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EOLIANITES AND KARST DEVELOPMENT IN THE MAYAN RIVIERA, MEXICO

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ABSTRACT

Coastal Quintana Roo, Mexico, including islands such as Cozumel and Isla Mujeres, contains numerous ridges of Quaternary eolian calcarenite in two packages, one Pleistocene and one Holocene. The Pleistocene eolianites are recognizable in the field by a well-developed terra rossa paleosol and micritic crust on the surface which contains a fossil epikarst. The foreset beds of these eolianites commonly dip below modern sea level, and fossilized plant root structures are abundant. The Holocene eolianites lack a well-developed epikarst, and have a calcernite protosol on their surfaces. The degree of cementation and the grain composition are not reliable indicators of the age of Quaternary eolianites.

The Pleistocene eolianites have been previously described (e.g. Ward, 1997) as exclusively regressive-phase eolianites, formed by the regression during the oxygen isotope substages (OIS) 5a and 5c). However, certain eolianites, such as those at Playa Copal, contain flank margin caves, dissolution chambers that form by sea water/fresh water mixing in the fresh-water lens. For such mixing dissolution to occur, the eolianite must already be present. As the flank margin caves are found at elevations of 2-6 m above current sea level, the caves must have developed during the last interglacial sea-level highstand, and the eolianites could not have formed on the regression from that or younger highstands. Therefore the eolianites must be transgressive-phase eolianites developed at the beginning of the last interglacial sea-level highstand, or either transgressive- or regressive-phase eolianites from a previous sea-level highstand that occurred earlier in the Pleistocene. There is no field evidence of oxygen isotope substage 5c or 5a eolianites as suggested by Ward (1997).

Most coastal outcrops show classic regressive–phase Pleistocene eolianites as illustrated by complex and well-developed terra rossa paleosols and epikarst, and dense arrays of fossilized plant roots. However, in addition to flank margin caves, other evidence of transgressive-phase eolianites includes notches in eolianites on the west side of Cozumel, with subtidal marine facies onlapping the notches.

The absence of a paleosol between those two units indicates that the eolianite is a transgressive-phase deposit from the last interglacial. All Holocene eolianites are, by definition, transgressive-phase units.

INTRODUCTION

The purpose of the research reported here was to take the well-established and field-tested Bahamian carbonate eolianite model to the Quintana Roo portion of the Yucatan Peninsula, an area called the "Mayan Riviera", and to examine the rocks there to see if they could be correlated to their Bahamian equivalents.

Eolian calcarenites are a major component of a number of young carbonate islands around the world. They are also now recognized to have been more abundant in the geologic past than previously thought (Abegg et al., 2001). Work in the last two decades has helped establish that eolian calcarenites are deposits that are tied closely to their allochem source, and are very sensitive to carbonate bank flooding events and positions, and hence, sea-level oscillations (e.g. Carew and Mylroie, 2001 and references therein). It was initially thought that these carbonate eolianites (to be called simply eolianites from here on) were produced solely by regressive conditions, as wave base passed through accumulated lagoonal sediments when sea level began to drop off of a carbonate platform. This scenario was demonstrated in Bermuda (Vacher and Rowe, 1997), but in the Bahamas, it was established that eolianites also form on the transgression as the carbonate platform is flooded by a sea level rise (Carew and Mylroie, 1995; 1997). The Bahamian data were especially compelling, as the archipelago is over 1,400 km long, stretching across 6.5 degrees of latitude and several climatic zones. The Bahamas are also tectonically stable, and the sea-level record preserved there is solely glacioeustatic.

In the Bahamas, therefore, each sea-level cycle should show a transgressive and regressive depositional phase for eolianites. Still-stand phases, although present, are volumetrically much less than for the other phases. Such phases have been clearly demonstrated for the Holocene as a transgressive suite of eolianites, and as a complete set of transgressive and regressive eolianites for the last interglacial sea-level highstand (oxygen isotope substage 5e or OIS5e) ~125,000 years ago (there are no Holocene regressive eolianites as the Bahamas have not yet seen a Holocene regression). For older units (pre-OIS5e), the record is less clear, but on-lapping relationships between the OIS5e units and older eolianites is clearly seen at numerous localities in the Bahamas. The conditions that produce eolianites on a transgression create features that are identifiable as different than the features produced in eolianites from the conditions of regression. These features can be distinguished in the field (Table 1), allowing eolianites to be classified in real time, without requiring geochronological or petrographic tools applied at a later time. Subsequent use of such tools, however, has confirmed interpretations made in the field in the Bahamas following the guidelines of Table 1.

There has been a strong debate in the literature concerning the existence of OIS5a eolianites in the Bahamas. While the case for such eolianites in Bermuda has been made (Vacher and Rowe, 1997), in the Bahamas such units cannot be distinguished by field criteria, but only by geochronological tools such as amino acid racemization (AAR), where the resolution of the method has been pushed to its limit. The debate is reviewed in Carew and Mylroie (1997), but the question remains open. What Carew and Mylroie (1995; 1997) classify as OIS5e regressive could be, in some localities, OIS5a units. In other localities, units of exactly the same character are seen to overtop OIS5e fossil reefs, with only a calcarenite protosol separating the eolianite from the reef. Protosols indicate only a short period of subaerial emergence, much less than the time frame

Transgressive Phase	Still-stand Phase	Regressive Phase
Fine-scale eolian bedding	Disrupted eolian bedding	Disrupted eolian bedding
Few vegemorphs	Abundant vegemorphs	Extensive vegemorphs
Penecontemporary cliffing and boulder paleotalus	Penecontemporary notching of beach and intertidal facies, and beach-face breccia facies	Lack of penecontemporary wave erosion
Penecontemporary sea caves	Rare sea caves	Lack of sea caves
Corals on wave-eroded benches	No corals on eroded benches	No penecontemporary benches
Lack of protosols	Protosols common	Protosols common
On lapped still-stand or regressive-phase deposits	Marine facies abundant	Commonly peleoidal/bioclastic
Predominantly eolianites, marine deposits rare	Ebb-tidal delta, lacustrine, and strand plain deposits	Eolianites overstepping marine deposits

Table 1. Diagnostic features of transgressive, still-stand, and regressive phase eolianites in the Bahamas (from Carew and Mylroie, 1995)

between the end of OIS5e and OIS5a (~35,000 years). Such field evidence strongly supports a OIS5e regressive-phase interpretation for all such outcrops. Still, the issue remains open.

Paleosols are a major tool in the development of a stratigraphy in eolianites. As eolianites are a unique depositional feature, a terrestrial limestone, they are created in a subaerial environment and remain there. Such exposure leads to the generation of an epikarst on the rock surface, and the accumulation of material on that epikarst to create a terra rossa paleosol. Terra rossa paleosols are orange to red accum-ulations of atmospheric dust, organic matter, and re-crystalized $CaCO_3$ to create a hard and resistant material that is extremely distinctive in the field. Terra rossa paleosols commonly contain the trace fossils of a variety of plant material, collectively called "vegemorphs" (Carew and Mylroie, 1995) to avoid differentiating between stems, roots and other traces of vegetative matter. As noted earlier, brief exposure times create an immature and poorly organized soil called a calcarenite protosol. They are commonly found within eolianites (almost always regressive-phase ones), or beneath eolianites that have on-lapped exposed subtidal units. They represent a time interval measured in hundreds or thousands of years, as opposed to the tens of thousands to hundreds of thousands of years represented by terra rossa paleosols. Holocene eolianites in the Bahamas, because of their youth (less than 6,000 years in age), have only a calcarenite protosol on their exposed surfaces; these eolianites are not old enough for significant terra rossa paleosol development. The single easiest criteria to separate Holocene from Pleistocene eolianites in the Bahamas is to look for the absence or presence, respectively, of a terra rossa paleosol. As eolianites only form during platform flooding events (sea-level highstands), and terra rossa paloesols form during the much longer platform exposure events (sea-level lowstands), they make excellent stratigraphic markers by which glacioeustatic cycles can be differentiated.

METHODOLOGY

The results reported here were obtained by simple field reconnaissance, utilizing criteria as laid down in Table 1 and from field experience in the Bahamas, as detailed in Carew and Mylroie (1995, 1997). Macroscopic field relationships are critical to subsequent interpretations. Such field relationships are more important than small sample analyses, such as thin sections, which may yield results unique to special conditions at a tiny locale.

Four main eolianite localities were studied as part of a reconnaissance trip made in December 2003: Isla Mujeres, Cancun, Cozumel, and Tulum (Figure 1). Subsequent to that trip, as part of co-author K. Kelley's Masters thesis, a major research trip was made in May and June 2004 to do detailed outcrop examination and sampling, with subsequent thin section analysis at Mississippi State University. The results reported here deal solely with the December 2003 reconnaissance. It remains to

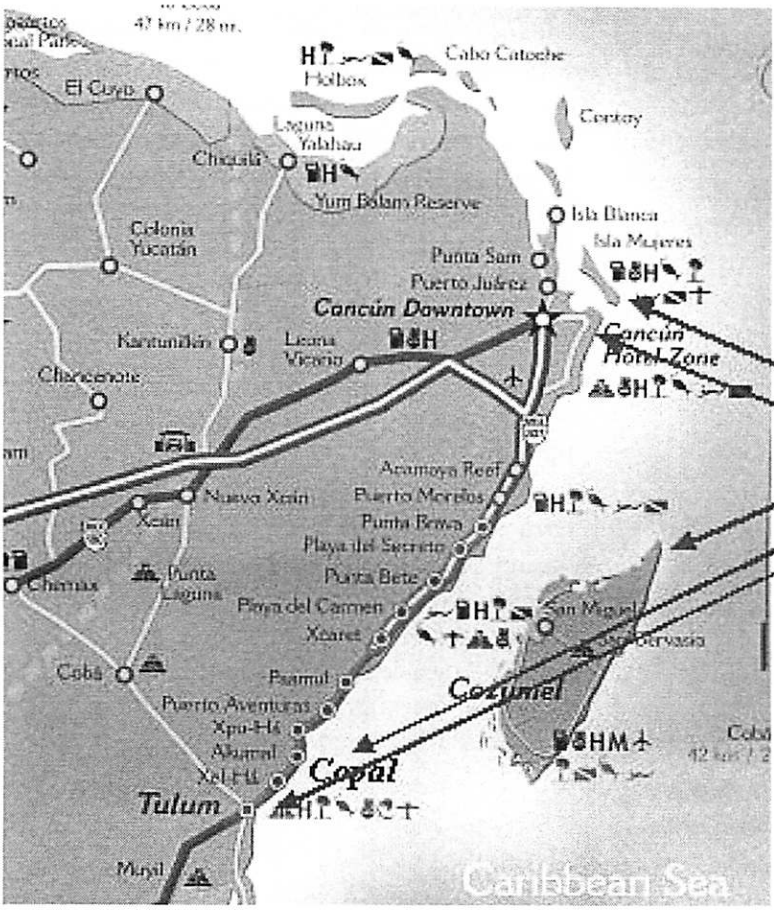

Figure 1. Map of the Yucatan Peninsula showing the main study locations.

be seen if the analyses performed later will substantiate interpretations made from the initial reconnaissance trip.

QUINTANA ROO EOLIANITES

The eastern side of the Yucatan Peninsula is part of the Mexican state of Quintana Roo (Figure 1). The Yucatan Peninsula consists primarily of Cenozoic carbonates, with Quaternary carbonates found mainly as a coastal band (Ward, 1997; Beddows, 2003). The Peninsula has a long tectonic history, including the Chicxulub impact event at the K-T boundary, but appears to have been tectonically stable since the middle Pleistocene. Rainfall is approximately 100 cm/yr, and temperature varies from 15 to 37 °C (Ward, 1997), all similar to the Bahamas but with a higher expression of continentality.

Quintana Roo is famous for its cenotes and well-developed flooded cavern systems formed in the Cenozoic rocks. The specific sites for this study were the eolianite outcrops studied by Ward (1997 and references therein), which compare to the Bahamian eolianites. In addition, while the large cave conduit systems of Quintana Roo have been studied for decades (Beddows, 2003), the development of caves in the coastal eolianites have not been previously discussed. Work in the Bahamian eolianites has shown that placement of a fresh-water lens within an eolianite (on a sea-level rise syngenetic or subsequent to the eolianite's deposition) would create a significant dissolutional environment in the fresh water – salt water mixing zone. Caves thus develop in the distal margin of this fresh-water lens, under the flank of the enclosing landmass and are called *flank margin caves* (Mylroie and Carew, 1995). They are important as indicators of past positions of the fresh-water

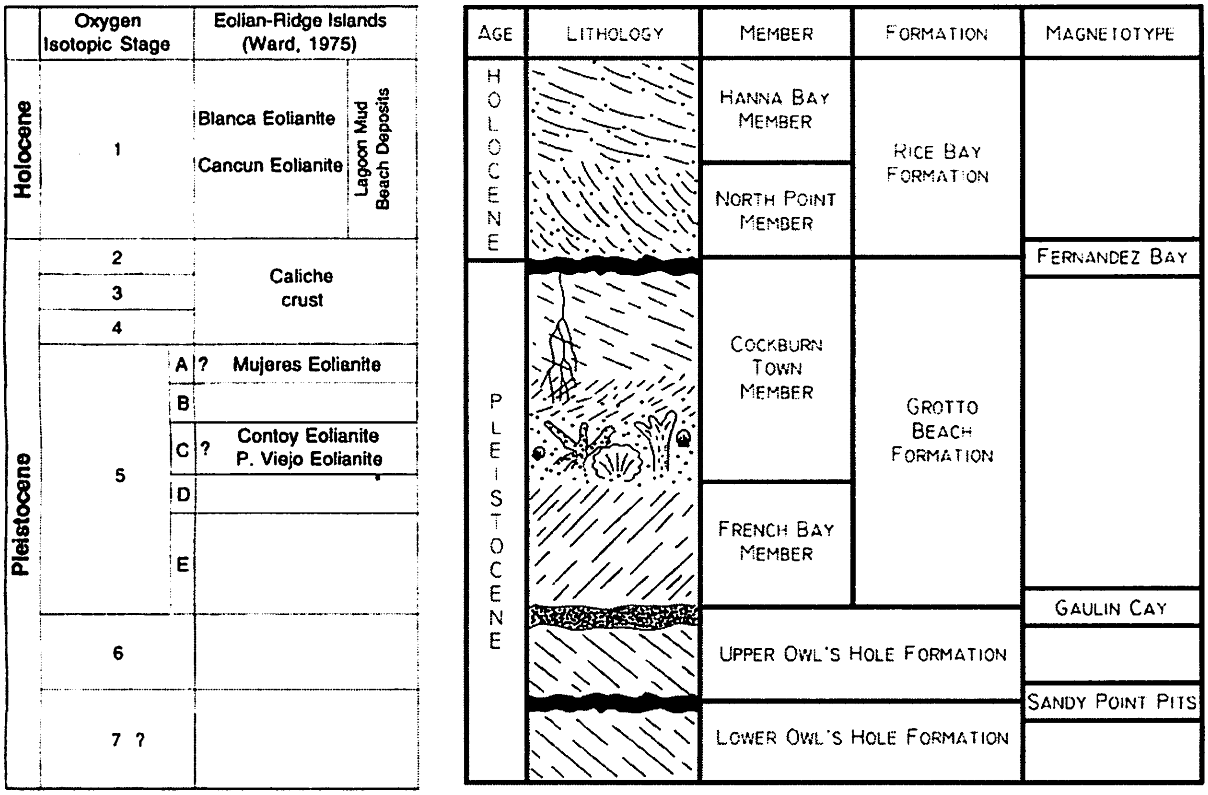

Figure 2. Comparison of the Ward (1997) geologic column for eolianites (left) with that of Carew and Mylroie from the Bahamas (right).

lens, and hence, sea level. As Ward (1997) had reported numerous Pleistocene eolianite outcrops in Quintana Roo, there was possibility that these rocks might contain flank margin caves. However, discussions with cavers working in the area (e.g. Patricia Beddows, Jim Coke) indicated that no such caves were known. They even suggested that, given the large conduit flow systems developed beneath the eolianites in older carbonates, such caves could not exist since these systems deliver fresh water from the interior directly to the sea.

Ward (1997) summarized the geology of the coastal and island eolianites of the Quintana Roo region. When his geologic column is compared to that of Carew and Mylroie (1997, Panuska et al., 1999), some parallels are found as are some discrepancies (Figure 2). Both columns have two Holocene units, but in the Pleistocene, Ward (1997) shows only OIS 5c and 5a units, whereas Carew and Mylroie (1995; 1997) show neither of these but show an extensive OIS5e eolianite suite, as well as units at least as old as OIS7 and OIS9, and perhaps older. Older eolinites were subsequently documented from Eleuthera (Kindler and Hearty, 1995; Panuska et al., 2002).

The presence of Holocene eolianites in the Ward (1997) geologic column is interesting, as the text of this paper implies that eolianites form as a result of sea-level regression following the highstand. Given that no such regression has occurred in the Holocene, the identification of Holocene eolianites in Quintana Roo is *de facto* evidence that transgressive eolianites also formed in the Yucatan as well as in the Bahamas.

RESULTS

Cancun

Based on the absence of any evidence suggesting a terra rossa paleosol was present or had been present, the eolianites located at the north end of Cancun were identified in the field as Holocene. Field observations indicated that there were two Holocene eolianites, with foreset beds dipping below modern sea level (Figure 3), and one with beds asymptotic to it (Figure 4). Based on the Bahamian model, that would mean that Ward's (1997) older unit, the Cancun Eolianite, was equivalent to the North Point Member of the Rice Bay Formation in the Bahamas. The Blanca Eolianite would be equivalent to the Hanna Bay Member of the Rice Bay Formation.

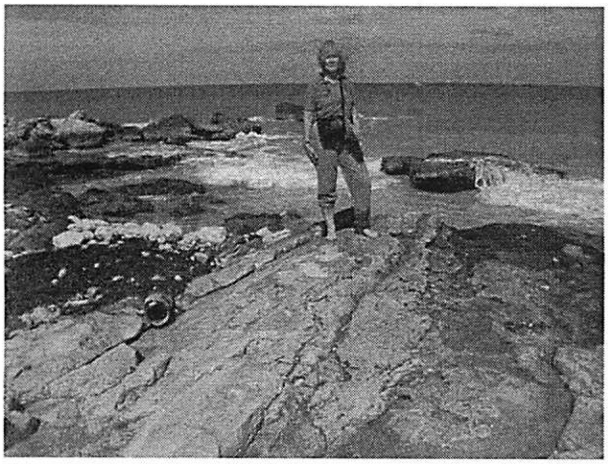

Figure 3. Outcrop of Holocene eolianite at the north end of Cancun. Foreset beds dipping below modern sea level indicate the unit's equivalence to the North Point Member of the Rice Bay Formation in the Bahamas.

Figure 4. Outcrop of Holocene back-beach eolianite at the north end of Cancun. Foreset beds are parallel to modern sea level, equivalent to the Hanna Bay Member of the Rice Bay Formation in the Bahamas.

Isla Mujeres

Isla Mujeres has eolianites with a well-developed paleosol and many vegemorphs (Figure 5), as well as numerous calcarenite protosols (Figure 6). These features are diagnostic of regressive-

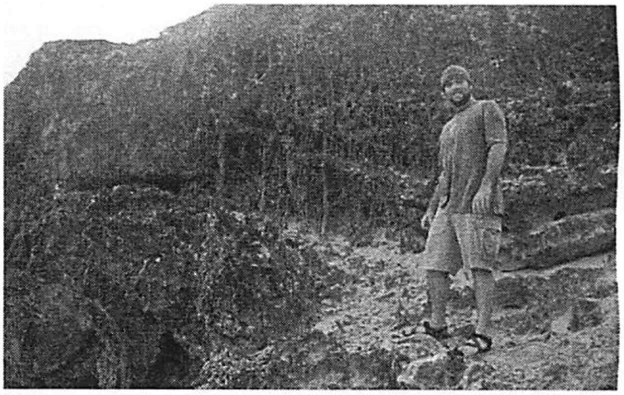

Figure 5. Outcrop of eolianites on Isla Mujeres, showing a well-developed terra rossa paleosol with extensive vegemorphs, equivalent to the Cockburn Town Member of the Grotto Beach Formation in the Bahamas.

Figure 6. Quarry on Isla Mujeres, showing a well-developed terra rossa paleosol at the top of the section, and two calcarenite protosols, one at the left below the terra rossa paleoosl, and one lower at the right just above the large box. Car tires for scale. The unit meets the requirements for a regressive-phase eolianite, equivalent to the Bahamian Cockburn Town Member of the Grotto Beach Formation in the Bahamas.

phase eolianites (Table 1). Because rocks with similar criteria are mapped as OIS5e regressive-phase in the Bahamas, (eolianites of the Cockburn Town Member, Grotto Beach Formation), these rocks are considered to be the equivalent.

Cozumel

Cozumel has mostly rocks of subtidal facies, but there are scattered locations of eolianites. On the east coast, there are numerous eolianites that show classic terra rossa paleosol and vegemorph development that in the Bahamas is associated with regressive-phase eolianites (Figure 7). In the Bahamas, these east coast units would be considered part of the Cockburn Town Member of the Grotto Beach Formation.

Figure 7. Coastal eolianite, east coast of Cozumel, showing a well-developed terra rossa paleosol with extensive vegemorphs, indicating equivlanece to the Bahamian Cockburn Town Member of the Grotto Beach Formation in the Bahamas.

To the north, on the west coast of Cozumel there are eolianites without well-developed vegemorphs. There is a wave cut bench on top of which are found subtidal facies deposits (Figure 8). This meets the requirements for classification of the eolianite as transgressive-phase, and thus, equivalent to the French Bay Member of the Grotto Beach Formation in the Bahamas.

Figure 8. Northwest coast of Cozumel. Eolianite outcrop with a terra rossa paleosol, and a notch. The notch appears to be wave cut during a past sea-level highstand (OIS5e), and the bench below the notch contains subtidal deposits. This criteria indicates that the unit is topped by an equivalent to the French Bay Member of the Grotto Beach Formation in the Bahamas.

Tulum

In the Tulum area there are a series of eolianites with numerous flank margin caves (Figures 9 and 10). As these eolianites must already have been in position before there could be a fresh-water lens to form them, they must have been deposited on the last transgression, or during an earlier one. The position of the caves, at a few meters above modern sea-level, indicates that the highstand was most likely during OIS5e. This allows correlation of these eolianites with the French Bay Member of the Grotto Beach Formation, or perhaps the older indicators (Owls Hole Formation). The eolianites lack the indicators of regressive phase development (few vegemorphs, no calcarenite protosols), so if they are not French Bay Member, they are from the transgressive-phase of OIS7, 9 or possibly 11.

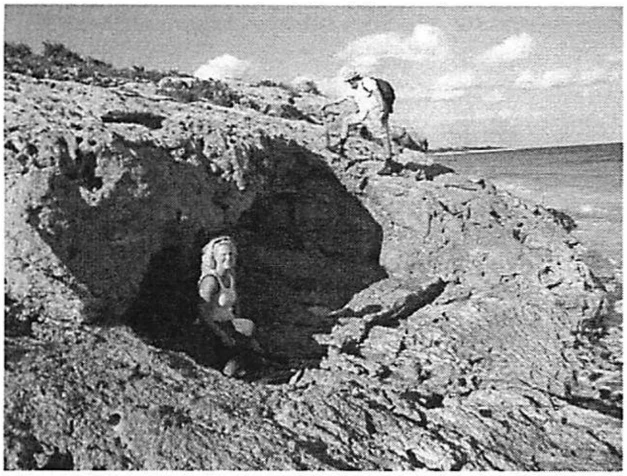

Figure 9. Flank margin cave along the coast in the Tulum area. Holocene sea-level erosion has breached the dissolutional chamber.

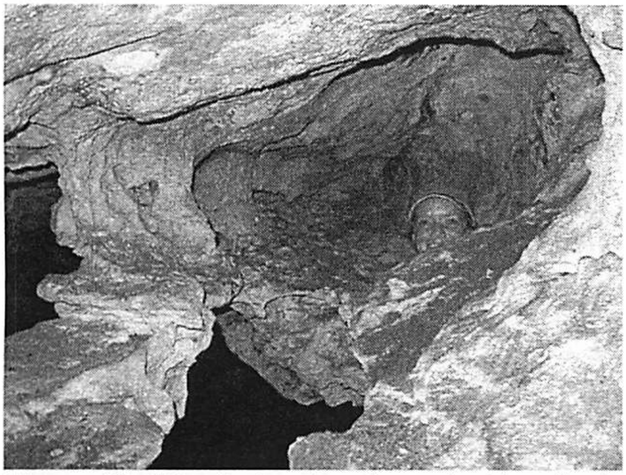

Figure 10. Dissolutional sculpture inside a flank margin cave developed in coastal eolianites in the Tulum area.

At the Tulum Ruins, the coastal eolianites reach heights above 20 m. Outcrops there show that the sequence is capped by a terra rossa paleosol. However, within the section there is a second (and perhaps a third) terra rossa paleosol (Figure 11). If the upper eolianite is OIS5e material, then the eolianite below the terra rossa paleosol must be older making the upper unit equivalent to the Bahamian Grotto Beach Formation, and the lower to the Owls Hole Formation.

DISCUSSION

The information provided here has both a major strength and weakness. The strength is that based on macroscopic field observations it seems to establish a new, Late Quaternary stratigraphy for eolianites in Quintana Roo, Mexico. Its weakness is that it offers no independent local data to corroborate those field observations. If some adjustments are made in the Late Pleistocene portion of that stratigraphic column, the existing stratigraphy of Ward (1997) correlates quite well with the Bahamas stratigraphy.

There are some problems with Ward's (1997) stratigraphy. There are no eolianites older than OIS5, though they are common in Bermuda and the Bahamas. The eolianite-paleosol-eolianite-paleosol sequence at Tulum suggests that at least one eolianite was deposited before OIS5. Flank margin cave development at Tulum also support older eolianites, although they could be OIS5e transgressive-phase eolianites.

Since OIS5e eolianites are recognized from Quaternary carbonate units around the world, the lack of these eolianites in the Ward (1997) stratigraphy is a major missing component. It is possible, that for reasons unknown at this time, OIS5e eolianites were never deposted in Quintana Roo. However, if this were true, then there must be older eolianites present, as the flank margin caves at Tulum require an already deposited eolianite at the OIS5e sea-level maximum. The wave-cut bench fronting the notch on the eolianites at northwest Cozumel has marine facies on top of it. These marine fossils are compelling evidence that the eolianite was a transgressive-phase unit deposited on the initial sea-level rise of OIS5e, which was then notched when sea level reached its high point. At this time the marine facies were deposited on the wave cut bench. There is no evidence that the wave cut bench truncated a pre-existing terra rossa paleosol, which eliminates an earlier sea-level highstand as being the agent of the eolian deposition at this site.

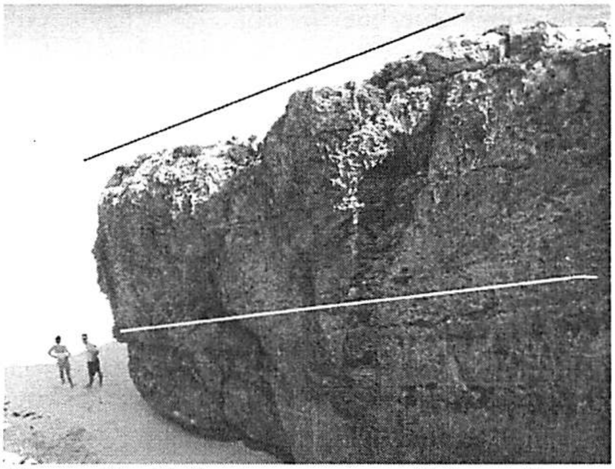

Figure 11. Eolianite outcrop at Tulum. The top of the outcrop (black line) has a terra rossa paleosol. Within the outcrop, at approximately the level of the heads of the people on the left, just below the white line, is a second terra rossa paleosol that cuts through the outcrop slanting upwards to the right. The top unit can be no younger than OIS5e, making the lower eolianite OIS7 or older. A likely Bahamian-equivalent would be Grotto Beach Formation over Owls Hole Formation.

Ward's (1997) OIS5c and OIS5a eolianites seem to us to be regressive-phase eolianites from the OIS5e highstand. OIS5c eolianites are not reported from anywhere else in the Atlantic Basin. OIS5a eolianites, are reported from Bermuda (Vacher and Rowe, 1997) and from the Bahamas (Kindler and Hearty, 1997). However their presence in the Bahamas has been hotly debated (Carew and Mylroie, 1997).

Ward's (1997) Holocene units correlate very well to the Bahamian Holocene stratigraphy. The older eolianite unit, the Cancun Eolianite, has foreset beds that dip below modern sea level, indicating deposition at a time when the platform was flooded and producing carbonate sediment, but before sea level reached its present position. The younger Blanca Eolianite has backbeach eolian facies that grade to modern sea-level position beach facies. These two eolianite units are equivalent to the North Point and Hanna Bay Members of the Rice Bay Formation in the Bahamas. In addition Ward (1997) felt that the eolianites of Quintana Roo were entirely regressive-phase, but the mere existence of Holocene eolianities means that they formed on a transgression, leading to interpreting some Pleistocene eolianties (such as at Tulum) as transgressive-phase in origin.

Loucks and Ward (2001) report C-14 dates from the Holocene eolianites. One date of 19,635 +/-845 ybp is from a Pleistocene coral in a storm deposit under one dune. That date is problematic as sea level was over 100 m lower at that time. It would have been difficult to place the coral at the modern sea-level elevation at the time at which it was found. The other Loucks and Ward (2001) dates are grouped at less than 4,000 ybp. Bahamian dates for the two Holocene units cluster at 5,000 ybp for the North Point Member, and 3000 ybp for the Hanna Bay Member (Carew and Mylroie, 1987). All of the older show foreset beds dipping below modern sea level, and all of the younger show beds congruent with modern sea level. The Quintana Roo dates show overlap between the Cancun and Blanca Eolianites. If the Bahamian model is correct, then the C-14 dates for Quintana Roo possibly result from contamination by young carbon, probably from vadose cements. If the Quintana Roo C-14 dates are correct, then the area had a different Holocene sea-level history than the Bahamas.

Work is currently underway on a large collection of samples from all the eolianites discussed in this report. Thin-section analyses may answer some of the questions raised by the preliminary field study. The field observations do suggest that the stratigraphy for Late Quaternary eolianites developed in the Bahamas, can be directly applied to the eolianites of Quintana Roo.

The presence of flank margin caves in the Quintana Roo eolianites is significant. As noted earlier, these caves are a diagnostic tool for dating the enclosing eolianite. For the caves to be present today, above modern sea level, requires that they developed during a past, higher sea level (assuming Late Quaternary tectonic stability for Quintana Roo). Regardless of the debate about some eolianites being OIS5c and OIS5a (Ward, 1997) versus OIS5e regressive (Carew and Mylroie 1997), the lack of flank margin caves in these terra rossa covered units is clear evidence that they are younger than the sea-level highstand of OIS5e, but older than Holocene.

The presence of flank margin caves at all is also significant. Quintana Roo has the world's largest, surveyed. underwater caves (Beddows, 2003 and references therein), a labyrinth of conduits carrying freshwater from the interior of the Yucatan Peninsula to the sea. Despite this mature and well-developed karst system, during the OIS5e sea-level highstand, mixing dissolution in fresh-water lenses within some coastal eolianites produced a second, totally independent cave system. These observations indicate that coastal fresh-water lenses may be de-coupled from regional flow systems, or at the very least, act with a separate flow identity.

CONCLUSIONS

The Quaternary eolianites of Quintana Roo appear to meet the eolianite stratigraphic model developed in the Bahamas. Given that both locations have exhibited Late Quaternary tectonic stability, and that both have been subject to the same open Atlantic Basin sea-level conditions, such a conclusion is not surprising. The issue of OIS5a and 5c eolianites versus OIS5e regressive-phase eolianites remains unresolved. The Quintana Roo eolianites offer no direct evidence to support either side of the debate. In broadest terms, both areas show OIS1, OIS5, and older OIS (7, 9, or 11, etc.) eolianites. The Quintana Roo C-14 dates for Holocene eolianites appear too young with respect to Bahamian equivalents, but perhaps contamination by young cements is the reason why, Such contamination would also explain the anomalous coral date from these units. The presence of flank margin caves helps place the age of some eolianites as OIS5e transgressive-phase or older. No such units were recognized by Ward (1997). The caves also have implications for the hydrologic behavior of fresh-water lenses when they have underflow from major conduit systems at depth. Work continues on rock analysis, which may help confirm or require re-evaluation of the conclusions reached here.

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