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Evolution of a Pharaonic harbor on the Red Sea: Implications for coastal response to changes in sea level and climate

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ABSTRACT

The evolution of coastal systems during the Holocene resulted from complex interactions and temporal shifts in the relative contribution of sea-level changes, climate change, and sedimentary processes. Along the Red Sea Coast, a 0.5–2 m highstand of sea level at 5 ka can be directly attributed to far-field effects resulting from the reduction in land ice following the last glacial maximum. At the ancient Egyptian harbor of Mersa/Wadi Gawasis, the site of the world's oldest archaeological evidence of long-distance seafaring, stratigraphic and geomorphologic evidence has been identified for this highstand. Here, wadi sediment input, enhanced by a period of wetter climate of the African Humid Period (early to mid-Holocene), forced the closure of coastal embayments, despite ongoing, relatively rapid sea-level rise. A stable, shallow bay persisted at Mersa/Wadi Gawasis as a result of coincidental aridization and a highstand of sea level during the mid-Holocene. This bay served as the primary harbor for ancient Egyptian trade along the Red Sea coast. During the late Holocene, shoreline progradation was dominated by sea-level fall, driven by isostatic processes. These results demonstrate the interplay of various global (sea level), regional (climate, sea level), and local (sedimentation, bathymetry) controls on the coastal evolution of the Red Sea and how these controls dictated the response of a complex civilization. Furthermore, they highlight the crucial role played by sedimentation in governing coastal response to changing sea levels.

INTRODUCTION

Recent studies have highlighted the complexities of coastal evolution and the importance of our ability to predict rates of change in both sea level and sedimentation for forecasting the impact of accelerated sea-level rise on coastal evolution (Blum and Roberts, 2009; Anderson et al., 2010). Coastal response to such changes is nonlinear and nonuniform, demanding a quantitative understanding of the relationships between global, regional, and local controls. Here we demonstrate the impact of interrelated changes in disparate forcings on the evolution of the Red Sea coast throughout the Holocene, emphasizing temporal shifts in the importance of sea-level changes, climate change, and sedimentary processes. During this period, equatorial regions underwent well-established shifts in both climate (deMenocal et al., 2000) and sea level (Mitrovica and Milne, 2002) that were of magnitudes similar to those forecast for the near future (Bindoff et al., 2007). Therefore, this study provides a tenable example of the complexities and uncertainties of climate change and its impacts on coastal systems.

The Red Sea, a semi-enclosed basin with a narrow opening to the equatorial regions of the world's oceans and a long history of human occupation, serves as ideal location to study the

impacts of these past shifts on coastal evolution and human civilizations. Along the Egyptian Red Sea coast, rapid aridization following the African Humid Period (deMenocal et al., 2000; Arz et al., 2003) coincided with the late stages of sea-level rise and a 0.5–2 m highstand ca. 5 ka. The resulting marine transgression drowned lowstand river valleys, forming coastal embayments that were later filled with riverine-derived clastic sediment. One such embayment, Mersa/Wadi Gawasis (MWG), is located at the mouth of a moderately sized wadi in northeast Egypt (Fig. 1), between the Mediterranean and African–southwest Asian monsoonal rainfall regimes and along the northeast edge of the Sahara belt. This region is currently dominated by extreme aridity, receiving only 1–2 mm/yr of rainfall (Edwards, 1987). Modern Wadi Gawasis

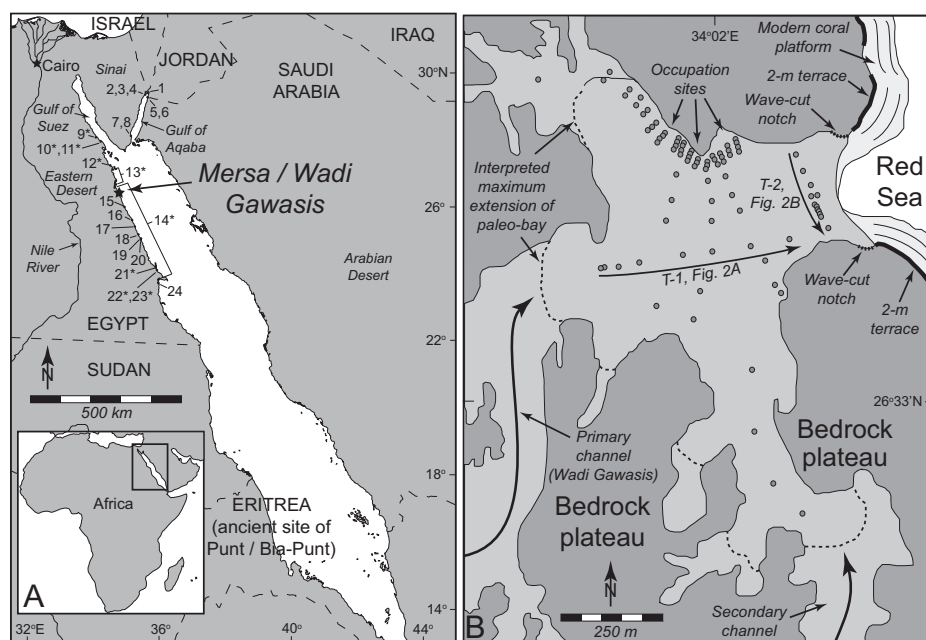


Figure 1. A: Map of Red Sea showing location of Mersa/Wadi Gawasis (MWG) (26°33'05"N, 34°02'08"E) at head of Wadi Gawasis, ephemeral river system with drainage area of ~50 km². Locations of Red Sea mid-Holocene highstand records in Egypt are numbered 1–14 (Table DR1; see footnote 1). Highstand records used in Figure 3 are noted with asterisks. **B:** Study area map of MWG. Sediment core locations are given as gray filled circles with two core transects referenced in text (T-1, cross-wadi transect, Fig. 2A; and T-2, entrance channel transect, Fig. 2B) noted. Higher elevation plateaus are composed of interbedded conglomerates and coralline limestone. Wadi floor is composed of eolian silts interbedded with coarser wadi-derived sediment.

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exhibits ephemeral river flow and carries little coarse sediment; occasional freshwater floods transport minor amounts of silt and sand that is derived from the reworking of eolian material.

Archaeological excavations 600 m landward of the coast at MWG (Fig. 1B) have documented the world's earliest evidence of long-distance seafaring, including inscribed stelae, bundled ropes, ship timbers, tools, papyrus fragments, bread molds, sandals, and remnants of storage boxes used for transport of goods. Additional evidence of long-term occupation at this site includes temporary shelters, rock-cut caves, ceremonial structures, and industrial areas. This site was used extensively during Middle Kingdom (12th Dynasty) time (ca. 4000–3775 yr ago) in ancient Egypt, when seafaring ships departed from this harbor for trade routes along the African Red Sea coast to the land of Punt, an unknown region located in the southern Red Sea where ancient Egyptians obtained rare and unique raw materials (Bard and Fattovich, 2010).

METHODS

A series of 87 auger cores (1–5 m), pulse-auger cores (4–6 m), and wash borings (7–16 m) was collected along 21 transects throughout MWG (Figs. 1 and 2; see the GSA Data Repository¹ for details). Samples were collected for sedimentological, malacological (Table DR2 in the Data Repository), foraminiferal (Table DR3), and radiocarbon analysis (Table DR4). A cross-channel core transect (T-2; Fig. 2B) was used to determine the maximum extent of the entrance channel to the lagoon.

Evidence for a higher-than-present sea level during the Holocene was surveyed at the site (see the Data Repository) and compared to sea-level predictions using the models described in Mitrovica and Milne (2003) and Kendall et al. (2005), which were run for a given ice history model and a range of different Earth (viscosity) model parameters (see the Data Repository).

RESULTS

Bay Evolution

Sedimentological analyses indicate that MWG is filled with a 2.5–4.0-m-thick sequence of eolian and riverine sediments composed of gravel, sand, and silt, and containing multiple fining-upward sequences related to wadi floods during the latest stages of the infilling of the wadi. These sediments are underlain by fine,

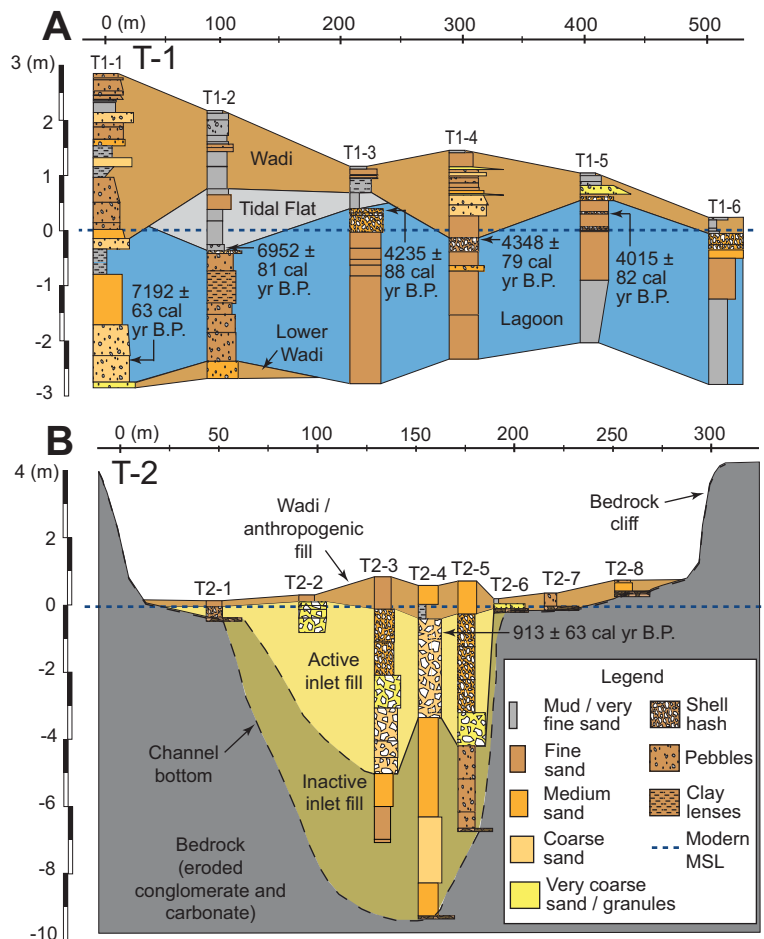


Figure 2. Stratigraphic logs from Mersa/Wadi Gawasis. Stratigraphic facies are discussed in text; calibrated radiocarbon dates are provided and reported with standard errors (Table DR4; see footnote 1). **A:** Cross-wadi section (T-1) with Red Sea to right; note specifically general thickening and coarsening of wadi sediments overlying lagoonal facies in landward direction, indicating dominance of sediment inputs during early stages of bay evolution. Wadi unit underlying lagoon is interpreted as early Holocene in age, deposited prior to transgressive flooding of embayment. **B:** Section across bay entrance (T-2). Upper surface corresponds to topography; channel transect was collected at narrow section of paleolagoon and is bordered to north and south (left and right, respectively) by ~4-m-high bedrock cliffs, as indicated in figure. At its maximum, bedrock-controlled channel was 10 m deep and 150 m across (cross-sectional area 1300 m²). MSL—mean sea level.

well-sorted sand containing abundant marine mollusks and benthic foraminifera. This unit generally coarsens upward from very fine silty sand (3–4Φ) with rare fine shell fragments to medium sand having larger, more abundant shell fragments. Analysis of mollusks collected from this unit reveals 24 species of bivalvia and 10 species of gastropoda, revealing an increase in diversity, abundance, relative frequency of gastropoda, and individual shell thickness from the inner, more protected, to the outer, less protected, regions of the paleo-bay. Generally, all identified species live in intertidal or subtidal muddy or sandy bottoms in the very nearshore or lagoons. Radiocarbon dates (Table DR4) from 29 mollusks found both in situ and reworked within this unit confirm a mid-Holocene age of 3.1–6.4 ka. Benthic forams collected from this unit represent five species (Table DR3); mod-

ern individuals are generally found in relatively shallow (<50 m), warm, brackish to hypersaline waters (salinity 35–53 ppt) and on generally sandy substrates (Murray, 1991). This unit is interpreted as a lagoonal facies derived from sediment introduced to the wadi during floods and redistributed by waves and tidal currents.

In the most exposed regions of the paleo-bay, the uppermost unit of the lagoonal sequence is highly bioclastic; radiocarbon dates (Table DR4) from shell samples in this unit (T-1; Fig. 2A) indicate that it was deposited during a rapid regression in the latest stages of infilling of the paleo-lagoon. Its coarse nature further implies that it was formed by shoreface reworking under conditions of moderate wave energy (Fig. 3).

In sheltered regions of the paleo-bay, lagoonal sediments are overlain by a 50–100-cm-thick sequence of tidal flat sediments containing mot-

¹GSA Data Repository item 2011211, detailed methods, description and results of sea-level reconstructions, list of Holocene sea-level highstand records, and results of malacological, foraminiferal, and radiocarbon analyses, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

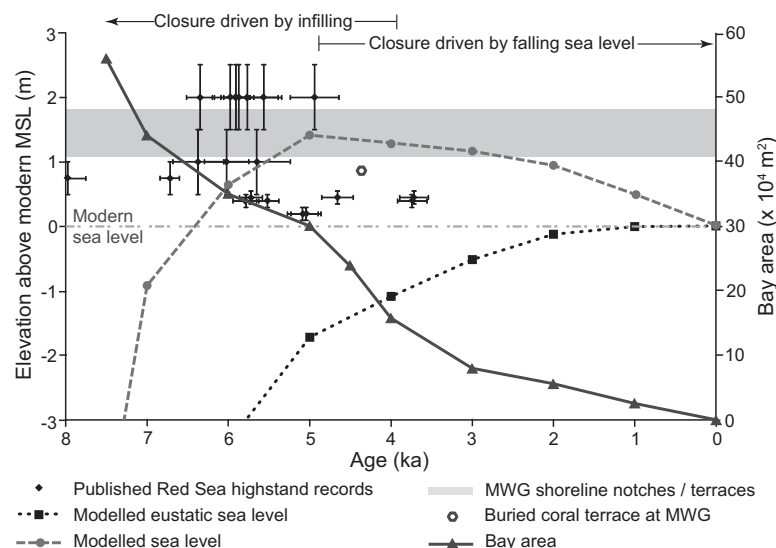


Figure 3. Records of recorded notches and terraces (Fig. 1; Table DR1; see footnote 1) are shown as diamonds with either published vertical error bars or, when not provided, with standard vertical error of ± 0.5 m to represent uncertainties in estimated elevations. Only records from narrow geographic window of central Egyptian Red Sea coast are plotted to ensure that spatial variation due to isostatic processes does not exceed a few decimeters (see Fig. DR2). Date of coral terrace from the paleo-bay is shown as open circle. Where applicable, raw radiocarbon dates have been calibrated using Marine09 (Reimer et al., 2009) and with local correction calibrated to reported data from a coastal site 80 km north of Mersa/Wadi Gawasis: $\delta R = 150$ yr; $\delta R_{\text{uncertainty}} = 45$ yr, and are reported with standard error of the mean. Gray horizontal box represents indicative elevation range of erosional notches and terraces at mouth of Wadi Gawasis. Dashed line shows one example of model output that provided compatible fit with observations (for information on the various model parameters considered, see the Data Repository [see footnote 1]). Dotted line shows eustatic component of modeled total sea-level change (dashed line) due to influx of glacial melt water into oceans (see the Data Repository). Solid line shows interpreted bay area through time, based on 20 radiocarbon dates taken throughout bay. MWG—Mersa/Wadi Gawasis; MSL—mean sea level.

tered oxidized fine sands and clays with stained oxidation surfaces, rootlets of *Avicennia marina*, and abundant *Terebralia palustris*, species commonly found in protected intertidal environments. This unit is located within ± 1 m above modern mean sea level (m MSL) and dated (*Avicennia marina* root mass) to 4910 ± 51 calibrated ^{14}C yr B.P. Adjacent to former occupation sites at the moderately exposed northern side of the wadi, the tidal flat unit is supplanted by a narrow coral-beach rock platform, overlain by large, thick-shelled bivalves and gastropods. This unit represents the active coral terrace when the bay was open and has since been buried by anthropogenic, eolian, and colluvial sediment.

Sea-Level History

Highstands of relative sea level have been reported for the mid-Holocene in nearly all of the world's ocean basins, and in many regions sea level has fallen 2–4 m since that time. This fall is driven by isostatic processes as the solid Earth adjusts in response to the mass exchange between ice sheets and oceans following the recent deglaciation. The unloading of ice from previously glaciated regions and the addition of water to the ocean basins both contributed to the observed mid- to late Holocene sea-level

fall at low latitudes (Mitrovica and Milne, 2002; Clark et al., 1978). Evidence for this highstand along the Egyptian Red Sea coast is well documented by coral terraces, wave-cut notches, and erosional benches (Table DR1). U/Th dating of coral terraces along the Egyptian coast within 50–200 km of MWG (Hoang and Taviani, 1991; Reyss et al., 1993; Arvidson, et al., 1994) indicates that sea level during the last interglacial was within a few meters of the estimated global mean value (Kopp et al., 2009). This difference is due to both isostatic and tectonic processes. These data indicate that the rate of tectonic motion is ~ 1 m/100 k.y. (if assumed constant in time), or ~ 1 cm/k.y., and thus did not contribute significantly to the Holocene highstand.

A series of wave-cut notches and a 3-m-wide erosional terrace located along the shore indicate a maximum highstand at MWG of 1.8 m MSL (Fig. 3; for details, see the Data Repository). These features are likely coincident with the buried coral terrace inside the paleo-bay, a unit that reaches a maximum elevation of 0.86 m MSL and has been dated to 4359 ± 85 cal ^{14}C yr B.P. Providing that such coral would have to live below the low-tide line, this implies a minimum highstand elevation of 1.1 m MSL. This observed highstand at 1.1–1.8 m MSL is

well within the ranges of highstand features located elsewhere along the Egyptian Red Sea coast (Figs. 1 and 3; Table DR1).

Sea-level predictions generated using an isostatic model for MWG encompass the highstand elevation range indicated by the observations (see Fig. DR1 and related discussion). One example of model output that compared favorably to the observations is shown in Figure 3. The model results are therefore consistent with our interpretation of shoreline features and the buried coral terrace in the wadi and provide a well-understood cause for the mid-Holocene highstand at MWG. However, the model predictions also indicate that sea level at MWG reached a maximum 2500 yr after the bay had reached its greatest extent (Fig. 3).

DISCUSSION

The drowning of the lower reaches of the wadi channel at MWG created a broad, protected lagoon landward of the present shoreline. This 6–8-m-deep bay reached its maximum aerial extent of 0.56 km^2 ca. 7500 yr ago. Stratigraphic evidence implies higher sediment inputs from the adjacent wadi system during the development of this paleo-bay, constraining its size and forcing partial closure despite ongoing sea-level rise. In a landward direction, lagoonal sediments generally coarsen; reworked shell-rich lagoonal facies are more regularly interspersed with purely riverine sediments; and riverine fining-upward sequences thicken from <1 m proximal to the center of the paleo-bay to >2.5 m in the most distal cores. Furthermore, the depth to the tidal flat sediments increases in a landward direction, indicating a dominance of sediment input during the early evolution of the paleo-bay. This observation is consistent with northeast Africa paleo-climate records, which indicate a significantly wetter climate at that time (Flohn and Nicholson, 1980; Ritchie et al., 1985; Bar-Matthews et al., 2000; Damnati, 2000; Gasse, 2000; Hoelzmann et al., 2000). Enhanced precipitation during the early to mid-Holocene would have significantly increased freshwater inputs into the drainage basin of Wadi Gawasis, accounting for a higher sediment load during the early stages of paleo-bay development and a reduction of the bay size even as sea level continued to rise.

The sea-level highstand coincided roughly with a shift to arid conditions in northern Africa beginning ca. 6 ka (deMenocal et al., 2000). This climatic alteration resulted in falling lake levels in northern Africa and Sudan (Ritchie et al., 1985; Damnati, 2000; Street and Grove, 1979); the rapid retreat of mesic taxa in fossil pollen records from African lake basins (Lamb et al., 1995; Lézine et al., 1990); replacement of the sedentary human populations in central and southern Sahara by mobile, pastoralist cultures

(McIntosh and McIntosh, 1983); and rapid aridization of northeastern Africa (Rognon, 1987; Legge et al., 2006). The reduction in precipitation within the Wadi Gawasis drainage basin caused by this shift would have reduced sediment input to the paleo-bay. Coincidentally, the end of the rapid postglacial sea-level rise and subsequent gradual fall in sea level from its maximum of 1–2 m produced a second phase of slow bay closure between 5 and 3 ka (Fig. 3). However, despite continued sea-level fall, the sharply reduced sediment influx provided for the maintenance of a shallow, stable lagoon fringed by mangrove-rich tidal flats and occupied by the ancient Egyptians as the harbor of Saww. For several hundred years during the late Old Kingdom and Middle Kingdom (12th Dynasty) of ancient Egypt, trading expeditions were sent out from this site to the lands of Punt and Bia Punt, located in present-day eastern Sudan and Eritrea. Abandonment of this harbor occurred by 3500 yr ago, coinciding with the reopening of riverine and land routes to Punt and Bia-Punt (Bard and Fattovich, 2010) and bay closure due to sea-level fall. A more rapid fall in sea level during the late Holocene combined with eolian sedimentation and infrequent riverine inputs forced complete closure of the paleo-bay by ~500 yr ago.

IMPLICATIONS AND CONCLUSIONS

This study not only identified the geological remains of an ancient Egyptian harbor along the Red Sea, but also underscores the importance of understanding the intricacies and interplays among various coastal forcings under conditions of changing climate. It establishes the temporally-dependent relative dominance of changes in sea level and climate in the evolution of this terrestrially- and marine-controlled system. The most striking examples at MWG are the dominance of sedimentary processes in the closure of the paleo-bay despite relatively rapidly rising sea level and the coincidental timing of both slowly falling sea level and climatic aridization, thereby allowing the establishment of a vital Egyptian trading harbor at this site. Future climate scenarios (Bindoff et al., 2007) predict spatially diverse changes in global, regional, and local factors that will ultimately dictate large-scale coastal evolution. It is therefore no longer enough to assume that accelerated sea-level rise will cause extensive lowland flooding; rather, the integrated impacts of local and regional climate changes, and their prospective effects on communities living in these zones, must also be considered and quantified.

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