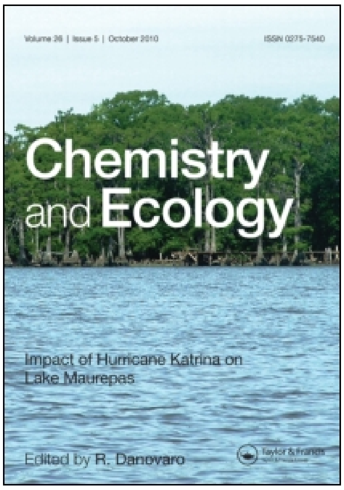

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Late Quaternary deposits from the Ligurian continental shelf (NW Mediterranean): A response to problems of coastal erosion

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To cite this Article Bozzano, A. , Corradi, N. , Fanucci, F. and Ivaldi, R.(2006) 'Late Quaternary deposits from the Ligurian continental shelf (NW Mediterranean): A response to problems of coastal erosion', Chemistry and Ecology, 22: 4, S349 — S359

To link to this Article: DOI: 10.1080/02757540600688036
URL: http://dx.doi.org/10.1080/02757540600688036

Chemistry and Ecology
August 2006, Vol. 22 (Supplement 1), pp. S349–S359

Late Quaternary deposits from the Ligurian continental shelf (NW Mediterranean): A response to problems of coastal erosion

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(Received 16 February 2005; in final form 10 February 2006)

The Ligurian continental shelf is a terrigenous platform characterized by variable extension and subsidence of the continental margin and thick accumulation of sediments originated by repeated sea-level oscillations. Its genesis and evolution occurred during the Plio-Quaternary, even if early erosive modelling in some sectors has been dated to the Late Miocene. The present morphology of the shelf is the result of transgressive–regressive Quaternary cycles. Using a high-resolution seismic grid of more than 1000 km, we have been able to define the seismostratigraphic characteristics of the Ligurian Sea shelf. On the basis of our studies, it has been possible to describe in detail the seismostratigraphy of the Late Quaternary and Holocene sediments that cover the shelf to various depths, in terms of sedimentary sources, for the purpose of distinguishing 'relic' deposits suitable for nourishing beaches undergoing erosion. From this detailed study of the evolution of the most superficial deposits, it is possible to distinguish between different sedimentary bodies deposited during a transgressive phase and located at a water depth ranging between 20 and 70 m; they are represented by relic sands cropping out at the sea bottom due to a relatively thin Holocene drape and could be explored for beach nourishment programmes.

Keywords: High-resolution seismic stratigraphy; Transgressive–regressive facies cycles; Sedimentary deposits; Beach nourishment; Coastal erosion

1. Introduction

The Ligurian continental shelf (figure 1) consists almost entirely of sedimentary construction shelves [1–3] lying on a rocky substratum slightly deformed by normal faulting [4]. The shelf is characterized by a sedimentary cover, which has mainly accumulated in the last 2–3 million years and been modelled by repeated transgressive–regressive facies cycles that have mainly been caused by Quaternary glacio-eustatic sea level variations [5–9].

The evolution of the Ligurian continental shelf during the Plio-Quaternary or, in some cases, Late Miocene, is characterized by sedimentary deposits that clearly record sea-level variations [10, 11]. Periods of highstands have caused aggradation and/or progradation of the

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Chemistry and Ecology
ISSN 0275-7540 print/ISSN 1029-0370 online
http://www.tandf.co.uk/journals
DOI: 10.1080/02757540600688036

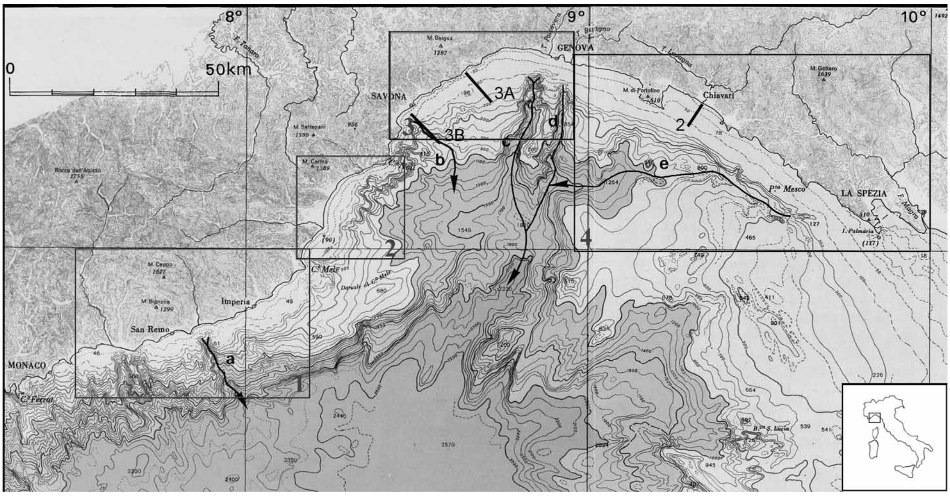

Figure 1. Bathymetric map of the Ligurian Sea showing the different sectors of the continental shelf (1: Ventimiglia and Capo Mele; 2: Capo Mele and Vado; 3: Vado and Genoa; 4: Genoa and La Spezia) taken during a high-resolution seismic investigation to detect sand deposits useful for beach nourishment. Arrows: Axis of canyons (a: Taggia; b: Vado; c: Polcevera; d: Bisagno; e: Levante). 2, 3A, and 3B show the location of sparker lines of figure 3 and figure 4.

continental shelf, while lowstands have produced notable erosive truncations and prograding structures as far as the shelf break [10, 12]. In particular, during the low sea level related to the Last Glacial Maximum, the continental shelf was exposed, and the watercourses deposited their solid load directly on the shelf itself, forming prograding bodies, Lowstand System Tracts (LST) [13]. Even if the watercourses that flow into the Ligurian Sea normally carry little water, they can periodically carry a notable solid load. The sediments forming this solid load have come from the progressive erosion of the Alps and Apennines [10]. The Plio-Pleistocene tectonic uplift of the western Alps and northern Apenninic thrust belt has steadily increased erosion and siliciclastic supply, favouring the transfer of large quantities of terrigenous material to the sea. Only a small part of this material, however, has gone to form narrow sedimentary shelf wedges [11, 14]. In effect, the continental margins of Liguria form a narrow morphological–structural transition zone between the Alps and Apennines and the deep-sea depressions [3, 15, 16]. In this general context, the Ligurian continental shelf has a notable morphological variability as a result of its complex structural evolution: a continental shelf surrounding the Northern Apennines and associated with the Ligurian-Provençal Basin and the evolution of the Tyrrhenian Sea [17, 18].

The western Ligurian continental shelf is particularly narrow and is clearly divided into distinct sectors by particular morphological features and tectonic alignments [1, 16]. It is mainly composed of rock lithologies with limited sedimentary deposits near the coast and Plio-Quaternary sediments further offshore [17, 19].

The eastern part of the continental shelf is a typical sedimentary domain, where subsidence, sedimentary input, and transgressive–regressive facies cycles associated with Quaternary glacio-eustasy have played a fundamental role in modelling the features of the continental margin [20–22]. The shelf assumes notable extensions only where one of the depressions, the Viareggio Basin, part of the Tyrrhenian Basin System [10, 13, 23], has been completely filled with sediments from the Magra, Serchio, and Arno Rivers [21]. In the innermost part of the Gulf of Genoa, the shelf preserves a modest, but not negligible, extension, while west of Capo Mele, its width is considerably reduced, practically disappearing at the heads of the main submarine canyons [24] (figure 1).

2. Materials and methods

A seismostratigraphic study of the Ligurian continental shelf has been carried out using more than 1000 km of high-resolution seismic profiles (3.5 kHz sub-bottom profiler and a 1–6 kJ sparker) in order to distinguish relic coastal deposits suitable for nourishing beaches undergoing erosion. The data recorded from four areas (figure 1) were then integrated with geological studies that started in the 1970s [1, 2, 11, 14, 15, 18, 19, 21]. The preliminary results have enabled us to distinguish areas where transgressive sedimentary wedges crop out at the sea bottom due to a thin Holocene drape. Some areas of the western sector were surveyed during an oceanographic cruise with high-resolution seismic profiles (using a 3.5 kHz sub-bottom profiler and 200–400 J boomer); 40 sediment vibrocores were collected in the spring and summer of 2004. In particular, 430 km of seismic lines were recorded in this area (figure 2) (157 km at San Remo, 123 km in the area of S. Stefano al Mare—Imperia and 150 km in the area of Albenga—Loano) calibrated with 40 sediment cores (23 in the sector Ospedaletti—Capo dell'Arma at a depth of 21–76 m, 15 cores between Albenga and Loano at a depth of 39–83 m and two cores in the area between Santo Stefano al Mare and Imperia, at a depth of 35–62 m).

Here, we discuss the detailed seismic stratigraphy of the area between Ventimiglia and S. Stefano to show the sandy-gravel deposits (with a thin mud covering) suitable for beach nourishment [25].

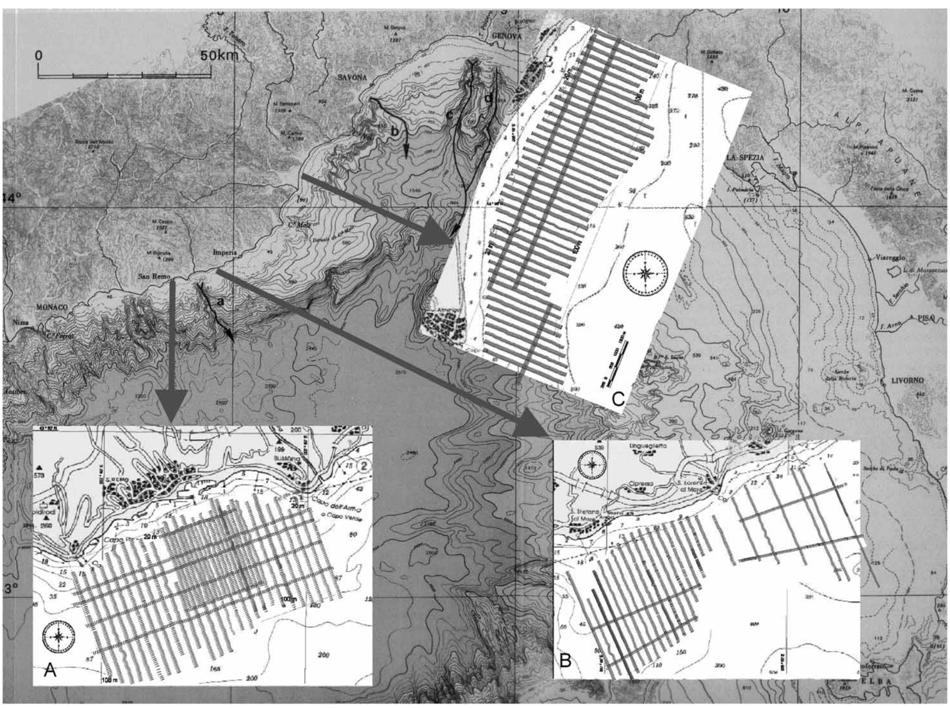

Figure 2. Map showing the three sectors studied with high-resolution seismic profiles. From west to east: (A) San Remo; (B) Imperia; (C) Albenga-Loano.

3. Results and discussion

The interpretation of the seismic profiles collected in various sectors of the Ligurian continental shelf allowed us to identify the main morpho-structural lineaments and to study the evolution of the prograding Pleistocene wedges and overlying Holocene sediments.

3.1 *Eastern Ligurian area*

To the east of Portofino, the continental shelf widens from west to east and has a Holocene muddy-clayey sedimentary cover of considerable thickness deposited by the Serchio, Magra, and Entella Rivers (figure 3) [21]. The evolution of the continental shelf is clearly delineated by a Late Quaternary unconformity erosion surface of the last glacio-eustatic cycle (Wurm III) (transgression surface (TS)), which was the first surface to be flooded during the consequent rise in the sea level and was located at the base of the transgressive system tract (TST) and/or transgressive erosion surface or ravinement surface (RS), which is a transgressive surface reworked during a relative sea level fall (forced regression), often at the top of thick Pleistocene prograding wedges [7, 26]. The shelf break lies at a depth of 120–150 m. The deposits of the last lowstand phase are distributed on the front of the shelf, at a depth of more than 120 m. Small portions of reworked coastal deposits have accumulated on the continental slope at a depth of about 200 m. This is an interesting Mediterranean example of cold fauna coastal sediments [6] being deposited at different depths on the slope and the shelf break during the last low stand, and it is similar to other sites in the Adriatic Sea [27–30].

The various regressive sedimentary bodies (LST) record the erosive action of the sea and the reworking of the sediments during the last sea-level rise [13]. The preservation of these bodies is due to the abrupt beginning of the transgression (or the sudden reduction in the sedimentary supply that compensated for its effects) or the rapid compaction and/or cementation of the deposits themselves, which preserved many of the morphological details of a coastal system. These relic bodies are overlain by a muddy cover of variable thickness related to a high-stand system tract (HST) with a maximum thickness (30 m) in the sector near the Entella River—Golfo Marconi.

3.2 *Central and Western Ligurian area*

The central and western sectors of the Ligurian continental shelf are generally much narrower than the eastern and relatively deep. Numerous submarine canyons cross the shelf, slope

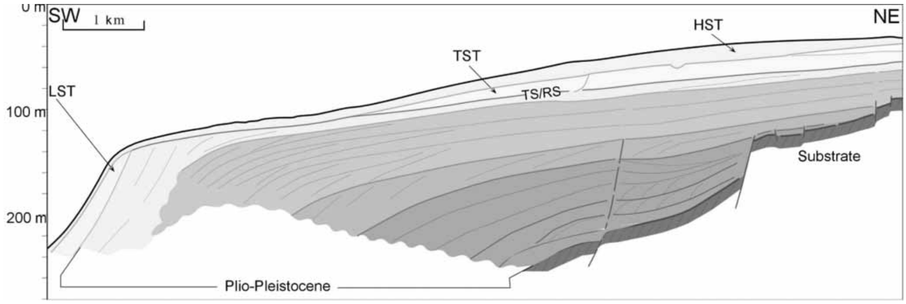

Figure 3. Example of a Ligurian platform prograding and aggrading on the Pre-Pliocene substrate from seismic line 2 (see figure 1 for location of seismic line 2). LST: low stand deposit, TS/RS: late Quaternary transgressive unconformity and ravinement surface; TST: transgressive deposit; HST: high stand deposit (Holocene).

offshore, and cut obliquely across the narrow continental shelf. The head of the canyon forms a trench on the continental shelf, and locally, the sedimentary bodies (figure 4) are subjected to notable erosive phenomena, transport, and gravitative collapse similar to a by-pass system. Due to the strong activity of the area, triggering seismotectonic phenomena and submarine slumps along the frontal zones, the shelf break lies at a depth of 90–110 m. The shelf here is usually characterized by an inner zone modelled by marine erosion and an unstable outer zone of sedimentary origin. The Holocene cover has a thin and variable thickness, due to the absence of important watercourses and the rapidity with which terrigenous sediments are carried to greater depths along the canyons cutting through the steep slope. The Holocene cover is almost continuous in the eastern part of this section and reaches its maximum thickness (over 30 m) in a relatively distal position, thinning more towards the shelf break than towards the land [19].

In particular, the continental shelf between San Lorenzo al Mare and Bordighera has a very variable width, being narrowest at the heads of the Taggia, Bordighera, and Roja Canyons, and

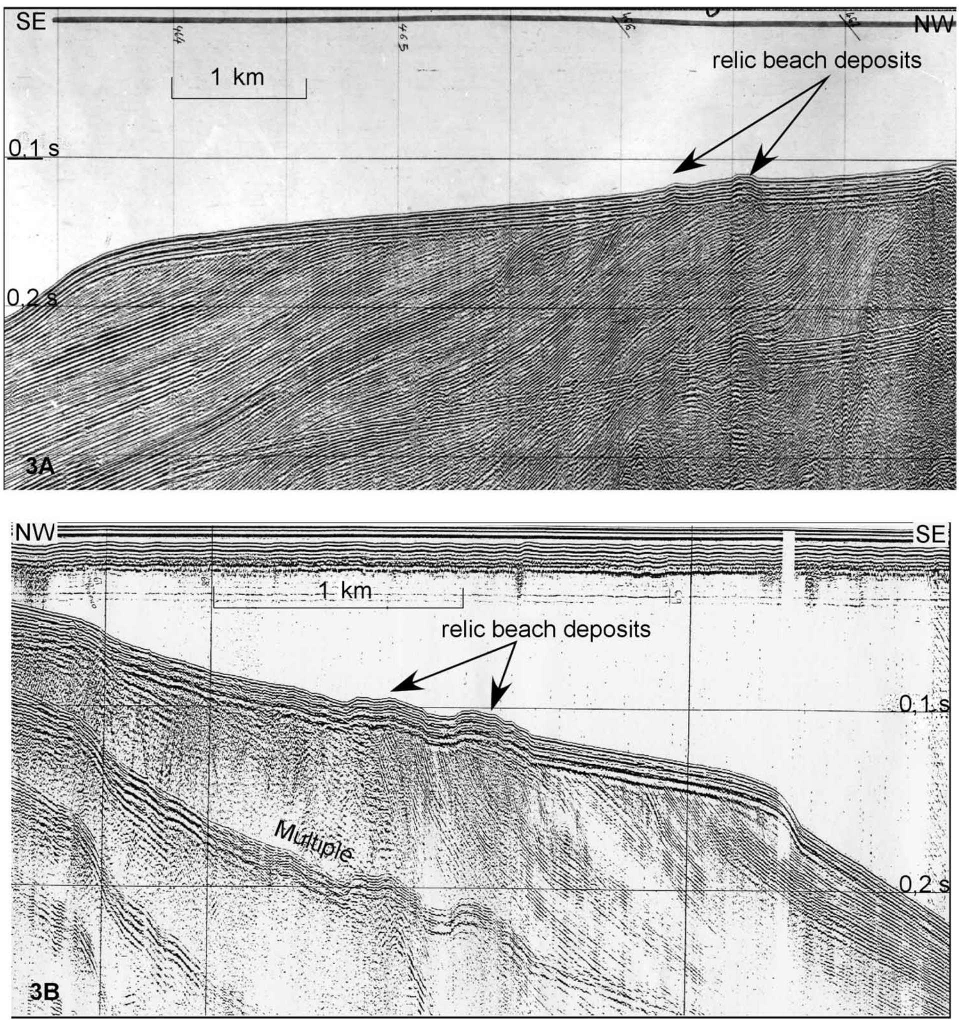

Figure 4. Seismic lines of the area to the west of Genoa showing several relic beach deposits: (3A) 6 kJ sparker lines near Voltri; (3B) 1 kJ sparker profile near Varazze. See figure 1 for location.

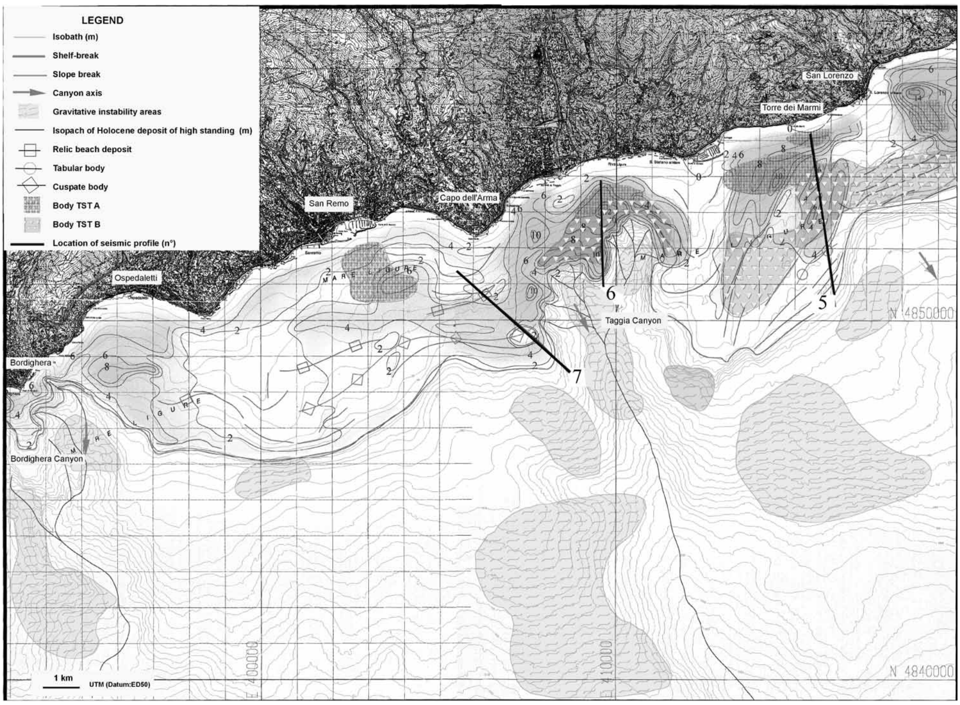

Figure 5. Map of the area from Bordighera to S. Lorenzo al Mare showing the morphological characteristics of the continental shelf. Darker lines: location of seismic profiles 5, 6, and 7.

an articulated morphology, and is delimited by the presence of a 'frontal accumulation' of very fine sediments characterized by an acoustically transparent seismic facies (figure 5).

It is easy to distinguish between two bodies related to the last glacio-cycle and partly overlying each other (figure 6). The lower, and more important, body (TSTA) gives an acoustic response typical of coarse-grained sediments on the landward side and finer, homogeneous

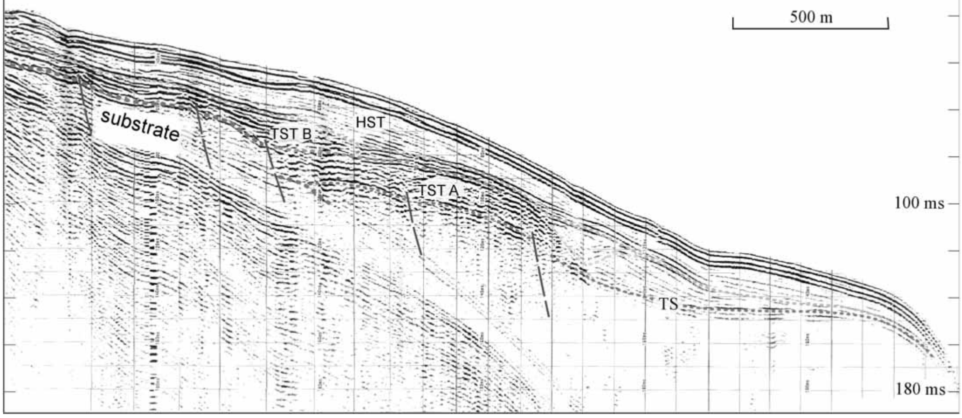

Figure 6. 1 kJ sparker line 7 of the continental shelf near Riva Ligure (see figure 5 for location) showing the Holocene cover (Highstand System Tract-HST) overlying postglacial sand deposits (Transgressive System Tract: TST B and TST A), the Late Quaternary unconformity (TS), and Pre-Pliocene substrate.

deposits prograding seawards. The upper body (TSTB), on the contrary, appears to have originally been discontinuous, situated in the areas of greatest detritic supply and more homogeneous from a textural point of view. It is thought to consist mainly of sands (figure 6).

The various bodies listed in figure 5 may be grouped into two layers of 20–25 m and 50–60 m, and the variability in their seismic signal suggests that the transgressive phase lasted for a relatively long period of time.

Other than the bodies already described, there are reliefs with little Holocene cover on the front of the shelf in the sector west of San Remo that are difficult to interpret (figure 7). In at least one case, however, they have the characteristics of relic coastal structures of great volume. Other bodies with the morphology of tabular accumulations are found in a median position on the shelf.

The available data do not allow us to establish whether there are other bodies than those already described closer to the coast (fossil coastal prisms), with the single exception of an area near Torre dei Marmi (figure 8). In several other places, there is evidence of terraces, but it is impossible to establish whether they are depositional or erosive terraces on the substratum with only very high-resolution seismic stratigraphy.

The Holocene cover in this sector is very thin, increasing in thickness towards the shelf break and, locally, towards the coastal prism, with limited and irregular areal extensions. The greatest thickness is found east of San Lorenzo al Mare (up to 16 m) and in local accumulations at the heads of canyons.

On the basis of the recent high-resolution seismic data, it is possible to state that in the offshore sector near the town of San Remo (Ospedaletti—Capo dell'Arma), the inner part of the continental shelf consists of an erosion shelf with frequent outcroppings of the substratum, which form small morphological traps where thin layers of sediment can accumulate. The outer part of the shelf probably consists of prograding Pleistocene wedges.

Figure 9 shows the morphosedimentary structure of the continental shelf of the area east of San Remo. The structural characteristics and the sedimentary deposits are substantially the same as those of the preceding profiles, but an interesting transgressive deposit can be seen at the site of Core 19. The preliminary sedimentological analysis of calibration core C 19, collected at the depocentre of the main transgressive deposit, at a depth of 63 m (figure 9), shows that there are sandy sediments under a 2-m-thick cover of pelitic sediments, with a maximum penetrated thickness of 2.9 m (log penetration graph). In particular, the core consists of 46% gravel, 47% sand, and 7% mud in the bottom interval (338–400 cm below the sea floor), prevalently sandy sediment (decreasing from 98 to 80% with depth) 200–338 cm below the sea floor.

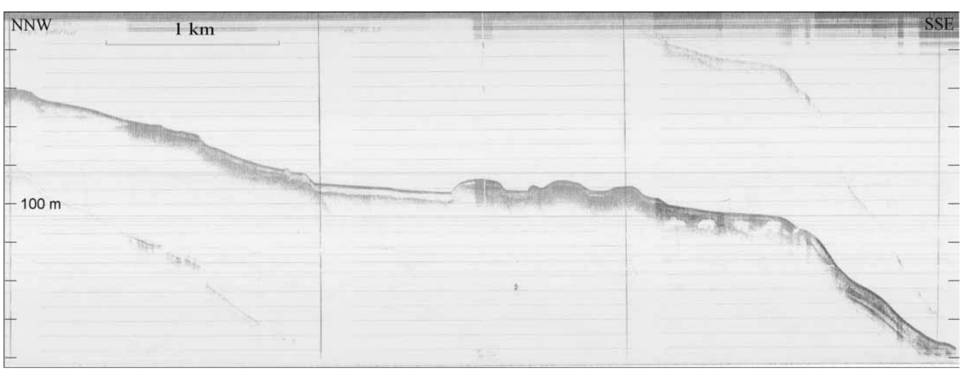

Figure 7. 3.5 kHz sub-bottom profile 6 (see figure 5 for location) showing what are probably relic coastal deposits located on the front of the continental shelf between San Remo and S. Stefano al Mare.

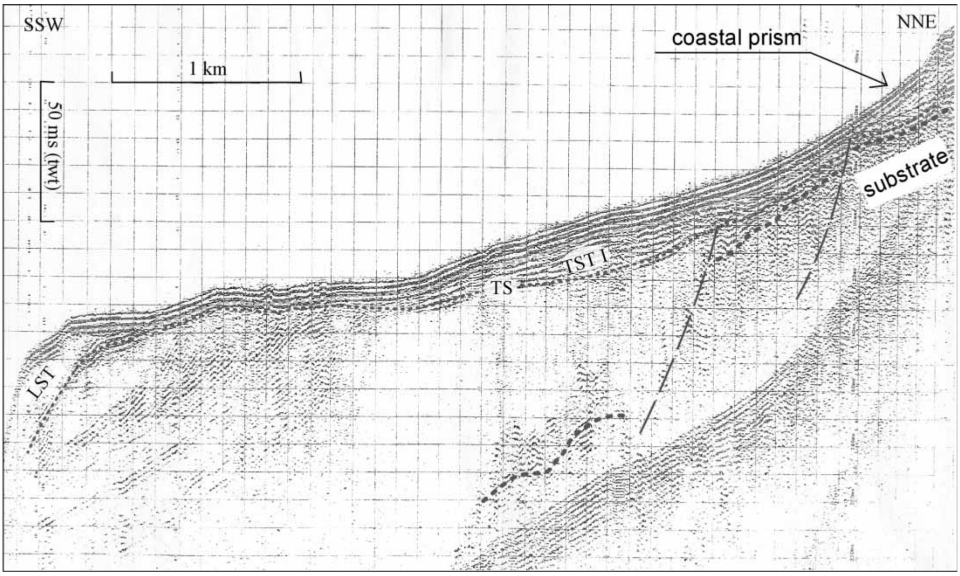

Figure 8. Sparker profile 5 (1 kJ) of the continental shelf near Torre dei Marmi (see figure 5 for location) showing the Late Pleistocene lowstand deposits (LST), the transgressive unconformity (TS) and transgressive sedimentary deposits (TST), the coastal prism overlying a paleocoastal prism and the Pre-Pliocene substrate with direct fault system.

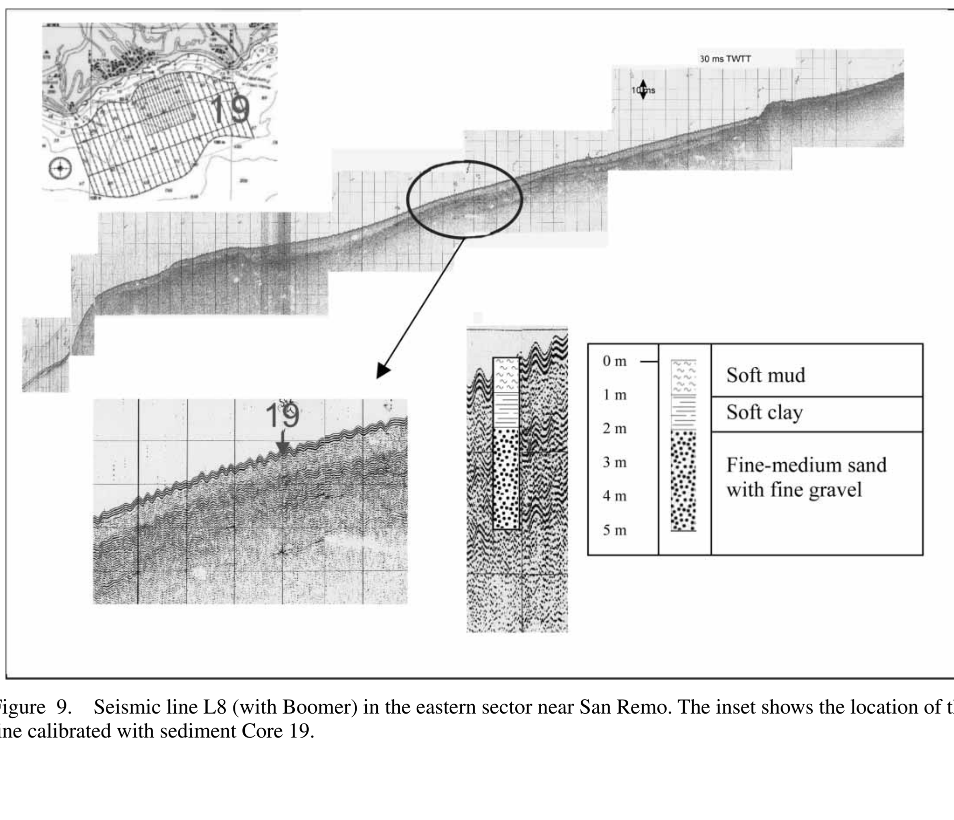

Figure 9. Seismic line L8 (with Boomer) in the eastern sector near San Remo. The inset shows the location of the line calibrated with sediment Core 19.

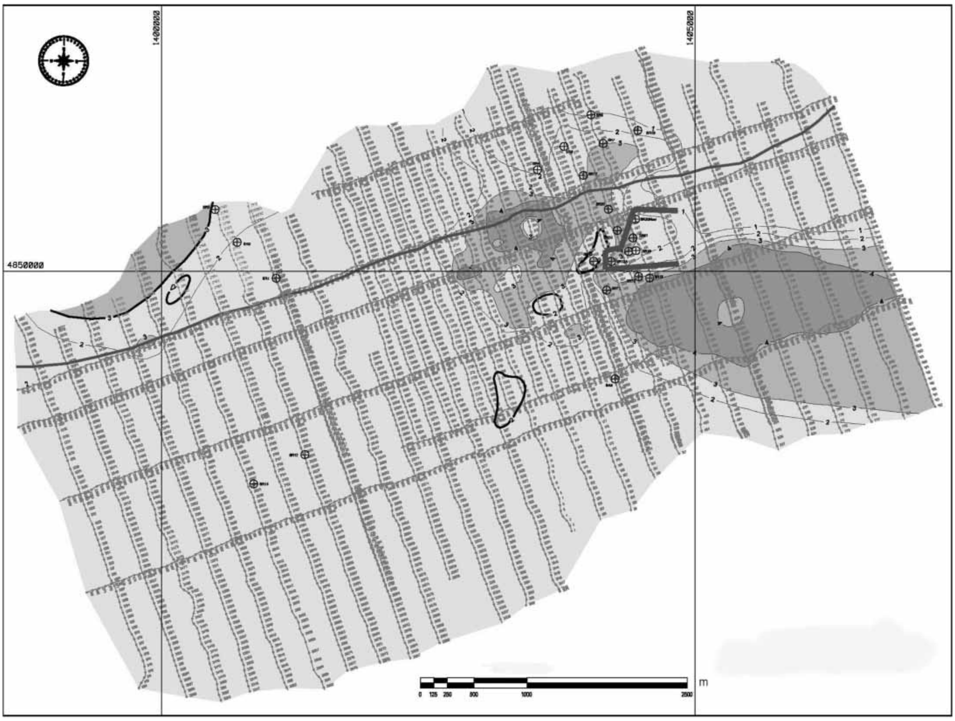

Figure 10. Map showing the thickness in metres (lines every 1 m) of the Holocene mud deposits, the sediment core sites, and the seismic line grid.

The distribution chart of the transgressive sediments (figure 10) shows two areas in which transgressive deposits lie between a depth of 20–40 m, parallel to the coast, on the inner shelf and 50–70 m on the outer shelf. The depocentres of these two sedimentary bodies, although situated in the same sectors, lie perpendicular to the coast. These deposits should probably be related to the rocky substratum that, although dislocated and subsident, downthrown by normal faulting, crops out in many sectors of the inner shelf, and to fluvial and deltaic structures that drained into a somewhat limited coastal plain during the low stand. The figure shows the areal distribution of the transgressive deposits; the lines, every 1 m, indicate the estimated maximum thickness of the deposits as 5 m. The most suitable area for dredging sediments for beach nourishment, because of its limited Holocene muddy cover and the sedimentological findings of the cores collected there, is also shown.

4. Conclusions

The various sectors of the Ligurian continental shelf show a similar geological evolution during the Plio-Pleistocene. The sediments accumulated along the coast, first filling minor tectonic depressions in the substratum and then gradually forming a stacking pattern of several Pleistocene prograding wedges.

During periods of high (interglacial) sea levels, the sediments formed coastal deposits that were subsequently reworked and redeposited on the outer edge of the continental shelf during periods of falling and low sea levels (glacial), when a substantial part of the platform emerged, and the watercourses practically emptied onto the shelf break. The deposits then formed a triangular prism with its most acute angle towards the land.

Where the process described above was accompanied by subsidence of the substratum on which the sediments rested, the sedimentary wedges continued to extend offshore (progradation) and vertically (aggradation); where no subsidence occurred, there was only progradation.

During the Late Quaternary, marine transgression (Versilian Sea Rise, *c*. 6000 yr ago) the sea reached its present level, and sedimentary deposits referable to deltaic or littoral systems (paleodeltas or paleobeaches) [18] were probably deposited at intermediate depths during stable moments in the transgression or during periods of steadily rising sea levels. On a global scale, at least two slowdowns or stases can be distinguished during this transgression [9, 28, 31, 32]. On a local scale, there were also other periods of eustatic rise due to sedimentation or tectonic uplift. During these periods, relatively coarse-grained detritic accumulations formed, and these can be grouped into two categories:

- extensive bodies (deltas, conoids, alluvial coastal plains, simple littoral systems, and lagoon barriers) where the sedimentary budget was too great for the dynamics of the zone; and
- local bodies where the local dynamics transformed a smaller sedimentary budget into morphological beach structures, sometimes also including dune structures.

The seismostratigraphic studies have shown that some sectors of the Ligurian continental shelf have coarse-grained sedimentary deposits suitable for beach nourishment. Those sectors are principally situated in front of coastal plains. On the basis of the evolution of the most surficial deposits, it is possible to distinguish between areas of sedimentary bodies of a transgressive phase at a depth of 20–70 m, with little recent sedimentary cover, shelf areas influenced by paleodeltas (i.e. between Albenga and Loano), and sectors with a relatively thin Holocene sedimentary mud cover.

The sector between Albenga and Ventimiglia, in particular, is ideal for the dredging of Late Pleistocene–Holocene sedimentary bodies, while it would be difficult to explore the eastern Ligurian sector due to the thick muddy cover lying over the deposits of interest or the absence of coarse-grained sediments (as in the sector around Genoa).

The shelf between Genoa and Savona has numerous interesting sites with coarse-grained deposits of limited extent and a thin muddy cover, but these sites need more detailed analyses.

In conclusion, in the areas of western Liguria, where there are relic deposits most suitable for nourishment purposes, the continental shelf has its greatest extent and is more or less divisible into two sectors: an internal sector (closest to the coast), which has an articulated morphology, due to a Pre-Quaternary sub-outcropping substratum or to the presence of post-glacial sedimentary bodies (relic beach deposits, tabular and cuspate bodies), and an external sector consisting of a sedimentary wedge that is poorly developed due to the subsidence of the frontal deposits. Pleistocene detritic bodies of a certain importance have formed on the continental shelf in this area, but the relative meagreness of the terrigenous input suggests that the transgressions probably underwent moments of stasis or relative slowdown and a combination of eustasy and neotectonics.

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