Holocene morphogenesis of Alexander the Great's isthmus at Tyre in Lebanon

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Edited by Jeremy A. Sabloff, University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia, PA, and approved April 6, 2007
(received for review December 21, 2006)

In 332 B.C., Alexander the Great constructed an ≈1,000-m-long causeway to seize the offshore island of Tyre. The logistics behind this engineering feat have long troubled archaeologists. Using the Holocene sedimentary record, we demonstrate that Alexander's engineers cleverly exploited a shallow proto-tombolo, or sublittoral sand spit, to breach the offshore city's defensive impregnability. We elucidate a three-phase geomorphological model for the spit's evolution. Settled since the Bronze Age, the area's geological record manifests a long history of natural and anthropogenic forcings. (*i*) Leeward of the island breakwater, the maximum flooding surface (e.g., drowning of the subaerial land surfaces by seawater) is dated ≈8000 B.P. Fine-grained sediments and brackish and marine-lagoonal faunas translate shallow, low-energy water bodies at this time. Shelter was afforded by Tyre's elongated sandstone reefs, which acted as a 6-km natural breakwater. (*ii*) By 6000 B.P., sea-level rise had reduced the dimensions of the island from 6 to 4 km. The leeward wave shadow generated by this island, allied with high sediment supply after 3000 B.P., culminated in a natural wave-dominated proto-tombolo within 1–2 m of mean sea level by the time of Alexander the Great (4th century B.C.). (*iii*) After 332 B.C., construction of Alexander's causeway entrained a complete anthropogenic metamorphosis of the Tyrian coastal system.

geoarchaeology | Mediterranean | tombolo | coastal geomorphology

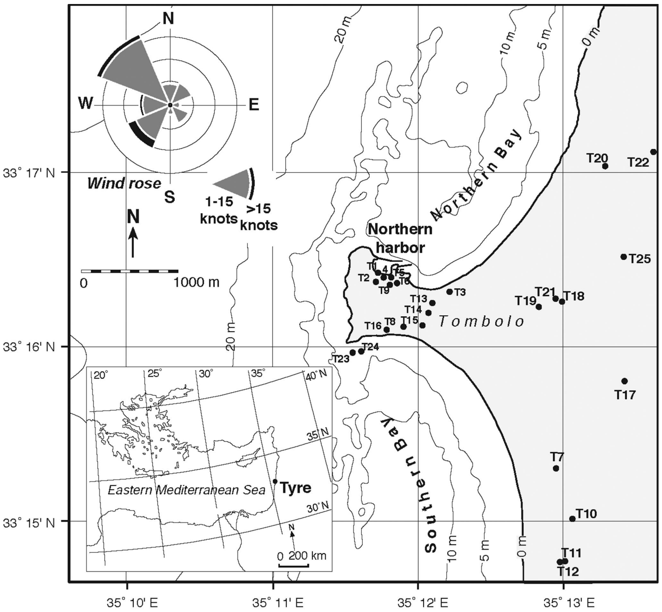

Fig. 1. Location of core sites on the Tyrian peninsula (black dots denote the sites).

Tyre's coastline is today characterized by a wave-dominated tombolo, a peculiar sand isthmus that links the ancient offshore island to the adjacent continent (Fig. 1). This rare coastal feature is the geological heritage of a long history of natural and human–environment interactions spanning some 8,000 years. In 332 B.C., after a protracted 7-month siege of the city, Alexander the Great's engineers cleverly exploited Tyre's unique geomorphological context to build a ≈1,000-m-long causeway and seize the island fortress. Here, we demonstrate that Alexander's causeway profoundly deformed Tyre's coastline and entrained rapid progradation of its natural spit.

Coastal sediments at numerous Mediterranean sites have been shown to be rich time series replete with data on the magnitude, variability, and direction of natural and anthropogenically forced change since antiquity (1–10). Within this context, the logistics behind Alexander's causeway have been a matter of archaeological speculation for some time. It has been conjectured that the key to explaining how Hellenistic engineers overcame the difficult physical conditions lies in the geological record (11). A number of authors have proposed informed morphogenetic scenarios based on aerial photography and classical texts (12). However, despite a rich North American literature on spit morphogenesis, little is known about anthropogenic tombolo formation and stratigraphy. Tombolo geology is complicated by a multiplicity of depositional environments (sublittoral zone, beach dunes, washover fans, marshes, lagoons, and tidal inlets), some of which are laterally continuous, whereas others are not. It is accepted that the overriding requisites for tombolo formation are: (*i*) high sediment supply, (*ii*) coastal processes conducive to the development and maintenance of the isthmus (e.g., wave diffraction), and (*iii*) a favorable geomorphic setting [island obstacle against the swell (13)].

Sunamura and Mizuno (14) have calculated that a tombolo forms where the ratio of the island's offshore distance to its length is ≦1.5; a salient forms where it is 1.5–3.5, and no protrusion of the coast occurs where it is >3.5. At Tyre, the present ratio is 1.47, at the very limit for tombolo formation. In antiquity, however, this ratio was much smaller, for example, 0.55 during the Iron Age. The large discrepancies are notably caused by tectonic collapse of the island bastion during the late Roman period and a reduction in size of the breakwater island by ≈470,000 m^2 or ≈50%.

Geomorphological and Archaeological Contexts

Throughout the Holocene, the Tyrian coastline has been protected by a broken chain of sandstone reefs, part of a drowned north–south ridge that runs parallel to the coastline (15, 16). The oblique stratification of these outcrops indicates that they are aeolian in origin. The defensive "impregnability" afforded by the offshore sandstone reefs attracted human societies from the Bronze Age onward. Successive cultures, including Phoenician,

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Author contributions: N.M. and C.M. designed research; N.M. and C.M. performed research; S.M. contributed new reagents/analytic tools; N.M. and C.M. analyzed data; and N.M. and C.M. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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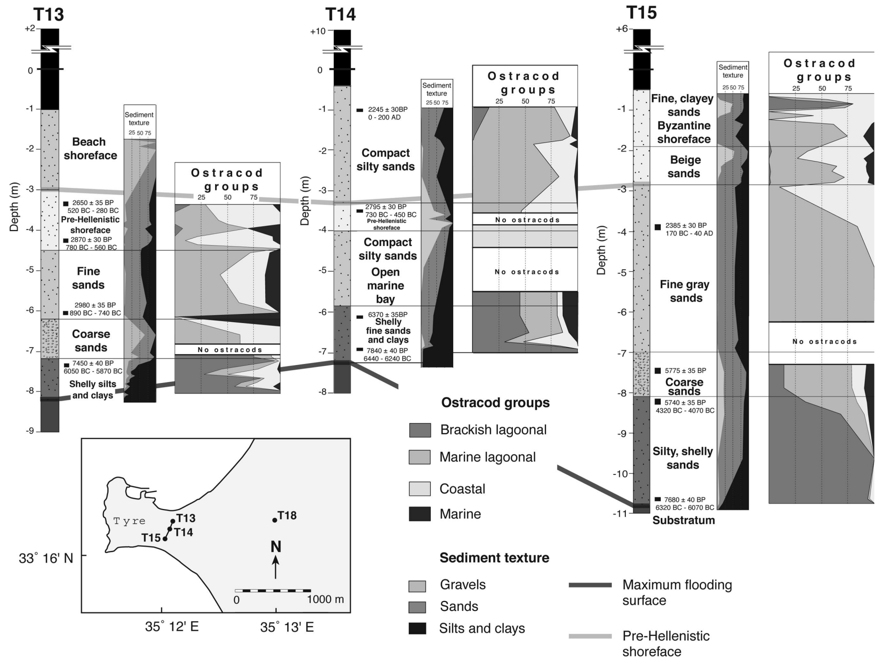

Fig. 2. Chrono- and ostracod biostratigraphy of tombolo cores T13–T15.

Persian, Hellenistic, Roman, and Byzantine, have significantly marked and modified the coastal landscapes (17, 18).

Tyre's tombolo comprises a west–east trending salient, 1,500 m long by 3,000 m wide (Fig. 1); the site lies ≈9 km south of the Litani delta. The latter, Lebanon's most important fluvial system, transits 284×10^6 m^3 of sediment per year (19, 20) and has been the primary sediment source for the isthmus during the Holocene. Given the microtidal regime (<45 cm), wave impact, longshore currents, and swell diffraction are the three key factors driving tombolo formation at Tyre. Dominant coastal winds and swell derive from the south–west, with periodic north–westerlies giving rise to multidirectional long-drift current. Wave data attest to extreme high energy sea-states, with wave heights of >5 m being measured every ≈2 years, and >7 m every ≈15 years (21–23). Ancient aerial photographs and engravings indicate important dunefields capping the tombolo until the 1950s. Rising up to 10 m above present mean sea level, these dunes have since been partially removed to accommodate urban growth and exhume the tombolo's archaeology.

Archaeological data from the Tyrian horst manifest ≈3 m of tectonic collapse since late Roman times (8, 24). This subsidence has resulted from the activation of the Yammuneh and the Roum-Tripoli Thrust, as well as slip along east–northeast transverse fault panels in the vicinity of Tyre (24). The Rosh Hanikra/Ras Nakoura fault marks the southern boundary of vertical displacements, with no evidence for coastal uplift being reported from northern Israel during the Holocene (25).

Results and Discussion

High-resolution analyses shed light on three critical aspects: (*i*) natural accretion of Tyre's early Holocene marine bottom, leeward of the island breakwater and akin to a stratigraphic trap; (*ii*) formation of a wave-dominated proto-tombolo after 6000 B.P. (this shallow sublittoral spit greatly facilitated the construction of Alexander the Great's sea bridge in 332 B.C.); and (*iii*) the wide-reaching anthropogenic impacts of this Hellenistic causeway.

Tombolo Origin and Early Holocene Development. A north–south transect comprising three cores, T13, T14, and T15, elucidates the tombolo's Holocene stratigraphy (Fig. 2). In this area, leeward of the island breakwater, the maximum flooding surface is dated ≈8000 B.P. consistent with the transgression of deltas throughout the circum Mediterranean (26). The lithostratigraphical and biostratigraphical signatures of this transgression comprise low-energy silts and sands rich in molluscan shells. Brackish-lagoonal ostracod species (*Cyprideis torosa*), with minor peaks of marine-lagoonal (*Loxoconcha* spp.) and coastal (*Aurila convexa*, *Aurila woodwardii*) taxa characterize the unit. Fine-grained sediments and brackish and marine-lagoonal faunas translate shallow, low-energy water bodies during this period. Shelter was afforded by Tyre's elongated sandstone island, which acted as a 6-km shore-parallel breakwater (Fig. 3).

Core T18 was drilled between Tell Mashuk and El Bass and constitutes the oldest portion of the continental salient *sensu stricto*. Two contrasting facies retrace the inception and progradation of the tombolo margin. The clay substratum is transgressed by fine-bedded marine sands dated ≈6000 B.P. Rapid beach ridge accretion is recorded with ≈1 m of sediment accumulation during a 300-year period. Marine-lagoonal (*Loxoconcha* spp., *Xestoleberis aurantia*) and coastal (*Aurila convexa*, *Pontocythere* sp., *Urocythereis* sp.) ostracod taxa characterize the facies. After 5500 B.P., transition from marine sands to choked lagoon sediments corroborates accretion of the salient with isolation of the spit lagoon. Such rapid coastal progradation is typical of the mid-Holocene stillstand regime and high sediment supply. Given the density of archaeological sites in the vicinity of these lagoon deposits (Tell Mashuk, Tell Chawakir), we posit that the area served as a natural anchorage for the Bronze Age settlers of Palaeo-Tyre.

Pre-Hellenistic Proto-Tombolo Phase. Between 8000 B.P. and 6000 B.P., the island dimensions were reduced from 6 to 4 km. Coarse sand and gravel transgressive deposits breached the leeward bay after ≈6000 B.P. Our data suggest that sea-level stillstand after this time was the most important factor in the initial development of Tyre's tombolo. A sharp decline in *C. torosa* is countered by peaks of coastal ostracod species. Outer marine taxa, including *Semicytherura* spp., *Callistocythere* spp., and *Neocytherideis* spp., attest to an important opening up of the environment.

We simulated the diffraction of the swell around Tyre island (Fig. 4) by using a steady-state spectral wave model (STWAVE)

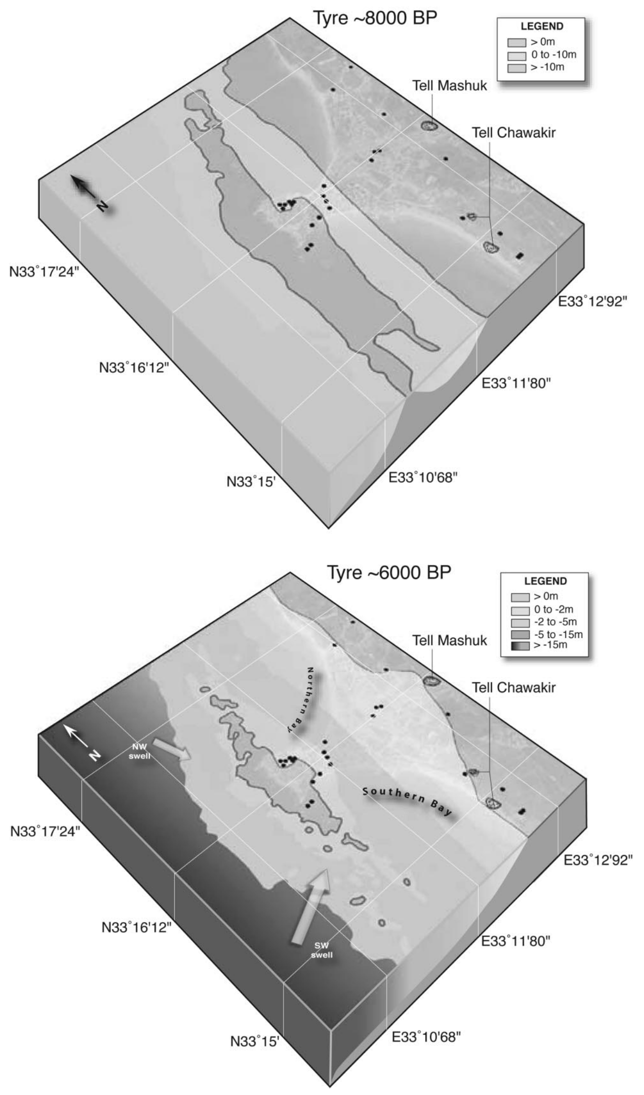

Fig. 3. Morphodynamic evolution of Tyre's tombolo between ≈8000 B.P. (*Upper*) and ≈6000 B.P. (*Lower*).

with a JONSWAP swell spectrum (27). A total of six model runs were completed for swell scenarios at 5500 B.P. and 2000 A.D. from 225°, 270°, and 315° (dominant swell direction). Wave spectrums were generated for each angle scenario by using a standard swell height of 2.6 m with a period of 6 s. The incoming swell, which is initially quasi-unidirectional (225°, 270°, or 315°), is spread by the lateral movement of energy into the shadowed area behind Tyre island. Projections at 5500 B.P. indicate that the majority of the swell incident energy is blocked by the natural north–south trending breakwater. As the wave energy that passes the obstacle spreads laterally into the shadow region, the total energy is distributed over a broader area, reducing the reconstructed swell height leeward of the island from >1.80 m west of the breakwater to <0.75 m on the eastern shadow side (Fig. 4). This shadow generated a significant natural shelter zone for deposition of sediment tracts. Our core transect falls in an area of very low estimated wave height (≈0.40 m), evoking the rapid accretion of the marine bottom. We conclude that the early accretion of the proto-tombolo took place in two areas: (*i*) along the continental margin of Palaeo-Tyre, the sedimentological data show that limited accommodation space led to the rapid progradation of a subaerial salient strandplain. This conclusion is corroborated by low wave heights along the coastal fringe; and (*ii*) in the wave shadow behind Tyre island, the models show a sharp fall in energy accompanied by a concomitant marine bottom shallowing.

A slowdown in sea-level rise permitted reworking of older sediments and introduction from land of Holocene continental sediments. Rapid rates of sedimentation (>0.3 cm/yr) after 3000 B.P. appear coeval with the anthropogenically forced erosion of surrounding watersheds, yielding increased sediment supply to coastal depocenters (Fig. 5). Climate records from the Levantine basin indicate transition to a cool wet climate during the Late Bronze Age/Early Iron Age and the Late Roman/Byzantine periods (28–32). The expansion of agriculture and human modification of surrounding watersheds, coupled with periods of increased mountain precipitation, notably between 3500–3000 B.P. and 1700–1000 B.P. (30), would have entrained increased amounts of sediment to base-level depocenters.

Wave diffraction and a fall in water competence engendered medium to fine-grained sediment deposition on the lee of the island barriers, culminating in a natural wave-dominated proto-tombolo within 1–2 m of mean sea level by the time of Alexander the Great (4th century B.C.; Fig. 6). High relative abundances of marine lagoonal and coastal taxa corroborate a middle-energy shoreface protected by the island; during Hellenistic times Tyre island had approximate dimensions of ≈2,500 m long by ≈750 m wide. Conditions conducive to the accretion of a proto-tomobolo are supported by our modeling of wave diffraction around Tyre island. Rapid spit growth may also have been amplified by earlier attempts to build a causeway on this underwater proto-tombolo, notably during the Babylonian siege of the city by Nabuchodonozor II (6th century B.C.; ref. 17). Like Alexander, it is probable that Nabuchodonozor II exploited the shallow proto-tombolo in an attempt to overcome the defensive bastion, although it is equivocal whether or not he completed his ambitious sea-bridge project.

Analogous chrono-stratigraphy has been elucidated at Alexandria (33) and concurs the importance of this pre-Hellenistic proto-tombolo phase, a unique sediment corpus resulting from limited accommodation space behind the island barriers. As at Tyre, ancient Alexandria comprised a long shore-parallel island whose reconstructed Hellenistic dimensions, ≈5,500 m long by ≈1,300 m wide, are approximately twice those at Tyre for the same period. By Hellenistic times, the summit of the tombolo is inferred to have lain 1–2 m below mean sea level (34).

Anthropogenic Forcing: Causeway Impacts. The Hellenistic causeway entrained a complete, anthropogenically forced, metamorphosis of Tyre's coastal system accentuating many of the proto-tombolo genetic processes. After ≈330 B.C., the city's bays were definitively segmented into two coves; cessation of the longshore currents generated two isolated littoral cells. Stratigraphic signatures record a shift in shoreline positions characterized by rapid coastal progradation on both flanks of the tombolo. In core T14, for example, a 6-fold increase in sedimentation rates is observed after the construction of the causeway from 6 ± 2 mm/yr before the Hellenistic period to 36 ± 2 mm/yr after this time (Fig. 2). Rapid rates of coastal deformation are also recorded at Alexandria after construction of the Heptastadion in 331 B.C., when average post-Hellenistic sedimentation rates doubled from ≈10 ± 2 mm/yr to ≈20 ± 2 mm/yr (34). The high level of statistical variance observed in Tyre's sedimentological data after this period translates the profound human impacts and segmentation of the tombolo into two isolated bays. Subaerial growth of the isthmus culminated in a cessation of north–south/south–north sediment transport across the tombolo. In this way, post-Hellenistic deposits in the southern bay (T15) are clearly differentiated from northern lobe deposits (T13 and T14), consistent with two independently evolving littoral cells. Rapid subaerial growth during the Seleucid and Roman periods can be attributed to a high sediment budget. We have relatively good constraints on the nature of climatic variability at these times

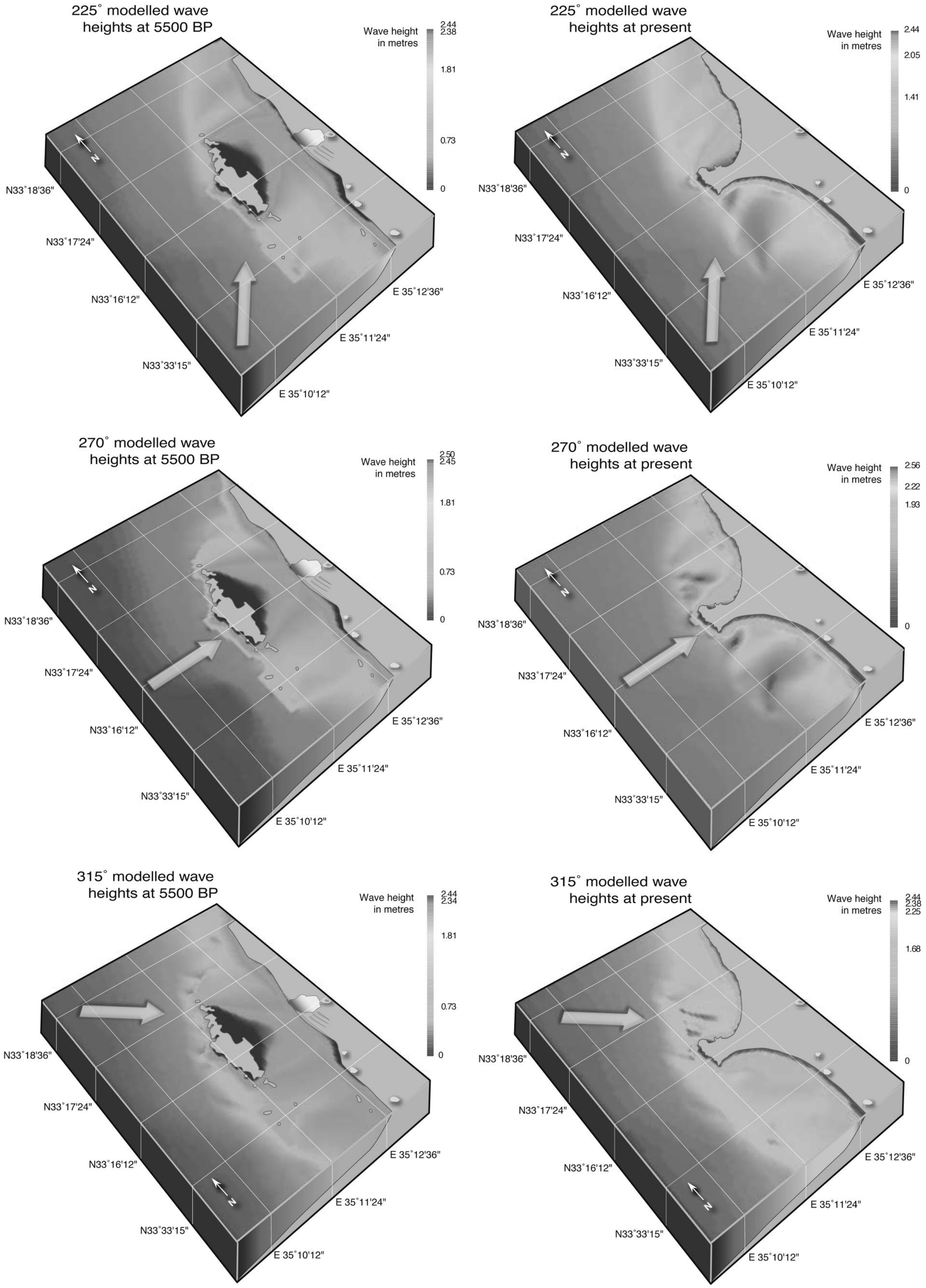

Fig. 4. Wave heights for 225° (*Top*), 270° (*Middle*), and 315° (*Bottom*) propagated swells.

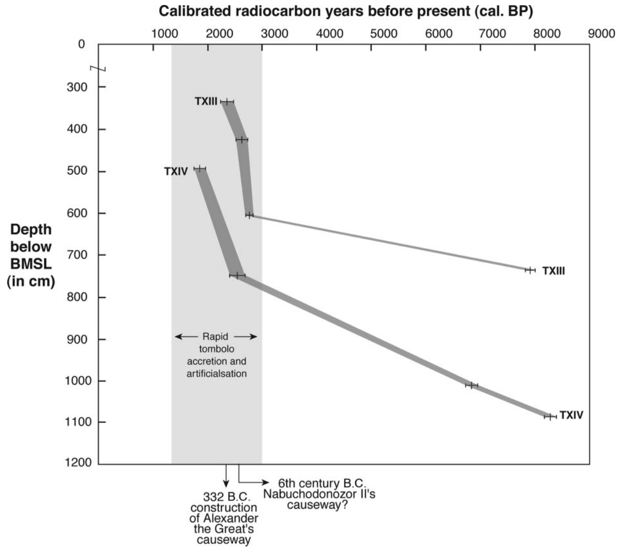

Fig. 5. Tombolo accretion rates. Rapid rates of accretion, >0.30 cm/yr, are attested to after 3000 calibrated B.P. This rapid sedimentation is attributed to anthropogenically forced erosion of surrounding watersheds, yielding increased sediment supply to coastal depocenters. Entrapment was further accentuated by Alexander the Great's artificialization of the salient during the Hellenistic period.

(29–31), concurrent with an increase in post-Hellenistic sedimentation rates by a factor of eight. During Roman times, this anthropogenically forced progradation accommodated urban growth (necropolis, hippodrome, etc.).

Conclusion

We expound a three-phase stratigraphic model of tombolo morphogenesis, comprising two natural forcing factors (geomorphic and relative sea-level change) and one anthropogenic. (*i*) Newly transgressed and protected shallow-marine environments are recorded at Tyre between ≈8000 and 6000 B.P. Natural protection was afforded by Tyre's 6-km-long Quaternary ridge. (*ii*) After 6000 B.P., decelerating sea-level rise, high sediment supply (especially after 3000 B.P.) and diffractive wave processes set up by the island obstacle engendered rapid spit growth. By Hellenistic times, we show the existence of a proto-tombolo within 1–2 m of mean sea level. (*iii*) After 332 B.C., construction of Alexander's causeway entrained a complete anthropogenic metamorphosis of the Tyrian coastal system. Rapid coastal progradation definitively segmented the leeward bay into two discrete coves.

Tyre's tombolo is an archetype example of anthropogenic forcing on Mediterranean coastal systems and stratigraphy. On a Holocene time scale, the elucidated stratigraphic evolution emphasizes the significance of geological heritage and the irreversibility of plurimillennial anthropogenic impacts in shaping coastal landforms.

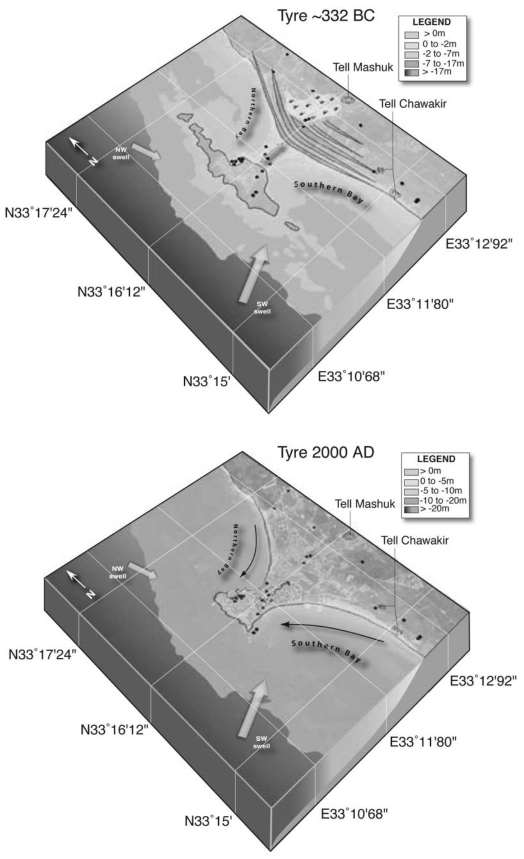

Fig. 6. Morphodynamic evolution of Tyre's tombolo between Hellenistic times (332 B.C.; *Upper*) and recently (2000 A.D.; *Lower*).

Materials and Methods

The stratigraphic data sets are based on a series of four cores (see Fig. 1), 8–16 m in depth. A north–south transect comprising cores T13–T15 was obtained with an aim to elucidate the stages of accretion of the sedimentary bodies. All cores have been leveled by global positioning system and altitudinally benchmarked relative to the present mean biological sea level. Interpretations are based on high-resolution lithostratigraphic and biostratigraphic studies of the sedimentary cores. See Marriner and Morhange (10) for detailed discussion of these methods. Radiocarbon and archaeological dates provide a chronological framework for the landforms and sedimentary bodies observed.

We thank J.-P. Goiran for assistance with fieldwork and the Directorate General of Antiquities (Lebanon), the Franco-Lebanese research program Cèdre, the Leverhulme Trust, United Nations Educational, Scientific, and Cultural Organization World Heritage, ECLIPSE (Environnement et Climat du Passé: Histoire et Évolution)/Centre National de la Recherche Scientifique, and the Association Internationale pour la Sauvegarde de Tyr for technical and financial support.

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