Late Quaternary transgressive large dunes on the sediment-starved Adriatic shelf

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Abstract: The Adriatic epicontinental basin is a low-gradient shelf where the late-Quaternary transgressive systems tract (TST) is composed of thin parasequences of backbarrier, shoreface and offshore deposits. The facies and internal architecture of the late-Quaternary TST in the Adriatic epicontinental basin changed consistently from early transgression to late transgression reflecting: (1) fluctuations in the balance between sediment supply and accommodation increase, and (2) a progressive intensification of the oceanographic regime, driven by the transgressive widening of the basin to as much as seven times its lowstand extent. One of the consequences of this trend is that high-energy marine bedforms such as sand ridges and sand waves characterize only areas that were flooded close to the end of the late-Quaternary sea-level rise, when the wind fetch was maximum and bigger waves and stronger storm currents could form.

We studied the morphology, sediment composition and sequence-stratigraphical setting of a field of asymmetric bedforms (typically 3 m high and 600 m in wavelength) in 20–24 m water depth offshore the Venice Lagoon in the sediment-starved North Adriatic shelf. The sand that forms these large dunes derived from a drowned transgressive coastal deposit reworked by marine processes. Early cementation took place over most of the dune crests limiting their activity and preventing their destruction. Both the formation and deactivation of this field of sand dunes occurred over a short time interval close to the turn-around point that separates the late-Quaternary sea-level rise and the following highstand and reflect rapid changes in the oceanographic regime of the basin.

Modern large-scale bedforms on continental shelves can form in response to oceanic currents, storm flows or tidal currents that impinge on the sea floor (Flemming 1988; Belderson *et al.* 1982; Harris 1988). Examples of active large bedforms also come from estuaries (Berné *et al.* 1993), bays (Berné *et al.* 1991) and semi-enclosed epicontinental seas (Field *et al.* 1981; Kuijpers *et al.* 1993). The recognition and sedimentological interpretation of bedforms that are inactive and drowned on modern continental margins can provide relevant stratigraphical information for reconstructing major changes in the oceanographic regime that took place during distinctive stages of the late-Quaternary sea-level rise; this is particularly important in epicontinental settings where the late-Quaternary relative sea-level rise determined not just the landward translation of the coastline but also major increases in basin extent and coastline length accompanied by possible changes in the oceanographic regime (Trincardi *et al.* 1994).

The North Adriatic epicontinental shelf (Fig. 1 inset) is sediment-starved and subject to a high-energy oceanographic regime (Cavaleri & Stefanon 1980; Mosetti 1985; Malanotte-Rizzoli 1994). This shelf is less than 30 m deep and presents a variety of bedforms that have a patchy distribution (Mosetti 1966; Brambati & Venzo 1967; Colantoni *et al.* 1979; Cavaleri & Stefanon 1980; Newton & Stefanon 1982; Correggiari *et al.* 1992). The bedforms in the North Adriatic are variable in size, are composed of sandy sediment, and rest on older alluvial lowstand or backbarrier transgressive deposits. Although several authors have pointed out the occurrence of bedforms in the Adriatic, no detailed inspection has been carried out to examine the morphology and sediment composition of any of the bedform fields.

This paper focuses on the geometry, sediment character and stratigraphical position of a small field (less than 100 km^2) of large asymmetric bedforms that occur between 20 and 24 m of water, offshore the Venice Lagoon (Figs 1 and 2). This field of large bedforms is one of the best developed of the North Adriatic and is located where the regional contour bends abruptly from ENE–WSW to about N–S (see the 20 m contour on Fig. 1). The bedforms are superimposed on one of the larger-scale reliefs that characterize the North Adriatic (Fig. 3). In this paper we call large dunes the asymmetric bedforms in the study area (see discussion in Berné *et al.* 1993) and shore-parallel mounds the underlying relief. Given the lack of current-meter data on this field of bedforms we prefer not to use a nomenclature (e.g. sand waves) that implies the knowledge of sedimentological process or a

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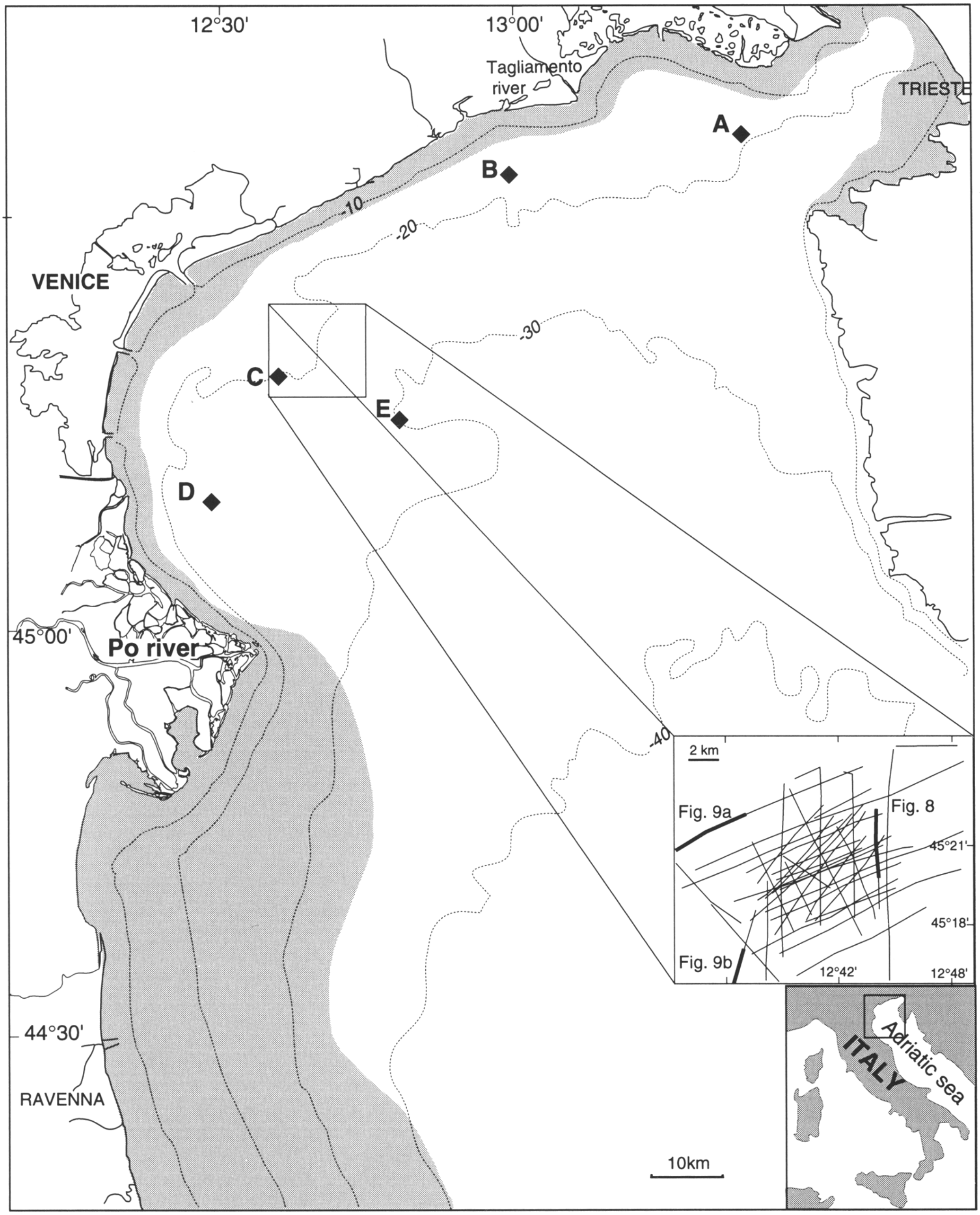
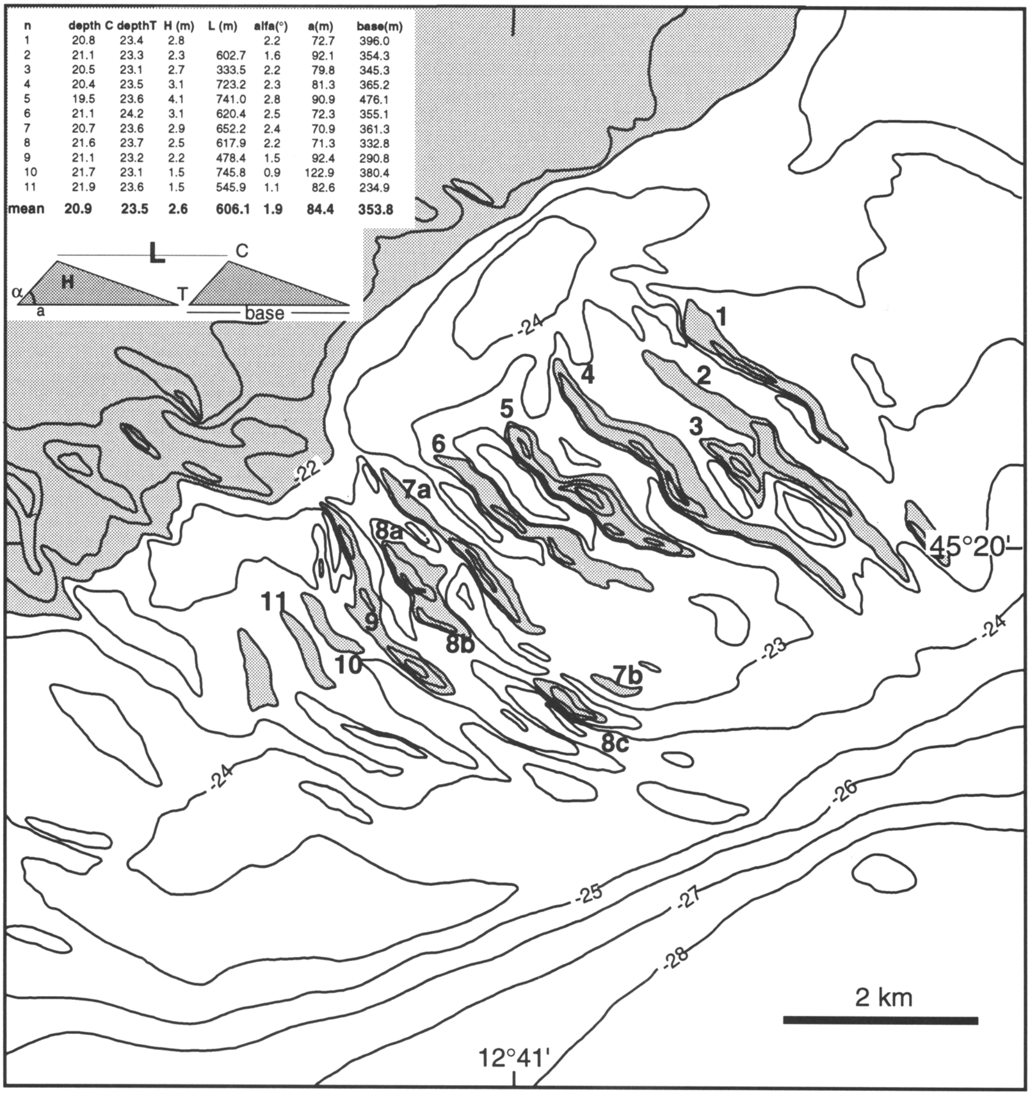


Fig. 1. Simplified bathymetry of the North Adriatic; regional contours are in metres. North of the Po delta, the highstand systems tract (HST; shaded area) consists of extensive barrier-lagoon systems, is undersupplied and shows a limited seaward extent. South of the Po delta the offshore extent of HST is greater. The inset shows the grid of seismic profiles collected in 1990 and 1991 in the study area. Capital letters denote other areas of the North Adriatic basin where the sea floor is characterized by bedforms of varied size: A, from Mosetti (1966); B, from Cavaleri & Stefanon (1980); C, bedforms in Fig. 9a,b; D, unpublished data of the Istituto per la Geologia Marina; E: sand ribbons, from Newton & Stefanon (1982). A B and C occur in water depths shallower than in the study area; D is in 20–25 m water depth; and E is in about 30 m of water.



n	depth C	depthT	H (m)	L (m)	alfa(°)	a(m)	base(m)
1	20.8	23.4	2.8		2.2	72.7	396.0
2	21.1	23.3	2.3	602.7	1.6	92.1	354.3
3	20.5	23.1	2.7	333.5	2.2	79.8	345.3
4	20.4	23.5	3.1	723.2	2.3	81.3	365.2
5	19.5	23.6	4.1	741.0	2.8	90.9	476.1
6	21.1	24.2	3.1	620.4	2.5	72.3	355.1
7	20.7	23.6	2.9	652.2	2.4	70.9	361.3
8	21.6	23.7	2.5	617.9	2.2	71.3	332.8
9	21.1	23.2	2.2	478.4	1.5	92.4	290.8
10	21.7	23.1	1.5	745.8	0.9	122.9	380.4
11	21.9	23.6	1.5	545.9	1.1	82.6	234.9
mean	**20.9**	**23.5**	**2.6**	**606.1**	**1.9**	**84.4**	**353.8**

Fig. 2. Detailed bathymetry of the sand-dune field in the study area; contours are at 1 m intervals. Shading denotes areas that are shallower than 22 m. Note that the main field of bedforms belongs to an elongated shore-parallel mound that is delimited landward by an erosional trough. The inset summarizes the main geometric parameters for each of the main bedforms in the study area. Values are averaged from measurements taken from several profiles across each bedform.

genetic interpretation (Allen 1980; Belderson *et al.* 1982; Robin & Hunter 1982).

Methods

The data base on the dune field offshore the Venice Lagoon comprises approximately 480 km of 3.5 kHz high-resolution seismic-reflection profiles and 250 km of Uniboom profiles collected during two cruises in 1990 and 1991 (Fig. 1, inset). Profiles were recorded at time intervals of 0.25 s; firing and recording intervals of Uniboom profiles were 0.25 and 0.125 s respectively. Vertical resolution is on the order of 0.5 m in both kind of profiles. Navigation was based on GPS (global positioning system), and absolute positioning errors are less than 50 m. Ridges were defined through a detailed bathymetric map contoured at 0.5 m and plotted at 1 m intervals after corrections

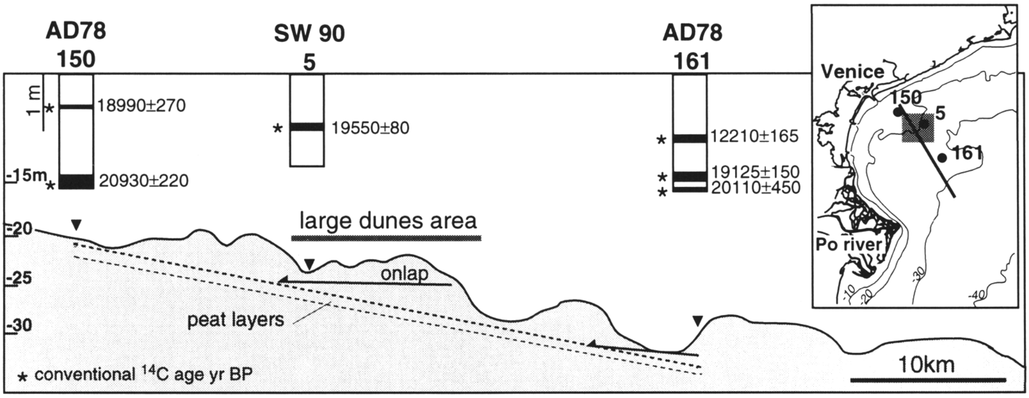


Fig. 3. Bathymetric profile showing extensive peat layers that originated during lowstand times and were drowned and transgressed during the late-Quaternary relative sea-level rise. In the North Adriatic, backstepping transgressive deposits form broad shore-parallel sediment mounds and troughs. The profile shows the location of sediment cores that contain ^{14}C-dated peat layers and the position of the sand-dune field discussed in this paper.

for velocity of sound in water and for tides. Sedimentological data on the large dunes came from four vibrocores; unfortunately, coring in the crests provided less than 1 m recovery. Gravity cores come from both the study area and the rest of the North Adriatic and allow dating and regional correlation of two peat horizons. About 30 box cores provide information on main variations in surface-sediment grain sizes on crests and troughs.

The Adriatic basin and the late Quaternary sea-level rise

Shelf morphology and surface-sediment distribution

The Adriatic Sea represents the largest (800 × 200 km) low-gradient epicontinental shelf in the Mediterranean area and corresponds to the Plio-Quaternary foreland basin of the Apennine chain. The thickness distribution of the late-Holocene highstand systems tract (HST) shows that modern deposition occurs south of the Po river delta, the main sediment entry point to the basin, and does not extend seaward more than 25 km from the modern coastline (Fig. 1) (Trincardi *et al.* 1994). Mean suspended-sediment discharge from modern rivers is negligible on the eastern side of the basin, very small in the north (where rivers deliver only 0.3×10^7 ton/year) and maximum on the western side of the basin, where the Po river and several smaller Apennine rivers provide a total of 3.9×10^7 ton/year (Frignani *et al.* 1992). The difference in sediment discharge rates north and south of the Po delta results in two contrasting regimes (Thorne & Swift 1991): river-mouth bypassing occurs where muddy sediment fed by the Po river as well as by other Apennine rivers escapes the shoreface and builds a prodelta wedge that is up to 20 m thick; on the contrary, in the north portion of the basin the shelf is sediment-starved, and modern rivers discharge into coastal-plain lagoons or build muddy prodelta wedges that are only a few metres thick (e.g. Tagliamento river; Fig. 1 and Stefanon 1979).

The modern sediment dispersal determines two distinct morphologic domains in the Adriatic epicontinental shelf: south of the Po delta and close to the western coast, the shelf floor is smooth and dips gently seaward; further offshore a rugged surface shows a variety of sediment mounds and ridges that are a few metres in relief and several kilometres in extent. This irregular sea floor extends close to the modern shoreface north of the Po delta and shows evidence of smaller-scale bedforms of varied orientation and geometry (Fig. 3).

The regional bathymetric gradient in the area north of the Po delta, if local roughness is averaged out, is less than 0.4 m/km and is the lowest in the Adriatic basin. The sea floor in this sector of the basin is mantled by a thin veneer of shelly sand between 10 and 50 cm thick (Colantoni *et al.* 1979; Trincardi *et al.* 1994). This veneer, which includes fragments of marine shells, fines upward and rests on a sharp erosional surface (ravinement surface; Trincardi *et al.* 1994). No gravel-size or pebbly lags are associated with the ravinement surface in any of the cores collected in the study area, or in the rest of the North Adriatic basin. This fact indicates that the depositional environments trans-gressed during the late-Quaternary were dominated by fine-grained sediment in a low-gradient alluvial plain.

Modern oceanography

The modern Adriatic sea is storm-dominated, microtidal and characterized by a cyclonic thermohaline circulation that forces riverine waters to flow southwards against the western side of the basin (Malanotte-Rizzoli 1994). The land-locked position, freshwater runoff and strong winter cooling of the sea surface control the formation of dense waters that flow to the south along the western side of the basin (Malanotte-Rizzoli & Bergamasco 1983; Malanotte-Rizzoli 1994).

The oceanographic setting of the North Adriatic is dominated by the following factors:

(1) tides – not generated by the direct action of gravity tidal forcing but depending on co-oscillation with Ionian Sea tides (Franco *et al.* 1982);
(2) seiches – associated with intensive winds from the SE accompanied by the passage of cyclonic areas on the Adriatic. Seiches may have diverse periods, the most important being that with 22 hour periodicity. During storm surges seiches can increase in amplitude to more than 80 cm;
(3) storm-generated currents and waves – set-ups in the north end of the basin can be in the order of 1 m (Franco *et al.* 1982). Waves up to 6 m in amplitude have periods in the order of 12 s. During November 1966 storm tide reached 1.9 m in the Venice Lagoon (Seibold & Berger 1982). During this event horizontal velocities of 112 cm/s may have developed in 22 m water depth by exceptional storm waves (Stefanon 1979).

During winter the North Adriatic is characterized by a two-gyre system driven by the vorticity input from a strong katabatic wind (named Bora) that blows offshore from the NE (Zore-Armanda & Gacic 1987). During winter the water mass in the North Adriatic is homogeneous and therefore the vertical shear is negligible so that the wind-induced transport is in the direction of the surface flow (Zore-Armanda & Gacic 1987). As a consequence, a cyclonic gyre has a shore-parallel component that affects the entire water mass in the shallow North Adriatic basin and in the study area.

Transgressive stratigraphy

Within the Adriatic basin, the late-Quaternary transgressive systems tract (TST) and related bounding surfaces show contrasting sedimentological expressions in cores and high-resolution seismic profiles taken from the central and deepest portion of the basin to the north (Trincardi *et al.* 1994). Low shelf gradients and decreasing sediment input relative to increasing basin size, favoured large landward shifts of the shoreline and resulted in the deposition of telescoped but thin transgressive parasequences. Following Thorne & Swift (1991) it is possible to split the late-Quaternary TST into its two basic components: the backbarrier and the marine components, separated by the ravinement surface. Where one of the two components is missing, the ravinement surface merges with either the underlying transgressive surface or the overlying maximum flooding surface (Trincardi *et al.* 1994; Saito 1994). The backbarrier wedge in the North Adriatic the late-Quaternary TST is typically a few metres thick and consists of a variety of backbarrier deposits truncated by the ravinement surface. In cores, the ravinement surface appears covered by a thin veneer of transgressive marine sands (Trincardi *et al.* 1994). The backbarrier wedge is thicker and more widespread in the basin sectors located south of the modern Po delta. The marine wedge above the ravinement surface corresponds either to muddy deposits under the influence of major rivers or to sandy deposits that are shaped into bedforms away from river inputs (Fig. 3).

Large dunes in the North Adriatic basin

Morphology

The bathymetric map of the area located 20 km SE of Venice contoured at 1m interval reveals a ridge-and-swale morphology in 20 to 24 m water depth (Fig. 2). The sand dunes rest on a large shore-parallel mound that is bounded landward by an elongated trough (Figs 2 and 3). Crest sinuosity is low and individual dunes are up to 2 km long and extend across the entire width of the underlying mound to the edge of the shore-parallel trough (Figs 4 and 5).

The large dunes are strikingly constant in length, shape, height, orientation and asymmetry (Figs 2 and 4). The spacing between them varies from 330 to 745 m; their height varies from 1.5 to 4.1 m. The orientation of the large dunes is NW–SE and normal to the regional contour; the dunes are relatively wide and

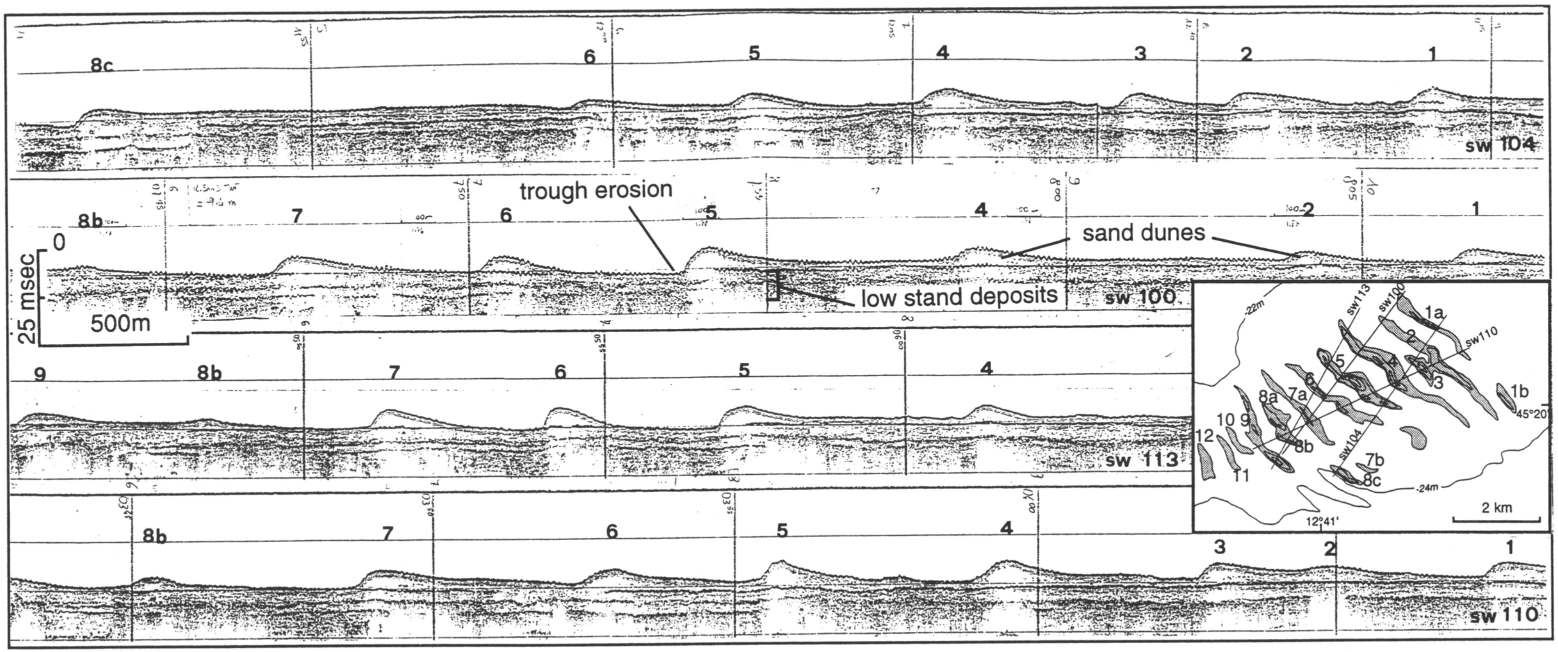


Fig. 4. High-resolution 3.5 kHz profiles across the dune crests document the lateral continuity of these features (numbers denote crests). The inset shows the tracks of profiles relative to the numbered bedforms. No internal surfaces can be detected within the dune crests; these features are undersupplied and erosion is evident in some of the troughs. Subhorizontal reflectors occur beneath the dune field and correlate throughout the study area. The shallowest reflector at the base of the dune field corresponds to a peat horizon, dated in three different sites in the study area (Fig. 6). This layer originated close to the 18-ka sea-level lowstand and occurs within fluvial deposits.

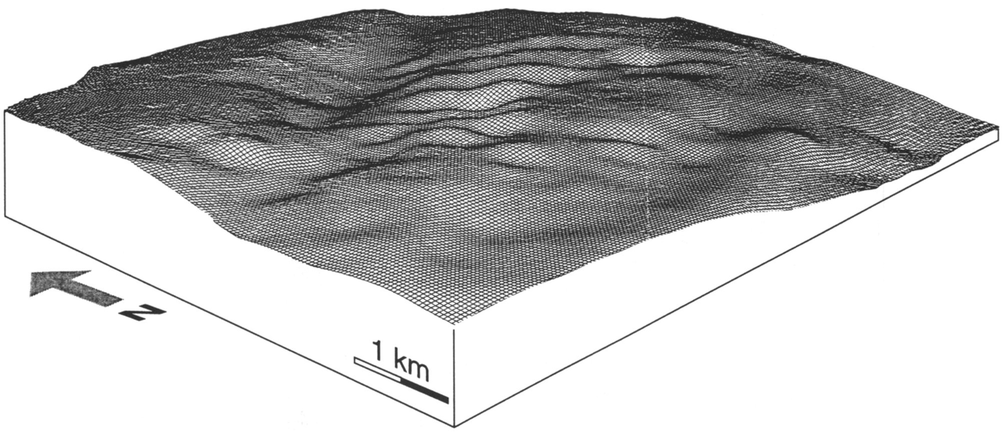


Fig. 5. Mesh diagram of the bathymetry in the study area (Fig. 1 inset), showing that the sand-dune field is superimposed on a larger-scale mound; this mound is roughly parallel to the regional contour and to the modern coastline. Note the shore-parallel trough on the landward limit of the bedform field.

markedly asymmetric with lee-side slopes of 0.9° to 2.8°, facing to the SW. The large spacing between dunes (Fig. 2) probably indicates that a reduced amount of sandy sediment was available. Furthermore, seismic profiles show clear evidence of erosion in some of the troughs; where erosion occurs, the uppermost regionally extensive peat layer is missing (Fig. 4). Trough erosion provides an additional source of sand to the dune field from the underlying fluvial sediments. A field of modern subtidal bedforms in the Bay of Bourgneuf is characterized by similar trough erosion; in this case the internal structure of the dunes is resolved and indicates climbing at a negative angle (Berné *et al.* 1991).

Sedimentology

Over two troughs and two crests we analysed 28 sediment samples that show grain sizes from fine to medium sand. Figure 6 shows schematic sedimentological logs of cores collected along one crest and the adjacent troughs; grain-size analyses were performed on both crest and trough samples. Figure 7 shows a scattergram that relates the graphic mean grain size versus sorting for all the samples: surficial sand samples from the upper 10 cm in the troughs are coarser and poorly sorted while the crest population is finer and moderately well-sorted. Within the 1 m of sand collected in the crest, however, this plot does not show major vertical trends in grain size. The coarser grain size in the trough population results from a more abundant bioclastic component while the lack of sorting is enhanced by the recycling of finer sediments from the units beneath.

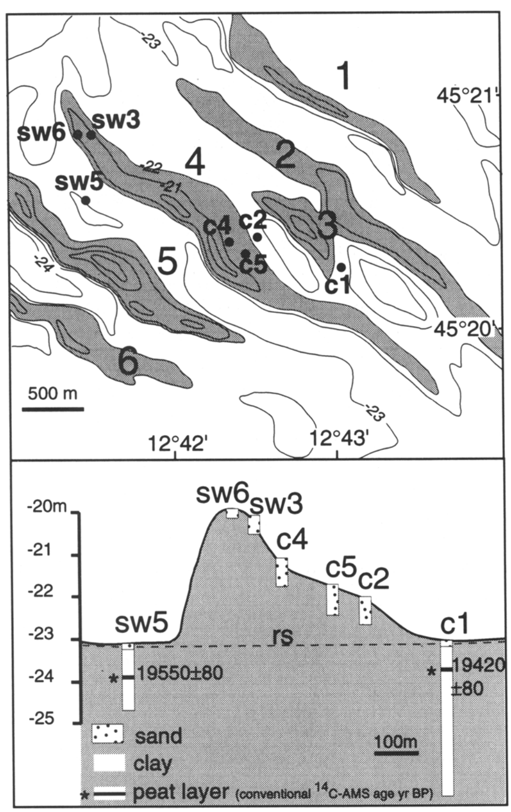


Fig. 6. Bathymetry of the central portion of the study area and location of cores recovered from the crest of dune 4 and the adjacent troughs. Sedimentological logs are projected on a schematic bathymetric profile. Note that the peat layer in cores SW 5 and C1 is about 19 ka old and belongs to the lowstand systems tract (LST). 'rs' denotes the coinciding transgressive and ravinement surfaces.

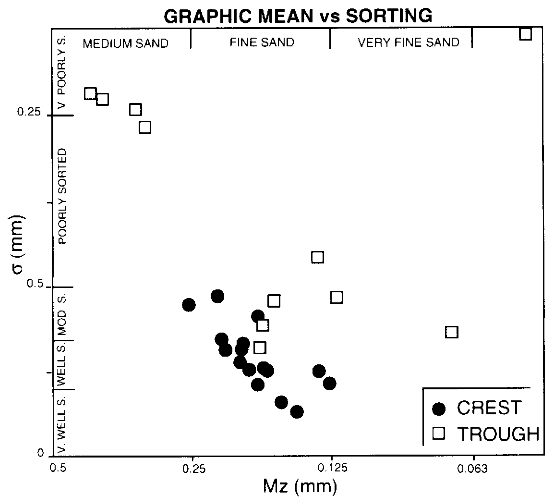


Fig. 7. Scattergram showing the grain size (graphic mean) versus sorting of surficial sediments. The crest population (filled dots) appears more sorted than the trough population (hollow squares).

The sand is lithic with quartz fragments and feldspars; the biogenic component is made of marine shell fragments, calcareous algae and serpulids; plant debris derived from *Poseidonia mattes* has been found as well. Coarse shell lags form in the trough, while the dune crests appear irregularly cemented. Foraminifera are rare (*Elphidium Crispum* and *Ammonia Beccarii*) but confirm that the sand ridges were reworked in a marine environment. The evidence of patchy cementation and the finding of *Poseidonia* roots on the ridge flanks indicate that the ridges are not active. The lack of any mud drape on top of the ridges is consistent both with the occurrence of starved conditions and with the effects of high-energy events. The occurrence of current ripples on some of the ridge crests (Colantoni & Gallignani 1980) indicates that during modern highstand conditions the ridges may be affected by exceptional storm flows, as suggested by Cavaleri & Stefanon (1980).

Stratigraphy

Laterally persistent subbottom reflectors identified in the seismic records below the sand ridge field are nearly horizontal or gently dipping to the south. Sediment cores provide some basic information on the nature and age of the units that lie immediately below the sand ridges (Figs 3, 6 and 7). These units were cored in the troughs, where the transgressive sand sheet is only about 10 cm thick; the sediment is a very fine-grained massive sand (0.09 mm); the sand is light grey, lithic and bears no evidence of biogenic content. Peat horizons are present within this massive sand and correlate throughout the entire study area; the shallowest regionally extensive peat horizon is found between a few metres and 80 cm below the sea floor (Figs 3 and 6). This correlatable peat layer is 19 ka old and was deposited in an alluvial plain environment, during the last glacial lowstand of sea level. The occurrence of this and other slightly older peat layers at shallow depths below the sea floor confirms that the study area was undersupplied during the following transgression. The peat layers that were deposited close to the last glacial maximum extend landward under the modern Venice Lagoon and are buried by coastal or paralic deposits of the HST that are younger than 5 ka (Fontes & Bertolami 1973; Trincardi *et al.* 1994). The gap in dates between 19 and 5 ka under the modern coastline deposits is derived from transgression under sediment-starved conditions and, from a sequence stratigraphical point of view, corresponds to the coinciding transgressive, ravinement and maximum flooding surfaces (Trincardi *et al.* 1994).

The shallowest peat horizon encountered in cores corresponds to a flat reflector that is weak in acoustic character and discontinuous laterally. The peat horizon is around 11.7 ka old and occurs only in the vicinity of the base of major sand ridges that helped prevent its erosion. The peat layer can also be correlated outside the study area in the North Adriatic (Colantoni *et al.* 1979); this layer, however, does not extend landward to water depths shallower than about 20 m indicating an onlap termination onto the older lowstand deposits (Fig. 3). The 11.7 ka old peat was deposited in an alluvial plain that was time-equivalent to a coastline located several tens of kilometres seaward in about 50 m of water, based on the published sea-level curves for the late-Quaternary (Fairbanks 1989).

A deep channel follows the northeast edge of the sand ridge field and can be traced for about 7 km; the thalweg is up to 10 m deep and about 100 m wide. The channel appears highly sinuous and presents a composite fill consisting of both lateral accretion (point bar?) and passive aggradation (Fig. 8). The flanks of the channel flatten under the ravinement surface indicating that this erosional feature belongs to the fluvial drainage system that originated across the Adriatic shelf close to the last glacial maximum. Smaller-scale erosional features are found below the sand ridge field; they are less than 2 m deep and filled by lateral accretion on low-angle beds. The fill consists of very fine sand and may represent an extra source of material for the ridges on this sediment-starved shelf environment.

Other fields of bedforms in the starved North Adriatic basin

Figure 1 reports all the available evidence of bedforms from the North Adriatic. Sand ridges and smaller-scale bedforms dominate the sea floor in water depths both deeper and shallower than in the study area (Fig. 9a, b). In water shallower than in the study area, bedforms of smaller size have a shore-normal orientation (A in Fig. 1 from Mosetti 1966). East of the study area, in water depths between 15 and 20 m large-scale bedforms have relief up to 3 m and spacing from 80 to 200 m (B in Fig. 1 from Newton & Stefanon 1982); their orientation is shore-normal (350°), the lee side dips westward, and the crests are capped and probably stabilized by patches of dead *Poseidonia* roots (Newton & Stefanon 1982). In deeper water, the transgressive deposit is reduced to a gravelly shell lag and is moulded into megaripples (Cavaleri & Stefanon 1980); periodic lineations spaced between 15 and 20 m and parallel to the coast are also found in 29 m water depth on hard and cohesive sea floor (E in Fig. 1 from Cavaleri & Stefanon 1980).

Starved bedforms on late-Quaternary shelves

The sand dunes present an unusual geometry given the water depth where they occur (20 to 24 m); the low height/width ratio seems to reflect the limited amount of sand available for the dunes and is consistent with the evidence of concurrent erosion in the troughs (Fig. 4); comparable trough erosion also occurs in other bedform fields outside the study area (Fig. 9a). Modern continental margins show several examples of bedforms that formed in sediment-starved environments close to the establishment of the modern high sea-level conditions. Figure 10 shows the empirical relation between bedform height and wavelength established by Flemming (1988); on this plot the sand ridges offshore Venice constitute an end member in which the wavelength is very large compared to other examples; smaller bedforms in the Adriatic basin, but in shallower waters, fall closer to the typical population. The large bedforms in the study area present a greater spacing because of the small amount of sand available. Where a limited volume of sand is available, bedforms evolve independently of the adjacent bedforms and appear isolated by the occurrence of flats (Perillo & Ludwick 1984); solitary bedforms observed in modern estuaries on low-gradient coastal plains are comparable in size and water depth to those observed in the study area (Aliotta & Perillo 1987).

In the Skagerrak basin at the entrance of the Baltic epicontinental sea, active bedforms are comparable to those observed in the study area; they are between 3 and 5 m high and show wavelengths of 250–600 m. These large-scale bedforms are attributed to non-tidal surge currents (Kuijpers *et al.* 1993), a mechanism that may have affected the sea floor in the North Adriatic. In the North Bering epicontinental shelf, large bedforms evolve under the influence of coast-parallel currents enhanced by wind forcing during storms (Field *et al.* 1981).

Discussion

The North Adriatic basin is a starved shelf setting where lowstand continental deposits are veneered by a transgressive sand lag that is only a few tens of centimetres thick. Where the thickness of the transgressive deposit increases, bedforms of various size and orientation are encountered. In contrast to the area just south of the Po delta, the North Adriatic basin does not show evidence of widespread and relatively thick backbarrier deposits in the late-Quaternary transgressive record (Colantoni *et al.* 1990; Trincardi *et al.* 1994). By studying the morphology, sediment composition and stratigraphical setting of one of the best developed fields of bedforms in the North Adriatic we have tried to answer two related questions:

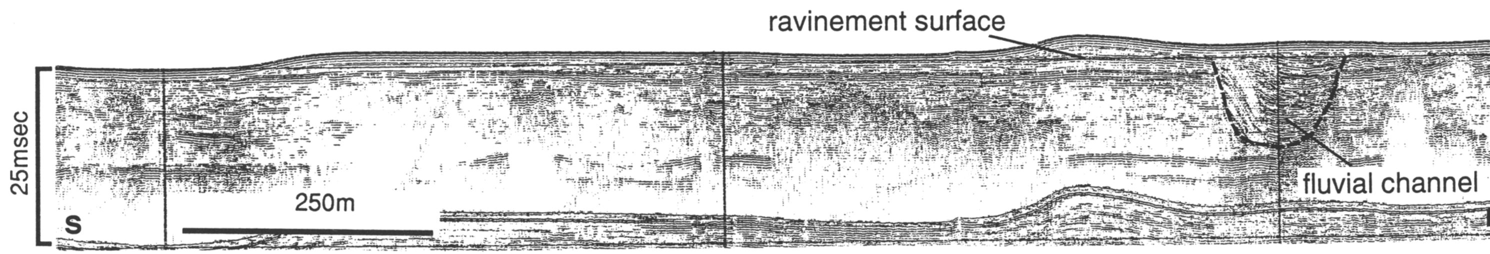


Fig. 8. High-resolution 3.5 kHz profile (located in Fig. 1 inset) showing a channel-fill deposit along the north and eastern edges of the dune field.

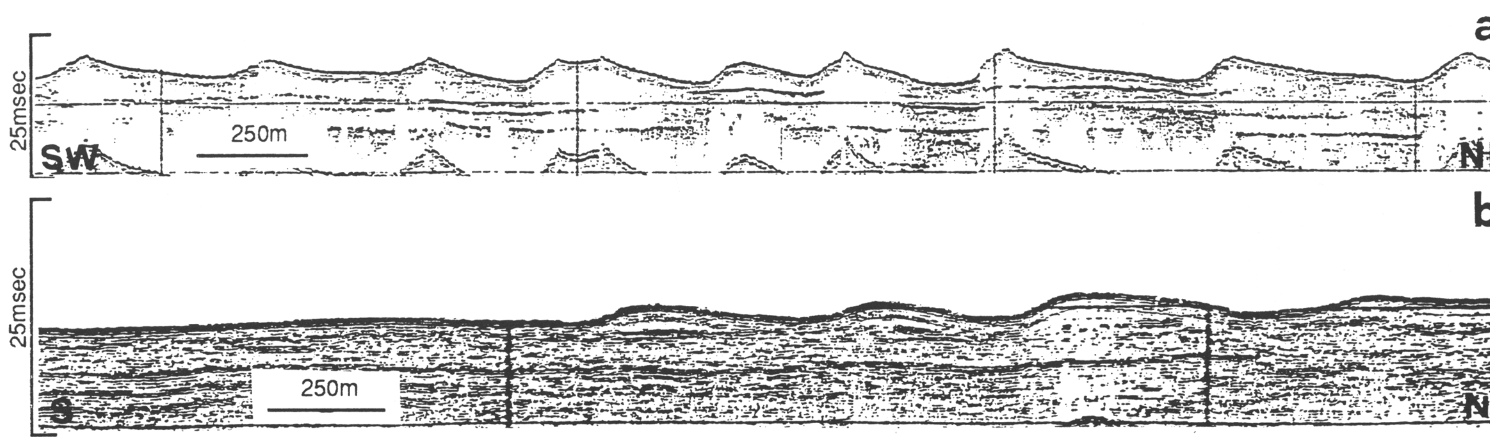


Fig. 9. Fields of asymmetric sand bedforms adjacent to the study area (see Fig. 1 for location) in shallower water (**a**), and in water depths comparable to those in the study area (**b**).

Location(reference)	spacing L(m)	height H(m)	water depth(m)
Torres Strait - Australia (Harris 1988)	80-750	2-6	16-18
Bass Strait - Australia (Malikides et al., 1989)	370	9	26-35
Adolphus Ch. - Australia (Harris, 1989)	102	3.9	20
Skagerrak Sea - Denmark (Kuijpers et al., 1993)	250-600;800-900	3.5-7	20-75
Chesapeake Bay (Perrillo and Ludwick, 1984)	200	2.1	10
Alabama Shelf - USA (Parker, 1992)	500	2	16-22
Long Island Sound - USA (Fenster et al., 1990)	118-300	4-12	35-90
Gironde Estuary- France (Berné et al., 1993)	37-182	1.5-6.7	15-25
Chesapeake Bay- USA (Ludwick, 1972)	60-245	1.5-3.4	3-18
Cook Inlet - Alaska (Bouma et al.,1980)	100-500	5-9	25-120
North Adriatic Shelf - Italy (Cavaleri and Stefanon, 1980)	80-200	1-3	20
North Adriatic Shelf - Italy **This study**	**330-745**	**1.5-4.1**	**23**

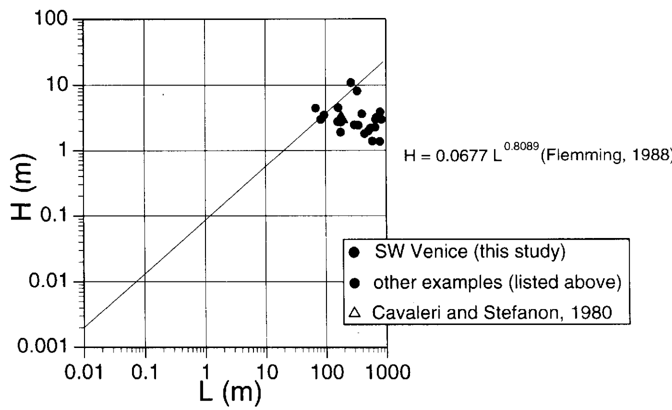


Fig. 10. Empirical relation between height (H) and wavelength (L) after Flemming (1988); on this kind of plot the sand dunes offshore Venice (black circles) clearly constitute an end member with larger spacing than in other examples because of the scarcity of sand available. Smaller bedforms in the Adriatic basin (white circles), but in shallower water depths, appear closer to the typical curve (from Cavaleri & Stefanon 1980). Examples of other large flow-transverse bedforms in shallow water on modern continental shelves are listed above, for comparison.

(1) what was the source of the sand on this sediment-starved epicontinental shelf where lowstand continental deposits are encountered within 1 m below the sea floor? and
(2) what are the mechanism and the timing of formation of these unusual bedforms relative to the late-Quaternary sea-level rise?

Two different kinds of sources may explain the accumulation of the sand that is necessary to create the observed bedforms: the breaching through lowstand alluvial plain deposits that underlie the transgressive surface by storm flows, or the drowning of a transgressive coastal sediment body. Evidence for both interpretations was found in late-Quaternary deposits on other continental margins (Stubblefield & Swift 1976; McBride & Moslow 1991). The first hypothesis requires an original ridge-and-swale morphology formed at the leading edge of the transgressive sand sheet and implies subsequent downcutting and removal of the sand from the troughs (Stubblefield & Swift 1976); downcutting stops and lateral erosion takes over when a deeper cohesive clay bed is encountered (Stubblefield & Swift 1976). In the study area this interpretation is consistent with the evidence of erosion in the troughs and would explain the unusual spacing of the large dunes for the limited water depth. However, the second hypothesis explains better why the sand dunes are superimposed on a larger shore-parallel mound (Figs 2 and 5); this large-scale relief could represent the legacy of a drowned coastal lithosome as a delta-front bar, a littoral spit or an ebb-tidal delta. In this scenario, the lithosome was drowned by the continuing transgression and since that time was progressively reworked into a ridge-and-swale topography. Shoreface attached and detached sand dunes are found along several modern coastal plain shelves either under the influence of major delta systems (Penland *et al.* 1988) or on sediment-starved barrier-island coasts (Field 1976; McBride & Moslow 1991; Siringan & Anderson 1993). In these settings significant amounts of sand are concentrated on the inner shelf by a variety of possible mechanisms that are commonly associated with the construction of river or ebb-tidal deltas (Siringan & Anderson 1993). Estuarine backfilling during sea-level rise may be accompanied by deposition in a delta-front environment; delta front deposition controls the formation of positive reliefs that rest over buried fluvial channels (Johnson *et al.* 1982). Studies on the Middle Atlantic shelf revealed the control of ancestral (lowstand) rivers on the thickness of the late-Quaternary transgressive sand sheet and thus, more indirectly, on the possible growth of bedforms (Knebel 1981).

In the North Adriatic the asymmetric dunes represent flow-transverse bedforms with the lee side facing consistently to the southwest. The orientation of these and other bedforms in the basin appears consistent with the shore-parallel circulation pattern that can be observed today; this pattern was established after the area was transgressed and drowned by the sea. The depth-average velocity required to produce sand waves like those observed in the study area is about 40 to 80 cm/s (from Rubin & McCulloch 1980). This velocity can occasionally be reached even today in the North Adriatic sea during exceptional storms or combined high tides and storm surges (Stefanon 1979; Mosetti 1985); however, storms of lower intensity but higher recurrence interval were probably capable of remoulding sand on the sea floor soon after drowning of the area but before the modern highstand was attained (Cavaleri & Stefanon 1980).

We suggest that the shelf has evolved to its present state through the succession of three discrete steps controlled by rising sea level and the onset of the modern hydraulic regime (Fig. 11): (1) the emplacement of a transgressive lithosome, (2) its drowning and marine reworking into a field of sand dunes and (3) the subsequent drowning of the reworked lithosome and its stabilization by early cementation and growth of *Poseidonia mattes*; these three steps all occurred in a short time interval close to the end of the late-Quaternary sea-level rise (Fig. 11).

The large dunes found in 20–24 m water probably formed after the modern circulation pattern was established in response to the substantial widening of the basin driven by the

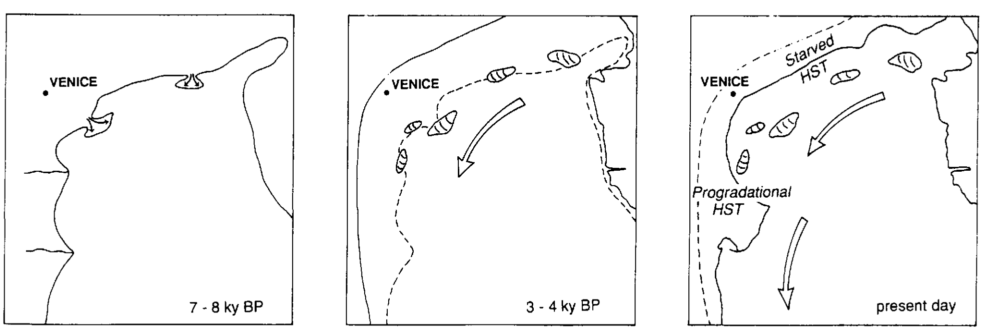


Fig. 11. Schematic reconstruction of the latest portion of the late-Quaternary sea-level rise and highstand in the North Adriatic shelf. Patches of bedforms formed wherever concentrations of sandy material were available along the shoreline. Left: ebb-tidal deltas and fluvial deltas provide concentrations of sand along the 7–8 ka shoreline. Centre: shoreline at time of maximum flooding (*c.* 3–4 ka BP): sand bodies are drowned and reworked into large dunes or smaller bedforms. Right: HST deposition reflects varied sediment input along the North Adriatic coast: where the HST is undersupplied, the sea-floor topography reflects the occurrence of reworked transgressive deposits.

late-Quaternary sea-level rise (Trincardi *et al.* 1994). However, the evidence of early cementation and the occurrence of dead roots of *Poseidonia* on their crests suggest that these features are not active during the present highstand. This observation implies that remoulding of sediment by marine processes into bedforms was most effective in the North Adriatic Sea for four concurrent factors that were maximized close to the turn-around point at the end of the transgression but before the onset of highstand progradation: (1) the decreased rate at which accommodation was created allowed more response time to physical processes (waves and currents) for re-equilibrating drowned deposits into bedforms and/or erosional features; (2) the decreased sediment discharge when river base level approached its highest position close to the end of the sea-level rise enhanced the reworking of older transgressive deposits on the sea floor; (3) the maximum widening of the semi-enclosed Adriatic epicontinental basin determined a larger fetch for the winds from the southeast and a stronger thermohaline circulation; and (4) the extension of the basin to an area that was probably more strongly affected by the very strong katabatic winds from the northeast.

The last two factors, in particular, can be taken into account when interpreting transgressive responses to high-frequency relative sea-level changes in ancient epicontinental basins. Indeed, compared to pericontinental margins, where changes in the balance between relative sea-level change and sediment input result in a relatively simple landward or seaward shift of the shoreline, epicontinental seas are characterized by larger variations in both basin size, coastline length, palaeogeography and oceanographic regime.

Conclusion

The large-scale sand dunes investigated offshore the Venice Lagoon constitute one of several fields of bedforms that originated during the latest portion of the late-Quaternary sea-level rise, in the North Adriatic Sea. We suggest that the sand dunes in the study area formed from the reworking of a drowned coastal lithosome accompanied by secondary erosion in the troughs and recycling of lowstand fluvial sand. The development of this sand dune field records an increased reworking under marine conditions, compared to other coastal lithosomes that were drowned in deeper waters during earlier phases of the late-Quaternary transgression.

Transgressive reworking is maximized in the shallow North Adriatic as a result of two sets of factors: those that characterize any continental margin close to the end of a transgression and those that are specific of a transgressed low-gradient epicontinental basin. Decreased rates of accommodation space and decreased sediment supply belong to the first set of factors; the onset of a stronger oceanographic regime in response to the widening of the semi-enclosed basin belongs to the second group and may have enhanced the potential for reworking of drowned transgressive coastal deposits close to the end of the sea-level rise.

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