

Seismic exploration of the deep structure and seismogenic faults in the Ligurian Sea by joint MCS and OBS acquisition: preliminary results of the SEFASILS cruise

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Abstract –The north Ligurian margin is a complex geological area on many accounts. It has witnessed several phases of highly contrasting deformation styles, at crustal scale and through shallow cover tectonics, simultaneously or in quick succession, and with significant spatial variability. This complex interplay is mirrored in 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 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.

I. INTRODUCTION

SEFASILS project (Seismic Exploration of Faults And Structures In the Ligurian Sea) aims in priority at studying the complete system of faults associated with the ongoing tectonic inversion of the North Ligurian margin and basin. The objectives are to explore structural and rheological parameters controlling the inversion processes of a rifted domain, and to better assess the

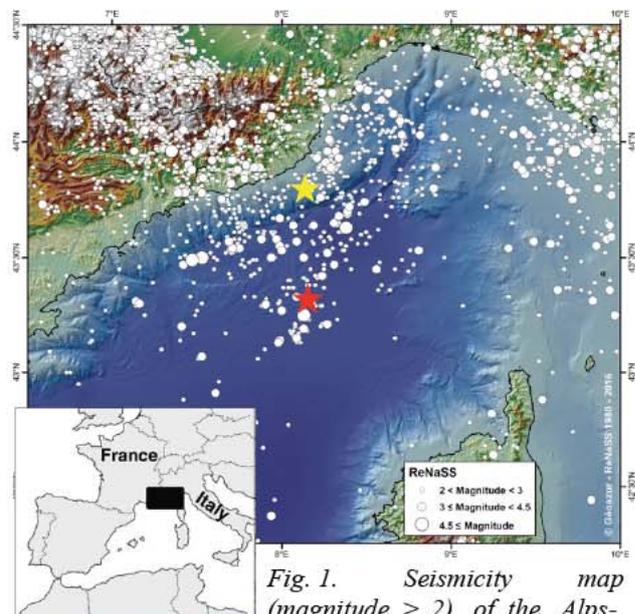


Fig. 1. Seismicity map (magnitude ≥ 2) of the Alps-Ligurian Basin junction, recorded between 1980 and 2016 (ReNaSS catalog). The yellow and red stars locate the approximate epicentres of the two major historical earthquakes (23 February 1887; $MW^*6.5-6.7$, and 19 July 1963; $ML = 6.0$, respectively).

related seismic and tsunami hazards on the highly populated and urbanized Ligurian Riviera (Fig. 1). In particular, we seek to explore the deep geometry of the

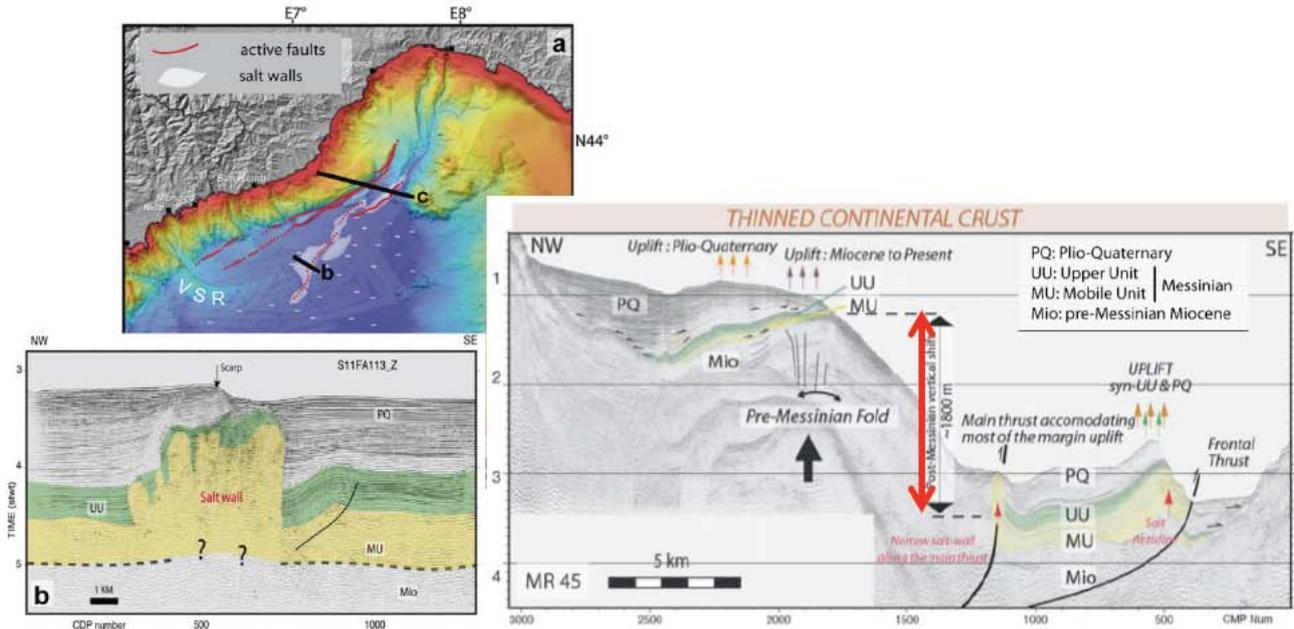


Fig. 2 a) Active inversion-related structural features in the northeastern Ligurian Sea: red lines for active reverse faults identified at the slope's toe, white patches for salt walls in the deep basin, VSR: Var sedimentary Ridge (modified from [1]). b) Salt walls (in yellow) in the basin, most likely resulting from interference between salt and deeper crustal tectonics [3]. c) Active reverse faults (thick black lines) at the deep margin most likely responsible for the ≥ 1000 -m uplift of the margin marked by the offset (thick red arrow) of the Messinian series (in green (UU)/yellow (MU)) [3]. b) and c) are high-resolution Fables and Malisar reflection seismic data, respectively.

fault system that crops out at the continental slope's toe between Nice and the Gulf of Genoa [1,2] (Fig. 2a). This feature is responsible for the margin uplift (Fig. 2c) and for the 1887 Ligurian earthquake (assessed magnitude up to Mw6.9, important damage from Menton to Genoa, 2-m high tsunami, more than 600 fatalities; yellow star on Fig. 1) [1]. The northern half of the basin is also characterized by an intra-oceanic seismic activity, occasionally exceeding Mw6 (Fig. 1) and occurring along faults that are yet to be identified. The sedimentary cover in the deep basin is indeed several km-thick and includes a thick, mobile, Messinian salt-bearing unit [e.g. 3,4,5], whose surficial tectonic expression can interfere with motions of deeper origin (Fig. 2). Thus the presence of voluminous and complex saliferous structures aligned over ± 70 km obliquely to the slope's toe, suggests the existence of underlying crustal faulting [6] (Fig. 2a,b). Defining the geometry at depth and the segmentation of these active inversion structures, as well as the relationship between the two fault systems, is essential to assess seismogenic potential and to advance our understanding of inversion processes (structural inheritance, possible partitioning of margin and basin fault systems...).

The nature and structure of the oceanic domain formed during the Oligo-Miocene opening of the Ligurian basin remain enigmatic [e.g.4,5,7]. The second objective of SEFASILS is to clarify the boundaries and structure of

crustal domains (continental, transitional, oceanic) (Fig. 3) in order to decipher the modalities of back-arc opening of the basin and the influence of the strong heterogeneity resulting from structural inheritance (also including alpine orogenesis) on the current inversion.

Both objectives can be addressed with the same deep seismic imaging techniques. The last deep reflection seismic acquisitions that took place in this area are more than 20 years old now [4,5]. Although a 3D tomography was more recently carried out from refraction seismic data over part of the North margin [7], 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.

II. 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 multiple to interfere with shallow to intermediate primary events, especially on the continental margins.

As a whole, the SEFASILS project includes joint acquisition of deep multichannel seismic reflection data (MCS) and sea-bottom refraction data (OBS lines with instrument spacing between 2 and 2.5 km, completed by land stations) over 3 profiles crossing the North margin

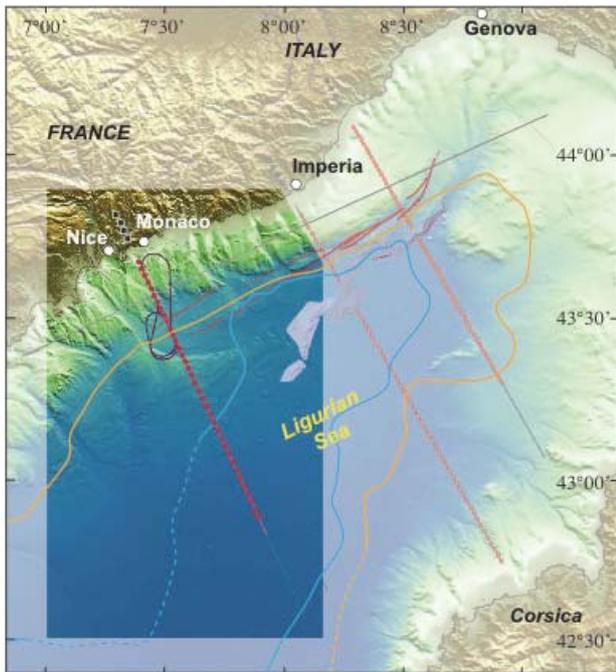


Fig. 3. Ship tracks followed for the acquisition of the profiles of leg 1, and in the lightly coloured area, those planned for leg 2. Red dot is for OBS and black square for land station. The orange and bright blue lines locate the limits between the continental/transitional and transitional/central domains of the basin, respectively. Red lines and grey patches are as in fig. 2a.

and a significant part of the Ligurian basin, one of the 3 crossing all the way to the Corsican margin. A fourth longitudinal profile, acquired solely in seismic reflection, intersects the 3 previous ones on the deep continental slope (Fig. 3).

A first leg took place in the fall of 2018 (November, 16 to 27) onboard R/V Pourquoi Pas? operated by Ifremer. Due to recent environmental regulations in Italian waters, authorizations were restricted to French and Monaco waters, only allowing data acquisition along the westernmost transect (Fig. 3). A second leg is planned (in 2020, pending clearance by Italian authorities) to complete the survey.

The wide-angle data were acquired by 4 land stations and 36 OBSs (from Geoazur, UBO, and Ifremer's pools) and using a source of 81.81 (4990 cu.in), provided by an array of 16 airguns (from 150 to 520 in³ each). Dominant frequencies range between ~5 Hz and ~50 Hz, with a peak at 27 Hz. Wide-angle seismic shots were acquired in 2 passes over the profile, with intercalated shot positions, so as to meet the dual goal of a sufficient density of shots, while keeping 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 an OBS gather. Deep refracted arrivals, exhibiting mantle velocities, can be observed up to the two extremities of the profile. 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 acquired with the same deep penetrating source as that used for wide angle seismic (albeit with a 45 s/~116 m shot interval), while a dedicated reflection source (14 airguns between 90 and 250 in³, yielding a total volume of 42.1 l/2570.0 in³) was used for the second line (SEFA14). Shot interval was

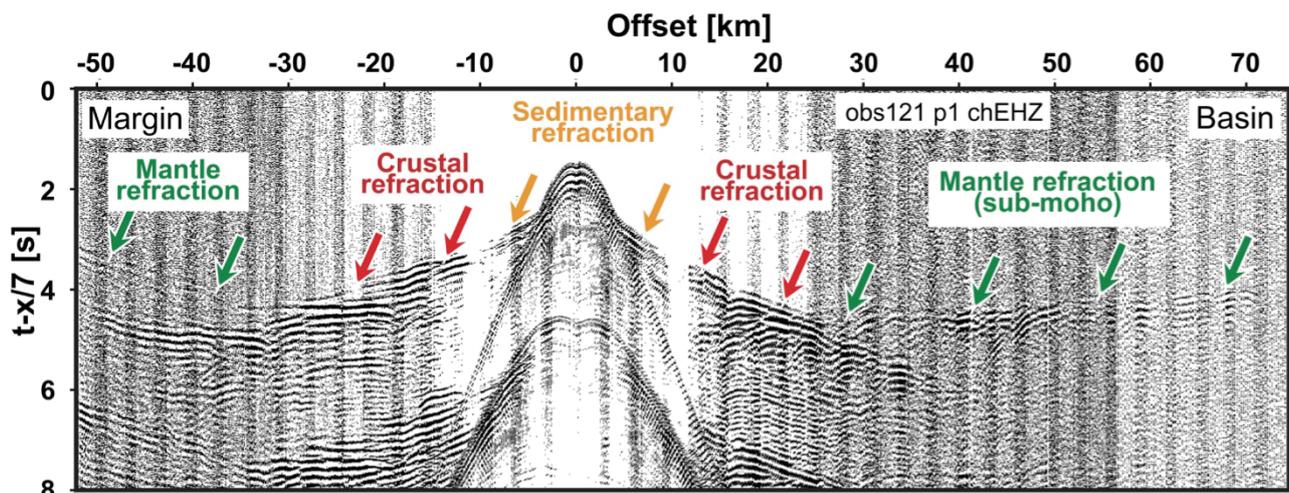


Fig. 4. Data from OBS 121 (located south of the Var ridge, approximately halfway along our OBS array). Two intercalated shot passes have been acquired and resulting data subsequently merged. Note the absence of water-velocity wraparound signals at large offsets, as a result of this two-pass acquisition. Note also the various refracted phases observed in first arrival, with mantle refractions well observable from 25-30 km offset onwards, on each sides of the instrument, up to both ends of the shot profile. Data are plotted with a 7 km.s⁻¹ reduction velocity.

20 s/~51 m. Dominant frequencies range between ~20 Hz and ~70 Hz, with a peak at 45 Hz. The recording of the two reflection profiles was made using the Sercel, 6000 m-long, 960-channel, streamer operated by Ifremer. The Ifremer mitigation protocole for marine mammals, which was scrupulously applied during the cruise, resulted in numerous shutdowns and ensuing manoeuvres responsible for the tortuous ship track of SEFA14 (blue line in Fig. 3).

III. DATA PROCESSING

In spite of the short duration of the cruise, quick formatting/pre-processing of data –both MCS and OBS ones– allowed to have a first glance at them and a quality control on board. Raw OBS data have simply been merged with navigation data from shots to produce classical OBS gathers (Fig. 4).

The post-cruise processing sequence applied to both MCS profiles with the CGG’s Geovation® software, 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 correction, (7) resampling from 2 to 4 ms, (8) first pass velocity picking, (9) multiple attenuation with 2D-SRME method (2 passes) followed by Radon demultiple, (10) second pass velocity picking, (11) deconvolution, (12) third pass velocity picking, (13) pre-stack Kirchhoff time migration.

Pre-stack depth migration is also performed using a Ray+Born imaging technique [8], slope tomography being tested to build the velocity model of migration [9].

IV. PRELIMINARY RESULTS AND DISCUSSION

Due to organizational constraints, post-cruise work began with the MCS data, and the following deals solely with these data. The profiles displayed here are part of pre-stack migrated Line SEFA14 (time or depth migration in Fig. 5 and 6, respectively), for which the higher frequency source gives a better resolution in the sedimentary series that we will focus on.

A. 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 well-known offshore the Ligurian Riviera [e.g. 2,3,4,5,6,10,11 and references therein].

The sedimentary cover, well defined in the mid-part of the profile (Fig. 5), exhibits, from top to bottom: (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, and the mobile unit (MU) consisting of salt, generally displaying a transparent seismic facies and locally forming domes and diapirs, and (3) the pre-

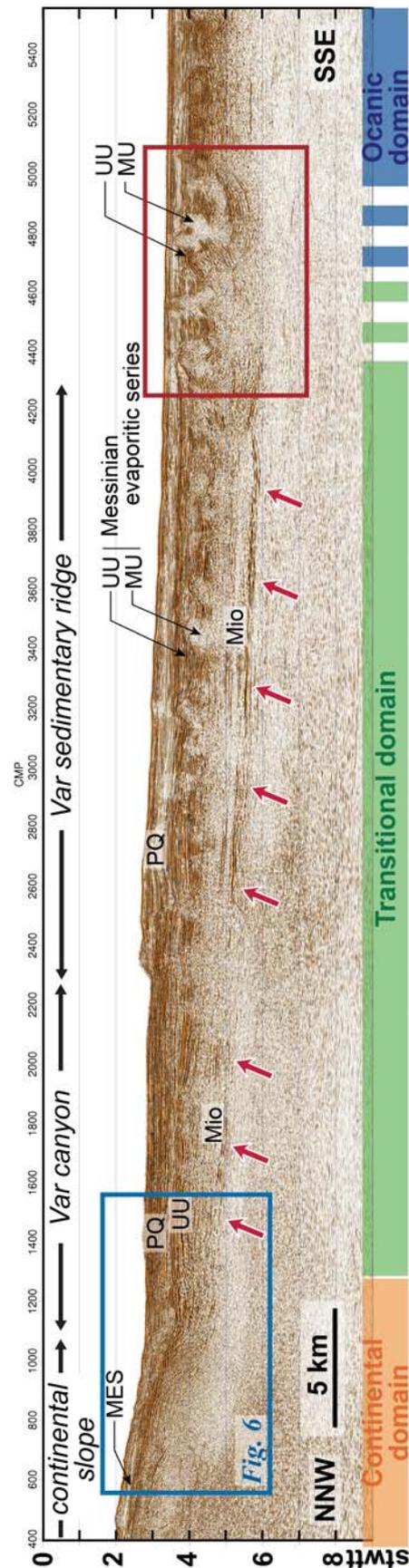


Fig. 5. Part of the pre-stack time migration of Profile SEFA14 (location on Fig. 3) from the deep continental slope in the north to the middle of the basin in the south. Four morphostructural domains (the continental slope, the Var canyon, the Var sedimentary ridge, and the deep basin) are identified from bathymetry and lateral variations of the seismic facies: PQ: Plio-Quaternary, UU/MU: Upper/Mobile Units and MES: Erosion surface/detritic units of the Messinian series, Mio: pre-Messinian Miocene. Red arrows point the top of the acoustic basement. stwtts: second two-way travel time.

Messinian salinity crisis series (Mio). Both PQ and Mio series are made of silico-clastic sediments. The 3 units are all post-rift sediments, lying over an acoustic basement whose top is marked by a high-amplitude, low-frequency flat reflection, slightly dipping toward the basin, observed between 5 and 6 seconds-two-way-travel-time (stwtt). 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 regions along the profile (Fig. 5):

- The continental slope is steep and narrow as for most of the Ligurian Basin margins [5] and results here from the rifting of the Alpine overthickened lithosphere [11]. It displays the MSC-related features classically described along Mediterranean margins and stemming from low-stand sea level: an erosional surface in the upper margin (MES) together with detritic series deposited on the deep slope [e.g. 6].
- The ~10-km-wide Var canyon where the PQ series are characterized by a higher amplitude than elsewhere, owing to coarse deposits channelled along the canyon, which is fed by the high alpine reliefs from the close hinterland [10].
- The Var sedimentary ridge is a Plio-Quaternary field of sediment waves built by turbidity currents in the Var deep-sea fan, illustrated by a thick and wavy, typical PQ distal seismic facies (Fig. 5). The ridge is the prominent right-hand levee of an asymmetric and curved, eastward-bended, channel-levee system [10], which the SEFASILS lines intersect southwards of the bend (figs. 2a, 3).
- The profiles end in the central part of the basin where voluminous salt domes disturb the geometry of the upper series and make any interpretation of deep structures more challenging. Further effort is needed to improve the seismic image here.

Three domains (the continental, transitional and central oceanic domains) were previously defined in the Ligurian Basin, based on available geophysical and geological data [4,5,7 and references therein] (Figs. 3,5). Their correspondence can be found in the SEFASILS morphostructural observables: (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; 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 [4]. The processing of our wide-angle seismic data will bring some much-needed information on these crustal domains.

SEFASILS penetrative MCS data allow imaging the top of the acoustic basement almost continuously along the

Transitional domain (Fig. 5). The flatness of this horizon indicates that, at the resolution provided by these MCS data, no crustal deformation has occurred in 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.

B. Possible clues for inversion-related crustal tectonics on MCS SEFASILS profiles

The clearest evidence for tectonic inversion on the SEFA lines is the convex up morphostructural profile of the continental margin marked in both bathymetry and MES geometry (Figs. 5,6). Petit et al. [12] show that the convexity of bathymetry is maximum on the Imperia Promontory and decreases to the west, up to the Nice area where the margin displays an equilibrium, concave up profile. Bathymetric profile is indeed convex up close to Nice, in the study area offshore Monaco (see location on Fig. 3). The bathymetric profile results from competing effects between submarine erosion and tectonic uplift, and numerical modelling shows that some efficient erosion may compensate a moderate recent uplift rate (of ~0.4 mmyr⁻¹) in the Nice area, whereas weaker erosion is overbalanced by an almost twice larger uplift rate eastwards, over the Imperia Promontory. The convex up morphological profile in the study area likely reveals an imbalance of the margin due to an inversion-related moderate uplift of the margin not fully compensated by erosion.

Over maximum uplift area of Imperia, morphology shows that imbalance mainly affects the bottom of the margin [12]. The structures observed downslope in the SEFASILS lines do not look like typical roll-over developed at deep margins of salt basins. Indeed there are hints that the most proximal small-offset listric normal

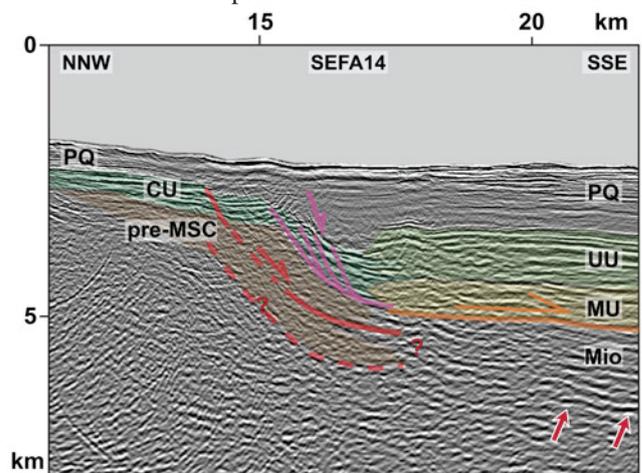


Fig. 6. Part of the pre-stack depth migration of Profile SEFA14 at the deep continental slope (located on Fig. 5). CU: Messinian clastic unit, pre-MSC: pre-Messinian unit, pink faults are related to salt tectonics, other legends as in Fig. 5.

faults offsetting the Messinian surface may root deeper than the salt decollement level (Fig. 6). This may indicate some interference between salt tectonics and gravity-driven instabilities resulting from the margin uplift. Relationships between such large-scale gravity-driven processes and deeper reverse faults as postulated by [1,2] need further analysis and interpretation.

Interference between salt tectonics and deeper crustal tectonics is also suspected in the deep basin at the limit between the transitional and central domains, where a ~10 km-wide group of huge salt structures affects the sedimentary series up to the seafloor, below which the top of the acoustic basement disappears (red frame on Fig. 5). This clearly evokes the salt walls described further north-east in the basin [6] and suggests that expression of tectonic inversion into the oceanic deep basin may prolongates westward off Monaco.

These hypotheses made from the very preliminary interpretation of the SEFASILS MCS lines must be complemented and confronted with results from wide-angle data, as well as existing geological and geophysical data, including seismic data of various resolution.

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