Journal of Coastal Research	9	2	481–493	Fort Lauderdale, Florida	Spring 1993

Geomorphological Evolution and Sedimentology of the Ombrone River Delta, Italy*

Lucia Innocenti† and Enzo Pranzini‡

†Dipartimento di Scienze della Terra
Università di Siena
Via della Cerchia, 3
53100 Siena, Italia

‡Dipartimento di Scienze della Terra
Università di Firenze
Via La Pira, 4
50121 Firenze, Italia

ABSTRACT

INNOCENTI, L. and PRANZINI, E., 1992. Geomorphological evolution and sedimentology of the Ombrone River delta, Italy. *Journal or Coastal Research*, 9(2), 481–493. Fort Lauderdale (Florida). ISSN 0749-0208.

The geomorphological evolution and nearshore sediments textural characteristics of the Ombrone River delta are here described. The delta evolution, as deduced from archaeological and historical sources as well as from traditional geological studies, has been influenced by changes in land use that occurred during the last 2,500 years within the Ombrone River catchment area. The sedimentological study has been carried out using different granulometric data analysis techniques, such as the comparison of graphic parameters, grain-size spectra map analysis, and cluster analysis. These results are concordant with data coming from numerical modelling of longshore transport energy. The resulting sediment grain-size uniformity is explained on the basis of the recent Ombrone River plain evolution, which prevented coarse sediments from reaching the outlet, and also by wave energy which attacks the beach and removes the fines even at greater depths.

ADDITIONAL INDEX WORDS: *Beaches, beach erosion, coastal morphology, coastal processes, foredunes, human impact, sediment transport, shoreline changes, textural parameters.*

INTRODUCTION

The population growth that affected the Mediterranean area since Neolithic times is responsible for a high rate of deforestation aimed at providing fuel for domestic use and wood for construction (first) and at expanding cultivated areas (later). A very rapid soil erosion was primed on hilly and mountainous areas, and large amounts of sediment were carried by rivers to their outlets. Moreover, since the end of the Holocene transgression (about 6,000 yr BP, according to FAIRBRIDGE, 1961) the higher sea-level caused a stronger deposition in coastal plains and a rapid progradation of the shoreline. In this scenario we must see the origin of many Mediterranean deltas, and certainly of all the Italian ones that MARINELLI, since 1926, recognized to be not older than 3,000/2,500 years. The evidence for this process comes both from geological and geomorphological data, as well from archeological findings.

The Ombrone River delta (Central Italy) has an origin and evolution similar to that of the nearby and most famous Arno and Tiber River deltas (ALESSANDRO *et al.*, 1990). The study of this delta is, however, more difficult because the Ombrone River coastal plain has undergone a less strong anthropozation that has produced fewer archeological settings, historical documents and maps.

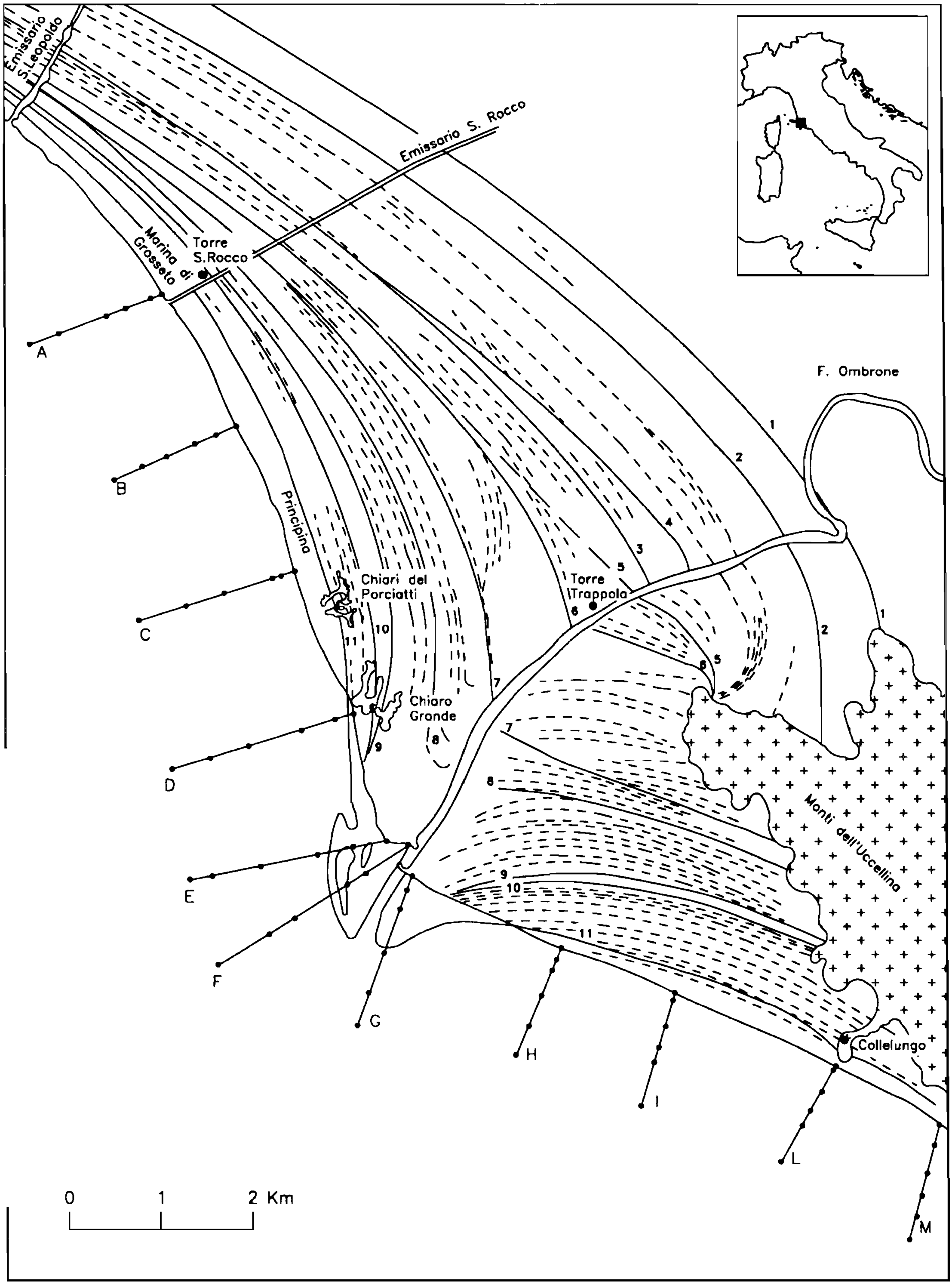
In the second half of the 19th Century all the Italian deltas were initiated by cusp erosion (PRANZINI, 1989) which was caused by changes in landuse within the watershed, land reclamation and river bed quarrying. This process is still going on, in the studied area, at a rate of about 10 m/yr [1].

The present sedimentological features of the emerged and submarine delta are closely connected to the history of this area and any study of the beach must be extended in space and time.

The spirit of the present research is to analyze the Ombrone River delta nearshore sedimentology in the light of the processes that have occurred within the river catchment area during the last 2,500 years, together with geomorphological evolution of the delta.

The sedimentological study is based on a nearshore sampling campaign accompanied by a bathymetric survey. The reconstruction of the

92018 received 26 February 1992; accepted in revision 29 May 1992.
* This research was funded by the Project "Dinamica e Caratteri Geoambientali degli spazi costieri" (Ministero dell'Università e della Ricerca Scientifica).


Emissario S. Leopoldo
Emissario S. Rocco
Torre S.Rocco
Marina di Grosseto
A
B
C
D
E
F
G
H
I
L
M
Principina
Chiari del Porciatti
Chiaro Grande
Torre Trappola
F. Ombrone
Monti dell'Uccellina
Collelungo
1
2
3
4
5
6
7
8
9
10
11
0 1 2 Km

geomorphological evolution is based on information coming from archaeological and historical sources as well as from ancient maps, traditional geological studies and remotely sensed data.

GEOGRAPHICAL SETTING

The Ombrone River delta occupies the eastern part of the Grosseto plain coastline (Figure 1). The plain was formed by sediments deposited by the river itself whose catchment area is 3,496 km^2. A small contribution to the plain formation has come from the Bruna River (562 km^2 basin) which flows more to the north (outside the study area). During the last centuries a large part of the Grosseto plain was occupied by lagoons and marshes that were reclaimed through river diversions. Most of these wetlands are presently located in interdune swales such as the Chiari del Porciatti and the Chiaro Grande (see Figure 1). Some branches orthogonal to the coast show that at least some of them belonged to the stream network draining part of the delta.

The lower part of the plain, affected by malaria into this century, was populated only after reclamation and now only a few rural communities and scattered houses are present except for two coastal towns, Marina di Grosseto and Principina, both on the north side of the delta, whose origin and expansion are related to the tourist industry. The south side of the delta is part of a regional park (Parco Regionale della Maremma).

THE DELTA FORMATION

At the end of the Holocene transgression the lower part of the Grosseto plain was occupied by a large lagoon in which the Ombrone River had its outlet. The lagoon was partly closed by a long sandbar (*bay barrier* in BIRD's (1984) sense) connected to the mainland on its southern end at the Collelungo headland (MORI, 1935). The lagoon was used as a shelter by the Etruscans and the harbour of Roselle, not yet found, was probably situated in its most internal part.

In spite of the sedimentary input of the Ombrone River, this lagoon persisted for a long time, as a result of the subsidence of the area (PRANZINI, 1991). When the Etruscans developed agriculture in the adjacent uplands, extensive soil erosion occurred (SMITH, 1986) and the lagoon was infilled. However, for the complete drying of the area, land reclamations were necessary.

After the Roman conquest Roselle changed its political functions and gradually declined; this should not be ascribed to the Roman presence, but to the filling of its harbour by sand and to the spreading of malaria following the development of marshes which replaced the pre-existing lagoons. This part of Tuscany underwent a period of abandonment, but remnants of the Etruscan period persisted not only as ghost towns but also in the new landscape, definitively deprived of the original forest.

If infilling of the lagoon was necessary for delta formation, the population growth during the Roman Imperial period was the main cause of the first cusp development. This feature is evidenced by beach ridges or/and low foredunes (BIRD and JONES, 1988) which can be found 5 km inland of the present outlet (Figure 1). On the northern part of the coast these ridges join together and grow in height to form three foredunes (MORI, 1935). The apex of such ridges seems to have been eroded before the deposition of new ones and are dated to the first centuries of the second millennium. This erosion has been explained as the consequence of a reduced sedimentary input from the Ombrone River, caused by depopulation of the area following the end of the Roman Empire (PRANZINI, 1989).

The new social and demographic development of the Central and Upper Middle Ages, with a more severe land exploitation, is marked by a delta progradation of about 2 km. An erosional phase is, however, evident in this period and may be related to the population decline caused by the Black Death that halved the population in Tus-

←

Figure 1. Location map (inset), foredunes and beach ridges of the study area; sample positions are plotted along depth sounding profiles A to M. (1) Innermost sand-ridge detectable on aerial photographs and satellite images (pre-Etruscan?). (2) Etruscan beach ridge. (3) Coastline during the Roman Empire (progradation phase). (4) Early Middle Ages coastline. (5) Middle Ages erosional phase coastline. (6) XIV Century coastline (Torre Trappola was built in 1283). (7) XV Century erosional phase coastline. (8) Coastline at the beginning of the fast progradation phase (XVI–XVII Century). (9) Coastline at the end of the fast progradation phase (XVII–XVIII Century). (10) Coastline due to a recent erosional phase (probably of the XVII–early XVIII Century; Torre S. Rocco was built in 1792). (11) 1883's coastline.

cany during the 14th and 15th Centuries (ALESSANDRO *et al.*, 1990).

Between the 16th and the 18th Century a more rapid population growth and forest clearing, required by the increasing need for energy in the developing industry, caused a delta progradation of about 2 more kilometers. Once again the accretion was not continuous, as suggested by the foredune shape analysis (PRANZINI, 1991).

An overall computation of the sediments deposited to form the delta, in its emerged and submerged parts (as shown by bathymetric soundings of the 1880's), shows that the mean annual river load during the last 2,500 years has exceeded 1,000,000 m^3. During the rapid accretion phases this value is likely to have quadrupled.

Even if large amounts of sediment were able to reach the river mouth and build the delta, the Ombrone River was still subjected to conspicuous land subsidence of the Grosseto plain. This has been measured, out of the reclaimed areas, at about 3 mm/year for the period 1891–1951 (SALVIONI, 1957).

On the basis of present sediment production rates, and referring to the values reported by WOLLMAN (1967; in PETTS and FOSTER, 1985) for the increase in soil erosion due to deforestation at middle latitudes, the river bedload (when the basin was fully wooded) was of the same magnitude as that required to counteract the subsidence of the plain. This explains the long existence of the lagoon in presence of a stable sea-level (PRANZINI, 1991). This situation is directly related to the sedimentological characteristics of the beach because it was not possible for the river to increase its slope and drive large amounts of gravels to the outlet, even if these gravels are abundant upstream of Grosseto (15 km from the present river mouth).

THE DELTA EROSION

Erosion of the delta started in the second half of the 19th Century, somewhat later than in the Arno River delta (PRANZINI, 1983). Similar to reasons that delayed the delta formation (marginal position to any social and economic development) also delayed the beginning of the erosional phase which resulted from human impact on rivers and their catchment area (*e.g.* river bed quarrying, land reclamations, reservoirs building, mountain and hilly agriculture decline and reafforestation).

PRANZINI'S (1989) model for erosion of a cuspate delta forecasts a contemporaneous erosion of the delta apex and progradation of the wings. The reduced sedimentary input is, in fact, more obvious near the river mouth than on distant beaches where input is facilitated by erosion of the cusp. Two equilibrium points shift gradually from the river mouth to the more distant beaches, thereby separating the central erosional part from the side parts which are accreting.

At present, about 11 km of beaches are being eroded (up to 6.5 km north and up to 4.5 km south from the outlet) with values as high as 10 m/year at the apex. The accretion of the distal part of the delta is decreasing as the supply of sediments from the apex is reduced. This shift is also caused by a reduction in wave energy on the apex and an increase on the wings as a result of erosion of the submerged part of the delta (AMINTI and PRANZINI, 1990).

By comparing bathymetric surveys of 1977 and of 1987, INNOCENTI (1990) computed a sedimentary deficit of about 800,000 $m^3\ yr^{-1}$ in the area affected by the erosion, a value consistent with the estimated sedimentary input rates in historical times.

SUBMARINE MORPHOLOGY

The study of the morphology of the submerged part of the Ombrone River delta is based on bathymetric soundings of the Istituto Idrografico della Marina Italiana (1881 and 1977) down to a depth of 60 meters, and on 11 bathymetric profiles surveyed in 1987 as a basis for the sampling of bottom sediments.

The volume of the sedimentary body forming the delta is quite large considering the lapse of time necessary for its formation: $2 \times 10^9\ m^3$ is the gross estimation made on the basis of the 1881 survey that shows the delta in its most prominent shape (PRANZINI, 1991).

Comparing this survey with that of 1977, we can assess that the offshore part of the delta is not affected by wave erosion, which cannot remove an appreciable amount of sediments at depths greater than 20–25 meters (BARTOLINI and PRANZINI, 1985). A slow morphological evolution is, nevertheless, present also on the offshore where slumping processes have been detected by subbottom profiling (BARTOLINI and PRANZINI, 1982).

The nearshore area is characterized by a generally low slope, slightly steeper in the southern part of the delta (5.5–9.1‰) than in the northern part (4.1–6.9‰) (values refer to the profile between 0 and -10 m). Another and more important difference between the two lobes is the presence in the north of a series of bars, 1–2 m high inside the −6 m contour; on the southern lobe, only a small bar is present on the profile near the river outlet.

This fact and the size of the sediments confirm the existence of a northward longshore drift already shown by D'ALESSANDRO and LA MONICA (in AIELLO *et al.*, 1975). As numerical modelling has shown (AMINTI and PRANZINI, 1990), this results from the strong south wind blowing over a fetch of 655 km. The northward transport is also caused by the southwest wind (fetch: 207 km), while the southward transport depends on the northwest wind, which has a fetch of only 50 km.

In this area heavy rains are associated with southerly winds and the Ombrone River sediments are mainly transported to the northern beach.

GRAIN-SIZE CHARACTERISTICS

The study of the grain-size characteristics of the beach sediments has been conducted on the basis of samplings conducted in July 1987 with a Van Veen bucket. Samplings were made at depths of 0, 2, 4, 6, 8 and 10 m along 11 profiles (A to M on Figure 1); a bathymetric survey was done at the same time with a Raytheon DE-719B echosounder, while topographic positioning was obtained from an Electronic Distance Meter AGA 216. All samples were dry sieved at ½ phi intervals and FOLK and WARD (1957) parameters computed; 1° percentile sizes and silt and clay (< 4 phi) percentage were also recorded (Table 1).

In addition to the analysis of graphic parameters, a comparison of grain size spectra maps (DOWLING, 1977) was made for the various sampling depths. Finally, a Cluster analysis in Q-mode was done to group samples according to their similarity.

Mean Size (Mz)

Sediment Mean size (Mz) ranges (in the study area) from 0.96 to 3.72 phi (from *coarse* to *very fine sands* according to the scale proposed by KRUMBEIN, 1934). Figure 2 shows the Mz/Depth graph, while in Figure 3 the areal distribution of the various size classes (with 1 phi interval) is represented.

The most evident result is the extremely dimensional homogeneity of the sediments, already pointed out by LA MONICA (1976). This must be interpreted as a consequence of the general evolution of the Grosseto plain (described in previous pages), and that explains why the Ombrone River is not able to feed the beach with considerable amounts of coarse sediments.[1]

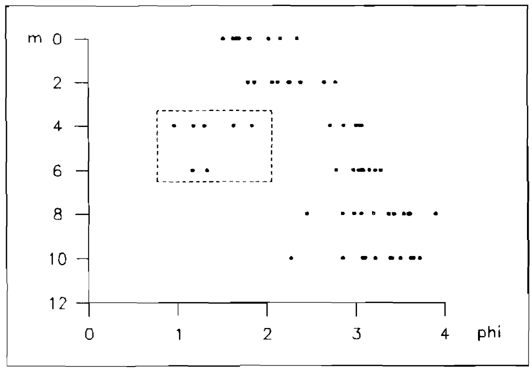


Figure 2. Mz/Depth scatterplot for sediments in the study area. Dashed line encloses points representative of bar sediments.

Because part of the sediments forming the beach are derived from old beach ridges, the scarcity of gravels shows that the hydraulic characteristics of the river are the same as when these ridges formed.

The analysis of Figure 2 shows a good relationship between depth and size, with coarser sands in the swash zone and finer sediments at depth. A deviation from this trend is caused by the presence of coarse sediments (the coarsest of all the samples) at depths of 4 and 6 m. These sediments (whose representative points have been marked on the figure) are present on the bars fringing the northwestern lobe, and probably formed by sediments moving northwards under storm waves, in accordance with mathematical modelling of longshore transport rates (AMINTI and PRANZINI, 1990). The stretching of the points at −8 and −10 m is due to the presence of shell fragments in the samples.

Figure 3 shows an asymmetrical distribution of the size classes in the area: coarser sediments occupy a narrow band on the southern beach whereas they extend offshore on the northern one. Very fine sands (3–4 phi) are present at 4 m on the

[1] No gravels were found during our summer sampling in the "swash zone," while LA MONICA (1976) has found them on both sides of the apex lying in a strip a few decimeters wide during winter and spring "berm" sampling in the early 1970's. We do not believe that this is related to long term variations but, rather, to seasonal ones. Anyhow, the occurrence of gravels on the beach does not seem to be significant in terms of frequence.

Table 1. *Grain size parameters of sediments in the study area; for each sample the associated cluster is shown.*

N°	M_z	σ_I	Sk_I	% < 4 phi	1° percentile size	Cluster
A 0	1.69	0.45	0.01	0.01	0.60	aa
A 2	2.77	0.39	0.02	1.78	1.29	c
A 4	2.71	0.57	−0.10	2.48	0.99	c
A 6	3.05	0.42	0.37	3.91	2.18	c
A 8	3.90	0.52	0.10	24.56	2.42	d
A10	3.72	0.43	−0.58	35.58	1.70	d
B 0	1.62	0.42	−0.02	0.02	0.48	aa
B 2	2.26	0.51	−0.16	0.22	0.82	ab
B 4	3.04	0.47	0.40	5.78	1.88	c
B 6	2.97	0.41	0.38	4.14	1.77	c
B 8	3.20	0.46	0.35	10.44	2.09	c
B10	3.39	0.42	−0.39	10.52	1.41	d
C 0	1.62	0.36	−0.00	0.01	0.60	aa
C 2	2.24	0.50	0.00	0.48	1.04	ab
C 4	1.18	0.53	0.09	1.13	0.07	b
C 6	3.22	0.46	0.26	8.07	2.12	c
C 8	3.59	0.40	−0.21	15.19	2.10	d
C10	3.50	0.37	−0.08	9.80	2.62	d
D 0	1.66	0.33	−0.01	0.00	0.78	aa
D 2	2.06	0.46	0.17	0.26	1.10	ab
D 4	0.96	0.38	−0.01	0.00	0.12	b
D 6	3.28	0.44	0.03	5.32	2.12	d
D 8	3.37	0.45	−0.05	9.09	1.86	d
D10	3.22	0.52	0.35	7.11	0.49	c
E 0	2.15	0.42	0.04	0.09	1.17	ab
E 2	1.79	0.42	0.04	1.22	0.63	aa
E 4	1.30	0.38	−0.01	0.11	0.33	b
E 6	2.78	0.43	0.01	1.95	1.25	c
E 8	3.06	0.39	0.33	2.94	2.02	c
E10	3.10	0.37	0.20	3.84	2.28	c
F 0	1.51	0.48	−0.07	0.00	0.10	aa
F 2	1.86	0.35	0.06	0.15	0.88	aa
F 4	1.83	0.46	0.01	0.32	0.27	aa
F 6	1.33	0.61	−0.10	0.27	−0.30	b
F 8	2.85	0.43	0.12	2.34	1.45	c
F10	2.85	0.44	0.13	2.29	1.32	c
LS	1.91	0.25	0.17	0.02	1.39	aa
G 0	2.02	0.31	0.09	0.01	1.15	ab
G 2	1.86	0.37	−0.01	0.07	0.53	aa
G 4	1.63	0.48	−0.05	0.08	0.30	aa
G 6	1.17	0.81	−0.13	0.40	−2.45	b
G 8	2.45	0.53	−0.24	0.80	0.98	ab
G10	2.27	0.60	−0.14	0.99	0.62	ab
H 0	1.81	0.38	−0.05	0.02	0.80	aa
H 2	2.12	0.44	−0.00	0.43	0.91	ab
H 4	3.04	0.44	0.26	2.93	1.86	c
H 6	3.03	0.42	0.32	2.89	1.90	c
H 8	2.98	0.39	0.32	2.17	1.90	c
H10	3.07	0.44	0.35	4.19	1.82	c
I 0	1.67	0.36	−0.01	0.01	0.78	aa
I 2	2.12	0.46	0.04	0.13	0.96	ab
I 4	3.00	0.37	0.32	1.88	1.89	c
I 6	3.08	0.41	0.40	3.66	1.96	c
I 8	3.43	0.44	−0.13	9.80	2.15	d
I10	3.41	0.52	0.07	9.25	1.72	d

Table 1. *Continued.*

N°	M_z	σ_I	Sk_I	% < 4 phi	1° percentile size	Cluster
L 0	1.80	0.35	0.02	0.00	0.85	aa
L 2	2.38	0.52	−0.24	0.56	0.90	ab
L 4	2.86	0.57	0.01	1.96	1.16	c
L 6	3.15	0.43	0.22	3.88	2.22	c
L 8	3.54	0.44	−0.22	15.13	1.99	d
L10	3.62	0.42	−0.31	20.79	1.99	d
M 0	2.34	0.32	−0.18	0.07	1.48	ab
M 2	2.64	0.36	−0.14	1.05	1.45	c
M 4	3.06	0.49	0.17	3.68	1.69	c
M 6	3.06	0.41	0.37	2.96	2.93	c
M 8	3.61	0.41	−0.29	18.32	2.00	d
M10	3.65	0.40	−0.36	22.51	2.45	d

Samples codes refer to the profile (letters from A to M) and to the depth (0 to 10 meters). Sample LS comes from the swash zone of the spit present on the left side of the outlet. See Figure 1 for sample position.

southern beach and beyond −6 m on the northern one. This additional evidence helps explain the difference in energy on the two lobes.

In front of the Ombrone outlet, inside the −10 m contour, no sediment with Mz higher than 3 phi has been found. This could indicate that, even if strongly reduced, the sedimentary input of the river is still active. North of the outlet, a tongue of coarse sediments, whose position coincides with that of the bars, shows the longshore drift direction.

Percentage of Fines (< 4 phi)

The map showing percentage of fines in the sediments (Figure 4) corresponds with sediment size (Mz) as expected for well sorted sediments, as these are. Fines are lacking in the swash zone and in the −2 m samples, even if coastal erosion has exposed clayey and silty sediments deposited in interdune swales. Their presence in suspension is evident both from the beach and from aereal and satellite images, but energy levels present in this area, even in summertime, do not allow their permanence near the swash zone.

Inside the −10 m contour, the percentage of fines is notable (> 20%) only off the delta wings, while it hardly reaches 1% off the river mouth. This fact is related to high wave energy on the top of the cusp.

1° Percentile Size

In Figure 5 data for the 1° percentile are plotted. Comparison with the Mz map shows a good correlation, acknowledging that the former has a higher variability as outlined by FRANK and FRIEDMANN (1973). In addition, while the Mz map shows that the coarsest sediments are present on the bar fringing the northern lobe, the largest size for the 1° percentile is found offshore from the river mouth, *i.e.* where sediments are deposited during floods.

Sorting (σ_I)

Sediments present in this area (Figure 6) range from *very well sorted* to *moderately sorted* (0.25 < σ_I < 0.81 phi), but the greatest bulk falls into the *well sorted* and *moderately well sorted* classes (0.35–0.50 and 0.50–0.71 phi) according to the scale proposed by FOLK and WARD (1957). (Data from LA MONICA (1976) show berm sediments ranging within the same extremes.)

These data should confirm the high energy of this environment if the relationship sorting/energy suggested by FRANK and FRIEDMANN (1973) is correct. According to FOLK (1966), fine sands are better sorted and therefore less sensitive as energy indicators. The different energy levels present on the various sectors of this beach interact with sediment dimensions giving a complex Mz/σ_I relationship.

For the swash zone sediments (Figure 6) a small inverse correlation exists, as coarser sediments are less sorted, confirming Folk's opinion. *Very well sorted* sediments are present in the swash zone on the left lobe, where higher energy gives a better sorting than one might expect (FOLK, 1966).

Similar conditions are found in the swash zone north of the river mouth, where erosion strongly attacked the shore during the last years. The complexity of the relationship existing between Mz and σ_I is evident in the sample collected on the southern part of the area (Profile M), where a *fine*

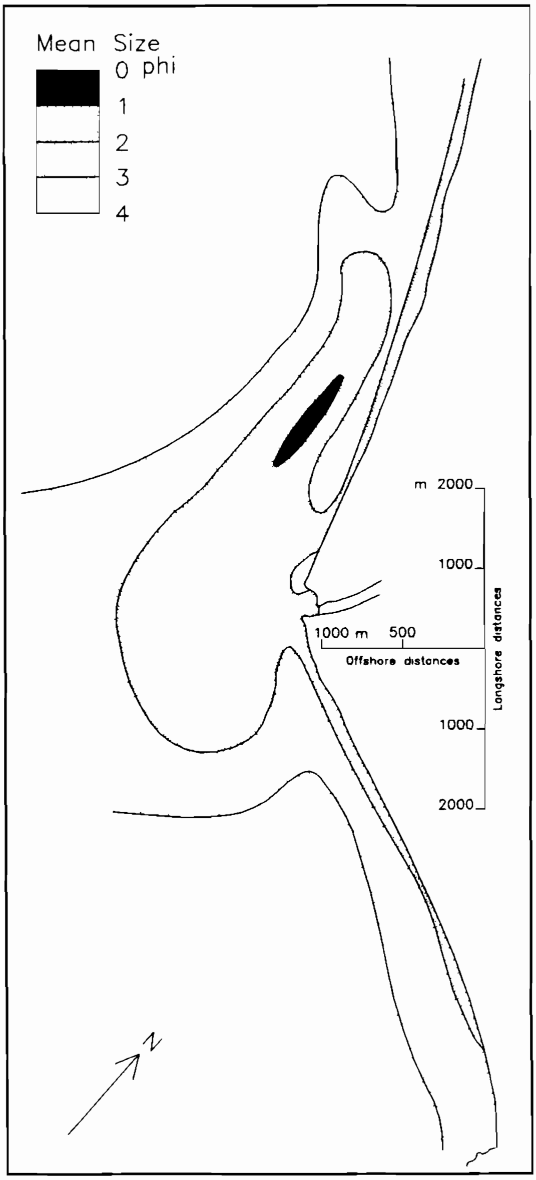


Figure 3. Ombrone River delta: mean size sediment (Mz) map. Offshore distances have been doubled for clarity.

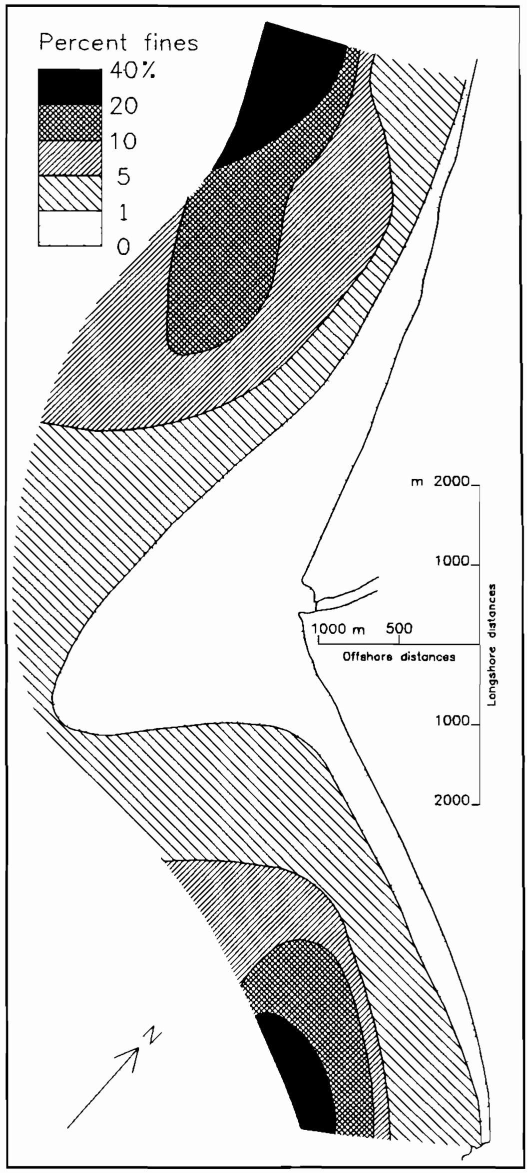


Figure 4. Ombrone River delta: percentage of fines (< 4 phi) map. Offshore distances have been doubled for clarity.

sand (Mz = 2.34) is *very well sorted* (σ_1 = 0.32) in spite of the low energy conditions affecting that beach.

The largest part of the submerged beach, down to 10 m depth, is covered by *well sorted* sediments. If this is normal for higher energy areas (breaking zone), the good sorting at greater depths (*i.e.* in lower energy conditions) can only be ascribed to the favourable dimensions of the sands.

Poorer sorting characterizes the sediments offshore 4 m depth in the most distant part of the outlet, and, considering the existence of *fine sands*, lower energy conditions must be expected here, as the numerical model shows.

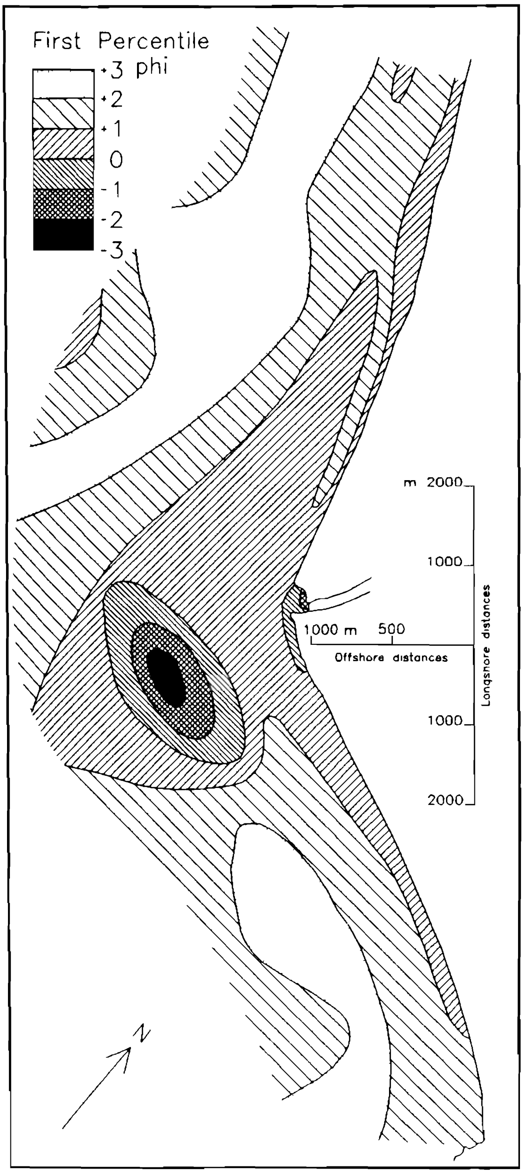


Figure 5. Ombrone River delta: 1° percentile size map. Offshore distances have been doubled for clarity.

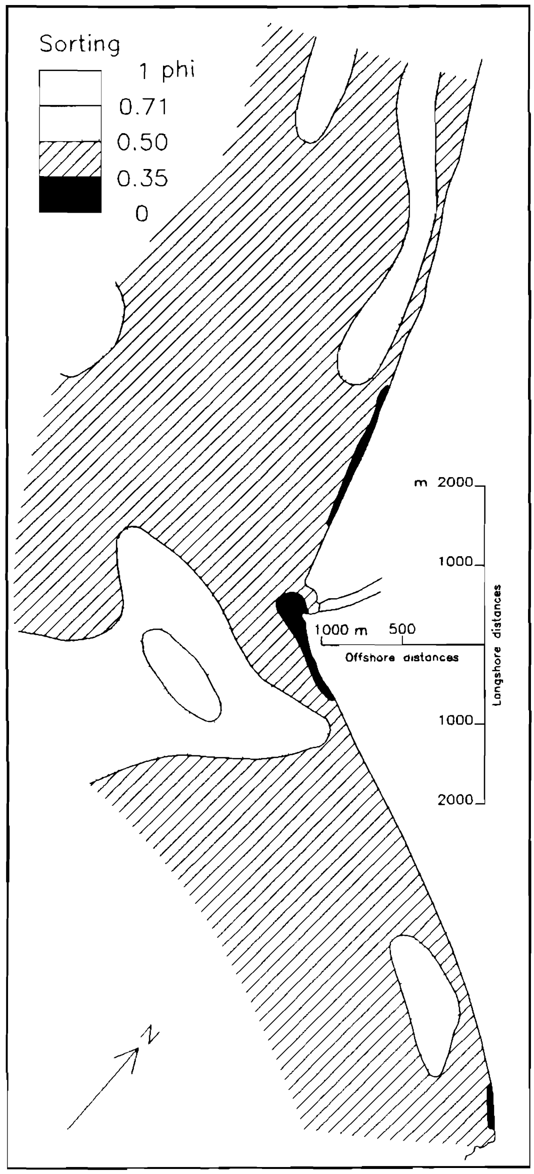


Figure 6. Ombrone River delta: sediment sorting (σ_I) map. Offshore distances have been doubled for clarity.

The least sorted sediments ($\sigma_I = 0.81$) are those present offshore the river mouth where river inputs have not been completely reworked yet.

Skewness (Sk_I)

Well-known papers support the idea that beach sediments are negatively skewed (MASON and FOLK, 1958; FRIEDMANN, 1961; DUANE, 1964). In this area 6 swash zone sediments are negatively skewed, 5 are positively skewed and one is symmetrical. South of Marina di Alberese an inverse proportionality exists between Mz and Sk_I, while proportionality is direct from Marina di Alberese to Marina di Grosseto.

Seasonal changes in skewness of berm sands of this area have been found by LA MONICA (1976)

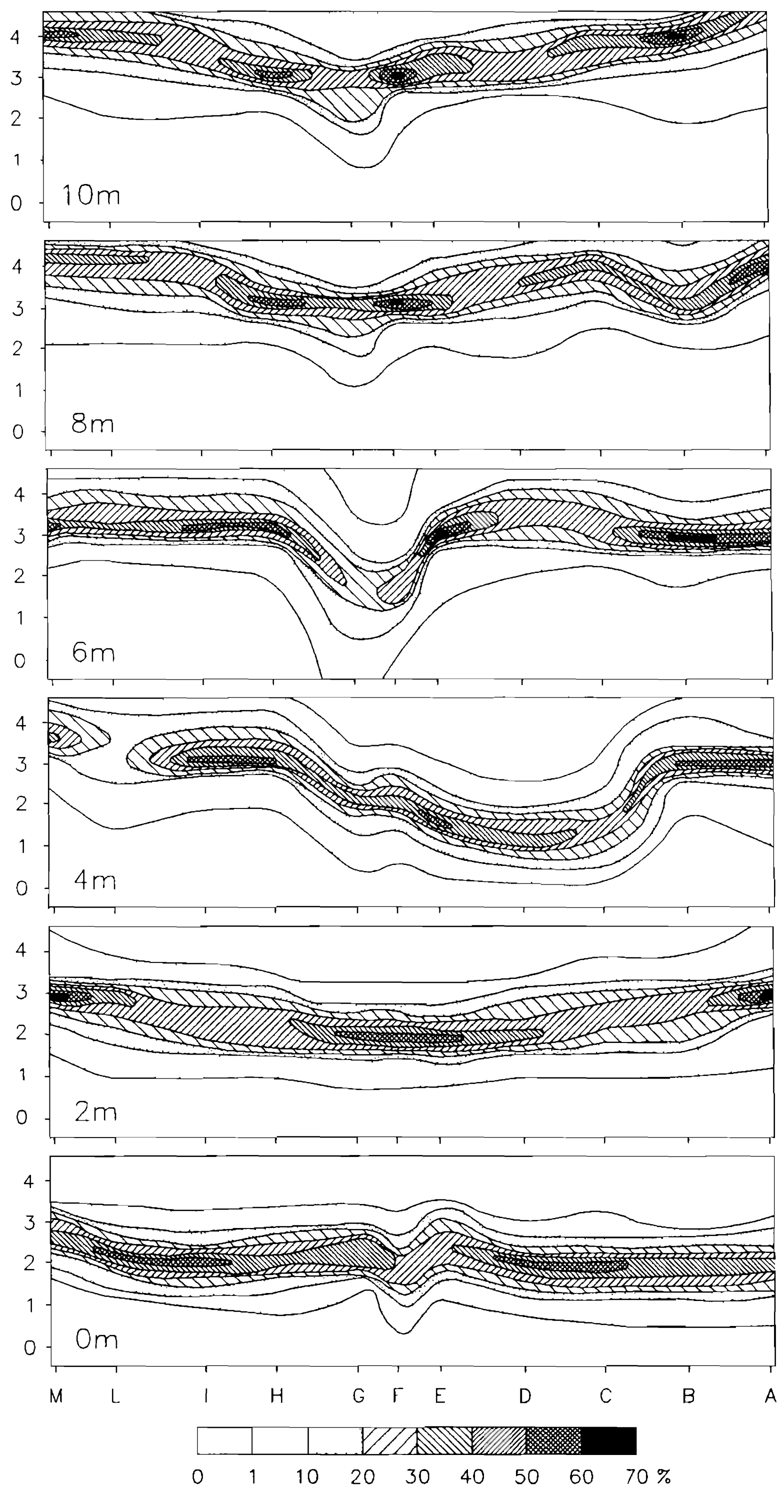


Figure 7. Grain size spectra maps for sediments at different depths.

with mainly negatively skewed sediments in winter and symmetrical or slightly positively skewed sediments in spring. Considering the totality of samples, no significant relationship appears between depth and skewness (χ^2 = N.S.).

Grain Size Spectra Maps

Grain size spectra maps were used to facilitate comparison among frequency curves of samples collected along profiles parallel or orthogonal to the beach (DOWLING, 1977; EVANGELISTA *et al.*, 1980). These researchers used them as indicators of drift direction whereas in this paper we also attribute them a significance in terms of energy.

Horizontal disposition of isolines for 0 and −2 m depths (Figure 7) proves a general homogeneity in the frequency curves and, therefore, similar energy conditions. Since sampling occurred in summer, when fair weather prevails in the Mediterranean region and moderate NW wind hits this coast, energy levels are the same in all the sectors of the delta as short waves break everywhere near the shore. Longshore transport or, rather, sediment redistribution in the nearshore causes this homogeneity.

The analysis of the spectra maps for −4 and −6 m shows strong differences between the apex and the two wings. According to the interpretation model of spectra maps adopted by EVANGELISTA *et al.* (1980), the divergence of the isolines from the river outlet towards finer dimensions shows longshore distribution of sediments in two directions. In addition, we can say that at these depths energy is higher at the apex and, for the −4 m map, on the northern lobe where submerged bars are present. Isolines in the maps for −8 and −10 tend to be, again, nearly parallel to the beach showing reduced sediment transport or more homogeneous energy conditions.

Cluster Analysis

Cluster analysis, carried out through the Unweighted Pair Group Method (SNEATH and SKOAL, 1963), allowed us to group samples on the basis of their affinity on a matrix N × M, with N samples and M variables (grain size classes). These groups of samples, when analyzed according to their spatial distribution, can lead to identification of sedimentary facies (FABBRI *et al.*, 1984; POLUZZI *et al.*, 1985).

Table 1 shows the cluster to which each sample belongs. Different groups were obtained for various Pearson's r coefficient: 4 groups (a to d) derived from selecting $r = 0.82$, while two sub-groups (aa and ab) are obtained from $r = 0.65$.

Facies a (Nearshore Sands)

This facies can be subdivided into two parts: aa is formed by *medium sands* ($1 < Mz < 2$ phi), and ab by *fine sands* ($2 < Mz < 3$ phi). The former are mainly swash zone sands and the latter are present at 2 m depth. Only in front of the river mouth are the two sub-classes present at greater depth and must be related to the river discharge. As far as sorting is concerned, the aa sub-cluster is composed of *very well* and *well sorted* sands, while the ab sub-cluster groups are *moderately well sorted* sediments. Differences are also present in sediment skewness, only the aa sub-cluster being composed of nearly symmetric sediments.

Facies b (Bar Sands)

Cluster b is formed by *coarse* and *medium sands* and, considering their position, it characterizes a bar facies. All the samples grouped in this cluster have the same mode (1.5 phi), while all the other clusters contain sediments with a mode including 2 or 3 grain-size classes. Sorting is more variable (*moderately* to *well sorted*) because in the bar near the river mouth a tail of finer sediments is found.

Facies c (Fine Sands)

Samples of this cluster are present at intermediate depths in a transitional band between high energy swash zone sands (cluster a) and low energy deep sands (cluster d); their good sorting, in spite of lower energy conditions, is explained by the previously discussed relationship existing between this parameter and Mz, being the last in the range 2–3 phi (FOLK and WARD, 1957).

Facies d (Very Fine Sands)

Sediments of this cluster are representative of the low energy environment present at a depth of 8–10 m at the wings of the delta. These *well sorted* sediments ($0.35 < \sigma_1 < 0.50$) are mainly negatively skewed, and their granulometric characteristics can only be explained by reference to the homogeneity of the sediments carried by the Ombrone River.

Even if clustering has proved to be highly Mz or Mode sensitive, man-independency in grouping samples gives the results a higher reliability.

CONCLUSIONS

The Ombrone River delta, from the swash zone to the -10 m contour, is characterized by uniformity of sediment grain-size. This is partly related to the recent evolution of the lower part of the river course, which has prevented the river from supplying the area with coarse sediments. On the other hand, high energy levels (peculiar of prominent shapes), do not allow the sedimentation of fines that, although often present in suspension as derived from the erosion of swales deposits, hardly remain in higher energy sediments.

Even if limited the differences in sediments do allow grain-size analyses to discriminate different environments and to reconstruct the sedimentary dynamics in the area. The results obtained through the three methods agree with those derived by geomorphological and hydraulical analysis.

ACKNOWLEDGEMENTS

We wish to thank L.E. Cipriani and F. Masini who carried out the Cluster analysis, R. Mania for drawing the grain size spectra maps and V. Zichella for the manuscript review. A.M. Dreoni, who patiently prepared the figures (in the various forms we enjoyed to try!) is actually to be considered as a co-author.

LITERATURE CITED

AIELLO, E.; BARTOLINI, C.; CAPUTO, C.; D. ALESSANDRO, L.; FANUCCI, F.; FIERRO, G.; GNACCOLINI, M.; LA MONICA, G.B.; LUPIA PALMIERI, L.; PICCAZZO, M., and PRANZINI, E., 1975. Il trasporto litoraneo lungo la costa toscana tra la foce del Fiume Magra ed i Monti dell'Uccellina. *Boll. Soc. Geol. It.*, 94, 1519–1571.

ALESSANDRO, V.; BARTOLINI, C.; CAPUTO, C., and PRANZINI, E., 1990. Land use impact on Arno, Ombrone and Tiber deltas during historical times. *Proceedings of the 1st Symposium of the EUROCOAST Association, "Littoral 1990"*. Marseille, pp. 261–265.

AMINTI, P.L. and PRANZINI, E., 1990. Variations in longshore sediment transport rates as a consequence of beach erosion in a cuspate delta. *Proceedings of the 1st Symposium of the EUROCOAST Association, "Littoral 1990"*. Marseille, pp. 130–134.

BARTOLINI, C. and PRANZINI, E., 1982. Late Pleistocene and Holocene sedimentary patterns on the Tuscan shelf. *Proceedings of the 11th Congress on Sedimentology*, I.A.S., (Abstract).

BARTOLINI, C. and PRANZINI, E., 1985. Fan-delta erosion in Southern Tuscany as evaluated from hydrographic surveys of 1883 and the late 1970's. *Marine Geology*, 62, 181–187.

BIRD, E.C.F., 1984. *Coasts.* Oxford: Basil Blackwell, 320p.

BIRD, E.C.F. and JONES, D.J.B., 1988. The origin of foredunes on the coast of Victoria, Australia. *Journal of Coastal Research*, 4(2), 181–192.

DOWLING, J.J., 1977. A grain size spectra map. *Journal of Sedimentary Petrology*, 47(1), 281–284.

DUANE, D.B., 1964. Significance of skewness in recent sediments, Western Pamplico Sound, North Carolina. *Journal of Sedimentary Petrology*, 4, 864–871.

EVANGELISTA, S.; LA MONICA, G.B., and LANDINI, B., 1980. Analisi granulometrica e dinamica dei litorali sabbiosi. *Preceedings 3°Congresso della Associazione Italiana di Oceanologia e Limnologia.* Sorrento, 1978, pp. 245–254.

FABBRI, A.G.; GUERZONI, S., and RAVAIOLI, M., 1984. Experiments of multivariate classification of sedimentary environments at the mouth of the Tiber River, Italy. *Bollettino della Società Geologica Italiana*, 27, 343–360.

FAIRBRIDGE, R.W., 1961. Eustatic change in sea level. *Physics and Chemistry of the Earth*, 4, 99–185.

FOLK, R.L., 1966. A review of grain-size parameters. *Sedimentology*, 6, 73–93.

FOLK, R.L., and WARD, W.C., 1957. Brazos river bar: A study in significance of grain size parameters. *Journal of Sedimentary Petrology*, 27, 3–26.

FRANK, W.M. and FRIEDMANN, G.M., 1973. Continental-shelf sediments off New Jersey. *Journal of Sedimentary Petrology*, 43, 224–237.

FRIEDMANN, G.M., 1961. Distinction between dune, beach and river sands from their textural characteristics. *Journal of Sedimentary Petrology*, 31, 514–529.

INNOCENTI, L., 1990. La dinamica dei sedimenti nel delta sommerso del Fiume Ombrone. Unpublished thesis, University of Siena, 156p.

KRUMBEIN, W.C., 1934. Size frequency distribution of sediments. *Journal of Sedimentary Petrology*, 4, 65–77.

LA MONICA, G.B., 1976. La costa grossetana. *In:* BARTOLINI *et al.* (ed.), *Ricerche sul regime e la conservazione dei litorali. Area campione Alto Tirreno.* Roma: CNR, pp. 48–59.

MARINELLI, O., 1926. Sull'età dei delta italiani. *La geografia*, 1–2, 21–29.

MASON, C.C. and FOLK, R.L., 1958. Differentiation of beach, dune and eolian flat environment by size analysis, Mustang Island, Texas. *Journal of Sedimentary Petrology*, 28, 211–226.

MORI, A., 1935. L'evoluzione della costa grossetana dal Pliocene ai giorni nostri. *Annuario 1932-1935 del R. Liceo-Ginnasio di Grosseto.* La Maremma, Grosseto, 21p.

PETTS, G. and FOSTER, I., 1988. *Rivers and Landscape.* London: Arnold, 274p.

POLUZZI, A.; CURZI, P.V., and BADALINI, M., 1985. Analisi quantitative di facies sedimentarie ed ambientali deposizionali dell'Adriatico centrale. *Acta Naturalia de L'Ateneo parmense*, 21, 59–78.

PRANZINI, E., 1983. Studi di geomorfologia costiera: IX—L'erosione del delta dell'Arno. *Quaderni del Museo di Storia naturale di Livorno*, 4, 7–18.

PRANZINI, E., 1989. A model for cuspate delta erosion. *Coastal Zone '89.* Charleston, SC.: ASCE, pp. 4345–4357.

PRANZINI, E., 1991. Geomorfologia del delta del Fiume

Ombrone. *Piano di bacino del Fiume Ombrone. Studi preliminari.* Firenze: Regione Toscana, 97p.
SALVIONI, G., 1957. I movimenti del suolo nell'Italia centro-settentrionale. *Bollettino di Geodesia e Scienze affini,* 16(3), 325–366.
SMITH, C.T., 1986. *Geografia storica d'Europa.* Bari: Laterza, 769p.
SNEATH, P.H.A. and SOKAL, R.R., 1957. *Numerical Taxonomy. The Principle and Practice of Numerical Classification.* San Francisco: Freeman, 570p.

□ RÉSUMÉ □

On décrit l'évolution géomorpholgique et les caractères texturaux des sédiments du delta de l'Ombrone. L'évolution du delta, telle qu'elle a pu être déduite des sources historiques et archéologiques, comme des études de géologie traditionnelle, a été influencée par les modifications de l'utilisation du sol qui sont intervenues durant les 2,500 dernières années. L'étude sédimentologique a utilisé plusieurs techniques d'analyse granulométrique, comme la comparaison de paramètres graphiques, l'analyse du spectre de répartition de la taille des grains et l'analyse de groupements. Ses résultats corroborent les données obtenues par une modélisation numérique de l'énergie de transport parallèle à la côte. L'uniformité de la taille des sédiments qui en résulte est expliquée par l'évolution récente de la plaine de l'Ombrone, qui a évité aux sédiments grossiers d'atteindre l'exutoire et aussi par l'énergie de la houle qui attaque la plage et ôte les fines même en profondeur.—*Catherine Bousquet-Bressolier, Géomorphologie E.P.H.E., Montrouge, France.*

□ RESUMEN □

Este trabajo describe la evolución geomorfológica y las características texturales de los sedimentos costeros en el delta del Río Ombrone. La evolución deltaica se dedujo de la información arqueológica, de la histórica, y de los estudios geológicos tradicionales influenciados por los cambios ocurridos durante los últimos 2,500 años en el área de influencia del Río Ombrone. Los estudios sedimentológicos se realizaron utilizando diferentes técnicas para el análisis de datos granulométricos, tales como la comparación de parámetros gráficos, el análisis de mapas granulométricos y análisis agrupados. Estos resultados concuerdan con los obtenidos por medio de la modelación numérica del transporte energético a lo largo de la costa. La uniformidad resultante en la granulometría se explica a partir de la evolución reciented de la planice del Río Ombrone, la cual impide que los sedimentos gruesos lleguen a la salida, y que la energía de la ola que ataca la playa, remueva los finos a profundidades mayores.—*Néstor W. Lanfredi, UNLP-CIC. La Plata, Argentina.*

□ Zusammenfassung □

Die geomorphologische Entwicklung und die Textureigenschaften der küstennahen Sedimente des Ombrone-Deltas werden hier analysiert. Die Entwicklung des Deltas wird erschlossen aus archäologischen und historischen Quellen sowie traditionellen geologischen Studien und zeigt starken Einfluß durch Wechsel der Landnutzung, welche in den letzten 2,500 Jahren im Einzugsgebiet des Ombrone stattfand. Bei den sedimentologischen Arbeiten wurden verschiedene Korngrößen-Vergleichstechniken benutzt. Die Ergebnisse stimmen überein mit Modellvorstellungen aus der Betrachtung der Transportenergie entlang der Küste. Die Gleichheit der feinen Korngrößen läßt sich erklären durch die junge Entwicklung der Flußebene des Ombrone, bei der einerseits grobe Sedimente die Mündung nicht mehr erreichen, andererseits sehr feine Sedimente durch die Wellenenergie auch in größeren Tiefen beseitigt werden.—*Dieter Kelletat, Essen, Germany.*