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Stratigraphic evidence for anthropogenically induced coastal environmental change from Oaxaca, Mexico

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Abstract

Previous interdisciplinary paleoenvironmental and archaeological research along the Río Verde Valley of Oaxaca, Mexico, showed that Holocene erosion in the highland valleys of the upper drainage basin triggered geomorphic changes in the river's coastal floodplain. This article uses stratigraphic data from sediment cores extracted from Laguna Pastoría, an estuary in the lower Río Verde Valley, to examine changes in coastal geomorphology potentially triggered by highland erosion. Coastal lagoon sediments contain a stratigraphically and chronologically distinct record of major hurricane strikes during late Holocene times. Three distinct storm facies are identified from sediment cores obtained from Laguna Pastoría, which indicate that profound coastal environmental changes occurred within the region and are correlated with increased sediment supplied from highland erosion. The *Chione*/*Laevicardium* facies was deposited in an open bay while the *Mytella*/barnacle facies and sand facies were deposited in an enclosed lagoon following bay barrier formation. We argue that highland erosion triggered major geomorphic changes in the lowlands including bay barrier formation by ~2500 cal yr B.P. These environmental changes may have had significant effects on human populations in the region. The lagoon stratigraphy further indicates an increase in mid–late Holocene hurricane activity, possibly caused by increased El Niño frequencies.

Keywords: Stratigraphic evidence; Coastal environmental change; Mexico; Late Holocene; Archaeology

Introduction

Paleoenvironmental data from Mesoamerica indicate that agricultural practices and deforestation by early sedentary village populations triggered erosion as early as 3450 cal yr B.P. in many areas of Mesoamerica (e.g., Deevey et al., 1979; Fedick, 1996; Killion, 1992; McAuliff et al., 2001; Metcalfe et al., 1994; O'Hara et al., 1993; Rosenmeier et al., 2002a; Whitmore et al., 1996). Anthropogenic landscape change intensified following development of urban societies during the Late/Terminal Formative (2350–1620 cal yr B.P.), although in many regions soil conservation technologies, especially agricultural terraces, were developed that effectively limited erosion and stabilized landscapes (e.g., Dunning and Beach, 1994; Fisher et al., 2003; Sluyter and Siemens, 1992; Spores, 1969). Significant cultural change, in some cases, occurred coincident with environmental degradation (Abrams and Rue, 1988; Paine and Freter, 1996; Rice, 1996; Rice et al., 1985; Webster et al., 2000; Wingard, 1996), although causal relationships between cultural and environmental change have been debated (Dunning and Beach, 1994; Fisher et al., 1999, 2003).

Most research on anthropogenic landscape change has focused on the relationship between local land use and environmental change. In this paper, we take a macro-regional perspective, presenting evidence from the Río Verde drainage basin of Oaxaca indicating that significant coastal morphological change occurred following anthropogenic erosion in the highland valleys of the upper catchment over 150 linear kilometers from our study site. We show that

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coastal geomorphic change resulted in the formation of estuarine environments and discuss the implications for the distribution and availability of resources used by pre-Hispanic peoples in the lower Río Verde Valley.

Previous geomorphic studies

The Río Verde is one of the largest rivers on the Pacific Coast of Mesoamerica in terms of both drainage area and discharge (Tamayo, 1964). The upper drainage basin of the Verde consists largely of several temperate highland valleys, including the valleys of Oaxaca, Ejutla, and Nochixtlán (Joyce and Mueller, 1997). These valleys lie at elevations ranging from 1500 to 2500 m above sea-level with mean annual temperatures of 16–20°C and average annual rainfall varying from 400 mm to 1000 mm. The lower drainage basin consists entirely of the Verde's coastal valley. The climate of the lower Río Verde Valley is hot and humid with mean annual rainfall of 1000–2000 mm and average temperatures ranging from 25°C to 28°C. The river descends from the highland valleys to the coast through deep, narrow gorges that leave little room for sediment storage. The river's gradient also shows an upward convex profile that flattens only within 30 km of the coast. These geomorphic properties mean that environments in the lower valley are sensitive to increased sediment loads resulting from changes in land use, climate, and tectonics in the highland valleys.

Broad-scale changes in Mesoamerican climate are beginning to emerge from the paleoenvironmental record (Metcalfe et al., 2000). Paleoclimate data for the southern coastal states of Mexico are very limited (Metcalfe et al., 2000); the research presented here is part of a larger project seeking to address this imbalance. Paleolimnological and geomorphic evidence from elsewhere in Mesoamerica indicates that climatic conditions have not remained stable (Conserva and Byrne, 2002; Curtis et al., 1996; Goman and Byrne, 1998; Hodell et al., 1995, 2001; O'Hara et al., 1994; Leyden, 2002; Leyden et al., 1996). The early–mid Holocene appears to have been relatively wet throughout Mexico, excepting the Basin of Mexico (Metcalfe et al., 2000). After this timeframe, climatic causes for environmental changes are difficult to determine from the palynological and isotopic record in Mesoamerica because of the obscuring handprint of human-induced vegetational changes (e.g., Deevey, 1978; Leyden, 2002; Rosenmeier et al., 2002b; Vaughan et al., 1985). Climatic drying is recorded in the Maya lowlands beginning about 3000 years ago, with the driest periods occurring in the last 1500 years (Brenner et al., 2002).

Over the time interval involved in this research, tectonic uplift would appear not to be a significant controlling factor. Ortega-Gutiérrez (1990) states that uplift rates since the Miocene are approximately 130 m/myr. In addition, the regional uplift was modified by crustal extension such that areas along the larger rivers in the highlands were down-thrown and experienced lower rates of uplift. Ortega-Gutiérrez (1990) specifically cites the Valley of Oaxaca as being representative of this process.

Previous geomorphological research in the highland valleys of Ejutla, Oaxaca, and Nochixtlán has involved the pedological and sedimentological study of stratigraphic profiles in incised drainages. Profiles consist of alluvial deposits resulting from upland erosion separated by paleosols that represent periods of land surface stability. A total of 27 paleosols were radiocarbon dated, which provides our chronology of highland geomorphic change. The highland research yielded evidence for multiple episodes of pre-Hispanic erosion (Joyce and Mueller, 1997; Mueller and Joyce, 2002). Two periods of erosion date to the mid-Holocene and were probably the result of climate change since only small populations of mobile forager farmers inhabited the region at this time. The late Holocene erosive episodes, however, correspond to the three most significant periods of pre-Hispanic land use change, which suggests that the erosion was anthropogenic. The most significant period of anthropogenic landscape change was during the Early Formative Period (4120–2755 cal yr B.P.), which marks the time of initial sedentism as well as population growth and agricultural expansion in the highlands (Balkansky et al., 2000; Marcus and Flannery, 1996; Winter, 1989).

Geomorphological, pedological, and archaeological investigations along the lower Río Verde flood plain (Joyce, 1991a,b; Joyce and Mueller, 1992, 1997; Joyce et al., 1998) documented dramatic fluvial landform changes during the Early/Middle Formative Period that were consistent with the expected effects of highland erosion on the drainage system. Environmental changes in the lower Verde's floodplain included an increase in sediment load, peak river flow, and the range between high and low flow rates. These changes caused aggradation, alluviation, stream migration, and a change from the previously meandering channel morphology to a braided form by the Late Formative Period, 2350–2065 cal yr B.P. Coarser-textured sediments from the highlands tended to remain in the braided channel as it migrated across the lower valley. The finer textured silts and clays with their higher cation exchange capacity and fertility were laid down as overbank deposits mantling the sands and lower, poorly drained positions. Increased channel aggradation along with increased overbank alluvial deposition would have thus expanded the agriculturally productive floodplain of the lower Verde. Our data indicate that the change in the lower valley was precipitated by anthropogenic erosion in the heavily populated highland valleys of Nochixtlán, Oaxaca, and Ejutla located 150 km north of the lower Verde region (Joyce and Mueller, 1997). The eroded material was then transported downstream to the lowlands increasing the sediment load of the river, thereby forcing it out of equilibrium.

While large quantities of sediment were incorporated into the lower Verde's floodplain, significant amounts of material would have continued downstream, eventually discharging into the Pacific Ocean. We hypothesize that sediment discharged from the river into the Pacific Ocean was carried eastward by longshore currents and deposited along the coast forming the bay barrier and the back-barrier lagoons.

Study region and core sites

Laguna Pastoría (16°00′N 97°35′W) is a brackish estuary located approximately 20 km east of the Río Verde's mouth (Fig. 1). Laguna Pastoría and a nearby sister lagoon, Chacahua, combine to form the National Park of "Lagunas de Chacahua," which encompasses almost 15,000 ha, of which 3525 ha are lagoons (Torres-Moye et al., 1993). The lagoon is protected from the Pacific Ocean by a roughly east–west trending bay barrier (Contreras, 1988; Lankford, 1977). The bay barrier is about 500 m wide and 2–4 m high. Low scrub vegetation (cacti, thorny bushes, small trees, and palms) grows on the barrier, which has a beach ridge complex.

Laguna Pastoría is approximately 9 km long and varies in depth with a 3–4 m maximum. Tides are microtidal (1 m). The Río Chacalapa, an intermittent stream, and the Río San Francisco both discharge seasonally into the northwest portion of the lagoon, and a narrow artificial channel joins the lagoon with the Pacific to the south, near the village of Cerro Hermoso (Torres-Moye et al., 1993). The sediment accumulating in the lagoon is estuarine mud with 10–25% organic matter and little to no sand. The water is brackish and supports a diverse array of mangroves (*Rhizophora mangle*, *Laguncularia racemosa*, *Conocarpus erectus*, and

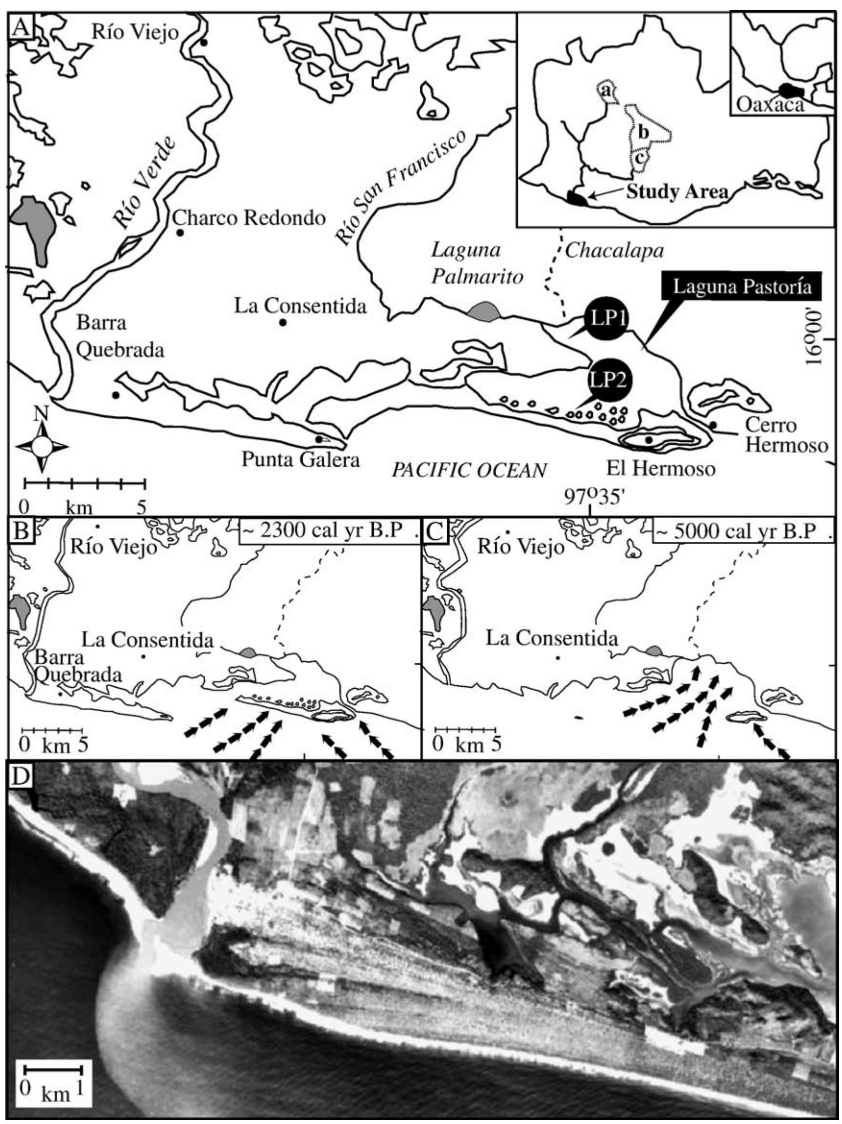

Figure 1. (A) The study site Laguna Pastoría and locations mentioned in the text. Contour interval is 50 m. The inset shows the state of Oaxaca and the key highland valleys (a = Nochixtlán, b = Valley of Oaxaca, and c = Ejutla). Stylized reconstructions showing the region at (B) 2300 and (C) 5000 cal yr B.P. The black arrows indicate the potential storm surge direction and penetration. Panel D shows the mouth of the Río Verde in an image taken in December 1999, notice the sand plume and its eastward movement, also note the beach ridges present on the bay barrier that encloses the Chacahua lagoon.

Avicennia germinans). The mangroves fringe the estuary and, immediately behind the bay barrier, discrete mangrove islands have formed (Fig. 1).

Estimates of relative sea-level rise are lacking for the immediate area; however, data from elsewhere along the Pacific Coast indicate that sea-level stabilized between ~6000 and 5200 cal yr B.P. (Atwater et al., 1977; Curray et al., 1969; Voorhies, 2004). The timing of sea-level stabilization is significantly earlier than our evidence for barrier formation, indicating that factors other than sea level were involved in barrier formation.

The evidence indicates that tectonics is not a significant factor in barrier formation. Lying just offshore, the subducting Cocos Plate has, since Miocene time, produced tectonic uplift rates of approximately 130 m/myr along the continental edge (Ortega-Gutiérrez, 1990). This converts to an uplift rate of just 13 cm/1000 years, a rate slightly less than sea level rise during the last several millennia. Current field observations also indicate no evidence of coastal uplift in the form of uplifted wavecut platforms or cliffs. Hillslope sediments and floodplain deposits are graded to present sea level. Thus, published data and field observations are consistent and indicate that crustal uplift is exceeded by sea level rise.

To test the hypothesized link between highland erosion and lagoon formation, two sediment cores were raised from Laguna Pastoría in June 2000 using a Livingstone Corer. The first core (LP1) is 5.36 m long and was collected from the northern portion of the lagoon (16°00′35″N 97°35′56″W), while the second core (LP2) is 2.09 m long and was collected to the south (15°58′34″N 97°35′19″W) immediately behind the barrier island and surrounded by mangrove islands (Fig. 1).

Laboratory methods

The sediment cores were X-rayed and magnetic susceptibility data were collected prior to lithostratigraphic description. Intensive loss-on-ignition (LOI) analysis was undertaken on both cores at 1-cm intervals (Liu and Fearn, 2000). LOI analysis followed standard protocols for establishing organic and calcium carbonate content as described by Heiri et al. (2001). Three A.M.S. radiocarbon dates were obtained from estuarine mud samples (Table 1 and Fig. 2). Ages of features not dated by A.M.S. radiocarbon dates within the sediment cores are estimated by assuming a constant rate of sedimentation between available radiocarbon dates. It is assumed in these calculations that sand and shell beds were deposited instantaneously. We also took five samples from the top 40 cm of the LP2 core for ^{137}Cs analysis. The samples were dried and ground and analyzed by gamma spectrometry using an intrinsic germanium well detector (ORTEC GWL-120). A spike in ^{137}Cs levels is associated with the beginning of nuclear weapons testing in A.D. 1954 (Appleby, 2001).

Stratigraphy

The two cores exhibit a varied and complex stratigraphy (Fig. 2). The dominant sediment matrix within the cores is of estuarine mud with discrete coarse shell and sand beds interbedded within the matrix. These beds vary in thickness from 1.5 to 28 cm and have abrupt lower and upper contacts with the surrounding sediment (Fig. 2). The condition of the shells varies from completely articulated to disarticulated, and mollusk fragments. The shells are orientated in all directions and are very rarely in growth position (i.e., direction of shell and palialsinus scar to sediment surface: Fig. 2).

The estuarine mud exhibits slight differences in organic content and coloration between the two cores (LP1 ~10% organic content and Munsell 5Y2.5-3/1; LP2 ~25% organic content and Munsell 10YR 3/2). Differences in estuarine mud between the sites probably reflect the proximity of the mangrove islands to LP2. Figure 2 shows the changes in calcium carbonate content with depth for both cores; maintained peaks (over several centimeters) in the carbonate signal correspond to the shell hash layers.

The mollusk facies comprise three distinct types: *Chione, Mytella*, and mixed mollusk hash. The *Chione* beds are principally composed of *Chione subrugosa* and some *Laevicardium elenense* as well as occasional unidentified gastropods. This facies is found in the lower sediments of LP1. *C. subrugosa* live in lagoons or on mudflats whereas *L. elenense* is most common offshore in depths up to 90 m and is rarely found intertidally (Keen, 1971).

The *Mytella* facies is dominated by *Mytella strigata* with some barnacles. *Mytella* lives in a variety of habitats

Table 1
Radiocarbon data from Laguna Pastoría

Site and depth (cm)[a]	Material dated	Laboratory number[b]	$^{13}C/^{12}C$ ratio (‰)	Conventional radiocarbon age (^{14}C yr B.P.)	Calibrated age range (2 σ) cal B.P.
LP1 231	Organic sediment	Beta 168001	−20.6	2290 ± 40	2352–2157
LP1 534	Organic sediment	AA 42080	−27.6	4213 ± 34[c]	4845–4632
LP2 141	Organic sediment	Beta 168002	−24.2	1550 ± 40	1531–1333

[a] LP1 = northerly site; LP2 = southerly site (Fig. 1).
[b] Radiocarbon assays by Beta Analytic Inc. and NSF-Arizona AMS Lab.
[c] Represents the average of three individual measurements.

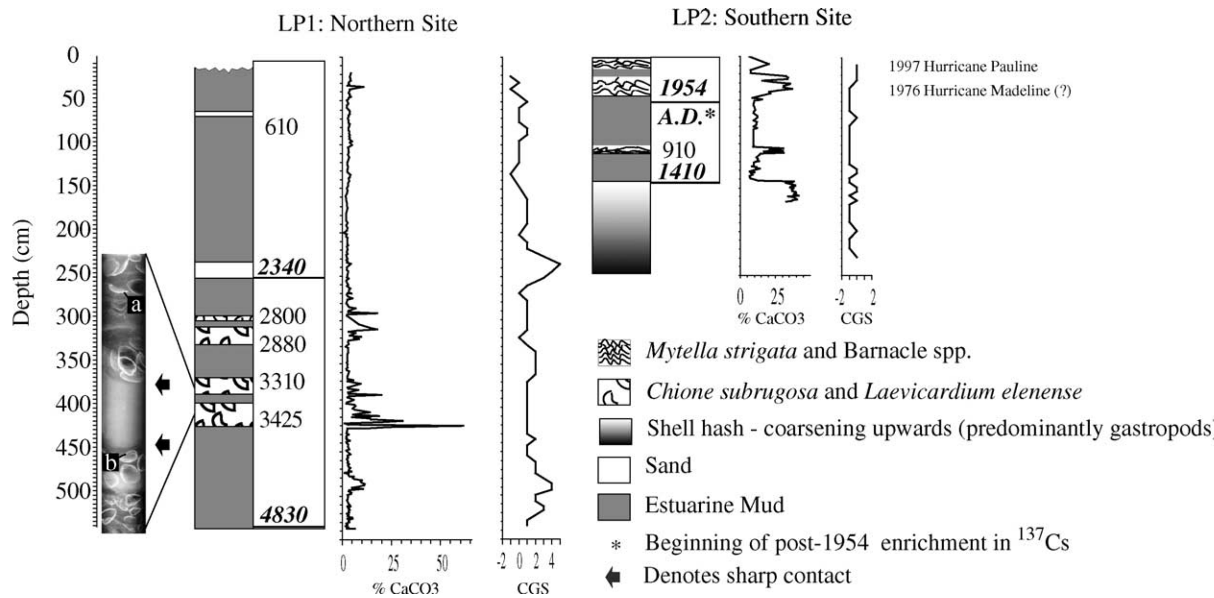

Figure 2. Laguna Pastoría core stratigraphy. Radiocarbon dates shown in bold italics, the remaining chronology is interpolated from those radiocarbon dates and ^{137}Cs Chronology. The X-radiograph shows two *Chione* mollusk beds (arrows indicate abrupt contacts) and an intervening bed of estuarine mud within the 3-m section of LP1. Note the varied orientation of the (a) disarticulated and (b) articulated mollusks within the mollusk beds and the absence of bioturbation and mollusks within the estuarine mud. The calcium carbonate signal derived from intensive LOI analysis shows the location and extent of the shell facies, while the magnetic susceptibility data from LP1 highlights the thick sand deposited at ~2340 cal yr B.P. Note that LOI analysis was not undertaken for the total length of the mixed mollusk hash at the base of LP2.

including mudflats, tidal flats, and shallow lagoons, and is commonly found attached to mangrove roots at Pastoría. Barnacles are typically upper intertidal dwellers, preferring to attach themselves to a firm substrate; this facies type is restricted to LP2. The *Chione* and *Mytella* facies are mutually exclusive, as *Chione* shells are not found in the *Mytella* beds and vice versa.

The mixed mollusk hash facies comprises one large bed (~1 m) at the base of LP2. This bed exhibits an upward coarsening sequence with unidentifiable compacted mollusk hash located in the basal materials; this then gradually grades into unidentified complete gastropod shells (2–20 mm), *Chione*, barnacles, and hash. Aigner (1985), working in Florida, also described upward coarsening molluskan assemblages, which he attributes to a shallowing trend in bay history.

The last facies type is composed of sand and is restricted to LP1. The two sand beds vary in thickness and grain size (0.5 and 18 cm thick). Figure 2 shows the magnetic susceptibility data, a strong peak is present between 231 and 249 cm at LP1 and marks the thickest sand deposit, because of limitations with the equipment's scanning range the second significantly thinner sand lens at 59.5–60 cm is not recognized. Sand content averages 47% and is dominated by fine- to medium-sized grains. The original deposition would have had higher sand composition but post-depositional infiltration of estuarine clays lowered the percentage value of sand.

Marked differences in biostratigraphy are found between LP1 and LP2 (Fig. 2). At LP1 prior to the deposition of the thick sand deposit, mollusk beds are characterized by *Chione* and *Laevicardium*, with the absence of *Mytella*. Following the deposition of the sand, no shell hash layers are found. However, lone shells of *Chione*, a razor clam, and small gastropods are found within the core. Indeed, the lithostratigraphy lacks any layering until a second sand deposit. At LP2, *Mytella* and barnacles characterize the shell beds with an absence of *Chione* and *Laevicardium*. We interpret the mud facies to represent the lowest energy conditions while the mollusk and sand facies reflect high-energy conditions.

We interpret the shell and sand beds at Laguna Pastoría to record storm surges associated with intense hurricane strikes (category 3 and higher). Davis et al. (1989) and Nichols et al. (1991) describe similar molluskan beds, which they also ascribe to hurricanes, while Liu and Fearn (1993, 2000), Donnelley et al. (2001a,b), and Bentley et al. (2002) describe hurricane-derived sand deposits in lagoon, estuarine, and salt marsh settings. A near surface *Mytella* (1–8 cm) facies in LP2 correlates with Hurricane Pauline, a category 4 hurricane, which hit the region in October 8th 1997.

Tsunamis generated by large earthquakes are known to produce sand layers in coastal deposits (e.g., Karlin and Abella, 1992; Atwater, 1987; Atwater and Yamaguchi, 1991; Nelson et al., 1996), which could be confused with storm deposits. The most recent tsunami hit nearby Puerto Escondido in November 1978. The maximum run up associated with this event was 1.5 m. Fourteen tsunami events have also been recorded to the south at Salina Cruz (200 km) since the 1950s, the run up ranged from 0.1 to 1.2 m.

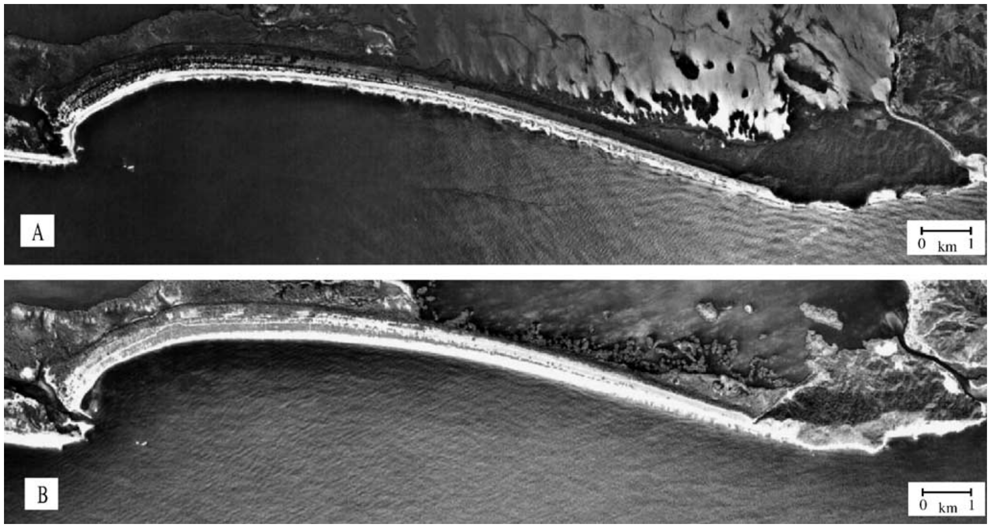

Figure 3. Photograph A shows the barrier that encloses Laguna Pastoría in November 1985 while photograph B shows the same view of the barrier in December 1999. Even though the most recent photo was taken 2 years after Hurricane Pauline, extensive washover fans are clearly visible when compared with the image of the barrier pre-Hurricane Pauline.

A tsunami with a reported run up of 4 m was also recorded for the Oaxacan coastline as a whole in 1787 (NGDC, 2003). Excepting the 1787 event, the run up for tsunamis has been low, <1–1.5 m, which would be insufficient to overwash the bay barrier complex (3–4 m). In contrast, the storm surge associated with Hurricane Pauline is estimated at 9 m at high tide, easily capable of overtopping the barrier. A comparison of aerial photographs, taken in 1985 (pre-Hurricane Pauline) and in December 1999 (post-Hurricane Pauline), shows extensive washover fans that extend into the back areas of the barrier and cover the dune and scrub vegetation. The barrier was not breached (Fig. 3). We therefore interpret the surficial shell hash layer in LP2 as attributable to Hurricane Pauline. Unfortunately, the top 14 cm of sediment from LP1 was lost during coring, this incorporates approximately the last 120 years of sedimentation and so near surface hurricane deposits between LP1 and LP2 cannot be correlated.

Bay to lagoon: a model of Holocene coastal evolution at Laguna Pastoría

The differences in the composition of the mollusk beds prior to and following 2340 cal yr B.P. are critical in understanding coastal geomorphologic evolution southeast of the mouth of the Río Verde. Our data indicate that the increased sediment load of the Río Verde documented by Joyce and Mueller (1997) and Mueller and Joyce (2002) dramatically affected coastal morphology. The mollusk stratigraphy and radiocarbon dating from Laguna Pastoría indicate that changes in coastal morphology did occur and were coeval with the latest documented changes on the floodplain.

Prior to approximately 2340 years ago Pastoría was a bay open to the Pacific Ocean (Fig. 1C). The storm surge associated with large storms (hurricanes) was pushed and focused into the bay. The surge carried shells of *Laevicardium*, a species that lives offshore in deeper water, into the bay where they were mixed with the locally growing *Chione* species. The last *Chione* deposit is dated by extrapolation to 2800 cal yr B.P., while an A.M.S. date immediately below the thick sand deposit from LP1 dates to 2340 cal yr B.P. This is the first appearance of a large amount of sand within the core; prior to this the sediment matrix was essentially devoid of siliceous sand sized material. The abrupt appearance of sand within the core at this time suggests the presence and accessibility of a local sand source within the system that was previously absent. These data indicate that the barrier must have formed at some time between 2800 and 2340 cal yr B.P.

The sand must have come from the newly formed bay barrier, which most likely formed with sediment that was eroded from the highland valleys of Oaxaca. The eroded sand from the highlands was carried south by the Río Verde towards the Pacific. While a large proportion of the rivers new sediment load was deposited on the floodplain of the lower Río Verde resulting in the significant changes in channel morphology (Joyce and Mueller, 1997; Mueller and Joyce, 2002), large quantities would have reached the mouth of the river. Sediment discharged from the river into the Pacific Ocean was carried east by longshore currents and deposited along the coast, resulting in the formation of a bay barrier and the development of lagoons through the enclosure of previously open bays (Cooper, 1994). The timing of the bay barrier formation and the Río Verde floodplain changes is coeval.

Analysis of air photos confirms that sediment flows into the Pacific and then trails southeast along the shoreline reflecting the longshore current (Fig. 1D). Small and large rocky outcrops located along the Chacahua/Pastoría shoreline, such as Punta Galera and El Hermoso, may have provided focal points for initial sand deposition at the time of bay barrier formation, as they are currently incorporated within the barrier complex (Figs. 1A and B). The absence of a well-defined river delta at the Río Verde's mouth (Fig. 1D) further attests to the presence of strong waves and longshore currents. It is unlikely that the Chacalapa or the Río San Francisco contributes a significant amount of coarse sediment to the lagoon even during high discharge events. The Río San Francisco flows into Laguna Palmarito (~1.5 km long), prior to entering Laguna Pastoría, and thus acts as a sediment trap; while the Chacalapa is an intermittent stream with its sediment load dominated by fine silts and clays (González and Rodráguez, 2002). The timing of the formation of the barrier island corresponds in time with the increase in sediment load, channel, and floodplain changes of the Río Verde that were triggered by highland erosion. These data indicate that anthropogenic-induced landscape change and the ensuing erosion in the highland valleys had dramatic effects on landscapes and peoples at significant distances downstream.

Following the formation of the barrier, the northerly portions of the lagoon, in the area of LP1, were protected from storm energy such that no coarse shell beds are found; instead, sand from the barrier island complex was transported into the back reaches during intense hurricane events. Prior to barrier island formation, no significant quantities of sand were found within the core, neither were shells of *Mytella* and barnacles, indicating that suitable habit zones for these species were not present. Once the barrier had formed, mangroves were able to colonize the calmer body of water immediately behind the barrier; islands formed possibly in areas with a shallower bathymetry. *Mytella* and barnacles live on the prop roots within the mangrove islands; however, during a hurricane, these mollusks are removed by surge water and deposited onto the underlying sediment.

Discussion

Geomorphic change

The change in fluvial morphology attributed to anthropogenic-induced erosion episodes in the highlands of Oaxaca (Joyce, 2002; Joyce and Mueller, 1997) increased the sediment load of the Río Verde such that it significantly affected coastal morphology. Sediment discharged from the river into the Pacific Ocean was carried east by longshore currents and deposited along the coast forming the bay barrier and the back-barrier lagoons. Our data suggest that the barrier had formed about 2500 cal yr B.P. Archaeological excavations at the site of Barra Quebrada demonstrate that the barrier island was in place by the early Terminal Formative Period (2065–1820 cal yr B.P.; Joyce, 1991a). Stratigraphic data from Barra Quebrada show that the early Terminal Formative occupation was in a setting that was periodically inundated, which indicates that the bay barrier was still forming at this time. No known archaeological sites dating to an earlier period than this are present on the barrier.

The core stratigraphy from LP2 (*Mytella* facies) also supports the hypothesis of a bay to lagoon evolution; sediments in the LP2 core are younger than the thick sand deposit from LP1, which we interpret as representing the initial formation of the bay barrier that closed off the bay. Subtidal and mudflat mollusks are not found within the storm facies at LP2, rather mollusks that prefer upper tidal conditions are found. This suggests that while hurricanes have struck the region in the past 1500 years, the barrier has served to dissipate the impact of the storm surge into the immediate back barrier region, effectively preventing the transport of marine mollusks (i.e., *Laevicardium*) into the lagoon and also protecting the subtidally living *Chione*. Instead, storm surges that breach the barrier remove mollusks living in the high tide zone and possibly cause localized sediment remobilization behind the barrier (González and Rodráguez, 2002).

Implications for regional archaeological sequence

The hypothesized changes in coastal geomorphology have important implications for understanding the regional archaeological sequence. Bay barrier formation caused a change in coastal morphology from an open bay to an enclosed back-barrier estuary. Estuaries are among the most productive ecosystems in the world (Voorhies, 2004) and are an important resource for people in the lower Verde region today (Alfaro and Sánchez, 2002). Archaeological and ethnohistoric data show that pre-Hispanic populations exploited the estuaries for key resources such as fish, shellfish, waterfowl, salt, and ornamental shell (Fernandez, 2004; Joyce, 1991a,b).

Given the high-energy wave environment along the Oaxacan Coast, it is possible that exploitation of marine resources would have been difficult until the estuaries formed. Indeed, La Consentida, the only excavated site in the region with primary deposits dating to the Early Formative (4120–2755 cal yr B.P.), yielded almost no remains of marine or estuarine resources despite the fact that it is located only 1.5 km north of the current estuarine system (Winter, personal communication; Fig. 1). Paleozoological studies of Late Formative (2350–2065 cal yr B.P.) deposits from excavated sites in the floodplain show that estuarine species were intensively exploited by this time, while open-ocean species were exploited infrequently (Fernandez, 2004; Joyce, 1991b). Paleozoological data suggest that the proportion of brackish water shell fish in the diet increased from the Middle Formative (2755–2350 cal yr B.P.) to the Early Classic Period (1620–1330 cal yr B.P.) (Fernandez, 2004), which is consistent with our model of lagoon formation. Human bone chemistry and paleozoological studies further indicate that during the Early Classic Period (1620–1330 cal yr B.P.) people at the site of Barra Quebrada on the barrier were consuming significant quantities of marine/estuarine resources (Joyce, 1991b; Fig. 1). Estuarine resources such as fish, shellfish, and waterfowl are highly productive and would have provided one of the few sources of animal protein in the region. Salt rendered from the salt flats (infilled estuaries) adjacent to the estuaries was also a critical resource that was exported to interior populations at the time of the Spanish conquest.

Settlement research in the lower Verde indicates a major demographic expansion following the environmental changes of the Early Formative (Joyce 2002, 2003; Workinger, 2002). Results of a regional full-coverage survey and excavation program indicate little settlement in the region prior to the Middle Formative (2755–2350 cal yr B.P.). From the Middle Formative until the end of the formative at ca. 1620 cal yr B.P., however, population as measured by the occupational area in the full-coverage survey increased greatly (Table 2). The creation of productive estuarine environments and the expansion of the agriculturally productive floodplain would have made the region more attractive to human settlement and are possible causal factors (among others) in regional population growth (Joyce and Mueller, 1992, 1997).

Another possible explanation for the small number of early sites is that floodplain aggradation and the marine transgression could have obscured or destroyed Archaic and Early Formative Period sites. Archaeological and sedimentological testing in the floodplain, however, indicate that earlier sites are not buried beneath later occupations. Deep tests have been excavated to sterile deposits at ten floodplain sites and with the exception of some redeposited Early Formative sherds at Charco Redondo, all occupations begin in the Middle Formative or later. The two other Early Formative sites in the region consist of low artificial mounds located on the coastal plain north of the estuaries. The sedimentological sampling program has excavated auger cores and test pits in “nonsite” contexts throughout the floodplain without locating buried sites. While sea-level rise could have destroyed early sites, this does not seem to be the case in other Pacific coastal regions of Mesoamerica, which have preserved some of the highest densities of Early Formative and Archaic Period sites in Mesoamerica (Brush 1969; Clark 2004; Voorhies 2004; Zeitlin, 1979). We argue that our settlement data indicate a significant increase in population beginning in the Middle Formative Period.

Table 2
Lower Río Verde Valley settlement data

Period	Uncalibrated age range (^{14}C yr B.P.)[a]	Calibrated age range (cal B.P.)	Occupational area (ha)
Early Formative	3750–2650	4120–2755	5
Middle Formative	2650–2350	2755–2350	64
Late Formative	2350–2100	2350–2065	299
Early Terminal Formative	2100–1850	2065–1820	446
Late Terminal Formative	1850–1700	1820–1620	699
Early Classic	1700–1450	1620–1330	807
Late Classic	1450–1150	1330–1060	605
Early Postclassic	1150–850	1060–740	452
Late Postclassic	850–428	740–505	2317

[a] These dates are uncalibrated and are the age ranges traditionally used by Oaxacan archaeologists. Archaeological dates used in the text are converted to calibrated ages using Calib 4.3 (Stuiver and Reimer, 1993, 2000).

Mid–late Holocene hurricane activity caused by increased El Niño frequencies?

Although the cores from coastal Oaxaca represent a preliminary archive of prehistoric hurricane strikes for the region, albeit complicated by the formation of the barrier island, the data from Laguna Pastoría suggest that the period between 3500 and 2300 cal yr B.P. saw more hurricane activity. Approximately 1 hurricane occurred every 240 years in contrast to the most recent period, which experienced 1 per 460 years.

Historic records indicate that in general there are more hurricanes in the eastern Pacific, unlike the Atlantic basin, during El Niño events, as changed wind patterns reduce wind shear in the atmosphere which favors storm formation (Philander, 1989). High-resolution analyses of sediment cores from Equador, the Galápagos Islands, and the Venezuelan coast have determined peak El Niño conditions during the mid–late Holocene. Rodbell et al. (1999) linked inorganic laminae within a sediment core from an alpine lake, Laguna Pallcacocha, in the southern Ecuadorian Andes with El Niño induced storm events. They determined a peak in El Niño frequencies between ~3500 and 2600 cal yr B.P. Riedinger et al. (2002) looked at the frequency of carbonate and siliciclastic laminae in a sediment core from hypersaline Bainbridge Crater Lake in the Galápagos Islands. They ascribe the laminae to El Niño activity and suggest that the frequency and intensity of El Niño events increased at about 3100 cal yr B.P. Haug et al. (2001) working with a core from the Cariaco Basin, off the Venezuelan coast, determined high amplitude fluctuations in iron and titanium levels between 3800 and 2800 cal yr B.P., which they postulate was caused by a southward migration of the Intertropical Convergence Zone, which may have enhanced El Niño conditions. Analysis of mollusk remains from archaeological sites on the central and north coasts of Peru also indicate an increase in El Niño frequency between 3200 and 2800 cal yr B.P., which is correlated with the abandonment of monumental temples in the same region (Sandweiss et al., 2001). These data indicate an increase in intensity and frequency of El Niño conditions between 2500 and 3500 yr ago, which is contemporaneous with the hurricane storm deposit record from Laguna Pastoría; this suggests that the increase in storm strikes was driven by more frequent El Niño conditions.

Conclusion

Our research differs from previous studies of pre-Hispanic Mesoamerican landscape change in that it takes a macro-regional perspective by examining the effects of erosion in the upper drainage basin of the Verde on environments and people in the lower valley more than 150 linear kilometers downstream. Early Formative erosion in the highland valleys, probably triggered by human impact, had complex effects on people and environments along the entire drainage basin. In the highlands, people responded to erosion through the use of soil conservation techniques, especially terracing (Balkansky et al., 2000; Spores, 1969). In the lower valley, however, sediments carried down the river from the highlands triggered major changes in floodplain and coastal geomorphology. The lower Río Verde shifted from a meandering to a braided pattern and alluviation forced floodplain expansion. Sediment carried down the river from the highlands to the coast also contributed to the formation of bay barriers and back barrier estuaries. The environmental changes in the coastal region probably had a largely positive effect on the productivity of agriculture and on estuarine resources used by human populations. The increasing productivity of these resources may have contributed to the demographic expansion in the lower Verde after 2755 cal yr B.P.

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