Quantified rates of geomorphic change on a modern carbonate tidal flat, Bahamas

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ABSTRACT

Comparison of aerial photographs and ultrahigh-resolution remote sensing data reveals changes in the geomorphology of a modern carbonate tidal flat. In the 58 yr between acquisition of the two data sets, several tidal channels have extended headward more than 100 m, channel bars have stabilized, the shoreline has eroded as much as 50 m, the inland algal marsh locally has prograded as much as 90 m, and many mangrove ponds have increased in size. These changes over the known time interval allow quantification of the rates of these geomorphic processes and suggest rates of migration of landforms to several meters per year. Some observed rates appear to be different than rates averaged over the past several thousand years, however, possibly because of changes in storm activity or circulation patterns. These data illustrate the dynamic nature of the entire coastal tidal-flat system, not just the shoreline, and reflect the system's response to factors including relative rises in sea level.

Keywords: Andros Island, remote sensing, sea level, sediments, carbonate, tidal flat, coastal.

INTRODUCTION

Tidal flats are complex environments. Because they include environments restricted to between mean low and high (spring and storm) tide, very small changes in sea level can lead to pronounced geomorphic, sedimentologic, and ecologic responses. As such, changes in the tidal-flat system may be harbingers of larger scale ecosystem, geomorphic, and deposystem reorganization.

In the case of a relative rise in sea level (as is now occurring on many coastlines), expected changes on tidal flats include shoreline erosion, encroachment of salt water, and increased flooding (Titus and Barth, 1984; Knighton et al., 1991). Although many studies of modern coastal and tidal processes emphasize the impact of sea-level rise on shoreline erosion, the entire sedimentary and ecological system should respond to such changes (Allen, 2000; Pethick, 2001; Shinn, 2001), not just the shoreline. With this perspective on landform change, Pethick (2001, p. 307) emphasized that ''prediction of the rates of . . . migration will be fundamental to the future management of the changing coastal environment.''

Many previous studies have assessed the processes and patterns of carbonate tidal flats and could yield valuable information on potential future changes. Process-based observations on modern tidal flats have provided sedimentologic insights (e.g., Shinn et al., 1969; Hardie, 1977), but do not provide precise information on how the tidal flats have changed through time. At the opposite end of the temporal spectrum, studies of cores from Holocene tidal flats and stratigraphic studies of ancient tidal flats have documented deposits from similar geomorphic and depositional peritidal systems and their evolution over several thousands to millions of years (e.g., see summaries in Wright, 1984; Shinn, 1986). The complex lateral and vertical facies relationships present in the stratigraphic record of tidal-flat systems have led many to suggest that their temporal evolution is complicated; however, detailed, quantitative insights on possible future changes have not been feasible.

In spite of the wealth of observations on the sedimentology and geomorphology of present-day carbonate tidal flats and their ancient analogs, there have been no detailed studies of the evolution of carbonate tidal flats at the historical scale (<100 yr). Nevertheless, this historical period is the appropriate scale for analysis of landscape change and shoreline stability at human time scales and the assessment of the possible impacts of sea-level rise. Geologically, this scale also represents an important temporal link between the observation of modern processes and those inferred from facies successions representing thousands of years on ancient tidal flats. This study aims to fill this temporal gap and to address the character, magnitude, and rate of changes in geomorphology on one type of modern tidal flat at the historical scale.

The purposes of this paper are to document and quantify historical changes in the morphology of a carbonate tidal flat and to discuss the possible role of sea-level rise on these changes. The results of this study represent some of the first quantitative descriptions of geomorphic changes on carbonate-dominated shorelines and tidal flats, illustrating the manner in which these systems respond to sea-level change, a matter of concern to many coastal nations. The data illustrate that the entire coastal system, including, but not limited to, the shoreline, is changing at geologically rapid rates. In addition, these observations provide valuable information on a widely studied modern analog of many ancient tidal-flat systems.

BACKGROUND

Location and Previous Work

The study area is the modern carbonate tidal flat on the northwest coast of Andros Island, Bahamas, that is as wide as 5 km and extends ~25 km along the western side of the island. On this microtidal (<50 cm) coast, Shinn et al. (1969) defined three general geomorphic zones: (1) marine, (2) channeled belt, alternately flooded and exposed with the tides, and (3) marsh, mostly above mean high tide. Each of these

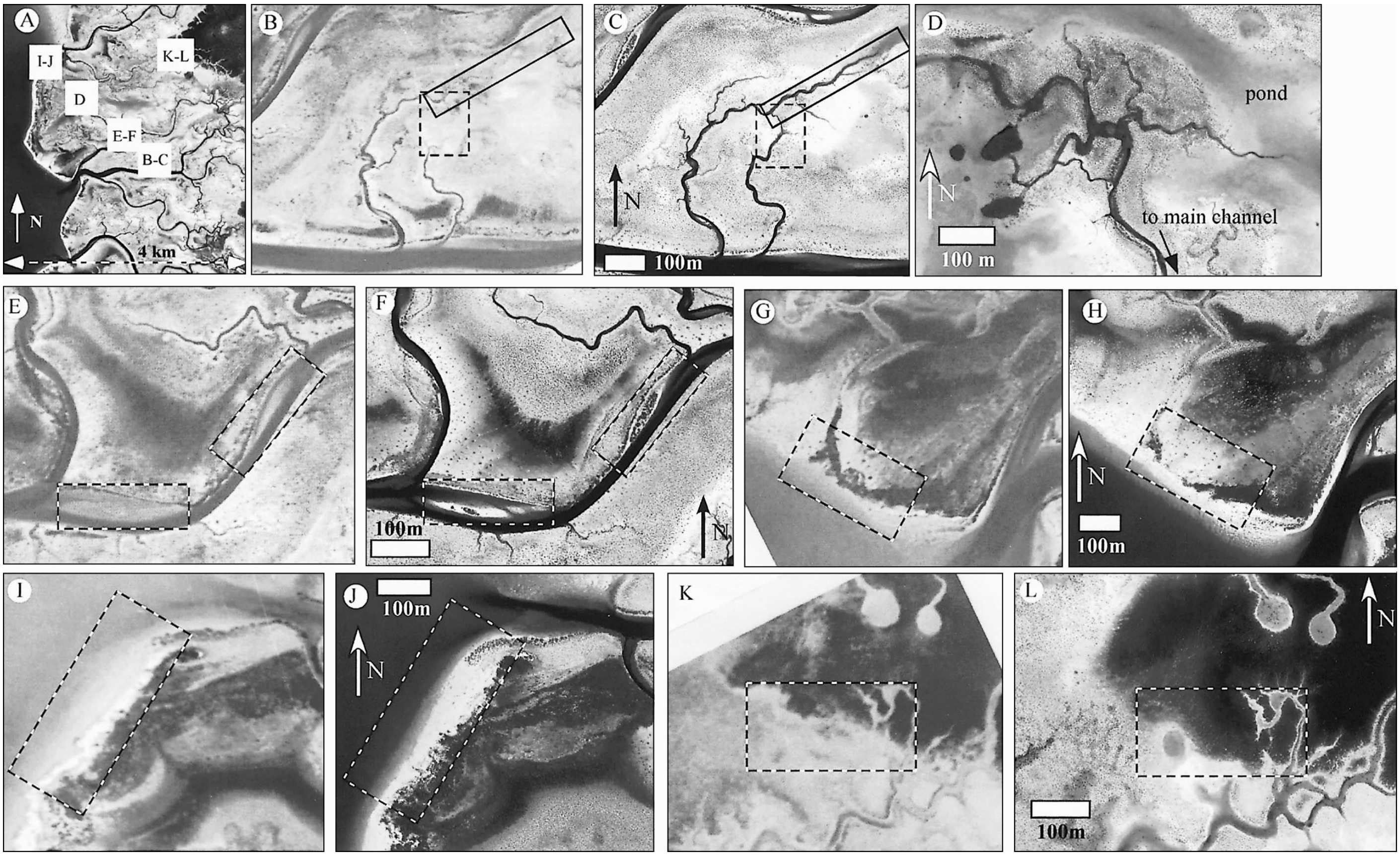

Figure 1. Paired images illustrating geomorphic changes on Andros tidal flats. In each paired set, first image is from 1943 aerial photo, second is from 2001 remote sensing data. A: Location map in Three Creeks area, northwest Andros Island. Locations of remaining figures are as indicated. B and C: Tidal channel extension (highlighted in boxes) and shrinking low algal marsh (dark patches just north of southern channel) due to pond expansion. D: Distributary system at end of tidal creek. These types of features suggest sediment transport into ponds. E and F: Channel bar stabilization (boxes) and shrinking low algal marsh (dark patch in center) due to expansion of shallow pond. G and H: Shoreline erosion. I and J: Shoreline erosion and extension of mangrove spit: K and L: Progradation of inland algal marsh. Shoreline is to west. Remote sensing images are copyright SpaceImaging.com, and are used with their permission.

zones can be further subdivided on the basis of their sediment types, biota, positions relative to tides, and depositional processes, and include subfacies such as beach ridge, mangrove pond, and channel. Previous studies of Andros Island tidal flats (Shinn et al., 1969; Gebelein, 1974; Hardie, 1977) included detailed mapping, sedimentologic analysis, and coring. We use the subfacies terminology of these earlier workers for consistency (e.g., we use ''low algal marsh,'' even though the primary biotic constituent is *Scytonema*, a cyanobacteria).

Methods

The fundamental data for the analyses of historical changes are aerial photographs from 1943 (provided by Lawrence Hardie of Johns Hopkins University) and an ultrahigh-resolution Ikonos remote sensing image collected in 2001. Ikonos data include panchromatic data with a pixel size of 1 m^2 and multispectral (red, green, blue, and near-infrared) data with 4 m^2 pixels (utilized, but not illustrated herein). The digital images are rectified so that distances can be measured directly from the data.

Many sedimentologic and geomorphic interpretations in this paper are based on comparison with the data of Shinn et al. (1969), Gebelein (1974), and Hardie (1977). However, detailed sedimentologic characterization of changes on the tidal flat is beyond the scope of this paper.

CALIBRATION OF REMOTE SENSING IMAGERY

Shinn et al. (1969) and Hardie (1977) observed that the biological and sedimentologic processes active in different tidal-flat subenvironments created characteristic shades or textures that were clearly recognizable on aerial photographs. The same zonation observed on aerial photos is also clearly discernable in the Ikonos data (cf. Fig. 1). Comparison of Ikonos data, previous interpretations, and field observations illustrates that on the remote sensing data, channels are dark, levees are light colored (caused by the high reflectance of the exposed sediment, the light colored *Schyzothrix* microbial mats, and the paucity of vegetation), the low algal marsh is dark but mottled (from the *Scytonema* microbial mats), and the mangrove ponds have a lighter shade, but speckled appearance (due to the presence of scattered scrub mangroves). On the remote sensing images, these subenvironments are clearly visible and are readily interpretable, and most areas appear similar to those apparent on the older aerial photos (Fig. 1). The differences between the two images are the focus of the rest of the paper because they illustrate areas in which the tidal flat has changed.

HISTORICAL CHANGES ON THE TIDAL FLAT AND RATES OF GEOMORPHIC CHANGE

Channel Extension

The most readily observable change that has occurred on the tidal flat is headward extension of many of the tidal channels (Fig. 1, A and B). In most cases, this extension appears to be caused by headward erosion, perhaps facilitated by burrowing organisms (rather than by pondward growth of small distributary systems suggested by geomorphic features; Fig. 1C). Some channels have extended more than 100 m into the tidal ponds, suggesting rates of extension to ~2 m/yr.

Channel Bar Stabilization

Channel bars form in the meanders of many of the main channels. Comparison of the aerial photos and the Ikonos data illustrates that some of the channel bars active in 1943 had stabilized by 2001 (Fig. 1, E and F). Several other features similar to the recently stabilized bars (e.g., lens shape, covered with vegetation, next to a channel) are present on the aerial photograph and remote sensing image, illustrating that channel bar stabilization is not limited to the last ~50 yr.

Shoreline Erosion

Comparison of the 1943 photos with the Ikonos image illustrates shoreline erosion in several places (Fig. 1, G–J). Local erosion of as much as 50 m corresponds to a rate of shoreline erosion of just <1 m/yr. These measured rates of erosion are similar to those measured from siliciclastic shorelines (Bird, 2000). In many areas, however, no easily discernable or measurable erosion has occurred. In one area, there actually appears to have been some accretion associated with mangrove colonization at the mouth of a tidal channel (Fig. 1, I and J), although erosion occurred just to the southwest.

Prograding Supratidal Inland Algal Marsh

In landward regions of the tidal flat, the supratidal inland algal marsh includes lithified and dried crusts and thick *Scytonema* mats. Comparison of the 1943 and 2001 images illustrates that locally this subenvironment has prograded seaward as much as 90 m (~60 m, if measured perpendicular to the sharp dark outer edge of the marsh) (Fig. 1, K and L). These magnitudes correspond to rates of progradation of 1.5 m/yr, although this progradation appears to be the exception rather than the rule, and most areas appear to be stationary.

Shrinking Low Algal Marshes and Expanding Ponds

In many areas on the tidal flat, elongate dark regions on aerial photos and Ikonos images represent an abundance of *Scytonema* mats in low algal marshes. On the 2001 image, many of these regions appear to have shrunk, with the concomitant enlargement of the mangrove ponds (Fig. 1, B, C, E, F). The magnitudes of retreat are as much as 250 m, corresponding to rates of migration of the environmental boundary >4 m/yr.

Channel Abandonment

Hardie (1977) and Shinn et al. (1969) noted the presence of several large, abandoned channels, especially in the southern Three Creeks region, south of Point Simon. Although no channels of this size were abandoned between 1943 and 2001, several smaller channels were abandoned in this time interval. Some of these channels now are overgrown with mangroves and other vegetation or were covered (e.g., by the beach ridge or levee), and so have no surface expression on the 2001 images.

Although several channels active in 1943 had extended and several channels active in 1943 had been abandoned, no new large channels appear to have formed in this area. Similarly, no measurable lateral channel migration occurred during this interval, although core transects (Shinn et al., 1969) suggest past migration.

GEOMORPHIC AND SEDIMENTOLOGIC PROCESSES

The results of this study illustrate historical geomorphic changes on this tidal flat. These results supplement the descriptions and interpretations of the previous work of Shinn, Gebelein, Hardie, and coworkers, and many of the observed changes on the tidal flat are consistent with their models of sedimentation. For example, Shinn et al. (1969) and Hardie (1977) noted the irregular northwest coastline of the island and examined the erosional nature of the intertidal shoreline in the Three Creeks area. They also noted that Williams Island (located near the bend at the western edge of Andros Island) included now-isolated tidal-flat deposits. On the basis of these observations, they interpreted this coastline to be erosional (in contrast with the inferred progradational coast of southwest Andros). The observations of historical shoreline erosion (Fig. 1, G–J) are consistent with the model of landward migration of the shoreline, but none of these previous studies quantified the rates of change.

Several surprises are also present in these results. For example, extension of tidal channels was not previously documented on this tidal flat, although the general landward migration of the channeled belt as a whole has been noted before (Shinn et al., 1969; Hardie, 1977). This extension appears to have occurred through at least two different processes, i.e., progradation and erosion. Progradation into tidal ponds (at a time scale longer than that considered for this study) is suggested by the features in Figure 1D, which illustrate a ‘‘birdfoot’’ distributary system at the end of a tidal creek. This type of morphology is common in the Three Creeks area and suggests that the tidal creeks are carrying sediment into the pond (cf. Shinn et al., 1969; Rankey, 2002), although none of these deltas has enlarged measurably since 1943. In contrast, headward extension caused by erosion, possibly facilitated by burrowing organisms, is visible in Figure 1 (B and C). Tidal-channel extension has been documented in macrotidal siliciclastic systems (e.g., Knighton et al., 1991; Shi et al., 1995), but is not widely recognized in microtidal settings, and has not been described in carbonate systems before.

Another unexpected result is the progradation of the supratidal high algal marsh. Shinn et al. (1969) and Shinn (1986) noted that the channeled belt is underlain by older supratidal marsh, and suggested retreat and onlap of the entire tidal-flat complex. The results of this study do not refute the longer term trend, but illustrate that there has been a turnaround, and now the supratidal high algal marsh is expanding away from land (seaward), albeit in only a few areas.

The lack of significant historical migration of the tidal channels is unexpected (however, see Wright, 1984). Although Shinn (1986, p. 13) noted that ‘‘lateral channel migration of more than 30–50 m has not been documented by coring,’’ Shinn et al. (1969), Hardie (1977), and Shinn (1986) recognized erosion on the outer banks of tidal channels, and suggested that they may be actively migrating. Several channels appear to have widened or extended (e.g., Fig. 1, B and C), but without pronounced lateral migration. The lack of significant channel migration is similar to the patterns observed in microtidal siliciclastic tidal flats (e.g., Luternauer et al., 1995), especially those with levee-stabilizing elements such as cyanobacterial mats.

INFLUENCE OF SEA-LEVEL RISE ON GEOMORPHIC CHANGES

Most locations in the western Atlantic and Caribbean region have been characterized by rising sea level through the Holocene (Lighty et al., 1982; Macintyre et al., 1995; Shinn, 2001), and it is this relative rise that accounts for the general pattern of coastal onlap of the tidal flats (Shinn, 1986). This rise appears to be continuing; Gornitz and Lebedeff (1987) estimated an average rise of sea level of ~8 cm between 1940 and 1980 in the Caribbean.

Anticipated results of a relative rise in sea level on shorelines and tidal flats include shoreline retreat and increased flooding (Titus and Barth, 1984; Komar and Enfield, 1987; Pethick, 2001), and the historical geomorphic changes on this carbonate shoreline are consistent with their being influenced by this relative rise in sea level. For example, the shoreline of this part of the tidal flat is eroding at rates of as much as ~1 m/yr.

Similarly, sedimentary and geomorphic effects other than coastline erosion should be expected to be associated with increased flooding (Pethick, 2001). As sea level rises, more water flows up tidal creeks, possibly leading to erosion at their heads (Knighton et al., 1991); such headward erosion is illustrated on these tidal flats by the tidal channels that are currently extending at rates to 2 m/yr. Similarly, increased flooding of the tidal flat could be expressed as an expansion of the low-lying ponds. Pond expansion would reduce the area of lower intertidal subenvironments such as the low algal marsh, unless they migrate up the depositional topography. In the absence of significant aggradation on the levees, however, it is more likely that the areas of low algal marshes simply are compressed. This low algal marsh contraction (at rates to 4 m/yr) is evident in many areas on the tidal flat.

Shinn (1986, p. 15) noted the presence of extensive levees on Williams Island, 3–4 km offshore of southwestern Andros Island tidal flats (~50 km southwest of the study area), and stated that the island ''is clearly an erosional remnant.'' If this statement is correct, extrapolation using the highest observed historical rates of erosion would suggest that the erosion in this area began ca. 3 ka; slower rates would suggest a longer period of erosion. This estimate seems unreasonable, however, because the platform wasn't flooded until 3–5 ka (Shinn, 1986), and the sediments had to be deposited before they could be eroded. Instead, erosion must have proceeded at a higher rate in the past. This conclusion is somewhat surprising, given that increased rates of coastal erosion might be expected with increased rate of rise of sea level (e.g., Bird, 2000). Instead of responding solely to the rate of rise of sea level, this carbonate coastal system may be responding to variation in other factors such as circulation or storm intensity and direction. Likewise, the lateral variability in the coastal system is highlighted by the interpretation (Gebelein, 1974; Shinn, 1986) that the southwestern coast of Andros Island has been progradational through much of the Holocene.

SUMMARY

Comparison of historical aerial photos and ultrahigh-resolution remote sensing imagery illustrates that many parts of the tidal flats of northwest Andros Island, Bahamas, are changing at geologically rapid rates. Changes include shoreline erosion, channel extension, and pond expansion. Collectively, these observations illustrate that many parts of the tidal-flat system (including, but not limited to, the shoreline) are responding in a manner consistent with that expected if caused by relative rise in sea level. However, the lateral complexity (erosional northwest coast and inferred progradational southwest coast) and the likely temporal variability (nonlinearity) show that sea-level change alone cannot explain all the geomorphic change.

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REFERENCES CITED

Allen, J.R.L., 2000, Morphodynamics of Holocene salt marshes: A review sketch from the Atlantic and southern North Sea coasts of Europe: Quaternary Science Reviews, v. 19, p. 1155–1231.

Bird, E., 2000, Coastal geomorphology: An introduction: New York, John Wiley and Sons, 322 p.

Gebelein, C.D., 1974, Guidebook for modern Bahamian platform environments: Geological Society of America Annual Meeting Field Trip Guidebook, Miami, Florida: Boulder, Colorado, Geological Society of America, 93 p.

Gornitz, V., and Lebedeff, S., 1987, Global sea-level changes during the past century, *in* Nummedal, D., et al., eds., Sea-level fluctuation and coastal evolution: Society of Economic Paleontologists and Mineralogists Special Publication 41, p. 3–16.

Hardie, L.A., ed., 1977, Sedimentation on the modern carbonate tidal flats of northwest Andros Island, Bahamas: Johns Hopkins University Studies in Geology 22, 202 p.

Knighton, A.D., Mills, K., and Woodroffe, C.D., 1991, Tidal-creek extension and saltwater intrusion in northern Australia: Geology, v. 19, p. 831–834.

Komar, P.D., and Enfield, D.B., 1987, Short-term sea level changes and coastal erosion, *in* Nummedal, D., et al., eds., Sea-level fluctuation and coastal evolution: Society of Economic Paleontologists and Mineralogists Special Publication 41, p. 17–28.

Lighty, R.G., Macintyre, I.G., and Stuckenrath, R., 1982, *Acropora palmata* reef framework: A reliable indicator of sea level in the western Atlantic for the past 10 000 years: Coral Reefs, v. 1, p. 125–130.

Luternauer, J.L., Atkins, R.J., Moody, A.I., Williams, H.F.L., and Gibson, J.W., 1995, Salt marshes, *in* Perillo, G., ed., Geomorphology and sedimentology of estuaries: Developments in Sedimentology 53: Amsterdam, Elsevier, p. 307–332.

Macintyre, I.G., Littler, M.M., and Littler, D.S., 1995, Holocene history of Tobacco Range, Belize, Central America: Atoll Research Bulletin, v. 430, p. 1–18.

Pethick, J., 2001, Coastal management and sea-level rise: Catena, v. 42, p. 307–322.

Rankey, E.C., 2002, Spatial patterns of sedimentation on a Holocene carbonate tidal flat, northwest Andros Island, Bahamas: Journal of Sedimentary Research (in press).

Shi, Z., Pethick, J.S., and Pye, K., 1995, Geomorphic change of saltmarsh tidal creek networks in the Dyfi estuary, Wales: Marine Geology, v. 128, p. 79–83.

Shinn, E.A., 1986, Modern carbonate tidal flats: Their diagnostic features: Colorado School of Mines Quarterly, v. 81, p. 7–35.

Shinn, E.A., 2001, Coral reefs and shoreline dipsticks, *in* Gerhard, L.C., et al., eds., Geological perspectives on global climate change: American Association of Petroleum Geologists Studies in Geology 47, p. 251–264.

Shinn, E.A., Lloyd, R.M., and Ginsburg, R.N., 1969, Anatomy of a modern carbonate tidal flat, Andros Island, Bahamas: Journal of Sedimentary Petrology, v. 39, p. 1202–1228.

Titus, J.G., and Barth, M.C., 1984, An overview of the causes and effects of sea level rise, *in* Barth, M.C., and Titus, J.G., eds., Greenhouse effect and sea level rise: New York, Van Nostrand Reinhold, p. 1–56.

Wright, V.P., 1984, Peritidal carbonate facies models: A review: Geological Journal, v. 19, p. 309–325.

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