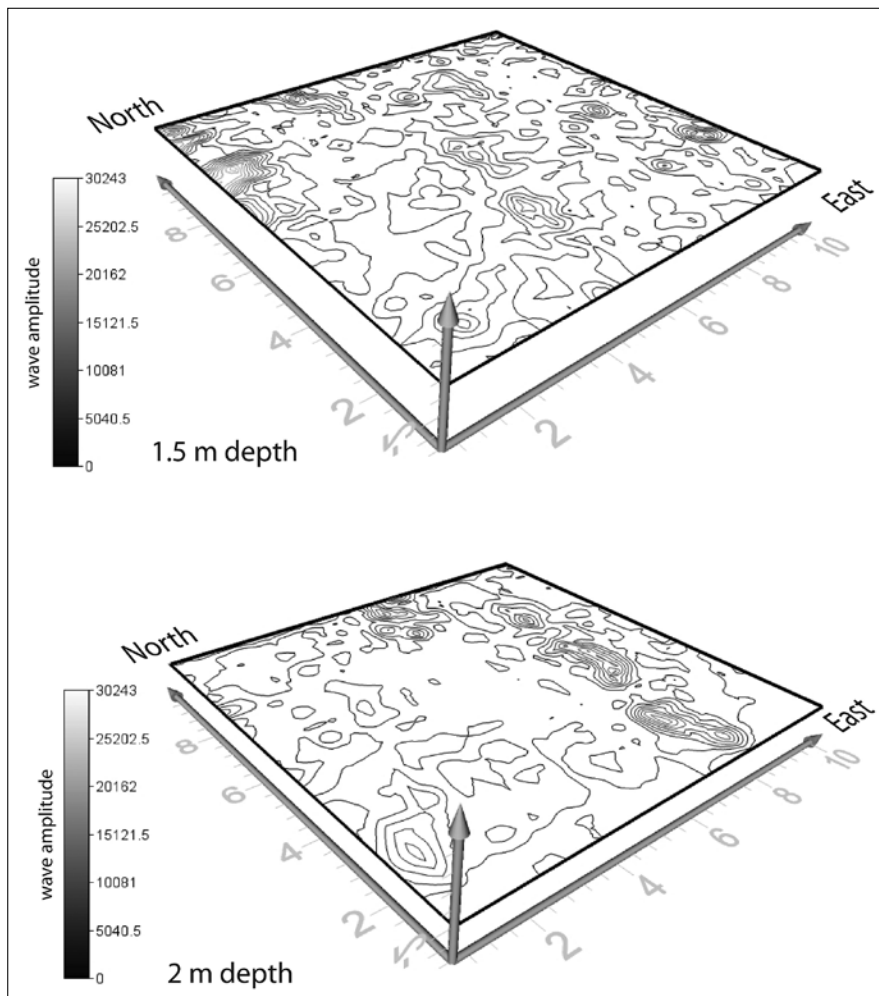


Fig. 8: Contour rendering of grid at Rejollada 1 showing slices at 1.5 m below ground level and 2 m below ground level. The limestone rubble can easily be seen on both plots as contours of higher amplitude reflectors.

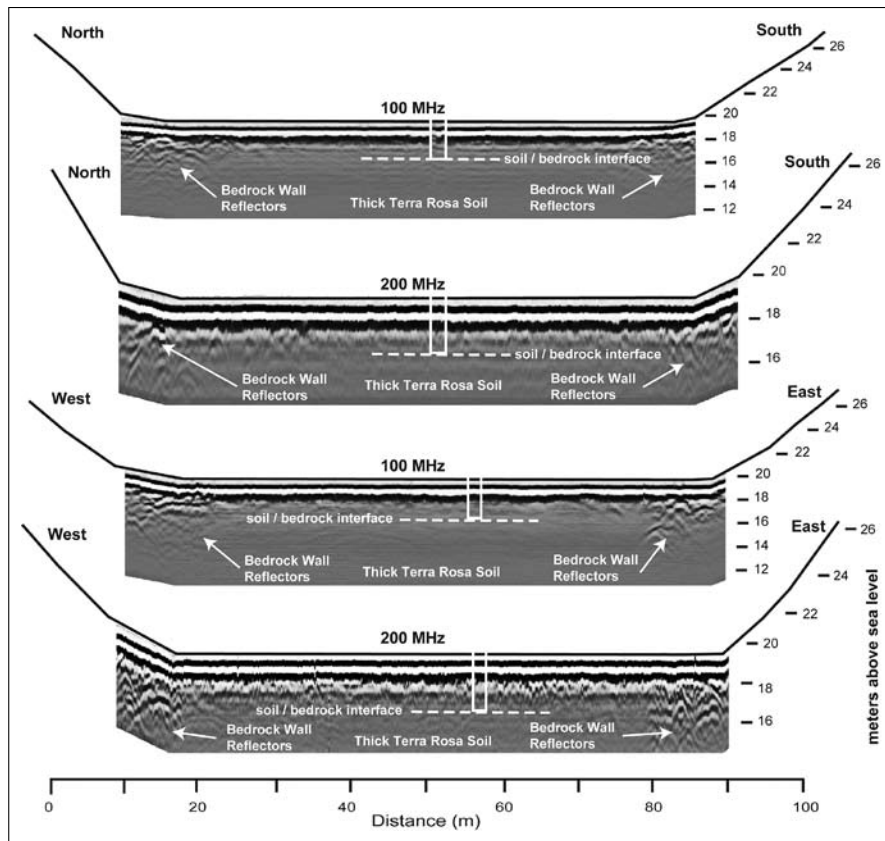


Fig. 9: GPR transects at Rejollada 2. Very steep contacts with the bedrock walls suggest the presence of major faults. The position of the soil pit is shown on each of the transects.

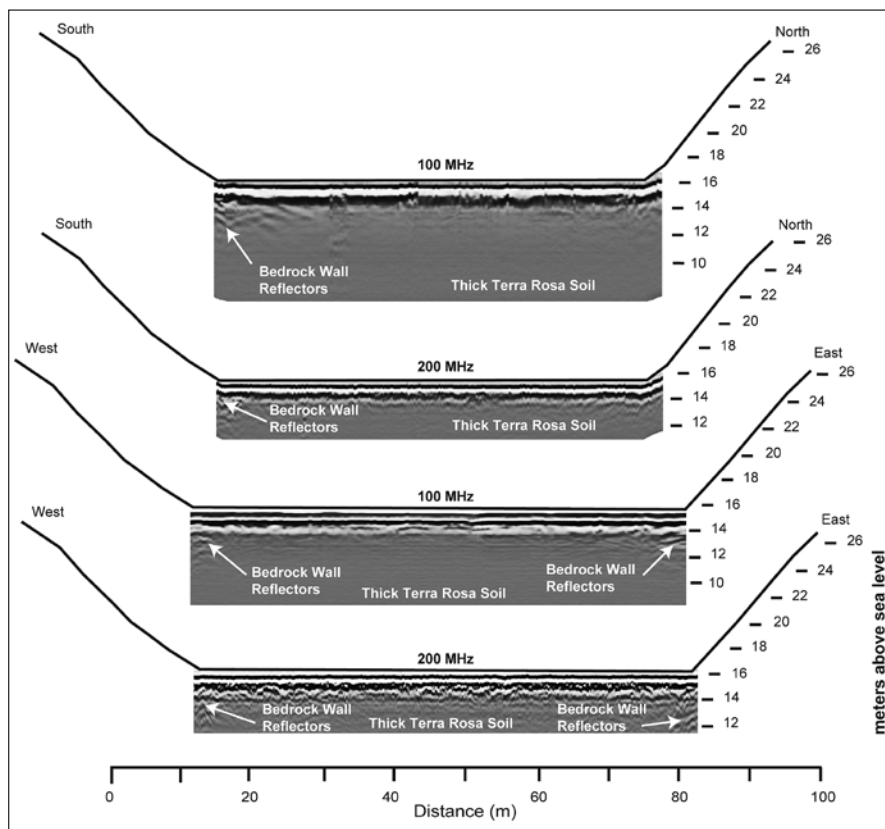


Fig. 11: GPR transects at Rejollada 3. Steep contacts with the bedrock walls (especially on the west-east transects) suggest the presence of major faults.

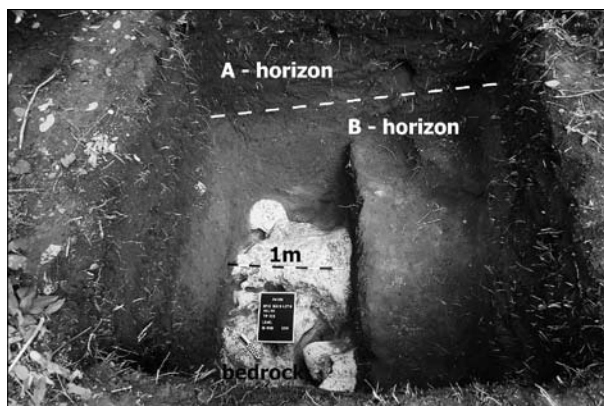


Fig. 10: Photograph of 2 x 2 m soil pit in the center of Rejollada 2 (Photo. K. Manahan).

DISCUSSION

The GPR survey confirms that soil depths in the bottom of the *rejolladas* average over 1m, and in *rejolladas* 2 and 3, over 2 m. This was confirmed by the test pit excavation in *rejollada* 2. The significance of this finding is enhanced when one considers that, on average, soils in the region outside of *rejolladas* seldom exceed 60 cm in depth over hollows and a few centimeters in depth over the rest of the terrain. In addition, the overall configuration of the *rejolladas* may help to predict where the thickest soils accumulate. *Rejollada* 1, though the largest, has the thinnest soil/sediment package; *rejolladas* 2 and 3, though smaller have thicker soils. This is most likely related to the overall relief. Deeper, steeper *rejolladas*, like 2 and 3, generally have more rainwater that washes down the slopes increasing the overall rate of dissolution (Weisbach *et al.* 2001). The Terra Rossa forms due to the presence of limestone. That is, carbonated waters - the result of dissolution - tend to break down clays and remove silica. Hence soils become depleted in both carbonates and silicates and become preferentially enriched in other minerals, in this case kaolinite, chlorite, boehmite, quartz, and talc (Isphording 1976) as well as aluminum and iron (Weisbach *et al.* 2001). The iron rusts when exposed to the atmosphere creating the characteristic red color. It

appears that where there is greater relief, and hence also greater washing across the surface by rainwaters, there are more favorable conditions to develop soils of the Terra Rossa variety.

In addition, the deepest *rejolladas* have bases closest to the water table. The GPR work proved very useful in determining overall *rejollada* configuration and presence of thick soils, but it unfortunately did not identify the water table. Al-fares *et al.* (2002) in a study in French karst, used the same PulseEKKO Pro GPR system with lower frequency 50 MHz antennae and achieved penetration of up to 30 m and clearly identified the water table. Thus there is great potential for identifying this horizon at Xuenkal using lower frequency antennae in future surveys. Based on the wave velocity through the materials at Xuenkal, 50 MHz antennae should penetrate up to 20 m below the surface, which should map the water table effectively in this environment. Other methods such as electrical resistivity could also better identify the water table (cf. Urish 1983). Even though we were unable to identify the depth and configuration of the water table, evidence from wells in the area suggests that the bottom of the deepest *rejolladas* sits within approximately 6 m of the water table.

CONCLUSION

The deeper soils of the *rejolladas*, together with their closer proximity to the water table, would have presented clear advantages to ancient farmers whose subsistence depended upon adequate seasonal rainfall. Extensive exploitation of the *rejolladas* with their significantly thicker

soils and greater proximity to the water table, may have been one strategy employed by the ancient Maya. We hope to investigate this possibility in more detail in the future; the GPR study of the *rejolladas* represents the first step in this direction.

ACKNOWLEDGEMENTS

Help in the field is gratefully acknowledged from Justin Lowry, Daniel Vallejo Caliz, Leonard Drinkard, Jessica Sudduth, and Jana Reeder. Comments from reviewers

Ivan Šprajc and Branko Mušič helped to improve the content of this paper.

REFERENCES

- Al-fares, W., Bakalowicz, M., Guérin, R. & M. Dukhan, 2002: Analysis of the karst aquifer structure of the Lamalou area (Hérault, France) with ground penetrating radar.- *Journal of Applied Geophysics*, 51, 97–10.
- Allen, M.F. & E. Rincón, 2003: The changing global environment and the Lowland Maya: past patterns and current dynamics.- In: Gomez-Pompa, A. et al. (eds.) *The Lowland Maya Area: Three Millennia at the Human-Wildland Interface*. Food Products Press, pp. 13–30, Riverside.
- Andrews, A.P., 1990: The Fall of Chichén Itzá: A Preliminary Hypothesis.- *Latin American Antiquity*, 1, 258–267.
- Conyers, L.B., 2004: Ground-penetrating radar for Archaeology.- Altamira Press, pp. 203, Walnut Creek, California.
- Fedick, S.L. & B.A. Morrison, 2004: Ancient use and manipulation of landscape in the Yalahau region of the northern Maya lowlands.- *Agriculture and Human Values*, 21, 207 – 219.
- Ford, D.C. & P.W. Williams, 2007: *Karst Hydrogeology and Geomorphology*.- Wiley, pp. 562, Chichester.
- Froese, D.G., Smith, D.G. & D.T. Clement, 2005: Characterizing large river history with shallow geophysics: Middle Yukon River, Yukon Territory and Alaska.- *Geomorphology*, 67, 391–406.
- Garza T. de G.S. & E.B.K. Basco, 1980: Atlas Arqueológico del Estado de Yucatán.- Instituto Nacional de Antropología e Historia, pp. 249, Mexico City.
- Gómez-Pompa, A., Flores, J.S. & M.A. Fernández, 1990: The Sacred Cacao Groves of the Maya.- *Latin American Antiquity*, 1, 247–257.
- González de la Mata, R., 2006: Agua, agricultura y mitos: El caso de tres rejolladas de Chichen Itza. – In: Laporte, B. & H.M. Arroyo (eds.) *XIX Simposio de Investigaciones Arqueológicas en Guatemala*, 18th–22nd July 2006, Finca la Aurora, Guatemala. Museo Nacional de Arqueología y Etnología, 305–318, Finca la Aurora.
- González-Herrera, R., Sánchez-y-Pinto, I. & J. Gamboa-Vargas, 2002: Groundwater-flow modeling in the Yucatán karstic aquifer, Mexico.- *Hydrogeology Journal*, 10, 539–552.
- Gordon, M.J., 1986: Dependence of effective porosity on fracture continuity in fractured media.- *Ground Water*, 24, 446–452.
- Hall, F.G., 1935: Physical and Chemical Survey of Cenotes of Yucatán, in *The Cenotes of Yucatán*.- Carnegie Institute of Washington Publication, 457, 5–16.
- Hildebrand, A.R., Penfield, G.T., Kring, D.A., Pilkington, M., Camargo, A., Jacobsen, S.B. & W.V. Boynton, 1991: Chicxulub Crater: A Possible Cretaceous/Tertiary Boundary Impact Crater on the Yucatán Peninsula, Mexico.- *Geology*, 19, 867–871.
- Houck, C. W., 2006: Cenotes, Wetlands, and Hinterland Settlement.- In: Mathews, J. & B. Morrison (eds.) *Lifeways in the Northern Maya Lowlands: New Approaches to Archaeology in the Yucatán Peninsula*. University of Arizona Press, pp. 56–76, Tucson.
- Ipschording, W.C., 1976: Weathering of Yucatán limestones: the genesis of terra rossas.- In: Ward A. & W. Weidie (eds.) *Carbonate Rocks and Hydrogeology of the Yucatán Peninsula, Mexico*. New Orleans Geological Society, pp. 259–274, New Orleans.
- Jol, H.M. & C.S. Bristow, 2003: GPR in sediments: advice on data collection, basic processing and interpretation, a good practice guide.- In: Bristow, C.S. & H.M. Jol (eds.) *Ground Penetrating Radar in Sediments*. Geological Society of London Special Publication 211, pp. 9–27, London.
- Kepecs, S. & S. Boucher, 1996: The Pre-Hispanic Cultivation of Rejolladas and Stone Lands: New Evidence from Northeast Yucatán.- In: S. Fedick (ed.) *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*. University of Utah Press, pp. 69–91, Salt Lake City.
- Leckebusch, J., 2003: Ground-penetrating radar: A modern three-dimensional prospecting method.- *Archaeological Prospection*, 10, 213–240.

- Lesser, J.M. & A.E. Weidie, 1988: Region 25, Yucatán Peninsula.- In: Bak, W. et al. (eds.) *Hydrogeology*. Geological Society of America, pp. 237–24, Boulder.
- López, L.A.M., 2008: Underwater Archaeological Exploration of the Mayan Cenotes.- *Museum International*, 60, 100–110.
- Morley, S.G., 1946: *The Ancient Maya*.- Stanford University Press, pp. 520, Stanford.
- Munro-Stasiuk, M.J. & T.K. Manahan, 2009: Ground penetrating radar (GPR) analysis of karst environments near the ancient Maya center of Xuenkal, Yucatán, Mexico.- *Papers of the Applied Geography Conference*, 32, 352–361.
- Neal, A., 2004: Ground-penetrating radar and its use in sedimentology: principles, problems and progress.- *Earth-Science Reviews*, 66, 261–330.
- Patch, R.W., 1993: *Maya and Spaniard in Yucatán 1648–1812*.- Stanford University Press, pp. 329, Stanford.
- Pope, K.O., Ocampo, A.C. & C.E. Duller, 1991: Mexican Site for K/T Impact Crater?- *Nature*, 351, 105.
- Pope, K.O., Ocampo, A.C. & C.E. Duller, 1993: Surficial geology of the Chicxulub impact crater, Yucatán, Mexico.- *Earth, Moon and Planets*, 63, 93–104.
- Proskouriakoff, T., 1974: *Jades from the Cenote of Sacrifice, Chichen Itza, Yucatán*.- Harvard University Press, pp. 217, Cambridge.
- SARH, 1989: *Sinópsis Geohidrológica del Estado de Yucatán [Geohydrologic synopsis of the State of Yucatán]*. Secretaría de Agricultura y Recursos Hidráulicos. Subsecretaría de Infraestructura Hidráulica. Dirección General de Administración y Control de Sistemas Hidrológicos, Mexico, DF.
- Sensors and Software. 2003: *EKKO_View Enhanced and EKKO_View Deluxe User Guide*.- Sensors and Software Inc. 132p.
- Springfield, V.T. & H.E. LeGrand, 1976: Karst hydrology of Northern Yucatán Peninsula, Mexico.- In: Ward, A. & W. Weidie (eds.) *Carbonate Rocks and Hydrogeology of the Yucatán Peninsula, Mexico*. New Orleans Geological Society, pp. 192–210, New Orleans.
- Tozzer, A.M., 1957: *Chichen Itza and its Cenote of Sacrifice : a comparative study of contemporaneous Maya and Toltec*.- *Memoirs of the Peabody Museum of Archaeology and Ethnology, Harvard University*, pp. 316, Cambridge.
- Triplett, K., Gutierrez, C. & T. Ardren, 2006 : *Ethnobotanical Investigations*.- In: Manahan T.K. & T. Ardren (eds.) *Report of the 2005 Proyecto Arqueológico Xuenkal Field Season*. Foundation for the Advancement of Mesoamerican Studies Inc., pp 25–29, Crystal Springs.
- Urish, D.W., 1983: The practical application of surface electrical resistivity to detection of ground-water pollution.- *Ground Water*, 21, 144–152.
- Weidie, A.E., 1985: *Geology of Yucatán Platform*.- In: Ward, A. et al. (eds.) *Geology and Hydrogeology of the Yucatán and Quaternary Geology of Northeastern Yucatán Peninsula*. New Orleans Geological Society, pp. 1–19, New Orleans.
- Weisbach, C., Tiessena, H. & J.J. Jimenez-Osornio, 2001: Soil fertility during shifting cultivation in the tropical Karst soils of Yucatán.- *Agronomie*, 22, 253–263.

