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DEPOSITIONAL HISTORY AND DIAGENESIS OF A HOLOCENE STRAND PLAIN, SANDY HOOK, SAN SALVADOR, BAHAMAS

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ABSTRACT

A model for the depositional history of a Holocene strand plain, Sandy Hook, San Salvador, Bahamas, is proposed based on data from sedimentologic, petrologic, and geophysical studies. Sandy Hook is comprised of carbonate sediments that have accumulated as a series of beach and dune deposits over the past few thousand years. A beachrock origin is proposed for zones of cemented sediments found at depths of less than 2 m across the strand plain. The evolution of Sandy Hook is linked to the origin, growth, and development of the adjacent lagoon and early Holocene dune deposits.

INTRODUCTION

Modern carbonate sand accumulations have been studied for several decades in the Bahamas because of their potential as analogs for ancient petroleum reservoir rocks. Much of the research has concentrated on eolian dune deposits and subtidal and intertidal sand shoals. Less is known about modern beach/strand plain systems which form by a combination of both marine and eolian deposition. Strand plains are relatively common in the Bahamas (Lind, 1969; Harris, 1979; Gerhardt, 1983; Garrett and Gould, 1984; Strasser and Davaud, 1986; Wallis et al., 1991); however, there is much to learn about vertical and lateral gradients of composition, texture, structures, porosity development, and diagenesis for these environments.

Carbonate strand plain deposits can be reservoir rocks for hydrocarbons (Stricklin and Smith, 1973; Baker and Scott, 1985). These deposits are productive because of enhanced porosity by micritization of skeletal fragments and by the development of moldic porosity. Unfortunately, criteria for recognition of strand plains in the ancient are poorly understood because of the lack of detailed work on modern examples.

Strand plains develop along wave-dominated shorelines where sediments are deposited in beach (foreshore and backshore) and dune environments. A strand plain is a wide beach-ridge system of multiple parallel beach ridges and swales which form by progradation of the shoreline. For this study the beach/strand plain system of Sandy Hook, San Salvador, Bahamas, was examined to determine its boundaries, heterogeneities, and diagenetic gradients. An integrated study including sedimentologic, petrologic, hydrologic, and geophysical techniques was conducted over a period of several years.

Sandy Hook is a Holocene strand plain (1.5 by 1.5 km) located on the southeastern margin of San Salvador, Bahamas. The strand plain system consists of beach/dune ridges (approximately 35) which have prograded to the east and which are arranged in several packages with distinct orientations (Fig. 1). An active beach and dunes are present and are partially cemented and eroded. Beachrock is exposed along the beach especially in the winter and grades landward into cemented dunes.

Sandy Hook is bounded by a Pleistocene limestone ridge to the north and a tidal channel/restricted lagoon (Pigeon Creek) to the west. Eastward of the

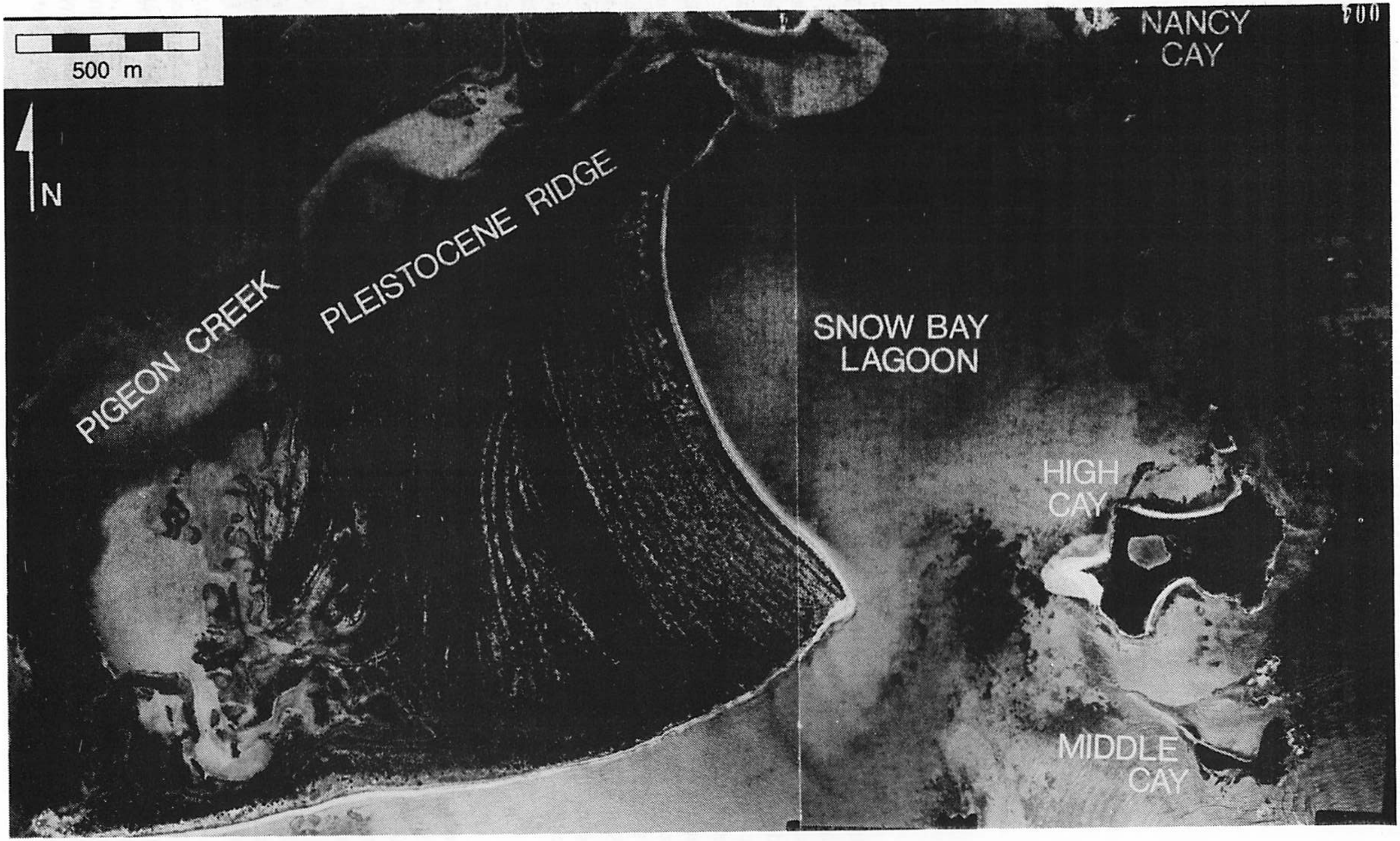


Fig. 1. In this high-altitude air photo, the low, arcuate beach ridges of Sandy Hook are clearly seen because of differences in vegetation between the crests and troughs of the ridges (1970; 1:10,000). Several different orientations of ridges are present and probably represent different intervals of deposition and erosion caused by varying wave climate.

strand plain are a sandy lagoon (Snow Bay) and eolian Holocene dunes (Nancy Cay, High Cay, Middle and Low Cays). High Cay is recognized by many historians as the first land sighted by Christopher Columbus in the new world. Sandy Hook is thought to be underlain by Pleistocene rocks.

METHODS AND RESULTS

The composition and structure of the Sandy Hook strand plain was investigated using a number of techniques. Seismic refraction and reflection surveys were performed over a portion of the strand plain. Refraction indicated a depth to bedrock of 6.5 to 10.5 m (Van Koughnet, 1992). A resistivity survey was also conducted. Results were very similar to those of Kunze and Weir (1987). A thin, discontinuous fresh-water lens was found.

A modified rotary drill was used to extract cores of the unconsolidated and partially consolidated sediments at four sites on the strand plain (Fig. 2). Cores were recovered to a depth of 2.5 m. Two pits were dug to examine sedimentary structures and insure in-place sampling. The pits were 3 by 3 m and 2.5 m in depth. Two zones of partially cemented sediments were encountered in cores and pits at sites B, C, and D. These cemented zones are bedded, range in thickness from 20 to 50 cm, have a sharp lower boundary and a gradational upper boundary, and dip seaward at angles similar to present-day beaches (approximately 9 degrees).

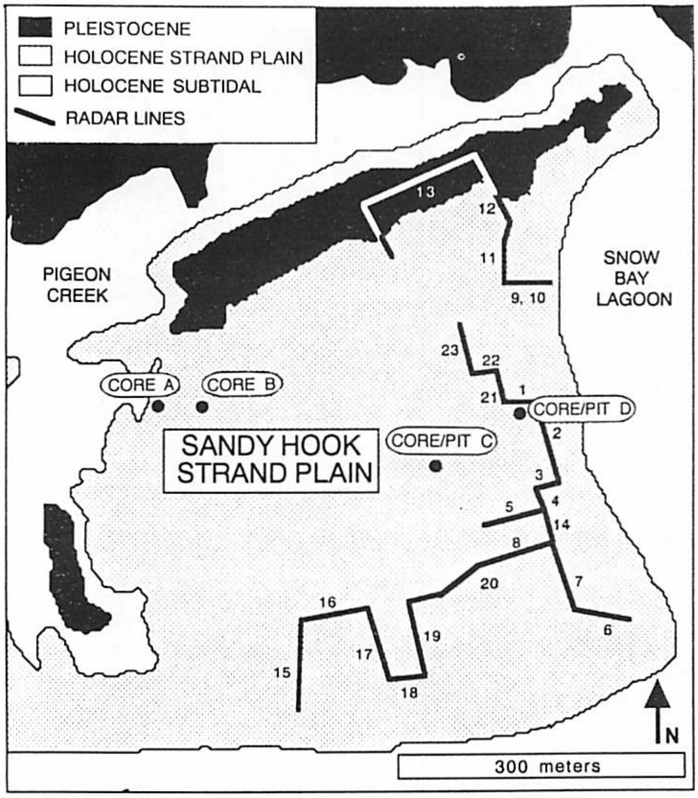


Fig. 2. Location of core and pit sites and ground-penetrating radar lines. GPR traverses are oriented parallel and perpendicular to the ridges.

Megascopic and microscopic examination of core and pit samples have shown that the sediments of Sandy Hook are fine to medium-sized carbonate sands comprised of peloids, rounded and abraded skeletal grains including molluscs and green algae, ooids, and aggregates (Kim, 1991; Figs. 3 and 4A).

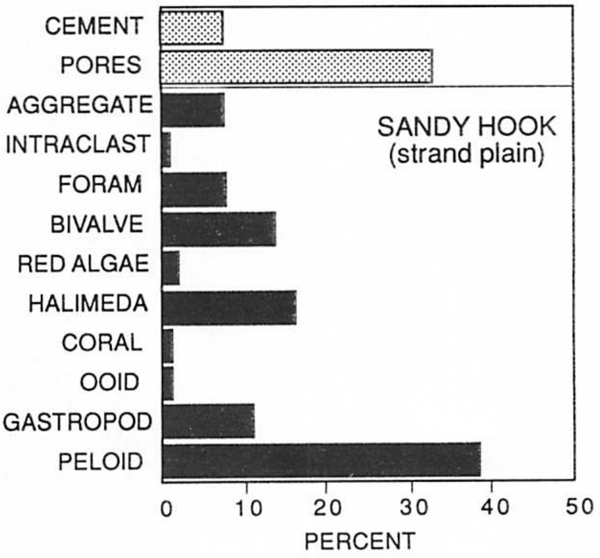


Fig. 3. Petrographic examination of samples from Sandy Hook reveals an abundance of peloids and skeletal grains. In this figure, the total percentage of grains adds up to 100%; the percent cement and pores are percent of the whole sample.

Cemented zones occur at depths between 1.5 and 2.0 m below the surface. Compositional and textural differences were not noted between unconsolidated and cemented sands. The grain-contact and rim cements are patchily distributed and occur as subhedral to euhedral, equant, blocky, calcite. Trace element and mineralogical analyses indicate that the cements are composed of blocky low-Mg calcite of a meteoric origin (Stoyka, 1992).

A ground-penetrating-radar (GPR) survey was performed across Sandy Hook primarily to determine

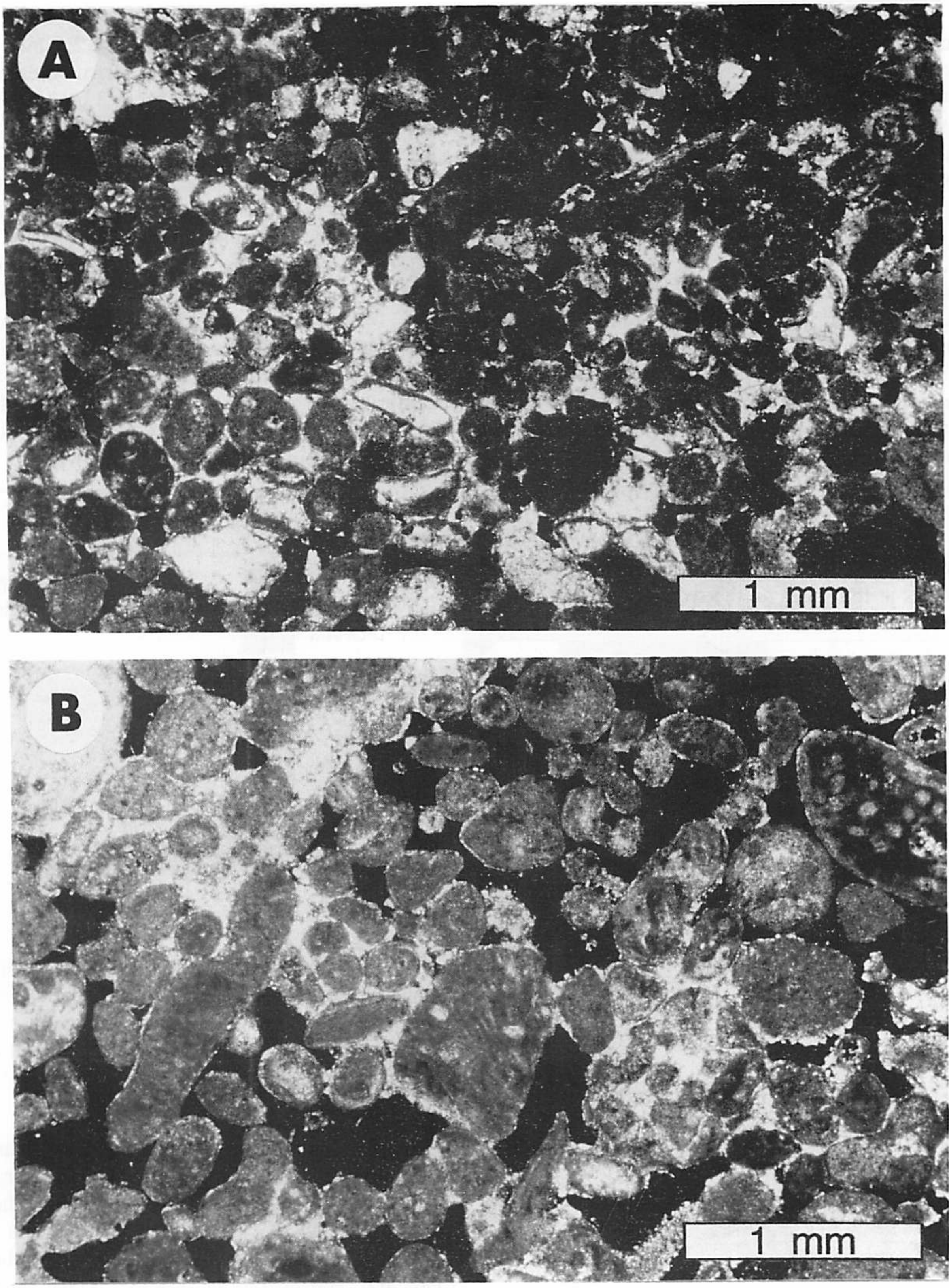
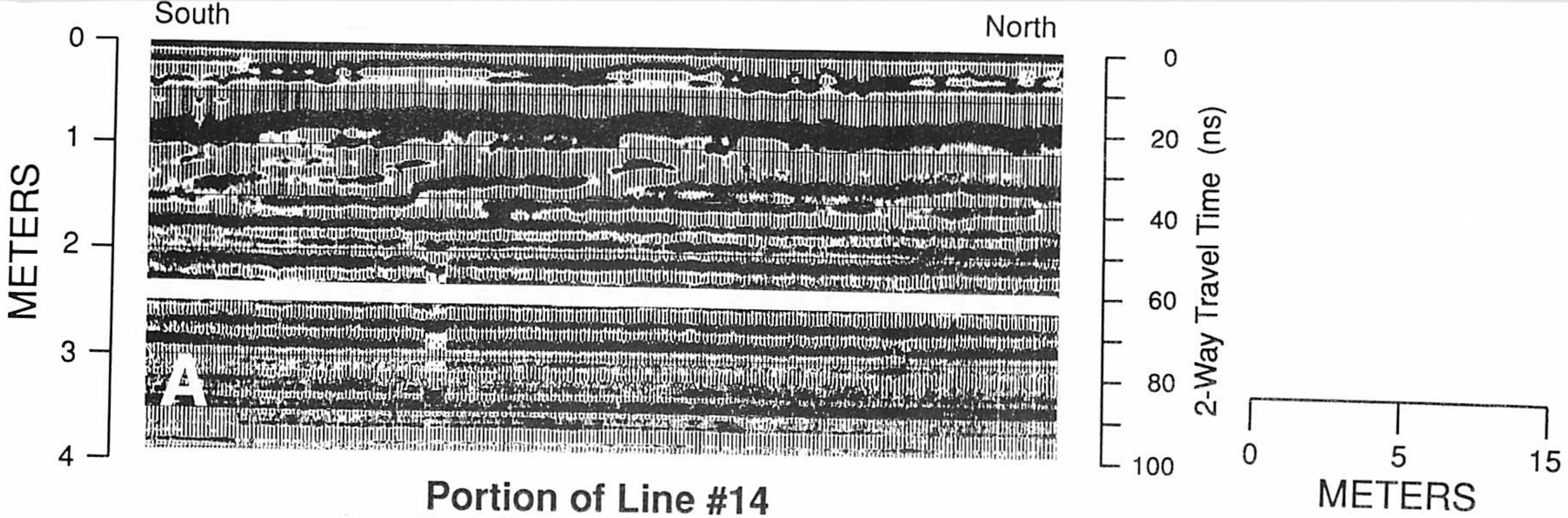
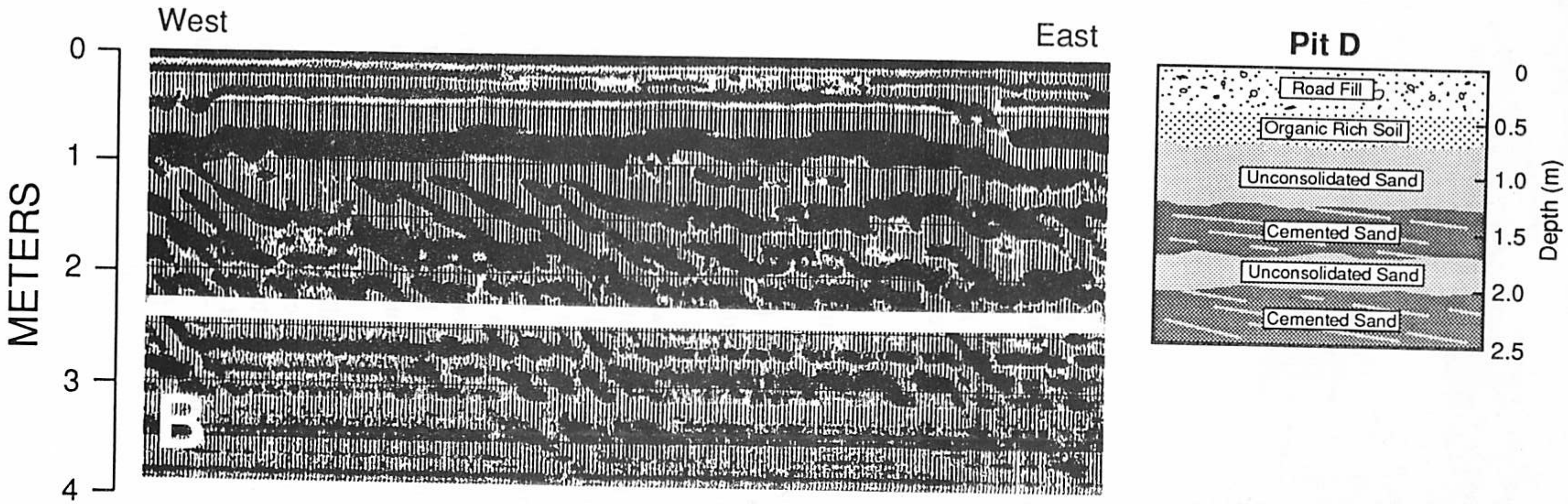


Fig. 4. A. Photomicrograph of partially cemented zone in Sandy Hook sediments. Blocky, low-Mg calcite is found at grain contacts and as rim cements. B. Photomicrograph of beachrock with blocky fresh-water cements like those from Sandy Hook cemented zones (from upper portion of beachrock at Bonefish Bay near the Old World Museum).



Portion of Line #14
Parallel to Shoreline



Portion of Line #8
Perpendicular to Shoreline

Fig. 5. A. Ground-penetrating-radar-trace from transect 14, taken parallel to the shoreline and containing only flat reflectors. B. Ground-penetrating-radar-trace from transect 8, taken perpendicular to the shoreline and showing reflectors dipping seaward. A schematic of Pit D is shown for comparison. Pit D was dug to a depth of 2.5 m, cemented zones are found at depths of 1.3 and 2.0 m. White lines in both A and B indicate approximate location of the water table. Note change in apparent dip of reflectors below water table in B.

Fig. 6. Slabs of beachrock dipping seaward into Bonefish Bay. The dip angle of the beachrock is similar to the dip angle of the ground-penetrating-radar-reflectors. Portions of the beachrock are nearly always bathed in marine water; the upper portion of the slabs are commonly exposed to meteoric waters. This difference may explain the difference in cementation.

the lateral and vertical extent and origin of the cemented layers recognized in the pits and cores (Fig. 2). Twenty-three traverses (a total of 1.6 km) were made at a variety of orientations relative to the beach ridges. The majority of the traverses were either parallel or perpendicular to the beach ridges. Traverses followed a system of roads built for a now defunct real estate development. The data were of good quality. Maximum depth of penetration was about 4 m.

The water table was located by GPR and is recognized by a change in apparent dip of the reflectors as the water causes a velocity decrease (Fig. 5). Depths to the water table ranged from 1.5 to 2.5 m and are in agreement with the resistivity survey and observations in the pits. The survey also revealed a series of horizontal reflectors on transects parallel to the shoreline (Fig. 5A) and a series of strong reflectors dipping seaward on transects perpendicular to the shoreline (Fig. 5B). Reflectors were located at depths of 1.5 - 3.0 m and occur at 0.5 m intervals. These reflectors have the same orientations, dip angles (6 to 9 degrees), and depths as the cemented layers revealed in cores and pits. These reflectors are thought to indicate the presence of the cemented layers over most of Sandy Hook. Apparently, the permittivity contrast between unconsolidated and cemented carbonate sand is strong enough to produce the radar reflections.

One possible explanation for these reflectors is that they are slabs of buried beachrock (Stoyka, 1992; Stoyka et al., 1992). Beachrock is formed as sediment is cemented in intertidal and spray zones along tropical shorelines (Fig. 6). The beachrock generally dips at the same angle as the beach it is forming on (5 to 15 degrees seaward).

Beachrock is typically cemented by a fringe of fibrous aragonite or micritic high-Mg calcite (Bathurst, 1975). Beachrock cements are thought to form under a thin cover of sediment and to originate by processes associated with the intertidal (beach) zone (e.g. evaporation of seawater, CO2 degassing of fresh meteoric waters, mixing of freshwater and seawater).

A beachrock origin would satisfactorily account for the GPR results, but the blocky calcite cements of the cemented zones are not what is typically expected for beachrock cements. The cements of Sandy Hook are more typical of fresh-water, meteoric cements. However, cements with this mineralogy and morphology can be present in the upper intertidal zone of beaches (Illing, 1954; Bathurst, 1975; Bain, 1989). Samples of beachrock were obtained along transects at two localities on San Salvador (Graham's Harbour and Bonefish Bay) for comparison with the cemented zones of Sandy Hook. Petrologic examination revealed that sediments lowest on the beach were cemented by fibrous aragonite (Fig. 7), and those highest on the beach were cemented by blocky calcite (Fig. 4B).

This evidence, along with the occurrence of the cemented layers in a Holocene prograding strand plain and the orientation of the cemented layers as observed through the ground penetrating radar survey and backed up by field examination in the pits, indicates that a beachrock interpretation for the cemented zones at Sandy Hook cannot be ruled out. Of course, it is also possible that sediments deposited as a beach were later exposed to meteoric conditions and cemented as

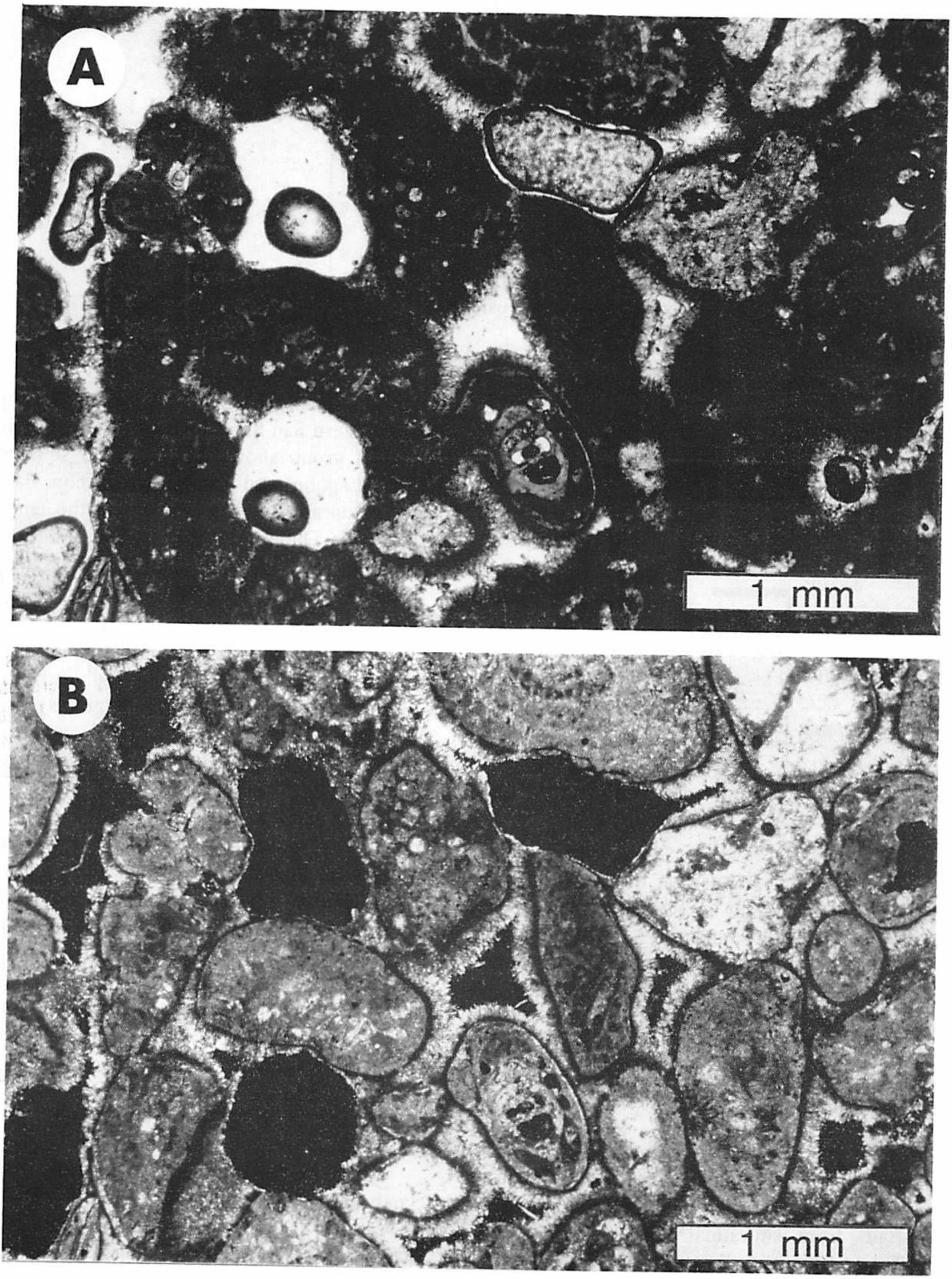


Fig. 7. Photomicrograph of typical beachrock with fibrous aragonite cement (from lower portion of beachrock at Bonefish Bay). A. Plane-polarized light. B. Crossed Nicols.

the beach system prograded seaward. The top of the fresh-water lens is presently near the level of these layers (i.e., at sea level), and cementation may be continuing today.

COMPARISON TO ADJACENT ENVIRONMENTS

A petrologic comparison of sediments and rocks from Snow Bay, Sandy Hook, and the Holocene dunes shows that there are only subtle differences in grain composition among these environments of deposition (Fig. 8).

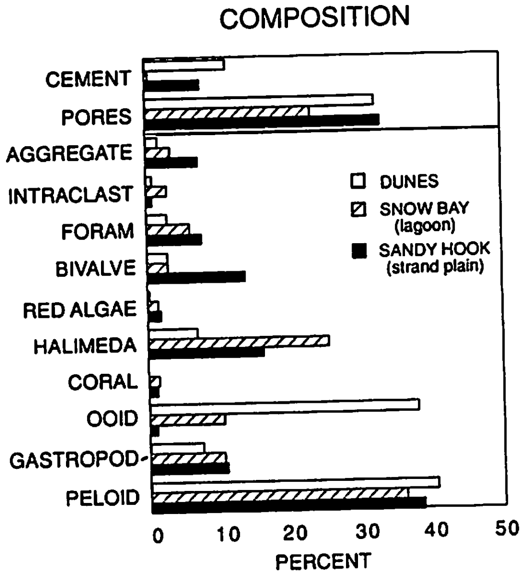


Fig. 8. The grain composition of sand units from southeastern San Salvador are similar. The sediments are dominated by peloids, and only slight differences in grain composition exist. Ooids are abundant only in the Holocene dunes (e.g. High Cay, Nancy Cay). As expected, Halimeda is most abundant in the lagoonal samples of Snow Bay. In this figure, the total percentage of grains adds up to 100%; while the percentage of cement and pores are percent of the whole sample.

Mean grain size and sorting values are different and can be used to distinguish subtidal (Pigeon Creek, Snow Bay) from supratidal (Holocene dunes and surficial strand plain) sediments (Fig. 9); however, a gradation of values exist and it is likely that if these sediments were preserved, they would be interpreted as one large undifferentiated carbonate sand body (Boardman et al., 1991; Kim, 1991).

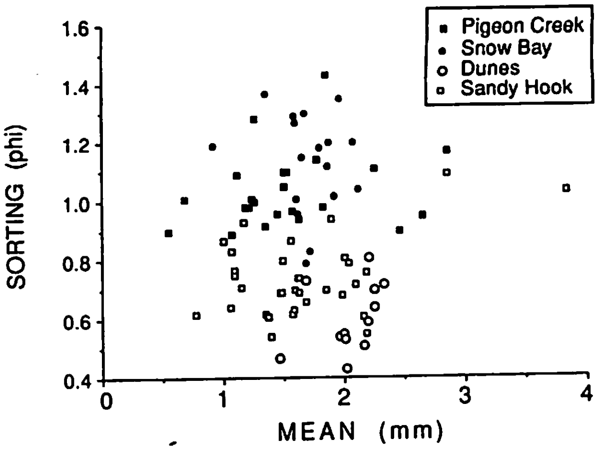


Fig. 9. Mean grain size and sorting of samples from southeastern San Salvador segregate themselves into a subtidal group shown by the filled squares (Pigeon Creek Lagoon) and filled circles (Snow Bay Lagoon) and a supratidal group shown by the empty circles (Holocene Dunes) and empty squares (Sandy Hook Strand Plain). The supratidal sediments are generally better sorted than the subtidal sediments.

All of the environments contain ooids. The early Holocene dunes have the highest percentage of ooids (approximately 40% of total grains). In both the subtidal and strand-plain sediments an upward-decreasing concentration of ooids is seen (Fig. 10).

In addition, oolitic clasts cemented by fresh-water cements are present in sediments from Snow Bay and Sandy Hook. Apparently, an ooid-generating event occurred early in the Holocene and dunes were created (e.g., High Cay which is composed of oolitic sediment cemented by fresh-water cement). Clasts of dune material found in subtidal and strand-plain sediments indicate that transport and mixing has occurred among the environments.

DEPOSITIONAL HISTORY

A model for the depositional history of the Sandy Hook area and its relation to the Holocene rise of sea level is shown in figures 11 and 12. Approximately 6,000 years ago, ooid-rich sediments were formed as the sea transgressed over the Pleistocene shelf. Ooids and bioclastic grains were blown into high eolian dunes located offshore from Sandy Hook such as High Cay and Nancy Cay. As sea level continued to

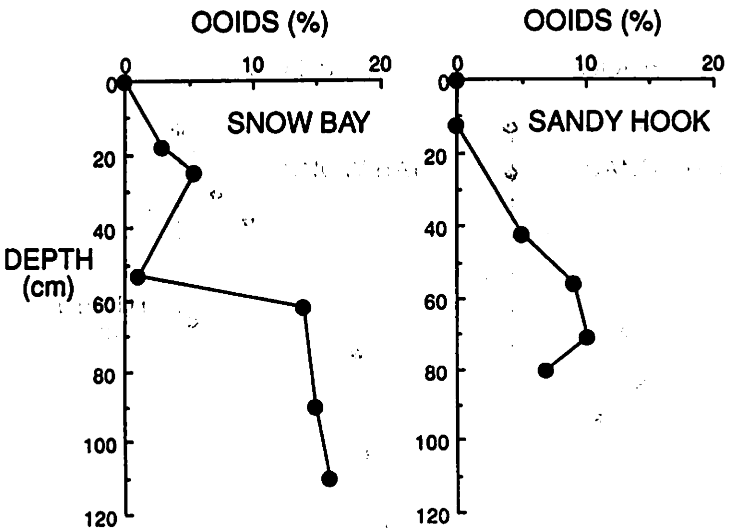


Fig. 10. In both Sandy Hook and Snow Bay sediments there is a slight increase in the proportion of ooids with core depth.

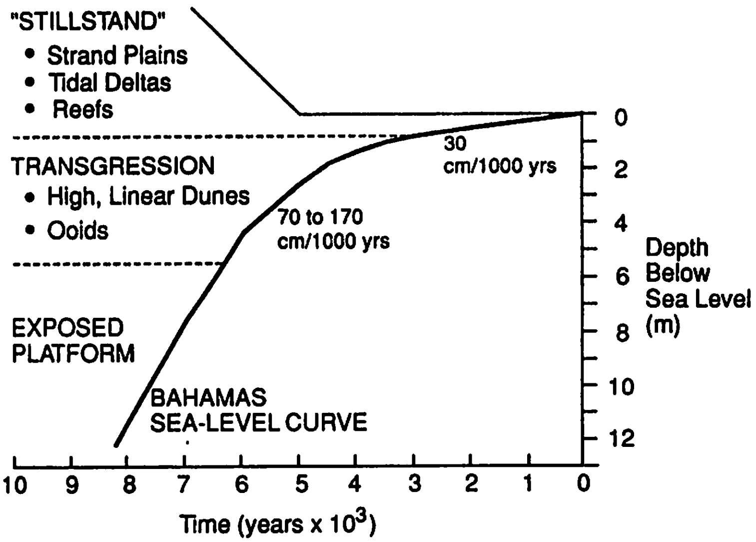


Fig. 11. Sea-level curve for the Bahamas (after Boardman et al., 1989) showing relative changes in rate of sea level rise through time and sequence of development for southeastern San Salvador.

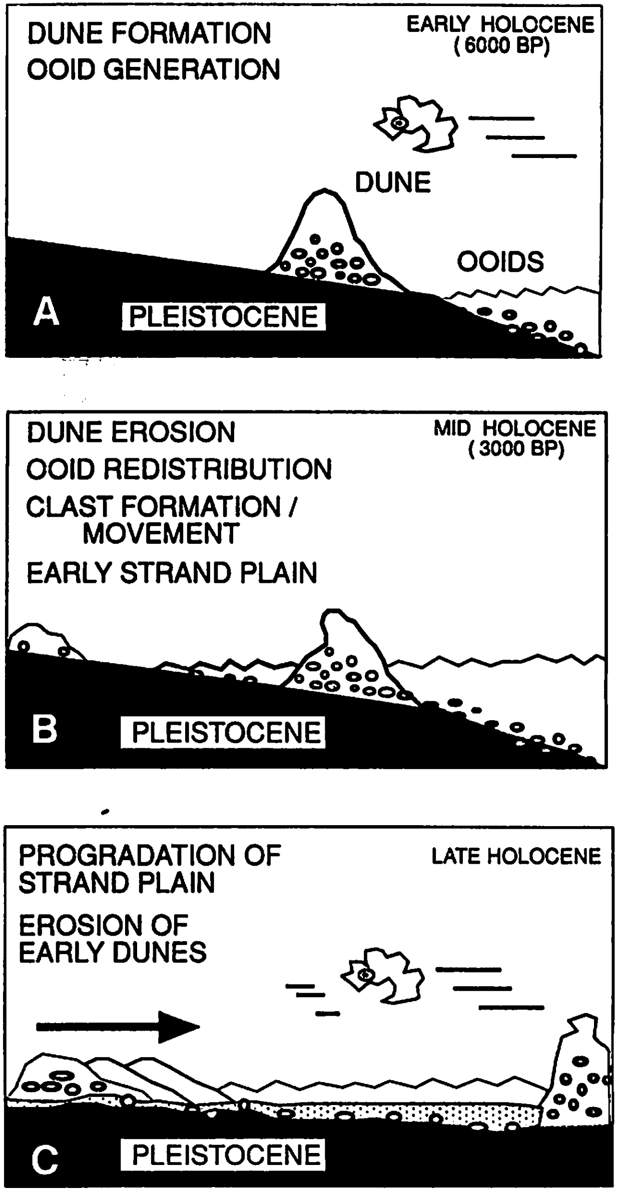


Fig. 12. The evolution of Sandy Hook is linked to the origin, growth, and decay of the early Holocene dunes and Snow Bay lagoon. A. An early Holocene episode of ooid generation and dune formation was followed by B. "drowning" of the dune and jumping of the shoreline to a position farther inland. Erosion of the early-formed dunes contributed an ooid-rich sediment to the lagoon and newly formed beach ridge. C. As the rate of sea level slowed, beach ridges were stranded as the shoreline prograded. Earlier formed sediment from the lagoon and from the early Holocene dunes were mixed with contemporary sandy sediments.

rise, the area behind the dunes was flooded forming a lagoon (Snow Bay) and coastal beaches (earliest Sandy Hook beaches). Ooid production either ceased or was overwhelmed by skeletal production of the lagoon. Erosion of the high dunes began, mixing ooids and oolitic clasts into lagoonal sediments. The rate of sea-level rise slowed 3,000 years ago, and the Sandy Hook strand-plain system began to prograde. This progradation has resulted in the formation of the series of beach/dune ridges that are observed today. Beach sands were cemented as beachrock along previously active shorelines that were buried during progradation. Progradation may have been greatest during major storms and each beach/dune ridge may be the result of a single storm event (35 storms in 3000 years = 1 storm/86 years). Large storms may also be responsible for the changes in orientation of the ridges across Sandy Hook.

CONCLUSION

Sandy Hook is a Holocene strand plain that has developed during the past few thousand years on the southeastern margin of San Salvador. Sediments from cores and pits on Sandy Hook are comprised of unconsolidated peloidal, skeletal, and oolitic carbonate sands in the upper 1.5 m underlain by cemented or partially cemented sands of similar composition down to 2.5 m. The cemented layers have been located across Sandy Hook using ground-penetrating-radar. The layers dip at the same angle as present-day beaches and are interpreted as slabs of buried beachrock. The depositional history of Sandy Hook is tied to the nearby lagoon and offshore early Holocene dunes. Mixing of sediments among the dunes, lagoon, and strand plain is indicated by compositional and textural similarities. Progradation of Sandy Hook has produced the series of beach/dune ridges that comprise the modern strand-plain system. Additional diagenetic studies of this Holocene strand plain may provide information useful for exploration of ancient strand-plain systems.

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