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Seismic Exploration of the Deep Structure and Seismogenic Faults in the Ligurian Sea by Joint Multi Channel and Ocean Bottom Seismic Acquisitions: Preliminary Results of the SEFASILS Cruise †

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Abstract: The north Ligurian margin is a complex geological area in many ways. It has witnessed several phases of highly contrasting deformation styles, at both crustal scale and that of shallower cover tectonics, simultaneously or in quick succession, and with significant spatial variability. This complex interplay is mirrored in the resulting intricate structures that make it hard to identify active faults responsible for both, the significant seismicity observed, and the tectonic inversion undergone by the margin, identified at longer time scales on morphostructural grounds. We present here the first preliminary results of the leg 1 of SEFASILS cruise, conducted in 2018 offshore Monaco, in an effort to answer these questions by means of modern deep seismic acquisitions, using multichannel reflection and wide-angle sea-bottom records. Some first interpretations are provided and point towards an active basement deformation that focuses at the limits between main crustal domains.

Keywords: Western Mediterranean; Ligurian basin; tectonic inversion; salt tectonics; crustal geophysical exploration; multichannel seismic imaging; wide-angle seismic recording

1. Introduction

The SEFASILS project (Seismic Exploration of Faults And Structures In the Ligurian Sea) aims chiefly at studying the complete system of faults associated with the ongoing tectonic inversion of the North Ligurian margin and basin [1,2]. The objectives are to explore structural and rheological parameters controlling the inversion processes of a rifted domain, and to better assess the related seismic and tsunami hazards on the highly populated and urbanized Ligurian Riviera (Figure 1).

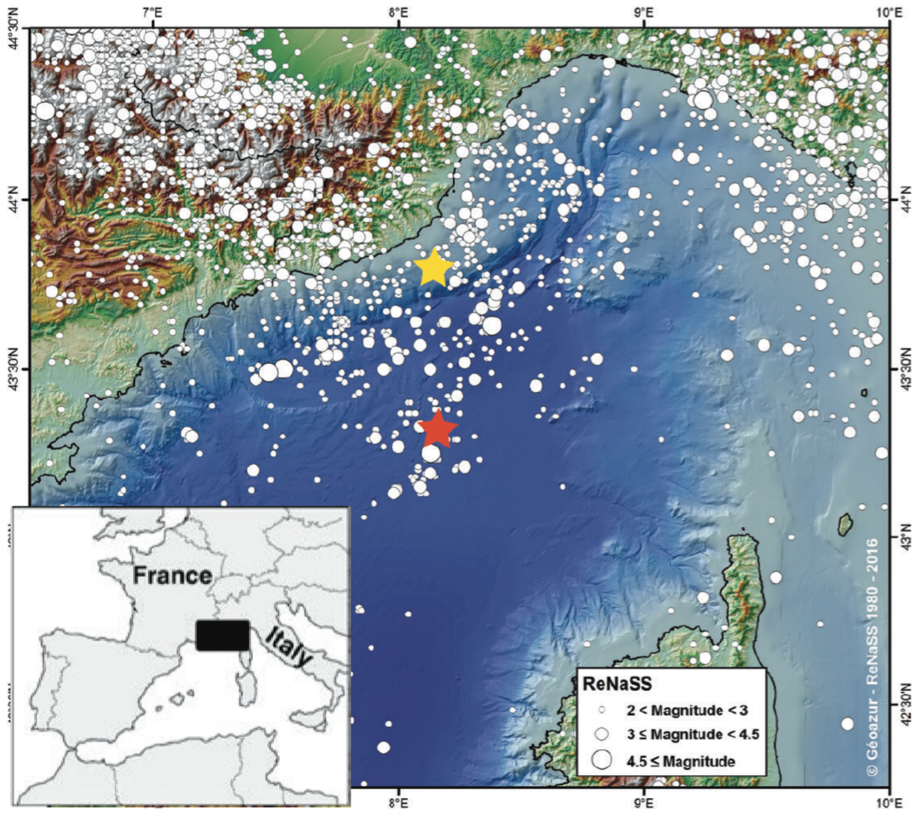

Figure 1. Seismicity map (magnitude > 2) of the Alps-Ligurian Basin junction, recorded between 1980 and 2016 (ReNaSS and SiHex catalogs). The yellow and red stars locate the approximate epicentres of the two major historical earthquakes: 23 February 1887; M_W~6.7–6.9 [3], and 19 July 1963; Ml = 6.0 [1], respectively.

In particular, we seek to explore the deep geometry of the fault system that crops out at the continental slope's toe between Nice and the Gulf of Genoa [4,5] (Figure 2a). This feature is likely responsible for the margin uplift, which is fairly pronounced offshore Imperia, vertically offsetting by more than 1 km the sedimentary sequence, including Messinian markers whose deposition postdates the rifting [6] (Figure 2c). It is also likely responsible for the 1887 Ligurian earthquake that affected the same area, with an assessed magnitude up to Mw6.9, some important damage from Menton to Genova, a 2-m high tsunami, and more than 600 fatalities [3] (yellow star on Figure 1). The tsunami polarity as well as the depth (10–12 km) and focal mechanisms of more recent local earthquakes all point to an active landward verging thrust fault beneath the margin, compatible with the tectonic uplift [2,3]. The northern half of the basin is also characterized by intraoceanic seismic activity, occasionally exceeding Mw6 (Figure 1) and occurring along faults that are yet to be identified; focal depths range between 10 and 20 km [7]. The sedimentary cover in the deep basin is several km-thick and includes a thick, mobile, Messinian salt-bearing unit e.g., [8–10], whose surficial tectonic expression can interfere with motions of deeper origin (Figure 2). The presence of voluminous and complex saliferous structures, aligned over ~70 km through the basin, obliquely to the slope's toe, thus suggests the existence of underlying crustal faulting [11] (Figure 2a,b). Defining the geometry and the segmentation of these active inversion structures down to rupturing depths, as well as the relationship between the two fault systems, is critical in assessing the seismogenic potential and to advancing our understanding of inversion processes (structural inheritance, possible partitioning over margin and basin fault systems).

The nature and structure of basement domains formed during the Oligo-Miocene opening of the Ligurian basin remain enigmatic, between continental, oceanic, or transitional, possibly including exhumed subcontinental mantle, partly serpentinised e.g., [9,11–14]. The second objective of SEFASILS is to clarify the boundaries and nature of said domains (Figure 3) in order to decipher the modalities of back-arc opening of the basin [15] and the influence of the strong heterogeneity resulting from structural inheritance (also including Alpine orogenesis) on the current inversion.

Both objectives can be addressed using deep seismic imaging techniques. The last deep reflection seismic acquisitions that took place in this area are more than 20 years old now [9,10]. Although a 3D tomography was more recently carried out from refraction seismic data over part of the North margin [12], there is still a need for reinvestigating these structures and the related questions by means of modern geophysical equipment. It is the very purpose of the SEFASILS project, some preliminary results of which are presented and discussed in the present paper.

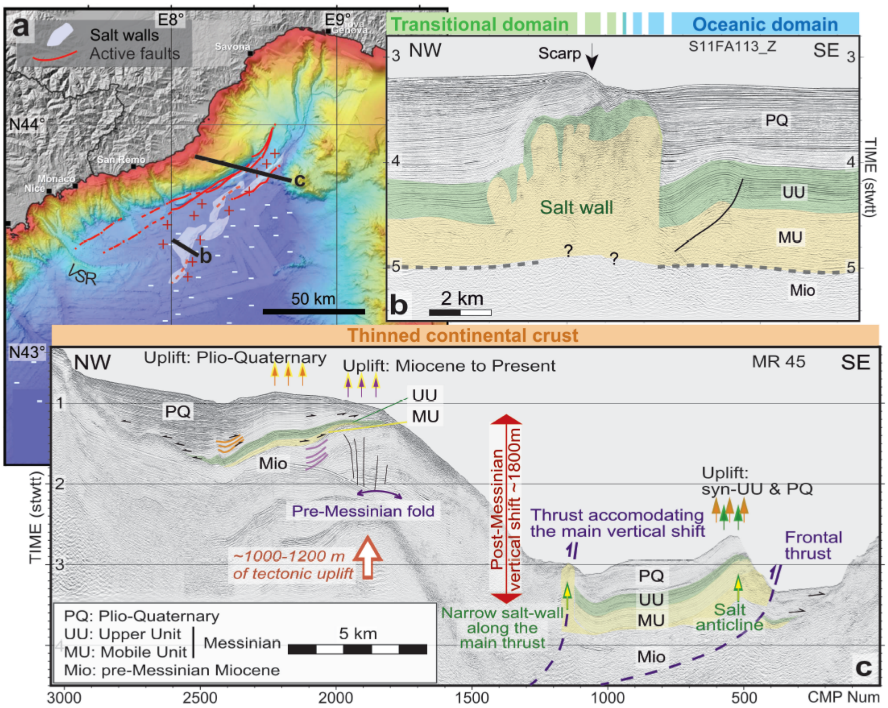

Figure 2. Results from previous shallow seismic studies in the Ligurian Sea. (**a**) Bathymetric map with active inversion-related structural features (modified from [4]): red lines for active reverse faults identified at the slope's toe, pale patches for salt walls in the deep basin; b and c stand for the surface trace of the profiles displayed in the two other panels of the figure; VSR: Var Sedimentary Ridge. (**b**) Salt walls in the basin, most likely resulting from interference between salt and deeper crustal tectonics [11]. (**c**) Active reverse faults (thick dashed lines) below the eastern margin, offshore Imperia, most likely responsible for its ≥1000-m uplift there, marked by the offset (double red arrow) in the Messinian series (in green/yellow for Upper/Mobile ones, modified from [11]). (**b**,**c**) are from high-resolution FABLES [11] and MALISAR [4] reflection seismic data, respectively. Basement domains are indicated [10].

2. Materials and Methods

2.1. Data Acquisition

Acquiring quality deep seismic data in the Ligurian Sea is a challenge due to the screening effect of the thick Messinian evaporitic series interlayered in the sedimentary cover, and to the rather shallow depth of the basin, causing sea-bottom multiples to interfere with shallow to intermediate primary events.

As a whole, the SEFASILS project includes joint acquisitions of deep multichannel seismic (MCS) reflection data and sea-bottom wide-angle data (lines of ocean bottom seismometers, with instrument spacing between 2 and 2.5 km, completed by land stations) over three profiles crossing the North margin and a significant part of the Ligurian basin, the middle one crossing all the way to the Corsican margin. A fourth longitudinal profile, acquired solely in seismic reflection, intersects the three previous ones on the deep continental slope (Figure 3).

A first leg took place during the fall of 2018 (16 to 27 November) onboard R/V *Pourquoi Pas?* operated by Ifremer. Due to recent environmental regulations in Italy lengthening permitting procedures, operations were restricted to French and Monaco waters, only allowing data acquisition along the westernmost transect (Figure 3). A second leg is planned (at the beginning of 2021, pending clearance by Italian authorities) to complete the survey and document structures offshore Liguria.

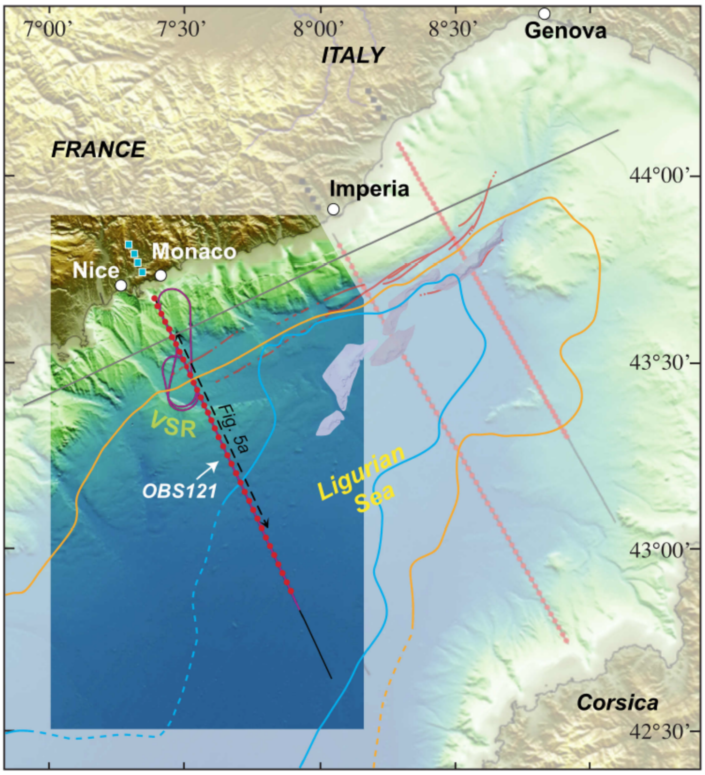

Figure 3. Ship tracks followed during the acquisition of the profiles of leg 1, together with those planned for leg 2, within the toned-down area (note the fourth transverse multichannel seismic (MCS) profile in grey to the north, connecting the three main lines across the basin, acquired both in MCS imaging and using Ocean Bottom Seismometers (OBSs), see text for details). Red dots stand for OBSs and blue squares for land stations. Purple and dark lines stand for MCS and OBS shot tracks followed during the cruise, respectively. The orange and bright blue lines separate the continental, transitional, and central domains in the basin, respectively [10]. Red lines, pale patches, and VSR label are as in Figure 2a. The black dashed line indicates the extent of the MCS profile displayed and discussed further.

The wide-angle data were acquired by four land stations and 36 OBSs (from Geoazur, UBO, and Ifremer's pools), using a source of 81.8 l (4990 in^3) consisting of an array of 16 airguns (from 150 to 520 in^3 each). Dominant frequencies range between ~5 Hz and ~50 Hz, with a peak at 27 Hz. Wide-angle seismic shots were acquired in two passes over the profile, with intercalated shot positions, to meet the dual goal of a sufficient density of shots, and a long enough delay between them to eliminate wraparound noise from preceding ones that commonly hamper the quality of OBS data at large offsets. Shot interval was constant (230 m on each subprofile, consistent with a ~90 s delay at 5 kt). Figure 4 provides an example of OBS gather. Deep refracted arrivals, exhibiting mantle velocities, can be observed as first arrivals beyond distances of ~25 km, up to the two extremities of the profile. Other sedimentary and crustal refracted phases, as well as subsequent reflections, can also be observed. Data quality varies, depending upon the quality of coupling between instruments and seabed.

Two MCS data sets were acquired with two different seismic sources along a profile coincident with the OBS line. The first one (SEFA13) was shot with the same low frequency source as that used for wide angle acquisition (albeit with a 45 s/~116 m shot interval), favouring sheer seismic energy at the expense of coverage, while a dedicated reflection source (14 airguns, between 90 and 250 in^3, yielding a total volume of 42.1 l/2570.0 in^3) was used for the second line (SEFA14), with a more balanced compromise between source power and repetitivity. Shot interval was 20 s/~51 m. Dominant frequencies range between ~20 Hz and ~70 Hz, with a peak at 45 Hz. The two reflection profiles were recorded using the 6000 m-long, 960-channel, Sercel Sentinel® solid state streamer operated by Ifremer. Some results of these MCS acquisitions are shown in Figure 5.

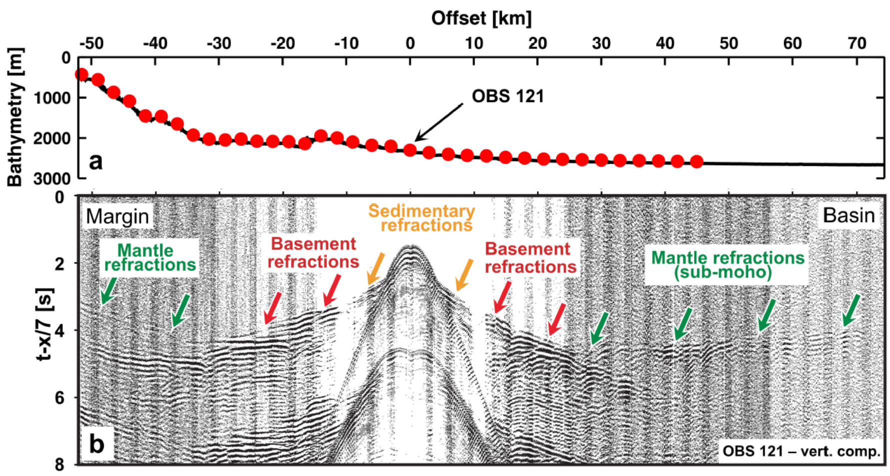

Figure 4. (**a**) Bathymetric variations over the OBS shot profile, with OBS positions denoted by red dots. (**b**) Data from OBS 121 (located in Figure 3) plotted with a 7 km.s^{-1} reduction velocity. Two intercalated shot passes have been acquired, and resulting data subsequently merged to avoid water-velocity wraparound signals at large offsets. Various refracted phases are observed in first arrival. Mantle refractions are observable from 15–20 km offset onwards (and as first arrivals beyond distances of ~25 km), on each side of the instrument, up to both ends of the shot profile.

2.2. Data Processing

In spite of the short duration of the cruise, quick formatting/pre-processing of data—both MCS and OBS—allowed one to have a first glance at them and a enact quality control. Raw OBS data were simply mixed with shot information from navigation data to produce standard OBS gathers after merging and sorting the two subsets corresponding to the two shot passes and applying minimum-phase bandpass filtering (Figure 4).

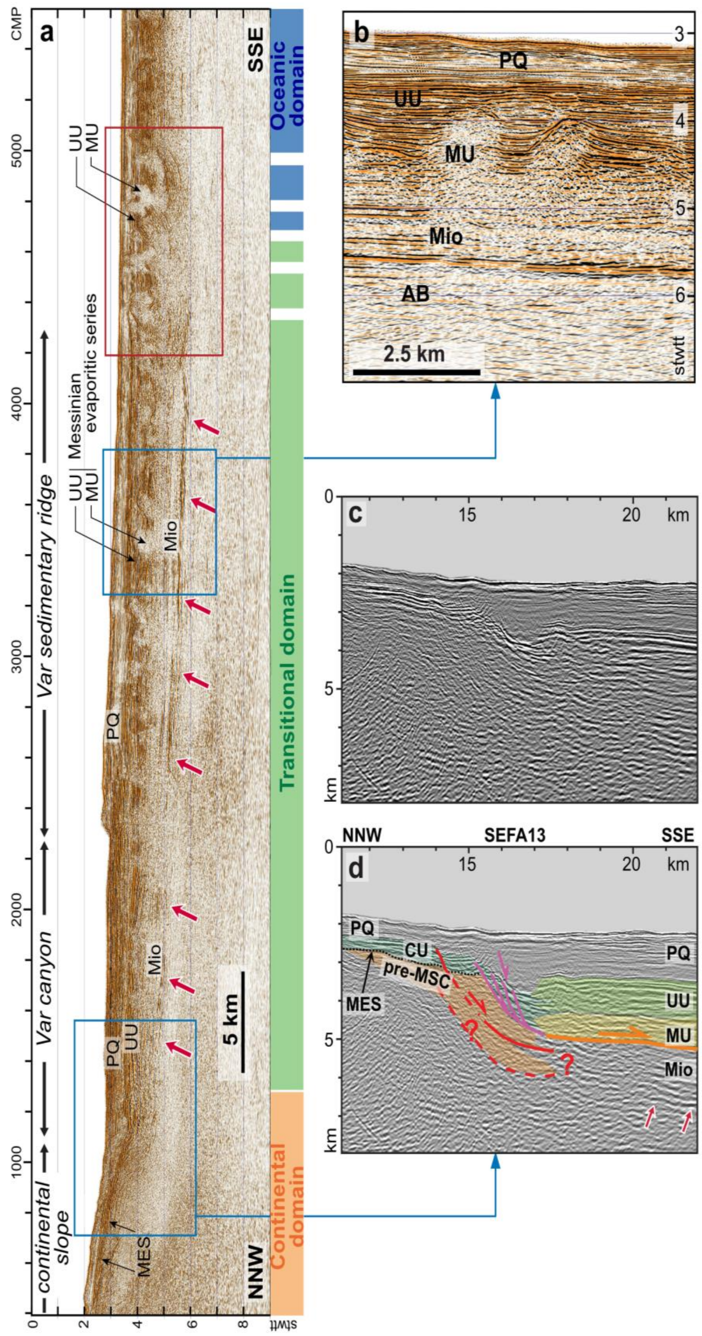

Figure 5. (**a**) Part of the prestack time migration of profile SEFA13 (see Figure 3 for location) from the deep continental slope (North) to the middle of the basin (South); stwtt: seconds two-way travel time. Four morphostructural domains (continental slope, Var canyon, Var ridge, and deep basin) are identified from bathymetry and seismic facies; PQ: Plio-quaternary, UU/MU: Upper/Mobile Units, MES: Messinian Erosional Surface/Detritic Messinian Units, Mio: Miocene (pre-Messinian). Red arrows point to the top of the acoustic basement. Extent of basement domains [10] are indicated. Blue frames refer to close-ups shown in (**b**), (**c**), and (**d**); red one refers to a zone discussed in the text. (**b**) Close-up on main seismic facies identified in the mid-part of the SEFA13 profile (framed in a); notations as in (**a**); AB: Acoustic Basement. (**c**), (**d**) Part of the pre-stack depth migration of profile SEFA13 at the deep continental slope (framed in (**a**): (**c**) uninterpreted; and (**d**) interpreted. CU: Messinian clastic unit, pre-MSC: pre-Messinian unit; the base of the Messinian salt (MU) is underlined in orange, pink faults are related to salt tectonics; note the convex up geometry of the Messinian markers on the margin and the deep rooting level of the red fault(s) (see text for explanations).

After a careful binning of the MCS data using shot and receiver navigation files, the postcruise processing sequence, applied to both reflection profiles using CGG's Geovation® software (version 6401) includes (1) field data transcription, (2) 2.5 Hz low-cut filter, (3) spherical divergence compensation, (4) noise attenuation in f-x domain, (5) trace editing, (6) cable and source corrections, (7) resampling from 2 to 4 ms, (8) first pass velocity picking, (9) multiple attenuation with 2D-SRME method (two passes) followed by Radon demultiple, (10) second pass velocity picking, (11) deconvolution, (12) third pass velocity picking, and (13) pre-stack Kirchhoff time migration.

Prestack depth migration is also performed using a Ray+Born imaging technique [16], Common Image Gather analysis [17], as well as slope tomography being tested to build suitable velocity models for migration [18].

Due to organizational constraints, postcruise work began with the MCS data, and the following results and discussion deal solely with these data. The profiles displayed are part of, respectively, prestack time (Figure 5a,b) and depth (Figure 5c) migrated data of line SEFA13, for which the processing is more advanced.

3. Results

3.1. Wide-Angle Data Quality

Regarding OBS data, only a crude, first-order interpretation of observed phases is presented here (Figure 4), for a single instrument lying in the basin, about halfway through the array (location on Figure 3). A complete range of refracted arrivals is observed, sampling from sedimentary units to the uppermost mantle, and followed up to the maximum ~70 km offset available here (and beyond on other stations). The critical distance from which mantle refraction are observed, together with strong postcritical Moho reflections, is in the 15–25 km range. A complete analysis of these data, comprising picking and inversion of arrivals travel times, is beyond the scope of this preliminary study. Some first-arrival travel time tomography will be performed, before exploiting the structural information carried by later phases, either through reflection tomography or full waveform inversion, pending signal to noise ratio is good enough to not skew the strongly nonlinear waveform inversion problem.

3.2. Main Stratigraphic and Structural Features on MCS SEFASILS Profiles

First of all, the main seismic facies and morphostructural features imaged in both MCS SEFA13 and 14 profiles are correlated with those observed offshore the Ligurian Riviera and well documented e.g., [7–11,19,20] and references therein.

The sedimentary cover, clearly defined in the midpart of the profile, exhibits, from top to bottom (Figure 5a,b), (1) the low-amplitude, high-frequency seismic facies of the Plio-Quaternary series (PQ); (2) the Messinian sequence, namely, the highly reflective set of reflectors of the upper unit (UU) known to be made of interbedded marls and evaporites [21] and references therein, and the mobile unit (MU) consisting of salt, generally displaying a transparent seismic facies and locally forming domes and diapirs; and (3) the pre-Messinian salinity crisis series (Mio). Both PQ and Mio series are made of silico-clastic sediments [8,19]. The three units lay over an acoustic basement whose top is marked by a high-amplitude, low-frequency flat reflection, slightly dipping towards the basin, observed between 5 and 6 seconds-two-way-travel time (stwtt). The syn- or postrift nature of the deeper unit (Mio) depends on the nature of the basement below (thinned continental crust or postbreakup mafic to exhumed ultramafic units), which is debated e.g., [9] and will be further discussed in the light of SEFASILS wide-angle seismic data. As elsewhere in the Mediterranean, the specific facies of the evaporitic series associated with the Messinian salinity crisis (MSC) provide an excellent set of temporal markers for seismic interpretation.

Lateral variations in these seismic facies define four main morphostructural domains along the profile (Figure 5):

- The continental slope is steep and narrow, as for most of the Ligurian Basin margins [10], and results from the backarc rifting that opened the basin [15,20]. In our study area, this extension took place just west of the Alpine overthickened lithosphere, but the eastern part of the basin was actually opened inside the orogenic domain itself, as attested by the position of the Alpine front on both Ligurian and Corsican sides. The slope displays the MSC-related features classically described along Mediterranean margins and attesting to low-stand sea levels: an erosional surface in the upper margin (MES) together with detritic series deposited deeper down along the slope e.g., [11];
- The ~10-km-wide Var canyon where the PQ series is characterized by a higher amplitude than elsewhere, owing to coarse deposits channelled along the canyon, fed by the high Alpine reliefs from the close hinterland [19];
- The Var sedimentary ridge, which is a Plio-Quaternary field of sediment waves built by turbidity currents in the Var deep-sea fan, characterized by thick and wavy typical PQ distal seismic facies (Figure 5a). The ridge is the prominent right-hand levee of an asymmetric and curved (eastward-bended) channel-levee system [19], which the SEFASILS line intersects just east of the bend (Figures 2a and 3);
- The profile ends in the central part of the basin, where voluminous salt domes disturb the geometry of the upper series and make interpretation of deep structures more challenging. Further effort is needed to improve the seismic image at depth here.

Three crustal domains (the continental, transitional, and central oceanic domains) were previously defined in the Ligurian Basin, based on available geophysical and geological data [9,11] and references therein (Figures 3 and 5a). Some correspondence can be found in the SEFASILS morphostructural observables, although not implying first order causality: (1) the continental slope is part of the continental domain made of thinned continental crust; (2) the Var canyon/channel and ridge/levee are part of the transitional domain, whose nature is discussed, possibly including exhumed lithospheric mantle [10]; and (3) the distal basin is part of the central domain where sparse wide-angle data indicate a basement made of anomalously thin (~4 km) oceanic crust, classically labelled "atypical" [9] or, alternatively, hyperextended (less than 3 km-thick) continental crust, possibly to the point of having outright exhumed serpentinised continental mantle beneath basinal sediments [14]. In this latter view, Dannovski et al. [14] conclude that no oceanic spreading would have taken place in the Ligurian Sea. The processing of the SEFASILS wide-angle seismic data will bring some much-needed information on these basement domains and their seismic velocity signatures, from the northern margin to far into the basin.

SEFASILS penetrative MCS data allow an imaging of the top of the acoustic basement almost continuously along the transitional domain (Figure 5). The flatness of this horizon indicates that, at the resolution provided by these data, no crustal deformation has occurred within this domain since the formation of the seafloor, during Miocene. By contrast, we discuss next whether some crustal deformation can be identified at the limits of this transitional domain.

4. Discussion

The possible clues for inversion-related crustal tectonics on MCS SEFASILS profiles are discussed here. The clearest evidence for such tectonic inversion on the SEFA lines is the convex upward morphostructural profile of the continental margin, marked both in the bathymetry and geometry of Messinian markers (MES, CU, Figure 5). Petit et al. [22] have analysed bathymetric profiles along the Ligurian coast. They show that the convexity of bathymetry is maximum over the Imperia Promontory and decreases to the west, all the way to the Nice area, where the margin reaches an equilibrium, concave upward profile. Here, the curvature of bathymetric profiles results from competing effects between submarine erosion and tectonic uplift. Numerical modelling shows that some efficient erosion may compensate for a moderate recent uplift rate (~0.4 $mmyr^{-1}$) in the Nice area, whereas weaker erosion is overbalanced by an increasingly larger uplift rate eastwards, reaching almost twice this value over the Imperia Promontory [22]. As stated above, our observations of the bathymetric and Messinian profiles in the study area, located offshore Monaco (Figure 3), are in agreement with this pattern. They reveal an already sensible imbalance of the margin immediately east of Nice, attesting to an inversion-related moderate uplift that dominates the erosional signal there.

Over the maximum uplift area of Imperia, morphology shows that such imbalance mainly affects the distal part of the margin [22] (Figure 2c). The structures observed downslope in the SEFASILS lines do not look like typical roll-over developed at deep margins of salt basins either. Indeed, there are hints for a first set of small-offset listric normal faults offsetting the Messinian surface and rooting deeper than the salt decollement level, whereas another set of listric faults, unambiguously saliferous, offset the same Messinian units more frankly, 1–1.5 km farther seaward (Figure 5d). This apparent dual setting results in only part of the extension at the margin's toe being related to salt, pointing towards some interference between salt tectonics and deeper reaching gravity-driven instabilities attributable to the margin uplift. These extensional faults, limited both in motion and most likely in horizontal extent, are syn- to post-Messinian (as attested by their offsetting all Messinian deposits) and thus have no relationship whatsoever with the anterior rifting phase of the margin. They seemingly root in the Pre-Messinian deposits and do most likely not affect the underlying basement. The relationship remains unclear between such gravity-driven processes and some expected deeper reverse faulting postulated by [4,5] to accommodate the observed uplift. No conspicuous evidence for such faulting seems to be observed here in the current state of our data processing and interpretation, although its existence is strongly supported by the observation of reverse focal mechanisms in the study area [2], and even more so eastward, from the analysis of possible crustal motions behind the Imperia 1887 coseismic tsunami [3].

Deeper in the basin, interference between salt and deeper crustal tectonics is also highly suspected at the limit between the transitional and central domains (Figure 3), where a ~10 km-wide group of huge salt structures affects the sedimentary series up to the seafloor. The top of the acoustic basement cannot be followed anymore there (red frame on Figure 5a). Such feature is clearly reminiscent of the salt walls described further northeast in the basin [11] (Figures 2 and 3), whose lateral continuity cannot be explained by mere salt tectonics and likely implies a deep tectonic driver. This can be tentatively related with the margin inversion, albeit observed farther into the basin, in agreement with the notable seismicity observed there (Figure 1). Observing an analogous salt complex crossing our profile points to a westward extension of this system, off Monaco and possibly further west, as its sheer size here does not suggest a nearby termination.

According to these first results, the inversion-related active deformation appears to be localized at the limits between the three main morphostructural domains (continental, transitional, and oceanic) previously described in the northern half of the Ligurian Basin, meaning that structural inheritance is one of the major parameters controlling inversion processes here.

These findings made from a very preliminary interpretation of the SEFA13 MCS line must be complemented with the analysis of fully processed SEFASILS MCS lines and confronted with results from SEFASILS wide-angle data, as well as with existing geological and geophysical data, including seismic profiles of various resolution, in order to get a broader picture of the peculiar tectonic regime at work over the North Ligurian margin.

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