Article

Morpho-Structural Setting of the Ligurian Sea: The Role of Structural Heritage and Neotectonic Inversion

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Abstract: The review of recent bathymetric and geophysical data collected in the framework of several research and cartographic projects have allowed a detailed reconstruction of the morpho-structural setting and the (neo)tectonic evolution for both the Alpine and Apennine margins of the Ligurian Sea (Italy). The widespread occurrence of erosional processes and sediment mass movements along the steep continental slope and within the system of submarine canyons reflect the close correlation between the active tectonics and the recent morpho-dynamic evolution of the Ligurian Margin. This relation is better constrained in the western sector (Alpine) of the Ligurian Sea, where the recent uplift of the continental margin is associated to a well-developed system of inherited structures reactivated under a compressive/transpressive regime and widespread seismicity. In the eastern sector, where the seismicity is lower or absent, the mass movements are limited to few areas (e.g., the Portofino slope) coinciding with seismic clusters. Additionally, this sector is characterized by moderate and episodic fault reactivations under a compressive regime. The evidence of compressive deformation along the inherited fault systems has been revealed in some areas of the Ligurian Sea where the post-drifting extensional tectonics is interrupted by episodic tectonic inversion (at least) during the Middle–Upper Miocene and the Plio–Pleistocene until present.

Keywords: submarine landslides; seafloor morphology; active tectonic; tectonic inversion; structural heritage; Ligurian Basin; Mediterranean Sea

1. Introduction

The Ligurian Sea represents the northern propagation of the Sardo–Provençal and Thyrrenian back-arc basins (Figure 1a,b) produced, since the upper Oligocene, by the southeastern-ward roll-back of the Apennines–Maghrebides subduction zone (e.g., [1] and references therein). This area is also known as the “Ligurian Knot” due to the coexistence of several crustal units inserted in a complex geodynamic framework (e.g., [2,3]).

Here, the Alpine (western sector) and Apennines (eastern sector) margins share distinct morphostructural architectures, due to their different geodynamic inheritances. In the western sector, the roto-translation of the Sardinian Corsican Blocks and the formation of a new oceanic crust in the Ligurian Sea [4–8] have driven, since the Early Oligocene, the rifting and subsequent drifting of the south Alpine collisional tectonic units. This resulted in the separation of the Ligurian Alps from the Corsican Alps (e.g., [1,4,9–15]). At the same age, extensional tectonics in the eastern area produced a narrow, NNE–SSE-trending graben system affecting the westernmost sector of the Apennines fold and thrust system (i.e., the proto-Thyrrenian Basin; [16]). The same sector of the Apennines Margin was affected, from the Upper Miocene–Late Pliocene, by a strong reactivation of the extensional tectonics responsible for the recent morpho-structural setting of the chain (i.e., the Thyrrenian-stage; [17,18]).
Despite the western Ligurian Basin being commonly interpreted as a Neogene extensional area produced by the Corsica–Sardinia roto-translation (with the present-day morpho-structural setting accomplished between 21 Ma and 16; e.g., [19]), in recent years, several studies have highlighted the evidence of post-drifting tectonic reactivation (e.g., [20–22]). Indeed, morphostratigraphic data from marine areas show how the Thyrrenian Basin underwent a significant subsidence during the Plio-Pleistocene (e.g., up to 1500 m; [16,19,23–27]), while the coastal areas of the continental shelf were characterized by a gradual uplift (e.g., [16,28–31]). Additional evidence of the post-Pliocene onshore tectonic uplift are the recent, steep continental slopes of the Western Ligurian Margin and the thick (up-to 600 m) Plio-Pleistocene marine deposits filling the Messinian paleo-valleys (e.g., [32,33]). The reactivation of along-slope step-faults and their conjugates likely drove the development of the Plio-Pleistocene margins’ morphology, dominated by a very steep slope intersected by a well-developed canyon system [34–37].

Four regional-scale processes can be taken into account to explain the episodic reactivations under compressive and extensional regimes along the Ligurian Margin: (i) north–south shortening resulting from the convergence of the African and European plates [38–41], (ii) rollback of the Ionian–Adriatic subduction [10,42,43], (iii) gravitational eastward collapse of the thickened Apenninic lithosphere [44] and (iv) lateral “extrusion” of the southwestern Alps toward the SE (e.g., [38,45–48]).

Despite several works concluding that the above-mentioned mechanisms must be combined to explain the tectonic evolution of the Alps–Apennine system along the Ligurian
and Tyrrhenian margins (e.g., [49–51]), some key-questions are still a matter of debate: (i) the role played by the different tectonic forces driving the opening of the Ligurian Sea since the Early Oligocene, (ii) the role of tectonic inheritance and fault reactivations along the Ligurian Margin and (iii) the relative chronology and distribution of the main extensional and compressive events.

Moreover, the complex structural architecture of the western Ligurian Margin, characterized by the interaction of deep crustal-scale structures with the shallower, post-Messinian sedimentary cover is still partly unknown; this leaves the dynamics of the compressive reactivation (e.g., tectonic inversion) of previous extensional structures still not fully understood.

In this work, we merged multiple datasets collected in the framework of several Italian and French research projects to obtain a more comprehensive picture of the tectonic processes that affected the different sectors of the Ligurian Margin (Figure 1b). The detailed morpho-structural analysis was integrated with the reinterpretation of previous geological and geophysical data. This allowed us to reconstruct the structural evolution for both the western (Alpine) and eastern (Apennine) margins of the Ligurian Sea, describing (i) the kinematic and relative chronology of the main tectonic structures, (ii) their spatial distribution along the margins, (iii) the role of structural inheritance in the tectonic evolution of the area and (iv) the present-day morpho-dynamic setting of the margin, highlighting the correlation among large mass-wasting phenomena, inherited faults and earthquakes clusters.

2. Geological Setting

The Ligurian Sea extends at the north-eastern corner of the western Mediterranean Sea (Figure 1a) and is bounded to the northwest by the southernmost propagation of the Western Alps, the WSW–ENE-trending Ligurian Alps. These are the results of the Europe/Africa continent collision which started in the Eocene (e.g., [2,52–54]), with the peak-shortening stage achieved during the Late Eocene/Early Oligocene period [54–56]. From the late Oligocene, the change of the continental fragments kinematics in the western Mediterranean region resulted in the switch from a contractional to extensional regime. This led to the opening of the Liguro–Provençal Basin (late Oligocene to early Miocene, e.g., [1,5,19,57]) and the Tyrrhenian Sea (Late Miocene to Pliocene; [58,59]) due to southeastward roll-back of the Apennines–Maghrebides subduction zone (e.g., [1] and references therein). In this framework, vertical movements in the Ligurian Alps were not limited to the orogenic stage, but protracted during the Miocene to Present, as shown by the low-temperature apatite (U-Th)/He and fission track studies [31,60] and the morphostratigraphic reconstructions of the Plio-Pleistocene sedimentary sequences [61–63]. These latter, locally exposed (e.g., in the Ventimiglia area: [62,64]), witness a post-Pliocene uplift of about 500 m [31].

The strong differential coastal uplift and basin floor subsidence likely triggered the widespread submarine landslides and gravitational movements affecting the post-Messinian sedimentary bodies found along the Ligurian Margin (e.g., [30,33,65,66]). Seismic lines interpretation has shown that these gravitational collapses are more common and volumetrically extended along the Ligurian Alpine Margin (between Savona and Imperia) than in the Apennines Margin (except for the Portofino area; [65,67]). Here, both the seismicity and active tectonic are very low or absent, while the occurrence of erosional and gravitational processes along the Alpine Margin matches with sectors of the chain characterized by widespread seismicity under transpressional/compressional tectonic regime (as indicated by focal mechanism solutions: e.g., [20,68,69]; Figure 2).

Although still not fully resolved, the late Miocene to Present exhumation of the Ligurian Alps is thought to be partially accommodated by a Pliocene, north-dipping blind thrust at the foot of the Ligurian Margin [8,26,70] (Figure 2). This north-dipping thrust system extends to the east from the gulf of Genoa and links westward to the Marcel Fault System (MFS hereafter; see also [21] and references therein) finally reconnecting to the edge
of the compressive Castellane Arc; this latter is the result of the lateral expulsion of the south-western Alps, within the framework of the half-closing Ligurian sea (see also [20]). The northern (deep) prolongation of this thrust is also thought to accommodate the Pliocene exhumation of the Argentera Massif [26]. Recent seismic investigations allowed to locate, at the base of the Imperia–Nice continental slope, the occurrence of a ~80-km-long transpressive fault system of the Plio-Quaternary age (the “Northern Ligurian Fault System”, NLFS therein; [69,71], Figure 2). Offshore, the interplay between the compressive and transpressive deformation produced the 40-km-long anticline of the Imperia Promontory and a network of NE–SW trending faults. The widespread occurrence of fault escarpments, sediment failures and sub-marine landslides [32,66] indicate recent activity of the NLFS, consistent with the historical and instrumental seismicity (e.g., the 1887 Imperia earthquake and related tsunamis; [21,22,72]).

Inland, the deformation of the Pliocene sediments was predominantly accommodated by NW–SE- and NE–SW-trending normal faults [61,62,64,73,74]. Nevertheless, the prolongation of the NLFS to the east of the Imperia Promontory remains unconstrained, as well as the propagation towards the Alpine and Apennine margins of the Ligurian thrust front system. Moreover, the coexistence of local, shallow extensional deformation and a regional, crustal compressional state of stress needs to be further investigated. In this framework, the proposed models for the Plio-Pleistocene compressive reactivations in the easternmost sectors of the Alpine and the adjacent Apennine margins remain openly debated.

Figure 2. Morpho-structural sketch and seismicity of the Ligurian Sea and adjacent area (inland geology modified after [61,75]). The extension of the “atypical” oceanic crust is derived from [8]. Earthquake epicenters (years 1985–2022) are from the ISIDE–INGV catalog available at https://doi.org/10.13127/ISIDE (accessed on 22 July 2022; [76]) and the focal mechanisms from [21]. Legend of the symbols: (1) “atypical” oceanic Crust (after [8]); (2) Canyon scarp; (3) Prominent slide scars area; (4) Normal fault; (5) Reverse fault; (6) Anticline axis; (7) Substratum high axis; (8) Inferred fault. AB: Argentera Bersezio Fault System; ST fault: Saorge Taggia Fault; SF: Stura Fault; CS: Celle Sanda Fault; SV line: Sestri Voltaggio line; MFS: Marcel Fault System; NLFS: North Ligurian Fault System; NPDZ: Northern Principal Deformation Zone; VaC: Var Canyon; RC: Roja Canyon; TC: Taggia Canyon; VC: Vado Canyon; BC: Bisagno Canyon; PC: Polcevera Canyon; PS: Portofino Slope; LC: Levante Canyon.
3. Materials and Methods

The present work is based on the integration of a dense grid of seismic reflection data and a high-resolution digital bathymetric model of the Ligurian Sea (a DTM with a spatial resolution between 5 and 25 m) with multiple pre-existing cartographic datasets (Figure 1b). These latter, collected and homogenized by the Servizio Geologico d’Italia in the framework of the EMODnet Geology 4 Project (Work Package 6 “Geological events and probabilities”; [77]), consist of: (i) the mapped morpho-structural elements derived by the Neotectonic Map of Italy at the scale 1:500.000 (C.N.R., P. F. Geodinamica, 1987), (ii) the “Structural Model of Italy” at scale 1:500.000 (P.F. Geodinamica, sottoprogetto Modello Strutturale d’Italia; [78]) and (iii) various structural reconstructions realized in the frame of several Italian (CARG project: [79,80]) and Italian–French projects (e.g., RiskNat EU Alcotra Project and MALISAR-Geóazur project).

The characters and ages of the main seismo-stratigraphic units described in this work (e.g., Plio–Quaternary, Messinian deposits and Miocene pre-evaporitic sequences) have been based on the seismic facies already recognized and described by previous authors (e.g., [16,19,22,71]). Above all, the Messinian evaporitic sequence represents the most prominent chrono-stratigraphic marker identified in the seismic profiles, being delimited by a well-marked and continuous reflector [22,71]. Towards the slope, detrital Messinian sequences overlie a marked erosive surface cutting both the Miocene basin deposits (locally deformed) and the pre-Miocene substrate [81]. On the maps (e.g., Figure 3) the “undefined substrate” represents the outcropping pre-Pliocene substrate mapped in the Structural Model of Italy [78]. These outcropping bodies correspond to Miocene sediments (e.g., the Messinian evaporitic/detrital or pre-evaporitic sequences) and Miocene/pre-Miocene acoustic basement (e.g., the Miocene volcanic/intrusive bedrock, the pre-Miocene basement or the allochthonous bedrock chaotic bodies; [78]).

The available historical and instrumental seismological data for the investigated area were also added from open-source database ISIDe, provided by the INGV and available at http://terremoti.ingv.it/ (accessed on 22 July 2022).

All the datasets were managed and analyzed within a single, GIS-based software (Geosuite AllWorks®; https://geomarinesurveysystems.com/products/software/allworks/ accessed on 22 July 2022) and the multi-scale 3D validation of the interpretations were obtained with QGIS (release 3.16.11).

3.1. Seismic-Reflection Data

The seismic reflection data were collected with different methodologies (Sparker 1-5-kJ and multichannel Air-Gun), thus integrating both high-resolution and high penetration lines; these are suitable to identify deep tectonic structures and the connected shallow sediment deformations.

In this work we reanalyzed the seismic records collected from the ‘70s to the ‘90s of the last century (e.g., Malito, Migeva, Lipro DISTAV-UniGe projects and MS seismic lines of Osservatorio Geofisico Sperimentale of Trieste OGS; https://snap.ogs.trieste accessed on 22 July 2022; [82]). The other, more recent datasets, were collected in several national and international research projects realized in the Ligurian Sea (e.g., CARG, MALISAR and Magic projects; [83,84]). These analogic (i.e., raster images) and digital seismic sections were converted in SEG-Y standard format and then processed and combined into a single GIS-based project.
The regional geomorphological setting of the Ligurian Margin presents two main areas with different characters. To the west, the margin is characterized by a narrow shelf with a highly articulate morphology (development of submarine channels and canyons) and very steep slopes (between 6°–11°; refer also to [66]), widespread seafloor erosion and sediment failure features. To the east, separated by the NNE–SSW-elongated Genoa Valley, the eastern margin presents a less complex morpho-bathymetric setting (Figures 2 and 3). Here, the sediment failures responsible for the recent seabed morpho-dynamic evolution are less diffused and focused on some prominent areas (e.g., the Levante Canyon and Portofino slope; Figures 2 and 3). Therefore, due to the occurrence of several morpho-structural units which share distinct morphobatimetries and local complex structural settings, the Ligurian Margin can be subdivided into two main domains: the Alpine Margin (to the west) and the Apennine Margin (to the east).

Figure 3. New morpho-structural map of the Ligurian Sea and adjacent areas integrated with the 1985–2022 seismicity [76]. Inland geology is derived by [61,75]; the extension of the “atypical” oceanic crust is from [8]. The seabed morphology is highlighted using a slope shader. The thickness (in seconds TWTT) of the Plio-Quaternary deposits is redrawn from the “Structural Model of Italy” [78]. GV: Genoa Valley; IP: Imperia Promontory; LS: Ligurian Seamounts; SB: Savona Basin; MS: Median Seamount. For the other acronyms refer to Figure 1.

3.2. Multibeam Bathymetry

The detailed analysis of the morpho-structural setting of the area, aimed to unravel the control exerted by tectonics on the present-day morpho-bathymetry, has been achieved thanks to a new digital bathymetric model (DTM), with a spatial resolution ranging between 5 and 25 m. The DTM was obtained by processing and merging Multibeam bathymetry data collected in the frame of the MALISAR and MAGIC projects (originally addressed to the mapping of active faults and geohazard-related seabed features). Most of the Multibeam data were collected during several MALISAR surveys (years 2006, 2007 and 2008) with a Simrad EM300 apparatus (onboard of vessel R/V Le Suroit) and restored with a grid resolution of 25 m. Additional high resolution Multibeam data were collected in the frame of Magic project with a Reason SeaBat 8160 apparatus (onboard of vessel N/o Universitatis) rendering the seabed surface with a grid resolution ranging from 5 m in the shelf areas to 20 m in the continental slope sectors. For the areas not covered by the high-resolution...
MALISAR and Magic surveys, the EMODnet bathymetric data (cell size resolution \(\approx 200\) m; https://www.emodnet-bathymetry.eu accessed on 22 July 2022) were used. The distribution of seismicity and paleo-seismicity data was analyzed to infer the link between the distribution/triggering mechanisms of seismic shaking and the geo-hazard-related features (e.g., occurrence of large submarine or coastal landslides, tsunamis, etc.). Used data were derived by scientific literature (references in the text) and the ISiDe database [76].

4. Results

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4.1. The Alpine Ligurian Margin (Western Sector)

The investigated portion of the Alpine Ligurian Margin extends between Genoa (to the east) and Ventimiglia (to the west) and consists of a narrow, sedimentary-constructed shelf with a steep slope affected by diffuse and moderate seismo-tectonic activity (Figures 2 and 3). A complex system of canyons and associated tributary channels carves the entire area of the slope, with widespread erosional and mass-wasting phenomena mainly affecting the thick hanging sedimentary masses of the Plio-Quaternary covers.

Despite these common characters, our new detailed reconstruction of the morpho-structural setting allowed us to distinguish two subsectors within the Alpine Ligurian Margin, characterized by different morpho-dynamic evolutions.

Between the towns of Ventimiglia and Taggia, the slope area is affected by a set of WSW–ENE-oriented step-faults (Figures 3 and 4a); here, the deformation is focused along the lower continental slope, where the faults length ranges from 5 to 10 km along the strike (Figure 3). Along the entire slope area, these step-faults are crosscut by a system of NNW–SSE-oriented normal faults, which are subparallel and locally delimitate the main submarine valleys (e.g., the Roja, Bordighera and Taggia Canyons; see also [84]). These latter are the most prominent morphobathymetric features, with significant erosional activity focused along the canyons’ thalwegs and flanks (Figures 2 and 3) and locally affects wide areas of the continental shelf (e.g., at the heads of Roja and Bordighera Canyons).

At the base of the slope and in the adjacent basin, the presence of a segmented WSW–ENE reverse-fault system (e.g., the Marcel Fault System by [69]; Figures 2 and 3) is confirmed. In the middle slope, seismic lines show compressive deformation (i.e., folding) of the Miocene deposits, truncated by the Messinian erosive unconformity underlying the thick Plio-Quaternary sedimentary cover (Figure 4a,b). This series of parallel folds represents the remnants of a middle/upper Miocene compressional tectonic event affecting Pre-Messinian slope deposits. Starting from the Lower Pliocene, these intraslope contractional structures are overprinted by the WNW–ESE and NNW–SSE normal faults responsible for their collapsing across and along the slope (see also [22,80,85]).
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Moving toward the northeast, between the towns of Taggia and Savona, the continental shelf became narrower (average extension: 4 km wide), with a steeper upper slope with respect to the western sector of the Ligurian Alpine Margin. In this sector, the submarine channels and canyons converge within a broad and flat intra-slope valley which connects, to the north, with the Vado Canyon and then to the Genoa Valley (Figures 2, 3 and 5a). This system of submarine canyons is delimited by the ENE–WSW-trending Imperia Promontory, a large and segmented anticline with a slightly curved trend (Figure 5a). To the north, this regional-scale fold gradually disappears beneath the sedimentary cover of the Savona Basin, where it reconnects to a series of N–S-elongated gentle folds affecting both the Pliocene and the evaporitic levels (Figure 5a,b). Along its southern flank, the Imperia Promontory is bordered by a steep slope where the Miocene bedrock crops out (Figures 5a and 6). This slope is interrupted by narrow and laterally continuous submarine terraces coinciding with subvertical ENE–WSW-oriented step-faults. At the base of the slope are a series of developed segmented ENE–WSW-trending reverse faults (Figures 5a and 6).

**Figure 4.** (a) Detail of the morpho-structural map of the Ligurian Sea for the sector between Ventimiglia and Taggia with the location of the seismic line MR58 (Figure 5b). Inland geology redrawn from [75]. RC: Roja Canyon; TC: Taggia canyon. (b) Seismic multichannel line (MR-58; MALISAR Project) showing the compressive reactivation in the Ventimiglia slope area. The section shows the recent compressive deformation at the base of the slope linked to the reactivation of the Marcel Fault System (MFS). In the middle slope area, the remnants of the Miocene compressive event (e.g., the Miocene deposits folding) are affected by Plio-Pleistocene normal faulting. Vertical exaggeration (VE) of 6 evaluated by assuming a seismic wave velocity of 2000 m/s (TWTT).
The analysis of the seismic lines covering the sector between Imperia and Savona has shown how the contractional structures developed in the Ventimiglia area extend further to the northeast. These propagates inside the Genoa Valley basin until reaching the opposite escarpment edge where the Ligurian seamounts thrusts are developed (Figures 5a,b and 6). Here, the occurrence of NNE–SSW-trending and ESE-verging thrusts (Figure 6) testify to the recent propagation toward the SE of a compressive deformation.
Figure 6. Multichannel seismic line MR45 (MALISAR Project) collected across the Imperia Promontory showing the recent compressive structures at the base of the slope (NW-dipping NLFS thrusts and related shallow folds; purple inset), within the adjacent intra-slope basin (SE-dipping back-thrusts; light blue inset) and in the shelf area (e.g., inversion-related reverse faults and basement highs outcrops; light blue inset). The location of the line is drawn in Figure 5a. Vertical exaggeration (VE) of 4.5 evaluated by assuming a seismic wave velocity of 2000 m/s (TWTT).

Within the intra-slope basin area, seismic lines show the occurrence of northwest verging compressive structures, coinciding with the above-described Imperia Promontory, closely related to the structuring of the main ESE-verging thrusts. These back-thrusts (Figure 7) propagate along the strike toward the NE up to the Savona Basin, where the Imperia Promontory is interrupted.

Figure 7. Single-channel Air-Gun section (IMP26; CARG Project, Imperia) showing the recent compressive deformations within the intra-slope basin near Imperia (SE dipping back-thrusts). Towards the shelf area, the recent inversion of the Miocene step faults suggests possible transpressive kinematic (e.g., positive flower structure). For the location of the section, see Figure 5a. Vertical exaggeration (VE) of 5.5 evaluated by assuming a seismic wave velocity of 2000 m/s (TWTT).
Moving to the shelf area, the WSW–ENE compressive structures and the related NNW–SSE transfer faults are more discontinuous and bound large Pre-Pliocene substratum highs (Figure 5a), often cropping out along the canyons where active erosion is dominating. This morphostructural setting is observed along the entire shelf area and is delimited at the Vado Ligure Canyon by a prominent NNE–SSW-elongated substratum high which intersects both the shelf edge and the upper slope.

Between Savona and Genoa, the shelf area becomes wider (average extension: 7 km wide) and is mainly constituted by a thick Plio-Pleistocene sedimentary prism. Toward the east, the continental slope is intersected by the N–S-oriented and deeply incised Polcevera and Bisagno Canyons (Figures 2, 3 and 5a). These are superimposed on two paleo valleys of tectonic origins deeply carved during the Messinian. The two canyons are filled by Plio-Pleistocene and Holocene sediments, which are progressively thicker moving towards the northern edge of the shelf and, the south, they converge within the Genoa Valley. This is a narrow tectonic depression delimited on its flanks by NNW–SSE-oriented normal faults which affect the Miocene deposits (Figures 2 and 3), locally reactivated under extensional kinematics during the Pliocene (e.g., the extensional Tyrrhenian phase).

The analysis of the earthquakes’ spatial distribution and their focal mechanisms shows a clustering along the major tectonic lineaments of the Alpine Ligurian Margin (Figure 2). It is noteworthy that major earthquakes between Ventimiglia and Imperia are distributed along the WSW–ENE lower continental slope, with focal mechanisms showing a reverse to transpressional kinematics (e.g., [22]). Moreover, low-intensity earthquakes (magnitude up to 2.5) cluster along the NNW–SSE-oriented normal fault systems where they may trigger large submarine landslides (e.g., offshore of Ventimiglia, Arma di Taggia and Imperia towns; Figures 2 and 5a). Additionally, the NNE–SSW-oriented structural high delimitating the Vado Ligure Canyon coincides with an evident cluster of low-intensity earthquakes that links to the south with the northern prosecution of the WSW–ENE-trending NLFS (Figures 2 and 5a). Additionally, in this case, the widespread submarine landslides can be correlated with the detected seismic activity. These latter decreases move towards the Apennine Ligurian Margin, except for the northeastern border of the Ligurian Seamounts and the Portofino area (Figure 2). Here, widespread submarine landslides (which are almost absent along the Apennine Margin) may match with low-magnitude seismic clusters (Figures 2 and 8).

4.2. The Apennine Ligurian Margin (Eastern Sector)

Along the Apennine Ligurian Margin, the wide continental platform extends from a minimum of 5 km (between the Genoa Valley and the La Spezia Graben) to a maximum of 35 km on the Viareggio Basin; it is intersected by few canyons which affect a limited portion of the outer shelf areas (Figures 2 and 3). Steep slopes with intense seafloor erosion and widespread retrogressive sediments failures are evident within the Genoa Valley (which, in this paper, marks the border between what we define as the Alpine and the Apennine Ligurian margins; Figure 3) and along the Polcevera and Bisagno Canyon flanks. To the southeast, erosional features are mostly concentrated within the narrow, well-carved thalweg of the NW–SE-oriented Levante Canyon (Figures 2 and 8) which crosses along the base of the upper slope with a meandering and locally sharply-deviating course. This complex morphology reflects the underlying network of NW–SE-trending normal faults segmented by a systems of NE–SW-trending transfer faults which cut the Plio-Pleistocene deposits. In this sector, excepts for the Portofino slope area (which is characterized by widespread mass wasting processes with large lateral continuity), the bulk of the erosion is controlled by the tributary channels of the Levante Canyon; the largest of these (the Sestri and Deiva Marina canyons) matches with the Messinian paleo-valleys delimited by the NE–SW-trending normal faults affecting the sedimentary deposits of the shelf (Figure 8a). Here, surficial deposits are strongly affected by erosional processes evidenced by canyon thalwegs with various incision depths, arcuated failure-related scars and deeply carved incisions scattered on the continental slope. (Figure 8a). A field of giant pockmarks is
present offshore of the Portofino area (Figure 8b) on top of the contourite accumulations (refer also to [86]).

Figure 8. (a) Detail of the morpho-structural map of the Ligurian Sea for the La Spezia Graben sector (Apennine Margin). The map is integrated with the 1985–2022 seismicity [76] and the inland geology (redrawn from [75]). The black lines are the location of the seismic profiles shown in Figures 9–11. LC: Levante Canyon; SC: Sestri Canyon; DC: Deiva Canyon; NPDZ: Northern Principal Deformation Zone; PC: Polcevera canyon; PS: Portofino slope. (b) Detail of the giant pockmarks field in front of the Portofino slope (PS).

This morphologically complex sector of the slope area is delimited, to the southeast, by a wide, flatter submarine valley: the La Spezia Valley (Figure 3). Its northern flank describes a steep upper slope, which gets gradually narrower to the south while, to the southwest, it is delimited by the Ligurian seamounts. Along the northeastern slope of the Ligurian Seamounts, the Sparker lines show evidence of inversion tectonics with the reactivations of NW–SE normal step-faults as reverse faults (Figure 9).
Figure 9. (a,b) Sparker seismic lines (6 kJ) recorded along the northeastern flank of the Ligurian sea showing normal faults reactivated as reverse structures during the Plio-Pleistocene (tectonic inversion). Vertical exaggeration (VE) of 5.5 evaluated by assuming a seismic wave velocity of 2000 m/s (TWTT).

Along the La Spezia valley, mass wasting processes are generally less extended if compared to the Bisagno and Polcevera canyons or the Portofino slope (as already observed by [65,66]).

Towards the south-east, the structural setting of the Apennine Ligurian Margin is dominated by the presence of the wide, NW–SE-elongated depressions of the La Spezia Graben, Viareggio Basin and Capraia Graben (or Ligurian Tuscan Graben System; LTGS
hereafter; Figure 3), which control the depocenters of the Plio-Pleistocene deposits (with thicknesses ranging from 0.5 to 2 s TWTT; see also [87]).

Towards the west, the LTGS is delimited by the large and continuous structural high of the Pre-Pliocene basement developed between the Ligurian Seamounts and the Capo Corso Promontory (Figure 3). This structural high (or Continental Corsican Northern Prong: CCNP hereafter) corresponds to a portion of the Corsican Continental Margin and is probably the northern remnant of the Corsican Alpine front. Both the LTGS and CCNP morpho-structural units show a complex structural setting which has recorded the polyphasic evolution of the margins since the Miocene, with a more recent reactivation in some sectors. Sparker seismic lines and multi-channel seismic records show (Figure 10a) the presence of NNW–SSE-elongated pre-Tortonian basins beneath the Holocene and Plio/Pleistocene sediments filling the LTGS basins produced by a first post-orogenic extensional phase of the northern Apennine (as already observed by [16, 67]). These pre-Tortonian basins are bounded by NNW–SSE-trending normal faults.

Figure 10. (a) Central sector of the La Spezia Graben: multichannel seismic line MS-75 (by MS-OGS) showing the Miocene deposits affected by the Pliocene extensional reactivation. To the southwest, the Pliocene deposits undergo compressive reactivation. Vertical exaggeration (VE) of 3.5 evaluated by assuming a seismic wave velocity of 2000 m/s (TWTT). (b) Sparker line Malito3 (6 kj) shows the effects of the Middle–Upper Miocene compressive event affecting the Miocene deposits. The section interpretation highlights the Plio-Pleistocene reactivations with negative flower structures (coinciding with the NPDZ; purple inset). Vertical exaggeration (VE) of 9 evaluated by assuming a seismic wave velocity of 2000 m/s (TWTT).

Locally, they are intersected by two systems of faults (oriented around ENE–WSW and E–W, respectively) which crosscut both the deepest area of LTGS and, westward, the CCNP (Figure 3). The northernmost of these ENE–WSW systems crosscuts the sector between the La Spezia Graben and the Ligurian Seamounts (Figure 10b), with the faults concentrated within a main deformation zone (the Northern E–W-oriented Principal Deformation Zone, NPDZ hereafter; Figures 2, 3 and 8). To the west, this fault system can be correlated
with a narrow and symmetrical structural high bounded by normal faults, while to the east, it results in a negative flower structures system (Figure 10b). A lateral change in the sedimentary cover thickness and migration of sediments’ depocenters (produced by local subsidence and/or uplift) are common features along this deformation corridor. Eventually, the NPDZ also divides the Plio-Quaternary La Spezia Basin in two distinct sectors. The northern one is wider (≈40 km) and deeper, while the southern one is narrower (≈20 km) because it is confined to the east by a series of NW–SE-elongated intrabacinal structural highs (which locally have an arcuated shape; Figure 3). These latter, developed in the Miocene deposits, show evidence of compressive kinematics (likely developed during the Upper–Middle Miocene compressional event; see also [16]) which have reactivated inherited, Lower–Middle Miocene structures.

Towards the shelf area, the ENE–WSW-oriented NPDZ becomes narrower and rotates to an E–W orientation (Figures 3 and 8), controlling the orientation of the Levante canyon head. Here, along the slope and shelf-edge area, the NPDZ intersects a set NW–SE-oriented step-faults. These latter are inverted normal faults which affect the Pleistocene sedimentary sequence (Figure 11).

![Figure 11. Sparker line LSP-05 (1 Kj; CARG Project, La Spezia) collected along the shelf area of the Apennine Margin showing the reverse faulting affecting the bedrock and the Plio-Pleistocene deposits. This seismic line also highlights how the Levante Canyon head coincides with the recent normal faulting reactivation. Vertical exaggeration (VE) of 5 evaluated by assuming a seismic wave velocity of 2000 m/s (TWTT).](image)

To the south, the LTGS is intersected by another ENE–WSW-trending fault system (the Southern E–W-oriented Principal Deformation Zone, SPDZ hereafter; Figure 3). To the east, the SPDZ intersects the Apennine Margin structures (e.g., LTGS) and the CCNP with a series of narrow and discontinuous structural highs developed along the E–W direction. Eventually, to the west, this faults system links the to the ENE–WSW-oriented normal faults developed in the Liguro–Provençal Basin, reconnecting to the limits of the oceanic crust (Figure 3).

**5. Discussion**

Despite the morphostructural differences existing between the Alpine and Apennine sectors, the integrated analysis of the bathymetric data and multiple seismic-reflection lines confirms the close link between the occurrence of the focused erosion/mass movements of sediments and the inherited faults along the Ligurian Margin [65,66]. Moreover, recent tectonic activity appears linked to the reactivation of older extensional structures under a
compressive/transpressive regime (refer also to Table 1), locally with associated clustered seismicity. The characters and implications of these findings are described in the following.

### Table 1. Chronology of the main tectonic events and structures for the Alpine and Apennine sectors of the Ligurian Margin. NPDZ: Northern Principal Deformation Zone; SPDZ: Southern Principal Deformation Zone; SS: Strike-Slip.

|                | Alpine Margin | Apennine Margin |
|----------------|---------------|-----------------|
|                | Ventimiglia   | Ventimiglia     | Imperia Promontory | Genoa Basin | Genoa Valley | North of NPDZ | Between NPDZ & SPDZ | SPDZ | Tectonic inversion |
| Plio-Quaternary| Thrusting/folding | Minor thrusting/folding | Thrusting (basin borders) | Normal faulting | Normal faulting | SS | Normal faulting | SS | Normal faulting |
|                | Normal faulting | Normal faulting | ? | ? | ? | ? | ? | Tectonic inversion |

5.1. Alpine Ligurian Margin

Along the Alpine Ligurian Margin, between Ventimiglia and Taggia (Figures 2, 3 and 4a), two systems of faults control both the distribution of the large mass movements affecting the lower slope areas (e.g., the set of faults oriented WSW–ENE; Figures 4 and 5; see also [85,88,89]) and the development of the main canyon system (e.g., the set of faults oriented NNW–SSE). Here, several earthquake focal mechanism solutions indicate the occurrence of a compressive and transpressive setting (e.g., [22,90]; Figure 2) confirming the presence and present-day activity of a south verging thrust fault system, likely related to the eastward propagation of the Saint Marcel fault system (see also [22]). In the shelf area, seismic data suggest that recent reactivations of normal faults also control the progressive retreat of canyon heads [84]. This occurrence is confirmed by the close link between the focused mass wasting processes within the canyon heads and the presence of NNW–SSE-oriented faults (Figure 4a,b). The present-day activity of these faults (reactivated under compressional regime) controls the location of a series of submarine landslides, as testified by the occurrence of kilometer-scale arcuated slide scarps aligned along buried faults (e.g., the MFS; Figure 4a,b). The scarps also coincide with clusters of low-intensity earthquakes (magnitude up-to 3 Mw) which could have participated in the pre-conditioning and/or the triggering of the mass movements together with additional factors (e.g., the increasing slope angle. See also [66]). Contractional tectonics affected the slope area also in the Upper Miocene–Middle Miocene, as testified by the remnants of the Miocene sediment folding (Figure 4b), overprinted by extensional Pliocene reactivation (Table 1).

The sector between Taggia and Albenga shows significant variations relative to the westernmost Alpine Margin. Here, the most prominent morphostructural features are the WSW–ENE-elongated Imperia Promontory and the subparallel intra-slope basin (Figures 5a,b, 6 and 7). Here, the steep slope with large slide scarps (up to 3 km long), the rectilinear fault escarpments and the adjacent narrow basin area with arcuated seabed scarps (Figures 6 and 7) represent the most evident shallow effects of the Plio-Pleistocene reactivation under the compressive tectonic regime of the WSW–ENE-oriented NLFS (e.g., [22,69]). This inverted reactivation of older extensional structures (e.g., [21,26,91]) propagates to the SE within the intra-slope basin where the compressional/transpressional
deformation produces co-axial back-thrusting whose intensity decreases towards the shelf edge (Figures 6 and 7). The focal mechanisms of the earthquakes detected along the NLFS confirm deformation under a compressive and transpressive regime (Figure 2). Indeed, the NLFS coincides with the potential source of historical large earthquakes and tsunamis (e.g., the 1887 Imperia earthquake/tsunamis), thus representing the most prominent geo-hazards element along the Ligurian coastal area (see also [69] with reference therein).

The northern terminations of the NLFS is generally considered, in the literature, as the sharp interruption of the Imperia Promontory (Figures 2, 3 and 5a), where the Savona Basin begins. Nevertheless, the occurrence of N–S-elongated gentle folds (likely linked to E–W contractional tectonics; Figure 5a) developed inside the Pliocene/Messinian sediments and the progressive anticlockwise rotation of their orientation toward the WNW–ESE direction (parallel to the trend of the Vado Canyon head in the upper shelf area), suggest that the NLFS can be extended further to the northeast, affecting a wider sector of the Alpine Margin (Figures 2, 3 and 5a). Our hypothesis is supported by two additional pieces of evidence: (i) the occurrence, along the NLFS prolongation, of a dense cluster of earthquake epicenters and (ii) the solutions of focal mechanisms which indicate compressive/transpressive kinematics, similar to those observed along the NLFS (Figure 2; see also [16,21,71]).

5.2. Apennine Ligurian Margin

Seismic lines reveal how compressive deformations active since the Plio-Pleistocene were not localized only along the Alpine Margin, but propagated (at a lesser extent) eastwards, towards the Apennine Margin. Indeed, NNW–SSE-oriented gentle folds and thrusts are developed also in the Genoa Valley, subparallel to the orientation of the deepest sectors of the Bisagno and Vado Canyons (Figures 3, 4 and 5a,b).

East of the Genoa Valley, in the Apennine Ligurian Margin, two morphodynamic elements deserve special attention: the Levante Canyon and the Portofino Slope area. Here, submarine landslides with various sizes develop, notably across the Levante Canyon head and along its flanks (Figures 2, 3 and 8). Between Portofino and the Ligurian Seamounts are also widespread, very thick accumulations of contourite bodies (e.g., [86]) which promote recurrent submarine landslides (e.g., with large rupture surfaces and massive foot accumulations). Despite the still-open discussion on the surficial or deep nature of this mass wasting phenomena (e.g., [30,65,66,86]), the striking finding from our data is the occurrence also in this sector of the margin of a strict correlation between mass wasting phenomena, NW–SE normal faults and recent-to-present-day seismic activity (clusters of epicenters with a magnitude of up to 3.2: Figures 2, 3 and 8).

This normal fault system, delimitating the northern sector of the La Spezia Graben, experienced polyphasic evolution and has been characterized by compressive reactivations (related to tectonic inversion) during the Plio-Pleistocene (Table 1). This reactivation affects mainly the northeastern flank of the Ligurian Seamounts and the shelf area near the Levante Canyon head (Figures 8, 9 and 11) and can be linked to the propagation toward the east of the regional stress responsible for the folding and thrusting of the Alpine Margin (e.g., along the NLFS). The propagation of deformation appears to be controlled by the (inherited) WSW–ENE-oriented NPDZ transfer faults system. This interpretation is consistent with (i) the strike-slip movement detected along the NPDZ, where the Plio-Pleistocene sedimentary basins and the younger Holocene sedimentary covers are affected by negative flower structures (Figure 10b) and (ii) the contractional strain concentration along the NW–SE faults systems delimiting La Spezia Graben (Figures 9a,b and 11).

The other regional WSW–ENE-oriented transfer faults system (the SPDZ) crosscuts the NNW–SSE-trending basins (i.e., the LTGS) opened during the first extensional phases of the Lower–Middle Miocene (Figure 3). To the west, the SPDZ extends toward the Liguro–Provençal Basin, which locally marks the WSW–ENE boundary between the oceanic crust and the thinned continental margin of the Corsican Block (e.g., west of the Median Seamount; Figure 3, see also [8]).
Published reconstructions of the oceanic crust formation mechanisms for the Liguro-Provençal Basin (e.g., [12, 48, 92]) take into account strain partitioning along the WSW–ENE-oriented transfer faults [16, 39, 93] to explain (i) the roto-translation of the Corsican Sardinian Block, (ii) the “rhombohedral” shape of the oceanic crust area in the northern basin and (iii) the distal Lower–Middle Miocene NNW–SSE thrusting with ENE verging along the northern Apennine [39, 48, 92–94]. Thus, we can consider the NPDZ and the SPDZ as the relics of this regional-scale transfer faults system which accommodated the opening of the Liguro–Provençal Basin (Figure 12a,b).

Figure 12. (a) Simplified 3D kinematic model of the Miocene drifting phase of the “atypical” oceanic crust [8, 12] of the Liguro–Provençal Basin showing the role of the inherited NPDZ and SPDZ accommodating the Ligurian Basin drifting. (b) Schematic tectonic map of the Upper–Middle Miocene and
the Plio-Pleistocene compressive deformations structures at the Alpine and Apennine margins and the inferred Upper–Middle Miocene compressive event (blue arrows) and the Plio-Pleistocene lateral “extrusion” of the southwestern Alps. The map also shows the distribution and the structural setting of the Pre-Tortonian basin areas (by [16], modified) which were partially reactivated during the following extensional and compressive events related to tectonic inversion. NPDZ: Northern Principal Deformation Zone; SPDZ: Southern Principal Deformation Zone; MFS: Marcel Fault System; NLFS: Northern Ligurian Fault System; ST fault: Saorge Taggia fault; SF fault: Stura Fault; CS fault: Celle Sanda Fault; SV line: Sestri-Voltaaggio line; LTGS: Ligurian Tuscan Graben System.

Their overall WSW–ENE trend is discontinuous and locally delimits the gently arcuated NW–SE structural highs (Figure 3 on map and Figure 10b on seismic line) produced by a later, Middle–Upper Miocene compressional event (Table 1). At the basin scale, the overall trend of the NPDZ and SPDZ describe a concave-shape similar to that of the Ligurian orocline (Figure 12b). Such geometry would be compatible with the N–S-oriented compressional phase related to a basin-scale tectonic inversion that also affected the onshore regions during the Upper Miocene (e.g., [95]). Notably, on the Alpine Margin, the remnants of this compressive Middle–Upper Miocene phase are also found in the folded Miocene sediments deposited along the Ventimiglia slope (Figure 4b).

5.3. Ligurian Margin Morphostructural Setting and Evolution

Along the Alpine Margin, the Plio-Pleistocene compressive deformation is chiefly localized at the front of the arcuated shelf slope developed from Ventimiglia (to the west) to Vado Ligure (to the east). This segmented deformation front includes (i) the southern sectors of the Marcel Fault System, (ii) the Northern Ligurian Faults System (NLFS) and, as shown by our findings, (iii) its northern prosecution inside the Savona Basin up to the Vado Canyon (Figure 12b).

Based on our reconstruction, the distribution and intensity of the compressive deformation is conditioned by the presence of several inherited faults systems. As described above, along the offshore Alpine slope area, the most intense compressive deformations are laterally delimited by the Taggia and Vado Canyons (Figure 3). Notably, these latter coincide with the seawards continuations of two on-land faults systems: the Saorge–Taggia and Celle–Sanda Fault systems (Figures 2, 3 and 12b), characterized by regional relevance and seismotectonic activity (e.g., [68]; refer also to the ISIDe earthquake database). In detail, the NW–SE-oriented Saorge–Taggia fault system, active since the late Miocene/early Pliocene, is characterized by dextral strike-slip kinematics associated to present-day seismic activity (earthquake magnitude up to 3.5; [96,97]). To the northeast, the NNW–SSE-oriented Celle–Sanda fault system marks the structural limit between the Savona crystalline unit and the Voltri meta-ophiolites unit (as inferred by [98]) and possibly represents the eastern prolongation of the E–W-elongated, left lateral strike-slip faults system separating the Western Alps from the Maritime Alps (e.g., the Stura Fault; Figures 2 and 3; see also [75] and references therein).

In this framework, these two in-land fault systems and their offshore prolongation would represent the kinematic boundary accommodating the lateral “extrusion” of the southwestern Alps toward SE [38,45–48].

This supports the hypothesis that the development of the compressional structures along the Alpine and (at a lesser extent) Apennine margins since the Plio-Pleistocene (Table 1) is not only linked to the gravitational collapse of the Alpine orogeny, but also to regional-scale tectonic.

Within the Apennine Ligurian Margin, the (attenuated) Plio-Pleistocene compressive tectonics affects only the northern sectors of the La Spezia Graben. Here, the NPDZ links to the NW–SE-elongated compressive structures which bound this sector of the graben (Figures 8, 9 and 11). This evidence is supported by the occurrence of seismic clusters and
the associated mass wasting phenomena at the head of the La Spezia canyon and in the Portofino slope area (e.g., Figure 8).

In the NPDZ (and to the south of the SPDZ), remnants of the WSW–ENE-oriented transfer faults, that have driven the opening of the Liguro–Provençal Basin since the Lower–Middle Miocene (e.g., [12]; see also Table 1), have played a significant role in the inversion of pre-existing normal faults. During the Pliocene extensional reactivation, the two WSW–ENE former transfer fault systems controlled the development of the La Spezia Graben and delimited the development of the deeper Viareggio Graben (e.g., up to 2-km-thick Plio-Quaternary sedimentary sequence). The Plio-Pleistocene compressional reactivation, mainly focused at the Alpine Ligurian Margin (e.g., along the NLFS), affected only the NPDZ. This limited the compressive deformations to the northwesternmost sector of the Apennine Ligurian Margin (e.g., the northern sector of the La Spezia Graben).

6. Conclusions

The review of the bathymetric and geophysical data collected along the Ligurian Margin in recent decades has enlightened how the morpho-bathymetry presents outstanding elements for a strong dynamism with a close correlation between the main active tectonic structures and the local geo-environmental elements of hazard (e.g., seismicity, mass wasting phenomena, etc.).

The reconstruction of the distribution, the geometries and the kinematics of the fault systems developed in the Ligurian Basin has depicted a complex regional scenario where the two distinct Alpine and Apennine margins share a common, polyphasic evolution.

The extensional tectonics are primarily responsible for their morphostructural setting and are interrupted by (at least two) regional-scale compressive events leading to tectonic inversion during the Middle–Upper Miocene and the Plio-Pleistocene.

Our reconstruction of the Plio-Pleistocene compressive event, which mainly affects the Alpine Margin (along the NLFS), demonstrates its propagation towards the northeastern sectors of the Ligurian Basin only partially affecting the Apennine Ligurian Margin. This propagation of the deformation is likely driven by regional-scale transfer fault systems (e.g., the NPDZ) inherited by the Corsican–Provencal Basin drifting stage.

Other inherited structures located along the Alpine Ligurian Margin are the seaward prolongation of in-land, regional-scale faults systems (e.g., the Saorge–Taggia and Celle–Sanda faults) and would thus represent the kinematic boundary accommodating the lateral expulsion of the southwestern Alps toward the SE.

This supports the hypothesis that the development of compressional structures along the Alpine and (to a lesser extent) the Apennine Ligurian margins since the Plio-Pleistocene is linked not only to the gravitational collapse of the Alpine orogeny, but also to regional scale tectonic inversion.

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