Physical classification of the Emilia-Romagna coast (Italy)

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Abstract

A coastal classification is proposed by the Geological, Seismic and Soil Survey (GSSS) of Emilia-Romagna Regional authority (RER). It derives from the integration of geological and morphological data regarding the coast located in the eastern sector of the Po Plain (Italy). Photo interpretation, the definition of geological and morphological settings and the reconstruction of the history of coastal systems are considered as powerful and crucial tools for studying the physical features of the territory and proved to be essential for recognizing the tendency of the littoral sectors. A coastal GIS was created for management, monitoring, modelling, and planning data. On the basis of geo-morphology, sedimentology, physical evolution, land use and harbour development, the RER coast can be divided into three main units: Rimini Coast, Ravenna Coast and Po Delta Coast.

Additional detail is introduced in Rimini and Ravenna Coast Units where a further seven sub-units are created. These sub-units are distinguished on the basis of the presence of defences and/or bar complexes, the type of defences and the sedimentary structures in the shoreface.

The classification parameters describe the physical system of RER coast, underlining its modification in time and space; in particular special consideration has been given to the relationship between human activity and coastal evolution (land use modification, dune destruction, defence and harbour construction, etc.). For these reasons the classification can be considered a powerful tool for coastal management, in particular for beach erosion and flood hazard analysis.

Keywords: Coastal classification, Photo interpretation, Geology, Morphology, Emilia-Romagna Region (RER).

Introduction

The study of the coastal territory of the Emilia-Romagna Region (RER) is nowadays supported by a huge set of data which constitutes a powerful tool for understanding the origin and dynamics of littoral environments; on the other hand the non-homogeneity of such data makes their management and integration quite problematic. This paper intends to develop the comparison and integration of these data, according to a more comprehensive and modern approach to costal studies through the use of digital formats in a GIS framework (Finkl, 2004) and to reach a concise scheme of territorial information at a regional scale. The result of this synthesis is the subdivision of the coast into segments with distinctive physical characteristics and the classification of the coast itself. In particular, classification is based on coastal geomorphological features, land use, depositional systems and shoreline evolution in accordance with several methods utilized in the Coastal Classification Mapping Project by USGS (http://coastal.er.usgs.gov/coastal-classification/).

Setting and history

The study area is located on the northern Adriatic coast and includes the south-eastern sector of the Po Plain and the southern edge of the Po Delta (Fig. 1a); in particular, it ranges from the coastal sector between the Po di Goro mouth to Cattolica.

The study area belongs to the Po Plain foreland basin limited by the Alpine chain to the north and the Apenninic chain to the south; over the last 40 My this basin has been progressively filled up by a thick sedimentary succession, recording the regressive evolution from a deep to a shallow marine environment and finally to the recent alluvial and coastal plain (Ricci Lucchi *et al.*, 1982).

The geological sketch map in Figure 1b shows the distribution of alluvial, deltaic and coastal deposits in the eastern sector of the Po Plain; an active protruding delta system develops in the north-eastern zone while an ancient delta system is fossilized in the central and in the south-eastern one. The alluvial plain built up by Apenninic rivers borders the Po delta systems to the south-west; southward the Po delta pinches out and a narrow

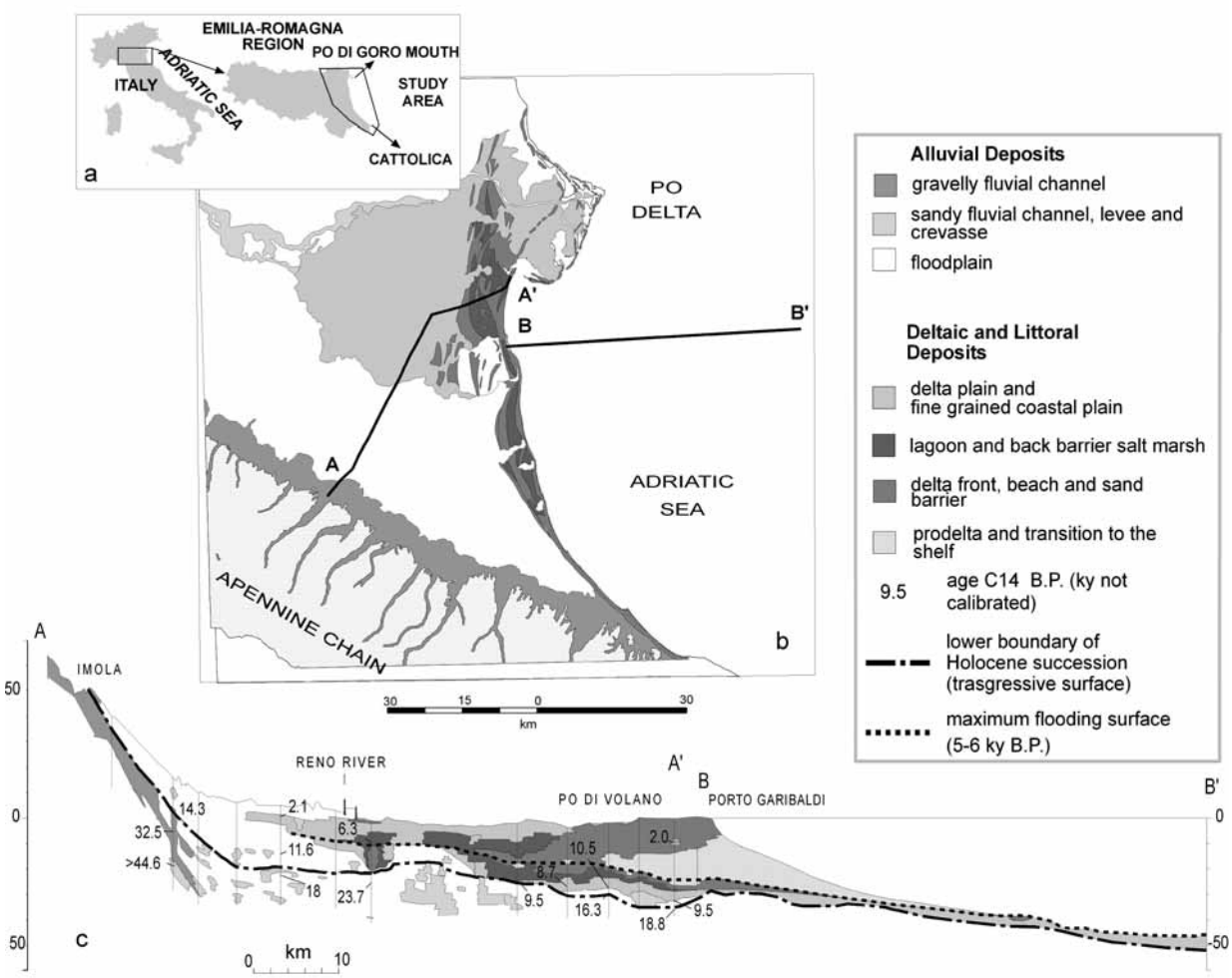

Fig. 1 - a) Geographic setting of the study area ; b) Geological sketch map of the eastern sector of the Po Plain; the distribution of recent alluvial, deltaic and littoral deposits is represented (modified from Carta Geologica di pianura dell'Emilia-Romagna in scala 1:250.000, Regione Emilia-Romagna, 1999); c) geological cross section depicting the stratigraphic framework of the Holocene deposits in the study area.

coastal system develops, the chain margin is close to the sea and alluvial fans directly limit the thin littoral strip.

The geological cross-section in Figure 1c derives from CARG data (Apat-Servizio Geologico d'Italia – Regione Emilia-Romagna, 1999, in press) integrated with offshore section of Carta Geologica dei Mari Italiani (Servizio Geologico d'Italia – CNR, 2001) and describes the architecture of the buried Holocene deposits from the Apennine hills to the Po delta plain and the Adriatic sea, showing the presence of a thick succession of deltaic and beach deposits within a transgressive-regressive sedimentary wedge. In the southern sector, the Holocene sequence is characterized by a sharp and erosional boundary between alluvial and littoral facies which are organized into a thin, condensed and discontinuous succession.

The distribution and age of the buried and outcropping coastal deposits highlights the evolution of the Po delta and Apennine coastal plain, in particular littoral and deltaic sands from the 5th century A.D.. are considered (Fig. 2): in the north the modern delta has developed since the 17th century, in the central area the ancient deltaic cusps from 5th to 18th centuries and in the south the narrow littoral strip is constituted by deposits of the entire period between the 5th and 19th centuries.

In the northern sector, due to the rapid progradation of the modern delta, the shore line has

advanced by approximately 20 km over the last five centuries; during this same period, in the central sector the shoreline advanced by approx. 2-5 km and in the southern sector it advanced by approx. 0.5-1.5 km.

Methodology and data set analysis

Physical classification is based on geomorphology, land-use, geological and sedimentological data, reconstruction of historical evolution and evaluation and assessment of the impact of large harbours. The data set is mostly derived from the Coastal Data Base of the Geological, Seismic and Soil Survey (GSSS) of Emilia-Romagna Regional authority (RER); this GIS database is developed and updated in order to provide access for future use and computer analysis (both spatial and chronological). The geodatabase stores data from previous works and is constantly being updated with recent studies regarding topographic and bathymetric surveys, land use and geo-morphological analysis carried out by GSSS in the last three years.

The data set used in this work is described below.

Land-use and coastal geomorphology

The study of geomorphological and land use changes involved a series of different stages: study of bibliographical references, field-work, observation and direct digitizing on the basis of different aged aerial-photos, topographic and geological maps. All primary data was imported into a Geographical Information System in the ArcGis environment. A GIS database was developed and updated with data deriving from different sources.

Data was analysed from a quantitative and qualitative point of view, while different thematic maps were created. The geomorphological and anthropogenic land use alterations were studied through photointerpretation of several aerial photos and satellite images from 1944 to 1998, as well as through field work. In order to increase the accuracy of photointerpretation, aerial photos were geo-referenced, stitched together, orthorectified, and brought into a GIS database. The finished images had a pixel resolution yielding adequate detail to map even small habitat units ($< 25m^2$). Photo interpretation is extended to a 1.5 km wide strip from the shoreline, between the Po di Goro mouth to the north and Cattolica to the south (about 130 km).

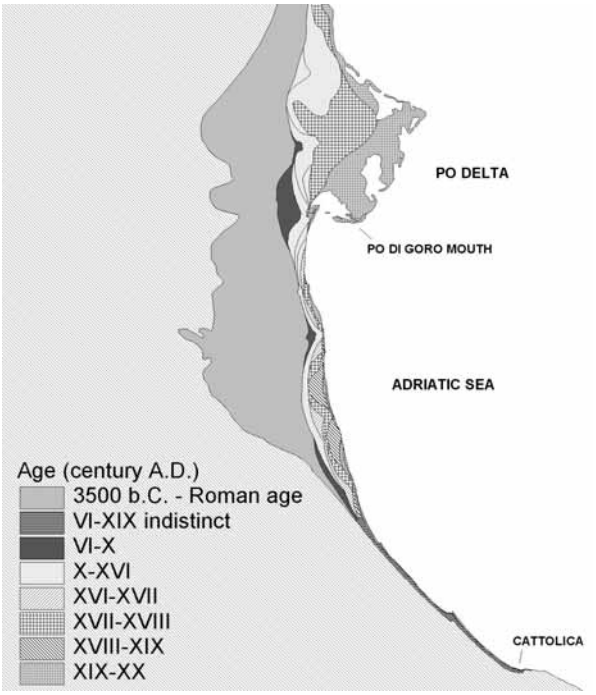

Fig. 2 - Sketch map of the distribution and archaeological dating of cropping and buried deltaic and littoral sands.

Interpreting land-use from an aerial photography implied to examine the spatial features with the purpose of identifying them, define their category, boundaries and relationships with the environment.

Mapping of coastal geomorphological elements was also carried out through photo interpretation. Photo interpretation is extended from the shoreline to the inner shoreface seaward and to the beach and dunes landward. Morphostructures are recognized and classified on the basis of shape, deposits and lateral relationships with natural environments and artificial structures (i.e. coastal defences).

Using GIS technology, land-use maps and coastal geomorphological maps were combined and a 1:5000 land-use/coastal geomorphological map was created and published on SGSS web-gis (http://www.regione.emilia-romagna.it/wcm/geologia/canali/cartografia/sito_cartografia/web_gis_costa.htm). Forty four items were used to classify the coastal territory and the near shore zone; in particular, they describe the distribution of urban areas, agricultural lands, coastal woodland, dunes, beaches, defences and shoals (Fig. 3).

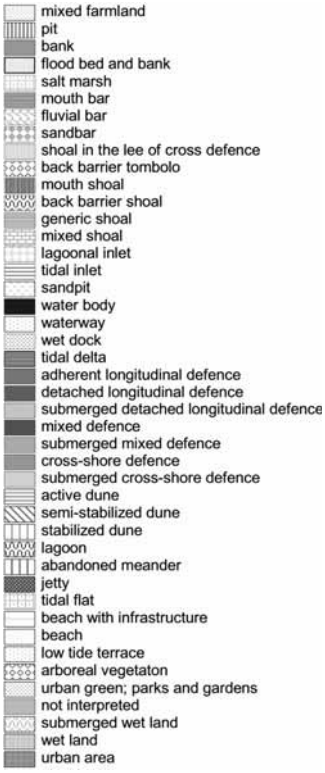

Fig. 3 - Legend of land-use and coastal geomorphology map.

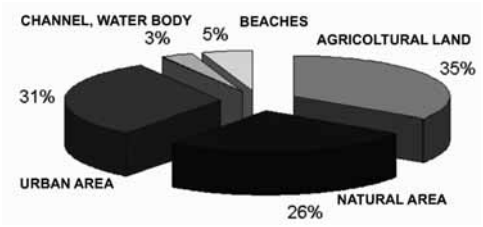

Fig. 4 - Diagram showing percentages of main land-use items in the study littoral strip (see text for details).

Figure 4 gives a concise overview of current day coastal land use (2000). Approximately 35% of the territory is covered by agricultural land, 26% by natural areas, 5% by beaches and 31% is urbanized.

Morphology

Morphological analysis was carried out by the integration of topographic maps ("Carta geomorfologica della pianura padana, Carta altimetrica e dei movimenti verticali del suolo della pianura padana", AA. VV., 1997; Emilia-Romagna Region DTM), a high resolution digital terrain model of the emerged coastal strip derived from LIDAR survey (Ciavola *et al.* 2006), and bathymetric profiles from the regional monitoring network.

A synthesis of the land elevation of the Emilia-Romagna Region coastal sector is shown in Figure 5: in the northern sector, dominated by the recent and ancient branches of the Po delta, land elevation is mostly depressed below sea level while in the southern sector, characterized by the Apennine rivers coastal plain, most of the mainland has an elevation of +2 m.

A digital terrain model derived from LIDAR survey, covering a strip measuring approximately 800 m close to the shore zone; the micro relief in this area is extremely detailed and allows us to describe local topographic complexity, dunes and defences.

The bathymetric profiles, spaced 500 m along the entire coastline, indicate the position of submarine sedimentary features. They have been used to create the seafloor DTM, interpolating the regional bathymetric survey carried out in 2000, and the offshore bathymetric map by CNR-ISMAR (Bologna) .

Geology and sedimentology

Gelogical data used in this work come from seven sheets of the Geological Map of Italy at the 1:50,000 scale (Apat-Servizio Geologico D'italia - Regione Emilia-Romagna, 1999, 2005 and in press*)* and from the geomorphological map of the Po plain at the 1:250,000 scale (AA. VV., 1997). They describe the lithology, stratigraphy and geomorphology of the eastern sector of the Po Plain and have concurred to identify morpho-depositional structures and to reconstruct the sedimentary evolution of the coastal system as briefly summarized above.

Stratigraphic and lithological data of the modern marine deposits of the adjacent sector of the Adriatic Sea derive from the Carta Geologica dei Mari Italiani Foglio NL 33-10 Ravenna (Servizio Geologico d'Italia – Istituto di Geologia Marina CNR, 2001) and from the sedimentological thematic map of central Adriatic sea (Brambati *et al.*, 1988).

In the study area the uppermost part of buried succession (10-15 m) belongs to the progradational part of the Holocene wedge (Amorosi *et al.,* 2005, *cum bibl.*; Fig. 1c) and is constituted by prodelta mud and silt overlain by deltaic and lit-

toral sand with local lagoonal to marshy organic mud and silt; the outcropping deposits are dominated by deltaic and littoral sand, mostly organized to generate dune and beach-ridge complexes. The Holocene wedge thins seaward (Fig. 1c) and pinches out in the sea at the 50 m bathymetric line where Pleistocene substrate outcrops at the sea-floor. In the shoreface Holocene wedge is mainly composed by sands whereas seaward they pass to prodelta mud and to sandy relict trasgressive deposits. The sedimentological map describes a homogenous lithological distribution along the entire RER coast, i.e. a seaward fining trend passing from sand in the foreshore to silty sand in the shoreface and to sandy silt in correspondence of the transition to the offshore .

Quantitative data on river discharge and direction and intensity of littoral drift are extrapolated from "Atlante delle Spiagge Italiane" (1985) and Idroser (1996).

Evolution of depositional environments and shoreline analysis

The historical evolution of the Po delta and coastal plain since the 5th century was considered (Fig. 2) and shoreline variation in the last 200 years was analysed (Fig. 6).

Distribution and dating of cropping and buried littoral sand was obtained by integrating geological data (see above) with literature reports and archaeological data (Stefani *et al.,* in press, Calabrese *et al.,* 2006) and testify the palaeogeographic evolution of the Po delta and coastal plain. Shoreline change was shown in Figure 6 by comparing coastal lines derived from different topographic maps (Napoleonic topographic map, 1814, cadastral maps from 1811 to 1835, topographic map of Istituto Geografico Militare, 1893-94) and aerial photos (1943 and 1998) (Moore, 2000). We have considered shoreline developments between the Po di Goro mouth and Cattolica and the variation of the shoreline is qualitatively estimated with a gap of about 50 years in the last two centuries (Fig. 6). The greatest coastline variability and dynamics are recorded in the northern and central sector until 2000 and are related to the activity of river mouths and consequently to the modification of their deltaic cusps. Moderate variability (mostly shoreline advance), are present in the southern sector up to 1943, after which the shoreline is relatively stable with the exception of minor changes influenced by local factors.

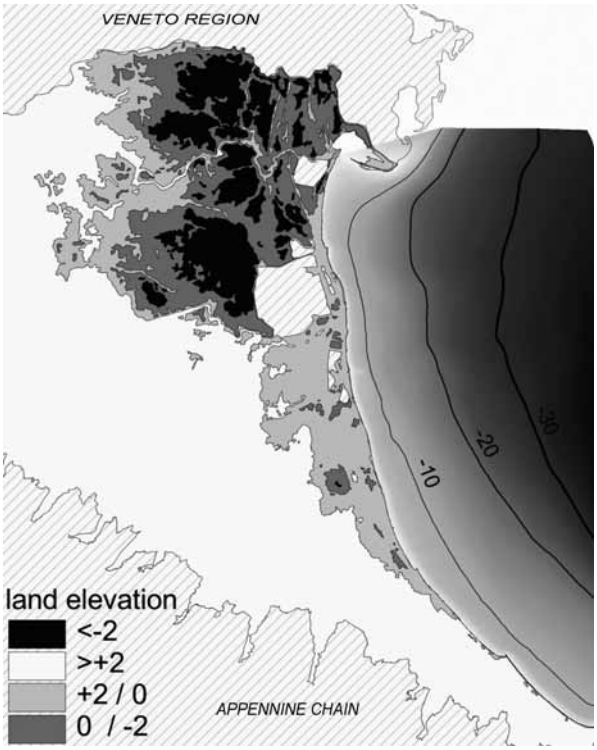

Fig. 5 - Sketch map of land elevation of the eastern sector of Po Plain and bathymetry of the adjacent Adriatic Sea.

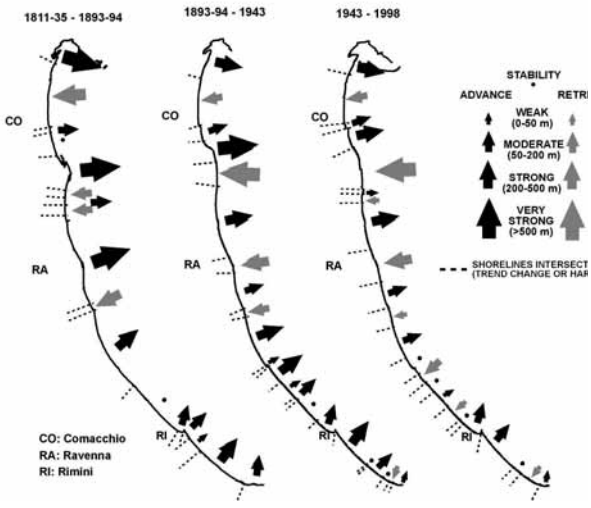

Fig. 6 - Trend of shoreline changes : comparison between shorelines of the years 1811-35, 1893-94, 1943 and 1998. Qualitative estimations of advance and retreat is shown.

Units	Rimini Coast	Ravenna Coast	Po Delta Coast
Coastal plain depositional elements	thin strip with dune-beach complexes No deltaic cusps	strand plain with deltaic cusps, dune-beach complexes and back-barrier lagoons and marshes	lobate mouths, spits and bays
Coastline shape	straight	undulating	articulated (spit and bay)
Beach	laterally continuous 10-200 m wide lidos always present	laterally discontinuous 0-300 m wide, lidos locally present	laterally discontinuous 10-30 m wide lidos absent
Dune	rare or absent (mainly for anthropogenic levelling)	frequent, Laterally discontinuous (60% of the littoral)	always present
Shoreface morphology	homogeneous width and slope (closing at 1,2-1,6 km wide and -7 / -8 m deep)	disomogeneous width and slope (closing at 0,6-1,2 km wide and -5,5 / -7,5 m deep)	shoreface closing not definable
Last 1500 yr trend	stability	irregular in time and space progradation	
Last 200 yr trend	stability	erosion of deltaic cusps accretion of inter-cusp areas	fast progradation
Last 50 yr trend	local variations due to the defences and harbours	erosion of deltaic cusps accretion of inter-cusp areas	fast progradation
Prevalent sedimentary processes (100 yr scale)	littoral drift	littoral drift/ fluvial processes	fluvial processes
Land use	urban	mixed (urban, farming, vegetation, wet land)	natural (vegetation, wet land, farming)
Large harbour/impact to the beach	Rimini harbour / asymmetrical accretion-erosion Cesenatico harbour / asymmetrical accretion-erosion	Porto Corsini jetty / symmetrical accretion Porto Garibaldi jetty / asymmetrical accretion-erosion	absent

Table 1 - Classification of the Emilia-Romagna coast: the units. Classification parameters in the first column and distinctive features of Rimini Coast, Ravenna Coast and Po Delta Coast are represented.

Impact of large harbours

Large harbours within the RER coast interact with sedimentary processes (see above) and have strongly influenced beach evolution and sand littoral drift along the shoreface, working as a sedimentary trap at a regional scale.

The impact on coastal dynamics is clearly visible at Rimini, Casenatico, Porto Corsini and Porto Garibaldi harbours.

The study was conducted by comparing topographic maps from the 19th century (from 1814 to 2005), aerial photos of different periods (1943, 1982, 1998, 2005) and bathymetric maps (1953, 2000).

At present jetties are approximately 120-300 m long across the shoreface, with the exception of Porto Corsini jetties, which are approximately 2500 m long. On the southern edge of Rimini, Cesenatico and Porto Garibaldi harbours, beaches have grown rapidly with a shoreline advance of 200-400 m over the last century and sand accumulation along the shoreface; in contrast, on the northern edge prevalent erosion and minor accretion have alternatively occurred.

At Porto Corsini rapid shoreline progradation and expansion of beaches and shoreface have occured at both edges of the harbour since the 19th century; its long jetties have also influenced the distribution of the fine-grained sediments in the outer shoreface and offshore.

Results of data set comparison: the coastal classification

Evaluation of data set leads to selection of classification parameters (Table 1). These parameters apply to the entire RER littoral sector and provide an optimum description of the physical system of the coast, underlining its modification in time and space; in particular the relationship between human presence and coastal evolution (land use modification, dune destruction, defence construction, etc.) has been considered.

The classification of the RER coast yields three units: Rimini Coast, Ravenna Coast and Po Delta Coast (Fig. 7). They are defined on the basis of the following parameters, grouped into three main classes:

i) Morphology and geology: characteristics of coastal plain depositional systems; shoreline dynamics, beach and dune development, shoreface morphology.

ii) Physical evolution: trends at 1.000s, 100s, 10s years time scale; main sedimentary processes.

iii) Land use : prevalent land use and harbours.

In our opinion these parameters best describe and synthesize the physical characteristics of the RER coast, underlining their modification in time and space.

The Rimini Coast (RIC)

This unit is about 50 km long and is characterized by dune and beach complexes that have built a thin littoral strip by means of alternation of depositional and erosional sedimentary phases over the last 2.5 *k*y (Figs. 1 and 2). The RIC is limited northward by the development of a wide delta plain and deltaic cusps (starting from the Savio River cusp) of the following unit, towards the south-west by the sharp boundary between the strand plain, the Apennine rivers alluvial plain and alluvial fans and to the south by outcropping Miocene-Pliocene deposits of the Northern Apennines.

In the present day, morphological evidence of dunes is rare or absent (1% of the dune/beach complex) due to human sand excavation and urbanization; beaches are meanly 80 m wide (min < 10 m, max about 170 m) and laterally continuous and lidos are present throughout. Urban areas are widespread and can be considered a distinctive feature of this unit. The coastline shape is mainly straight with an interruption at Rimini (Fig. 8) and Cesenatico harbours where the coast has an asymmetrical arrow morphology seaward. The presence of these harbours influences the sea floor bathymetry because of the control of jetties on the sedimentary littoral drift: at the southern edge of both harbours sand accumulation is greater than at the northern edge. Along the rest of the coast the shoreface displays homogenous width and slope, shoreface boundary and transition to offshore is placed at about 1.2/1.6 km from the shoreline at about -7/-8 m deep.

Several Apennine rivers cross the coastal plain and discharge in the sea. Most of the discharged bedload comes from the Rubicone and Marecchia Rivers (Idroser, 1996) but sand redistribution along the coast due to marine processes prevails over the river sand supply thus northward littoral drift dominates the entire RIC, hindering the development of river delta cusps (Idroser, 1996).

Coastal plain and shoreline geometries are stable at the 1.000s and 100s years time. In the last 50 years local variations are mostly attributable to the building of coastal defences and harbours.

The Ravenna Coast (RAC)

This unit is about 60 km long and is characterized by a strand plain built up by southern Po delta branches and Apennine rivers since the Roman Age (Figs. 1 and 2). The RAC is limited north-

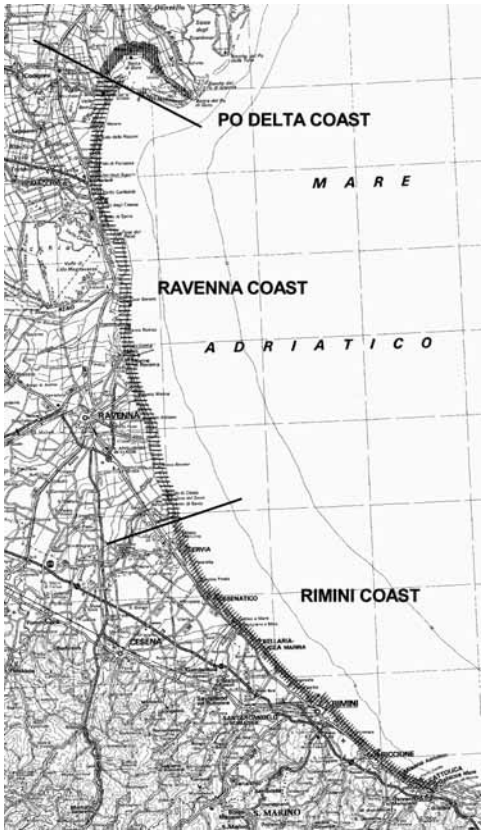

Fig. 7 - Geographic location of the unit shown in Table 1.

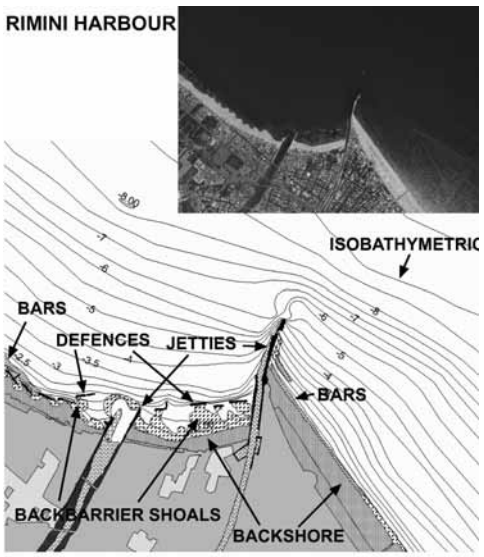

Fig. 8 - Morphological features of the backshore and shoreface in the Rimini harbour area; comparing the north and south sides of the jetties, bathymetric lines highlight the variation of sea floor morphology.

ward by the Goro lagoon and the modern Po delta and westward by the transition to the ancient and fossilized delta plain.

Dunes and beaches are more articulated than in the RIC and back-barrier lagoons, marshes and littoral spits are also well developed.

Dunes are frequent and laterally discontinuous, their linear development is 60% with respect to the length of RAC and their aerial extension is 30% with respect to that of the dune/beach complex; they are often fragmented by crossing paths and are seriously damaged locally by human impact. Beaches are laterally discontinuous and varying in shape (0-300 m wide, mean 60 m); lidos are locally present.

Land use is mixed: urban areas, farmland, vegetation and wet land are randomly spread.

The present day main deltaic cusps are related to, from the south to the north: Savio River, Fiumi Uniti River, Reno River. At the Po di Volano mouth a littoral spit complex has developed.

The coastline shape is mainly undulated because of both convex deltaic cusps and concave wide gulfs between cusps. At present, erosion of the deltaic cusps and the accretion of the intercusp areas are ongoing and the coastline shape is gradually tending to straighten overall.

In the RAC both marine and fluvial morpho-depositional features are recognizable, although marine processes overcome fluvial ones. The dominant sedimentary marine processes have established a wave-dominated coastal plain (Anthony et al., 1996) characterized by a strong northward littoral drift responsible for creating the Po di Volano spit; on the other hand fluvial processes have been severe since the 19th century A.D.. and have been generated wide deltaic cusps.

The RAC offshore is directly influenced by the sedimentary dynamics of active Po Delta, i. e. southward dispersal of fine-grained sediment (Frignani et al., 2005, cum bibl.).

Porto Garibaldi harbour intercepts the northward long shore drift and, trapping sediment in its up-current side, determines the fast growth of the southern beach. On the other hand, Porto Corsini harbour is located where natural beach accretion has occurred since the 19th century due to the shoreline straightening process (see above) and its impact as a sedimentary trap is less marked; in contrast, it has clearly influenced dispersal and deposition of fine sediments in the outer shoreface and in the offshore.

Shoreface morphology is more articulated than that of the RIC, beach profile closure is at -5.5/-7.5 m *m.s.l.* depth, corresponding to 0.6/1.2 km from the shoreline.

Depositional systems and shoreline geometries show a relevant dynamicity at the 1.000s, 100s and 10s years time scale. The morpho-depositional dynamics in the RAC were characterized by activity/abandonment and avulsion of deltaic branches and river mouths causing several alternations of erosion and progradation through time; beach-ridge and dune complexes of different ages juxtapose each other and record this complex evolution.

In particular, ancient Po di Volano deltaic cusps developed to the north of RAC; the river mouth lost efficiency and progradation stopped from the 16th century. Modern Reno River deltaic cusps grew in continuance of the ancient Po di Primaro ones. The Po di Primaro mouth was active in the period between the 6th and the 17th centuries, the Reno river was subsequently connected to it and the river mouth actively worked from the second half of 18th century to the first half of 19th century. Between the 16th and the 18th centuries the Montone, Ronco and Savio Rivers also developed prominent deltaic cusps (Fig. 2).

The Po Delta Coast (PDC)

This unit is about 60 km long, considering the whole active delta. The studied southern sector within the RER boundary is about 15 km long and is characterized by the Po di Goro river mouth and relative sandbank and back barrier lagoon (Fig. 1).

This PDC sector belongs to the southern part of the modern Po delta and is limited to the south by the Po di Volano deltaic cusps of the previous unit.

Dunes are widespread and present throughout; beaches are laterally discontinuous and variable in size, 10-30 m wide, with an absence of lidos.

The coastline shape is complex in relation to the morphology of the barrier-lagoon system.

In the submerged realm morpho-depositional lineages are difficult to recognize, indeed, unlike the units described above, in the PDC the shoreface expands over the Po delta front and is strongly influenced by fluvial processes and delta configuration. As a result, the shoreface seaward boundary is often uncertain and sedimentary structures, such as bars and scours, are not attributable solely to marine processes.

Units	Rimini Coast			Ravenna Coast				Po Delta Coast
						Transition to the delta		
Sub-units	A	B	C	D	E	F	G	
Defences and/or bar complexes	both	bar complexes	defences	defences, locally bar complexes	bar complexes, locally defences	defences, locally bar complexes	bar complexes	bar complexes
Type of defences	detached coast-parallel, coast-normal, submerged	rare coast-normal	detached coast-parallel, locally coast-normal	detached coast-parallel, coast-normal, submerged	rare coast-normal	detached coast-parallel, attached coast-parallel, coast-normal	absent	absent
Sedimentary structures in the shoreface	shoals behind detached coast-parallel defences, longitudinal bars, shoals in the lee of coast-normal defences	longitudinal bars	shoals behind detached coast-parallel defences	shoals behind detached coast-parallel defences, shoals in the lee of coast-normal defences, longitudinal bars	longitudinal bars	shoals behind detached coast-parallel defences, shoals in the lee of coast-normal defences, longitudinal bars	longitudinal bars, shoals of littoral spit	longitudinal bars, shoals of littoral spit
Zone	Cattolica-Riccione	Riccione-Molo Rimini; Cesenatico nord-Lido di Savio	Rimini nord - Molo Cesenatico	deltaic cusps (Foce Reno-Casal Borsetti, Foce Savio e F. Uniti-Punta Marina)	inter-cusps areas (Bocca Bevano, Porto Corsini, Lido degli Estensi)	Porto Garibaldi-Lido delle Nazioni	Volano mouth	

Table 2 - Definition of the seven sub-units (A-G): classification parameters, in the first column, and sub-unit distinctive features are represented.

Land use is mostly natural and vegetation and wet land are widespread; farming land, recently drained, is also common.

Depositional systems developed recently and have shown strong dynamics since the 19th century, dominated by the growth of Po di Goro mouth and the recent evolution of the Goro sandbank. The Po di Goro mouth has experienced fast progradation since the second half of the 19th century, when hydraulic engineering works began channelling waters from the northern branches (Po di Venezia,Po di Maistra) to southern ones (Po di Tolle, Po di Donzella, Po di Goro). The Goro sandbank has developed since the 20th century and is mainly built up by spit complexes that testify to western littoral drift superimposed on fluvial progradation towards the south-east.

The Sub-units

The variability of several physical features within these coastal units suggested to introduce a further detail in Rimini and Ravenna Coast Units, where seven sub-units are created. These sub-units are distinguished on the basis of the following parameters (Table 2):

- coastal defences and/or bar complexes;
- type of defences;
- sedimentary structures in the shoreface.

In Figure 9 the boundaries of the sub-units are shown.

Coastal defences influence sedimentology and shoreline morphodynamics and they are a sign of persistent critical phenomena such as beach erosion and sea flooding during storms. Long shore bar complexes are also indicative of the morphodynamic condition of the shore and are most common in the absence of coastal defences.

Coastal segments were further distinguished on the basis of coastal defence type, taking into account their different interaction with marine processes, i.e. the presence of detached coastal-parallel defences vs. coastal-normal defences.

Identification of sedimentary structures in the shoreface through photo-interpretation and morphological analysis of bathymetric profile provides another parameter for classifying sub-units and the analysis of the distribution and type of shoals and bars discriminates different coastal tracts.

Sub-unit classification may provide a useful tool for developing more specific studies for coastal managment, i.e. risk analysis or engineering projects.

Within the RIC three sub-units, A, B, C are defined. The RAC is subdivided into four sub-units, D, E, F, G. Each sub-unit is about 4 to 12 km long.

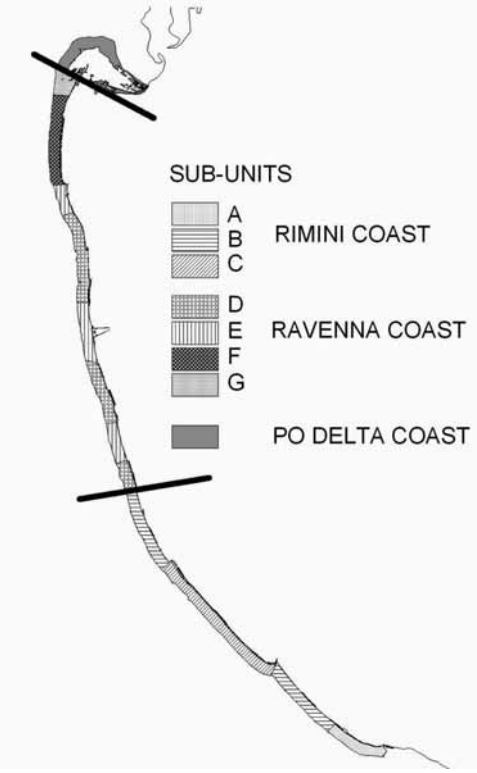

Fig. 9 - Subdivision of the Emilia-Romagna coast into sub-units.

Sub-units within RIC are characterized by the following features (Fig. 10):

A: coastal defences and longitudinal bar complexes are both present; coastal defences are detached coast- parallel, coast-normal and submerged; sedimentary structures in the shoreface are shoals behind detached coast-parallel defences, shoals in the lee side of coast-normal defences and longitudinal bars; the sub-unit description refers to one coast segment from Cattolica to Riccione.

B: bar complexes are widespread in the shoreface and coastal defences are uncommon (mostly coast-normal defences); in the shoreface sedimentary structures are mostly longitudinal bars and generic shoals are locally present; the sub-unit description refers to two coast segments: from Riccione to Rimini and from Cesenatico to Lido di Savio.

C: coastal defences are dominant and mostly detached coast-parallel, locally coast-normal, while bar complexes are rare or absent near the shore; shoals behind detached coast-parallel defences are common; the sub-unit refers to one coast segment from Rimini to Cesenatico.

Sub-units within RAC are characterized by the following features (Fig. 11):

D: coastal defences are widespread, bar complexes are locally present; defences are detached coast-parallel, coast-normal and submerged; sedimentary structures in the shoreface are shoals behind detached coast-parallel defences, shoals in the lee side of coast-normal defences and longitudinal bars; the sub-unit refers to three coast segments including deltaic cusps of the Savio, Fiumi Uniti and Reno Rivers.

E: bar complexes are widespread, coastal defences (mostly coast-normal) are locally present; in the shoreface sedimentary structures are mostly longitudinal bars and generic shoals are locally present; the sub-unit refers to three coast segments including the inter-cusp area of Bocca Bevano, Porto Corsini and Lido degli Estensi.

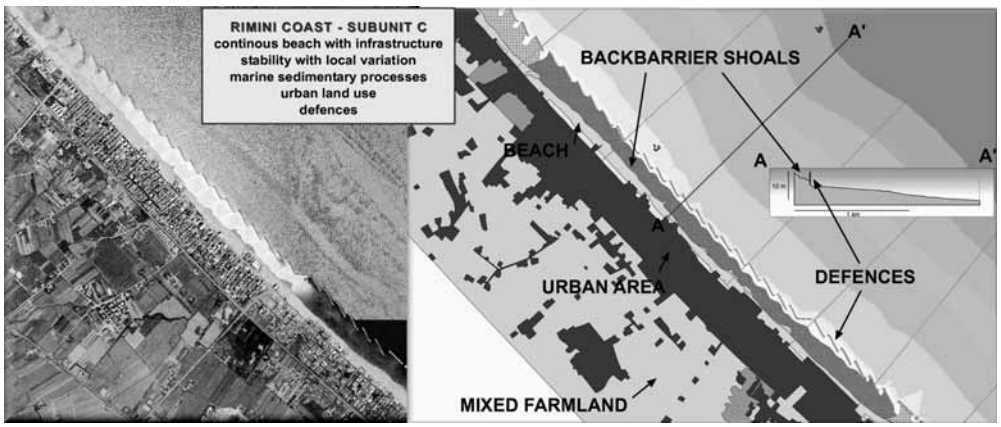

Fig. 10 - Example of Sub-unit C within the Rimini Coast.

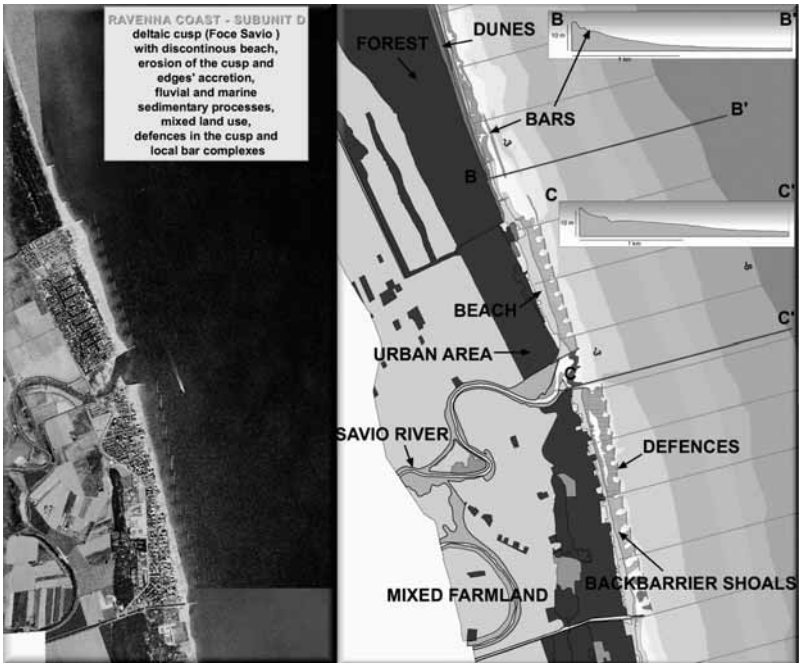

Fig. 11 - Example of Sub-unit D within the Ravenna Coast.

Sub-units F and G, though belonging to the RAC, develop at the transition to the delta and feature intermediate characteristics with regard to the units RAC and PDC.

F: coastal defences are widespread, bar complexes are locally present; defences are detached coast-parallel, attached coast-parallel and coast-normal; sedimentary structures in the shoreface are shoals behind detached coast-parallel defences, shoals in the lee side of coast-normal defences and longitudinal bars; the sub-unit refers to one coast segment from Porto Garibaldi to Lido delle Nazioni.

G: bar complexes are widespread, coastal defences are absent; in the shoreface longitudinal bars are dominant and shoals of littoral spits complexes are also present; the sub-unit refers to one coast segment corresponding to the Po di Volano mouth.

Some sub-units present similar parameters but they diverge because they belong to different units; for example sub-units A vs D and sub-units B vs E.

Conclusion

The proposed classification of the Emilia-Romagna Region coast is the result of an integrated comparison of different information levels elaborated in a GIS environment: geology, geomorphology and sedimentology, shoreline evolution, land use, coastal defences and harbours.

Powerful tools for studying the physical coastal features of RER include photo interpretation of aerial photos, integrated with high resolution DTM and detailed topo-bathymetric analysis; besides, the definition of geological and morphological settings and the reconstruction of historic coastal system dynamics help us to recognize the aptitude of the coastal sectors and to evaluate the impact of large harbours, highlighting the characteristics of recent sedimentary drift and accumulation at a regional scale.

Classification parameters are derived from this integrated analysis and they enable us to define three units and seven sub-units.

The units describe three wide sectors in which setting and recent and historic evolution differ in terms of geological and structural conformation, the dynamics of the Po fluvio-deltaic system and the land use of the coast.

The Rimini Coast is characterized by a narrow coastal plain, supplied by Apennine rivers and closed to the mountain margin. The historical coast line changes are relatively moderate while

land use modifications are significant in terms of land exploitation for urban and tourism. Near shore processes are dominated by northward sand littoral drift at the regional scale whereas at the local scale seasonal or annual sand erosion and deposition do not have sufficient space to achieve a natural balance because of urban pressure on the beach and extensive coastal defences on the shoreface.

The Ravenna Coast is characterized by a wide coastal plain supplied by both the Po and Apennine rivers and has experienced a strong historical coast-line variability. Land use is mixed, variable from urban to natural widespread near shore zone. Delta front erosion and shoreline straightening have been ongoing over the last century and are still the dominant coastal processes today.

The Po Delta Coast is characterized by a rapid progradation of the mouths of deltaic branches. At the Po di Goro mouth, a spit and bay configuration has developed over the last century and nowadays is rapidly evolving at a seasonal and annual time scale. In the PDC land use is natural and environments are characterized by a marked dynamism.

The definition of the seven sub-units within the Rimini and Ravenna Coasts is based on the presence of coastal defences, the development of bar complexes and shoals in the shoreface.

The sub-units share coastal tracts showing common physical features within each unit and emphasize the different defence strategies applied to settle the closely-fought contest of natural evolution vs. human settlement.

The study points out where and how the main modifications occur at different time scales (1000, 100, 10 years) along the RER coast, and helps to understand the dominant anthropogenic and natural driving forces behind coastal dynamics. This knowledge suggests new approaches to costal problems such as flood hazard and beach erosion; for example in the RIC the increase of natural near shore zone should be promoted, in the RAC delta front erosion should be tackled taking into consideration the fact that local coastal defences are not the appropriate solution to oppose long term processes like shoreline straightening; on the other hand in the PDC the preservation of natural environments as public property should be promoted.

The classification of the RER coast therefore offers stakeholders (Municipal, Provincial and Regional) a clear synthesis of the physical characteristics and trends of the coast and constitutes a practical coastal management tool.

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