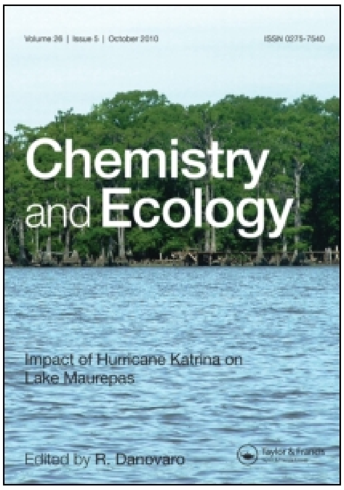

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Discovery of Versilian deposits suitable for beach nourishment on the continental shelf of Western Liguria

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In this paper we present the results of a study conducted in collaboration with the Ligurian Region, in the framework of the E.U. Beachmed-e Interreg IIIc Project, to distinguish relic coastal deposits on the continental shelf, suitable for beach nourishment. These deposits are related to transgressive-regressive sedimentary cycles, and they are due to Quaternary glacio-eustatic sea level variations. In fact, during the sea level low stand associated with the last glacial maximum (c.18–20,000 yBP) the sea level was 110–120 m lower than its present level and the continental shelf was exposed. During the Versilian Transgression the coastline migrated from the shelf break to its present position. This migration was not continuous and conspicuous sediment bodies, associated with deltaic or littoral systems, were deposited during static periods. The results of a marine geology campaign with seismostratigraphic and sedimentological analyses enabled us to distinguish gravelly and sandy littoral deposits at depths of 20–40 m near the coast and 60–80 m on the outer shelf, in areas with only a thin Holocene mud cover (high stand deposits).

Keywords: high-resolution seismic stratigraphy; regression-transgression; sedimentary deposits

1. Introduction

One of the most recent developments in marine geology has been the search for relic coastal deposits suitable for the nourishment of beaches undergoing erosion. The study of sedimentary deposition during recent glacio-eustatic transgressive-regressive cycles can facilitate finding such relic deposits [1–5]. In particular, during the lowstand phase of the last glacial maximum (c. 18–20,000 yBP - LGM), the greater part of the present continental shelf was exposed, the average sea level was 110–120 m lower than today and watercourses deposited their sediment, forming progradant bodies (*Lowstanding System Tract*) [6–8].

During the Versilian eustatic rise (LGM-6,000 yBP) the coastal zone migrated from the shelf-break to its present position. As this migration was not continuous, sedimentary deposits associated with deltaic and/or littoral systems (paleodeltas and/or paleobeaches) accumulated at intermediate bathymetries during periods of slowing down or stasis in the eustatic rise, forming morphological structures and sedimentary deposits that can be identified seismically [1,9,10]. On a global scale, at least two periods of stasis in the transgression can be recognised [7,8,11,12].

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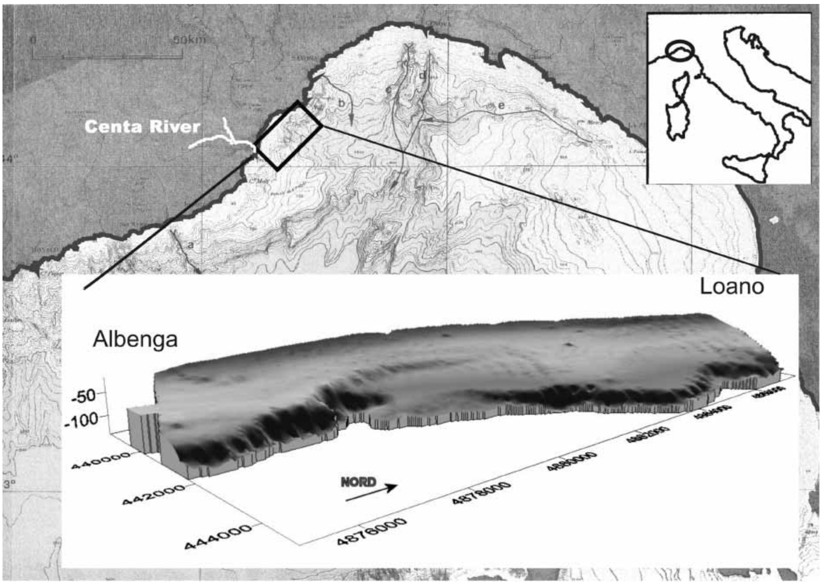


Figure 1. Study area between Albenga and Loano, western Ligurian Sea, showing the morphological setting of the continental shelf and the zone where the transgressive deposits are overlain by a thin Holocene muddy cover (<3 m).

In those sectors of the Ligurian Sea where transgressive sedimentary bodies (*Transgressive System Tract*) are traceable (Figure 1) it is possible to distinguish at least two phases referable to slowing down or stasis [13–16].

Seismic studies and core sampling on the continental shelf between the mouth of the Centa River and the town of Loano (Province of Savona) in 2004, as part of the European Interreg III B – Western Mediterranean Programme (Beachmed Project), revealed the presence of relic transgressive deposits that are usable for beach nourishment [17,18].

2. Study area

The area of the continental shelf studied, between the towns of Albenga and Loano (Figure 1), is the largest Ligurian coastal plain [15,19]. It is fed by various watercourses, the main one of which is the Centa River. The study area has the typical structure of the Ligurian Alpine shelf [20]. The sedimentary deposits, before prograding offshore, fill a tectonic trough in the substratum (*half graben*) [10,21], and the width of the continental shelf is strictly dependent on the size of the filled trough.

In this sector the continental shelf is wide, regular and characterised by an internal sector, in which the acoustic substratum is sometimes suboutcropping, covered by a muddy Holocene deposit of variable thickness [22]. Instead, the external sector of the continental shelf is characterised by a thick progradant sedimentary deposit, with frequent gravitative events along the continental slope or inside submarine canyons, causing regressive erosion of their heads or the shelfbreak itself (Figure 2) [23].

The morphological situation of the Albenga-Loano section of the continental shelf has, more than in any other part of the Ligurian margin, allowed the accumulation of transgressive littoral and deltaic deposits during the sea level rise following the last glacio-eustatic cycle (c. 18–20,000 yBP). These deposits, progradant towards the coast, are clearly distinguishable, with stratigraphic patterns that confirm the transgressive character of the sequences. Holocene highstand deposits,

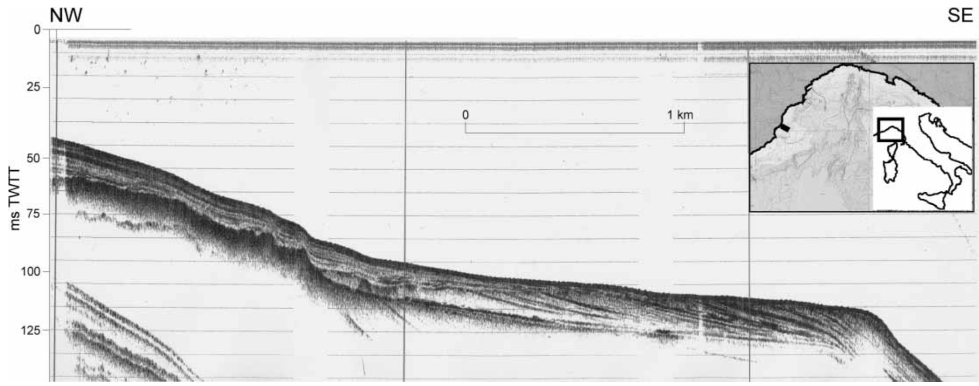


Figure 2. Seismic line of the continental shelf (cross-section). Some of the transgressive and regressive surfaces and progradant sedimentary bodies are recognisable. (Sub Bottom Profiler 3.5 kHz.)

mainly consisting of mud [7,12,22], have covered the study area with a layer of mud that generally decreases from the coast to the outer shelf, depending on fluvial input and coastal and marine currents. This layer is only less than two metres thick in certain limited areas.

3. Materials

3.1. *Seismostratigraphic data*

The geophysical survey, which involved taking 150 km of seismic lines (with a 3.5 kHz Sub-Bottom Profiler and a 200–400 J Boomer) with a distance of 300 metres between each line, allowed us to distinguish relic transgressive deposits of substantial thickness in areas with a limited muddy cover (Figure 3).

The analysis of the seismic lines highlighted two littoral cordons at depths of about 60 and 80 metres that are referable to periods of slowing-down or stasis during the Versilian transgression. These periods allowed the deposition of coastal sediments with good lateral continuity.

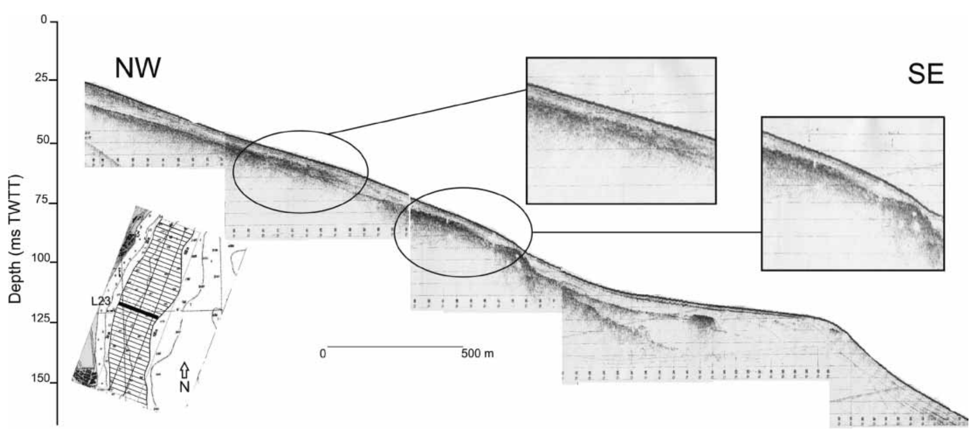
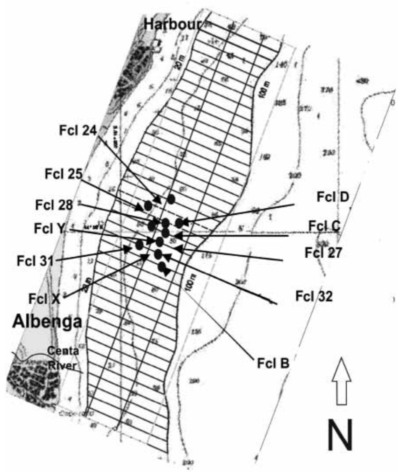


Figure 3. 3.5 kHz seismic Line 23 showing the superficial transgressive deposits and a Holocene muddy deposit of variable thickness. The two littoral cordons are circled (Beachmed Project, August 2004).



Core	Depth m	Latitude	Longitude	Penetration m	Recovery m
FCL 21	59,7	44° 05,2825'N	008° 15,6301'E	4,9	3.2
FCL 23	58,0	44° 04,8509'N	008° 15,2890'E	5,7	3.9
FCL 24	57,0	44° 05,1239'N	008° 15,4184'E	5,6	5.6
FCL 25	42,4	44° 05,1194'N	008° 15,0495'E	3,9	3.4
FCL 27	64,0	44° 04,6368'N	008° 15,3401'E	3,7	2.2
FCL 28	60,0	44° 04,9762'N	008° 15,4111'E	5,1	4.0
FCL 29	83,0	44° 05,1196'N	008° 16,1132'E	6,1	4.0
FCL 31	39,0	44° 04,6417'N	008° 14,7797'E	5,5	3.6
FCL 32	58,0	44° 04,5281'N	008° 15,1923'E	6,0	4.5
FCL A	59,8	44° 04,3162'N	008° 15,1939'E	4,5	3.8
FCL B	59,5	44° 04,3998'N	008° 15,2159'E	5,5	4.3
FCL C	64,2	44° 04,7912'N	008° 15,4155'E	3,9	2.3
FCL D	68,0	44° 04,9135'N	008° 15,5276'E	5,0	2.5
FCL X	54,0	44° 04,5659'N	008° 15,0992'E	3,6	3.1
FCL Y	58,8	N 440222,5	E 4880831,9	4,2	3.5

Figure 4. Grid of seismic lines and core-sampling sites recorded during the 2004 cruise.

3.2. *Sedimentological data*

In August 2004, 15 vibracores were collected from areas where the transgressive deposits had a limited muddy cover. Figure 4 indicates the seismic lines of the detailed study in the area of greatest interest and the vibracore sites.

The textural analysis of the cores enabled us to characterise the sedimentary deposits and calibrate the geophysical data.

4. Results and discussion

The seismostratigraphic results allowed us to identify some reflectors distinguishing five seismic layers (Figure 5). The reflectors can be briefly described as follows:

(1) Sea-sediment interface;
(2) A reflector visible almost everywhere, with medium to low reflectivity;
(3) A reflector mainly visible in the sectors nearest the coast, which is discontinuous with a medium reflection;
(4) A reflector with a medium to medium-high reflection;
(5) A reflector with a medium to low reflection;
(6) A reflector that is only distinguishable very occasionally due to the limited penetrative power of our instruments.

The layers distinguished are listed below:

- Layer A is specifically characterised by a moderately transparent reflection that sometimes shows a flat parallel stratification.
- Layer B is almost always traceable under Layer A; it has a flat-parallel to undulating-parallel internal geometry.
- Layer C is very similar to the layer above. It has an undulating parallel internal organisation and good continuity.
- Layer D is the most interesting layer from the point of view of future exploitation. It has a medium to medium-high reflectivity which varies from sector to sector. Near the coast it has an extremely chaotic geometry and lenticular structures, while in the outer zone near the shelfbreak it has a clinoform progradant geometry. The seismic dip lines emphasised the

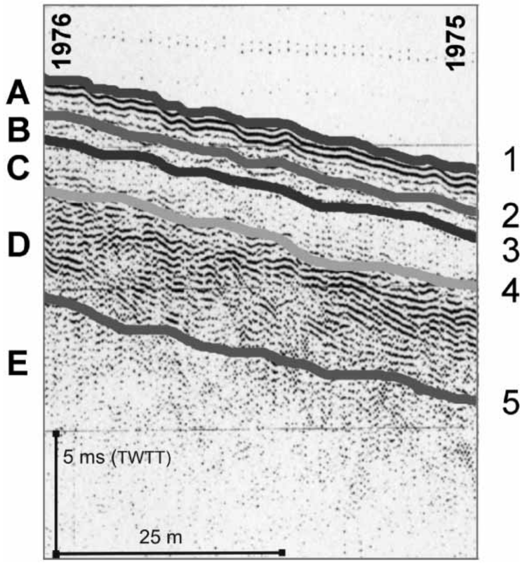


Figure 5. Detail of Line 23 between fixes 1975 and 1976; the reflectors 1–5 and their associated layers A–E (SBP 3.5 kHz; Beachmed project, 2004).

presence of various littoral deposits that represent moments of slowing down or stasis during the transgression, while the longitudinal seismic lines highlight the existence of channel-fill structures and the migration of the channels themselves.

- Layer E is difficult to distinguish but its reflectivity indicates sediments of interest for future exploitation.

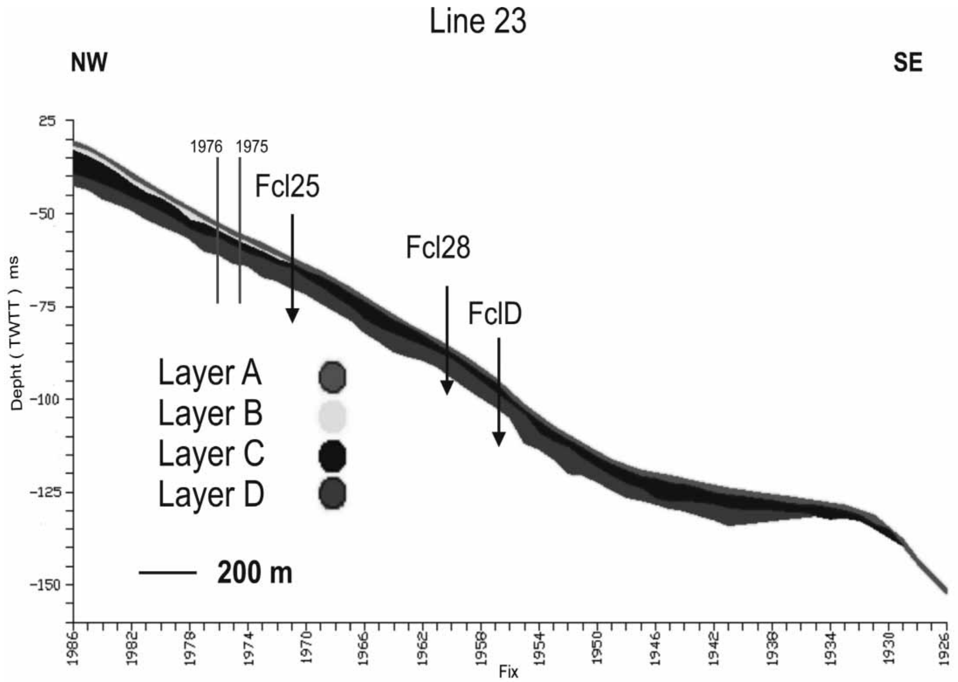


Figure 6. Details of SBP L23 profile, across to the continental shelf. The core-sampling sites (FCL25, FCL28, FCLD) and the detail of Figure 5 (fixes 1975–1976) are indicated with black lines.

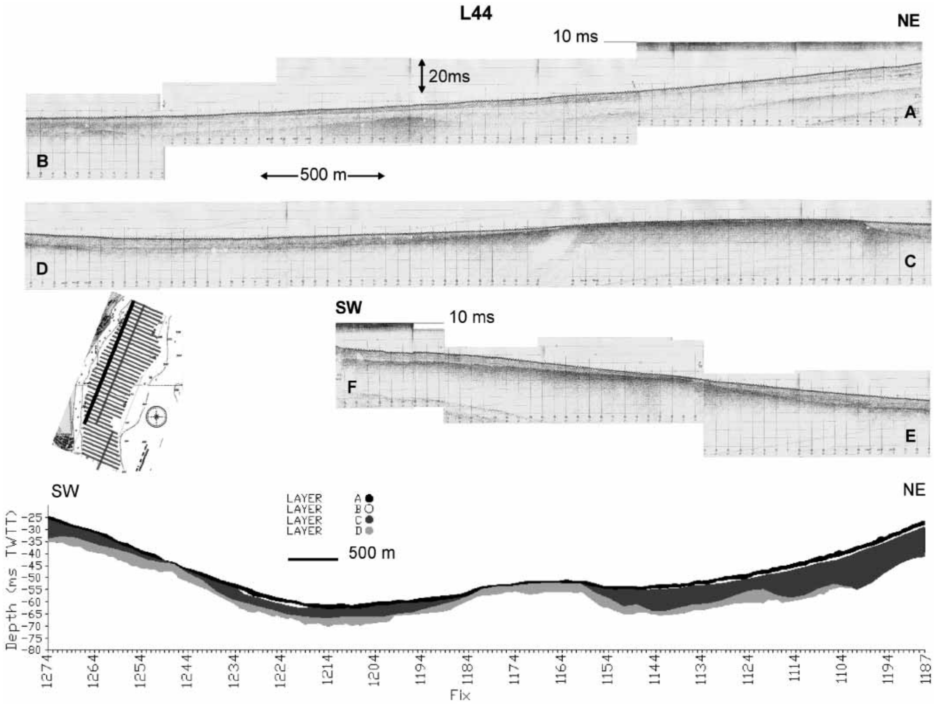


Figure 7. SBP L44 profile parallel to the coast. The lateral distribution of the distinguishable layers is indicated at the bottom. Layer C could be divided into two subunits with a greater thickness in the eastern section.

The profiles indicated in Figures 6 and 7, referring to Line 23 (transversal) and Line 44 (longitudinal) provided a general indication of the spatial distribution of the deposits in the study area.

The seismic data were calibrated with the sedimentological analyses. Table 1 shows the findings of the seismic data (layer thicknesses) and the sedimentological characteristics of core FCL 24 (Figure 8). The hatchings correspond to the layers A–D distinguished in the seismostratigraphic study.

The triangular diagrams reported in Figure 9 show: (a) the Folk classification [24] of all the core levels analysed, subdivided into seismostratigraphic layers. All the samples of Layer D are

Table 1. Grain-size analyses of Core FCL24. The greyscale of the levels refers to the different seismic layers (as in Figure 5): black = A; white = B; dark grey = C; light grey = D.

Core	Samples/Bsf (cm)	Depth (m)	% gravel	% sand	% mud	% silt	% clay
FCL 24	A/25-31	57.0	1.76	4.97	93.28	71.28	22.00
	B/94-100		1.91	25.74	72.35	58.05	14.30
	C/112-118		1.43	38.92	59.64	48.84	10.80
	D/197-203		1.05	26.63	72.32	65.32	7.00
	E/229-235		0.30	49.80	49.90	45.40	4.50
	F/259-265		61.95	27.84	10.21	8.91	1.30
	G/299-305		53.67	37.12	9.20	8.00	1.20
	H/351-357		62.30	34.59	3.11		
	I/434-440		65.92	29.22	4.86		
	J/522-528		74.59	21.88	3.53		

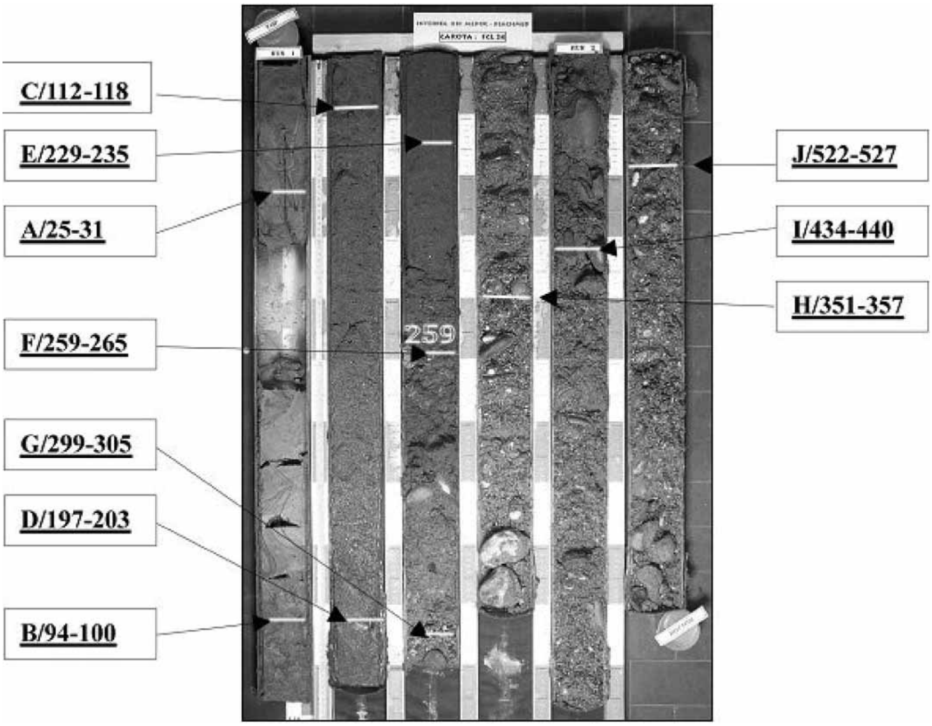


Figure 8. Photograph of core FCL24. The levels analysed in the laboratory are reported in the figure. It is possible to note the presence of pebbles below 259 cm.

characterised by sand and gravel fractions while those of Layer C are characterised by all fractions in different percentages; the uppermost sediments fall within the sandy and muddy fractions. The results of the textural analyses of each core reported in the Shepard diagram (Figure 9b) [25] show that because of the sand and fine components the sediments fall entirely within the

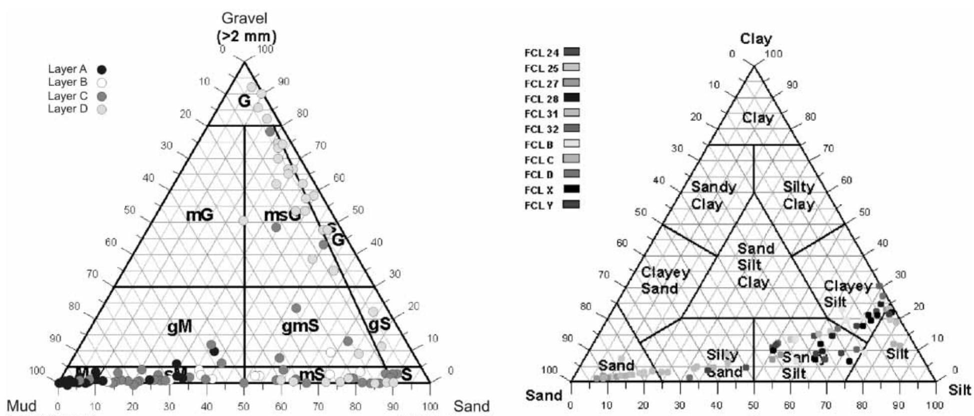


Figure 9. Triangular diagrams of the grain-size analyses of the cores. (a): subdivided into seismostratigraphic layers (Folk, 1957 modified, [24]) G: gravel; mG: muddy gravel; msG: muddy sandy gravel; sG: sandy gravel; gS: gravelly sand; gM: gravelly mud; gmS: gravelly muddy sand; mS: muddy sand; mS: muddy sand; sM: sandy mud. (b): Shepard (1954) diagram of the sandy and muddy components [25].

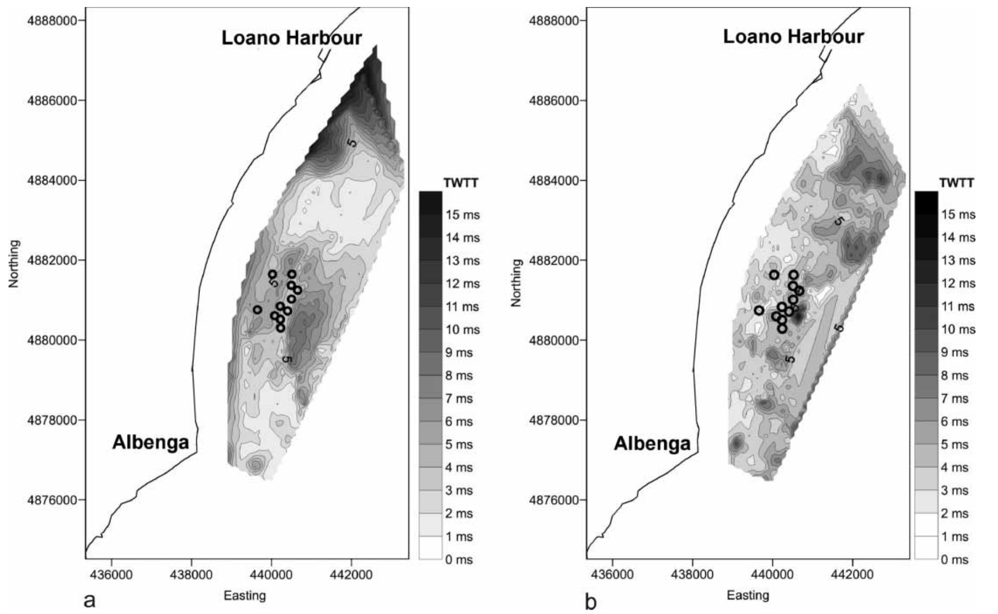


Figure 10. (a): Chart of the distribution of the muddy Holocene sediments and the fine transgressive layers, (A + B + C); (b) chart of the contour lines of the coarse transgressive sediments (D). The core-sampling sites are indicated with circles.

sand and silt fractions, with a maximum clay component of 30% in the uppermost layers of the samples.

The mapping of the layers identified (Figure 10) enabled us to determine the distribution of the coarse-grained sediments of Layer D (Figure 10b) In the north-eastern sector of the area there is a general increase in the thickness of potentially recoverable sediments, with average values above 5 ms. The central sector, where the core sampling was undertaken, has the least muddy cover with an average thickness of 4 ms and two limited areas with thicknesses of up to 8 ms and 12 ms.

5. Conclusions

On the basis of the seismostratigraphic analysis of the seismic facies it was possible to determine the map of the Layers (A + B + C) (Figure 10a) deemed suitable for local beach nourishment, and the contour lines of thickness/width of Layer D (Figure 7b) deemed suitable for dredging. The high-resolution seismic results indicated two major littoral deposits, lying at depths of about 60 and 80 metres, where the Holocene highstand muddy cover is less than three metres thick. The seismostratigraphic analyses revealed that the sequences were divisible into five principal layers that were probably attributable to paleobeach systems. The textural analyses of the cores showed that under a muddy cover of between two and three metres it is possible to find intermediate layers with a sandy fraction between 41% and 74% and a gravelly fraction between 0% and 39%. The lower layers are characterised by an increase in the gravelly fraction (22–59%) and a decrease in the muddy fraction (1–4%) with a sandy content between 38% and 77%. Our findings show that, because of their textural characteristics and muddy fraction, the sediments of Layer D are suitable for beach nourishment along the Ligurian coast. In fact, Ligurian regulations on the characteristics of nourishment sediments specify a maximum muddy fraction (5% in fragile coastal areas and 8%

in other areas). The quantity of usable sediments has been estimated with a contouring programme as about 2,400,000 m^3.

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