Rebuttal letter Torrente et al

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ABSTRACT

We respond to the comments by Torrente et al 2023 on our article (Loreto et al. 2021) in the form of a rebuttal letter because their comments are just about very specific aspects of how the view the interpretation we present in the paper figures rather than on the general contribution and conclusions of our paper. The observations raised by Torrente et al on the seismo-stratigraphic, tectonic and age interpretations of the faults, and on the evolution of the Tyrrhenian Basin from the Serravallian to present and on the proposed detachment model were discussed in order to clarify the interpretation. Furthermore, Torrente et al complain that a series of articles published by them considered crucial for the understanding of the Tyrrhenian evolution were not cited in Loreto et al.; we have shown that we have quoted the most relevant literature used to support our models.

2. FAULTS INTERPRETATION AND STRUCTURAL MAP The authors wrote in the abstract: "We present a new tectonic map focused upon the extensional style accompanying the formation of the Tyrrhenian back-arc basin." Given the importance of this map (Figure 7 of Loreto et al.) in the article, it is worth discussing further some aspects of the mapped faults: structural (a) (geometry, location, salt tectonics role, tectonic model, etc.), age of the structures (b). 2.1 In some cases, the evidences provided to support a fault interpretation are insufficient, while for other faults, the interpretation along the profile does not correspond with the map. Below, we discuss some cases of questionable faults, drawn in the Central Tyrrhenian (MEDOC 8 profile; Fig. 1b

2.1.1 **a**: insufficient evidence is provided to support the fault interpretation, as the offset of this fault cannot be evaluated because no seismostratigraphic unit was identified in the western sector. **b:** Moreover, some seismic lines collected in this sector of Sardinia published in Lymer et al. (2018) show the continuity of PQ unit toward the west.

a) we mapped the fault based on the geometry of basement (fault) blocks and strata, no stratigraphy was defined and no finite offset values were given, but that fact does not prevent to have the fault properly located. There are hundreds of examples in the literature showing a similar approach in many different extensional basin around the world, a number of them from our own work.

b) we do not explicitly or implicitly contradict Lymer et al. (2018) in our work.

It is also contradictory that Torrente et al. support these and other comments citing the paper of Lymer et al (2918), which presents low penetration seismic data that in most cases do not image the entire sediment cover, let alone the top of the crystalline basement. In contrast our data images the entire sediment package, the top of the basement and often the entire crust with reflection from the Moho. Perhaps Torrente et al. are not aware of the significance of the difference between data presented by Lymer et al. (2018), collected with 1 airgun and a 150 m long streamer, and our data collected with a multi-airgun source one order of magnitude larger in volume and with the signal recorded on streamers 2400 to 4500 m long. The bare difference in the images makes some of the claims untenable.

2.1.2 A W-dipping normal fault was reported in the Orosei Channel. **a)** The fault reaches the seafloor and minor E-dipping normal faults within the Plio-Quaternary deposits. **b)** The Orosei Channel fault interpretation can be disputed because: i) the convex upward morphology of the base of the PQ was associated to Messinian salt diapirs (Lymer et al., 2018); ii) the reflectors of the PQ unit seem to be continuous across the canyon (the thickness unit is similar in the both sides of the canyon). **c)** Furthermore, it should be noted that the black horizon lacks a hangingwall cutoff. In conclusion, the illustrated interpretation, shows no stratigraphic/structural evidence of the Orosei Channel fault.

a) The fault does not reach the seafloor in any seismic line published from that area.

b) The Orosey Canyon departs from Sardinia and crosses the Cornaglia terrace. Most of the salt diapirism is present in the central part of the Cornaglia Terrace, and is not not observed in deep penetration seismic data between Sardinia and the Baronie Smt (Fabbri et al., 1980) e.g. MCS line MEDOC 8. Lymer et al (2018) data imaged only the Upper Unit of the Messinian evaporites and not the Mobile Unit. They mapped faults close ours. Our seismic data shows the basement structure which further supports our interpretation. That the PQ unit might be continuous, which we do not agree, would only mean that the fault was not active at that time.

c) That the black horizon lacks a hangingwall cutoff does not contradict our interpretation.

2.1.3 East of the Baronie Smt, it was reported insufficient evidence of an E-dipping normal fault. **a)** First, its offset is undefined because in the footwall block there are two black horizons while in the hanging wall block only one. **b)** Furthermore, it is unclear why in the footwall block a continuous stratigraphic horizon changed nature, from the gently dipping base of Messinian deposits (red color) to steep dipping undefined horizon (black color)? **c)** It is also important to consider the lateral change of the seismic facies from transparent to continuous reflectors. Are the latter tilted? Does it suggest an uplift of the Baronie Seamount? Finally, the black reflector of the footwall block is a geophysical pitfall as it corresponds to the multiple reflector of the red horizon and the same seismic facies is present above and below the black horizon (Fig 1b).

a) fig 4b of Loreto et al. caption: "Remarkable reflections are pointed out with black lines". Only when the interpretation can be made with confidence the reflectors were colored in green (base PQ) pink (x unconformity), and red (base of Messinian deposits). In our specific case we identified one of these reflections on the faults hangingwall and two on the footwall. The image shows clearly that a fault connects the lower reflector of the footwall and that the fault was active until Messinian. However, the comment is irrelevant concerning the presence of an East dipping fault.

b) We used colored reflectors when the unit was clear, while when unclear we mapped them but did not assign an age and marked them in black. So, in this specific case we mapped some reflectors in black to show the general trend of the margin, but we are not sure if they represent part of the same stratigraphic units. The reflections are steep on the eastern side of the Baronie block in the seismic image (black arrows in Figure 1) and display gentler dip on the opposite side.

c) The lateral changes of reflectivity could be due to the presence of evaporite within Messinian deposits, being this small basin locate to East of Baronie Smt (red arrow in Figure 1); or it could be generated by the AGC used for display. The multiple of the seafloor (marked blue) that is, 6 s-TWT, and thus much later that the multiple indicated by Torrente et al e (Figure 4 in Loreto et al). The black reflector (Green arrow in figure 1) are thus primary and not multiple.

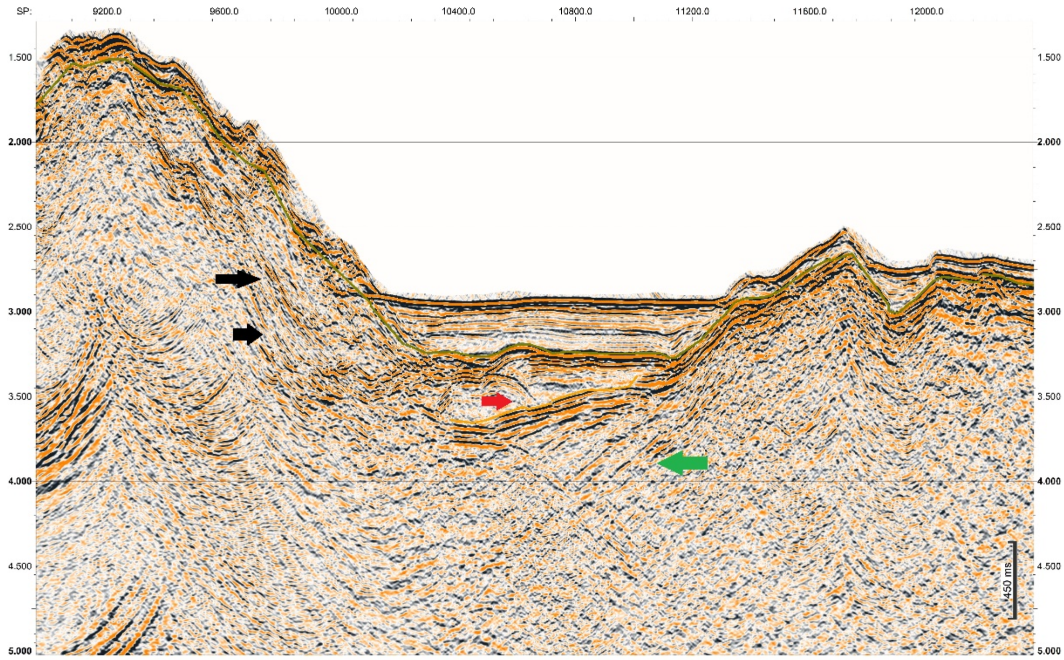

Figure 1- detail of basin narrowed between Baronie and Marussi seamonts. Black arrows point out at very steep horizons; red arrow point out at transparent sediments likely associated to evaporites; green arrow point out to steeper deeper horizons related to pre-Messinian rocks.

2.1.4 **a)** Reverse faults are reported in the Ustica Ridge, and Sisifo and Alcione volcanoes, but the relevance of these structures is open to debated. At the Ustica Ridge, near the Drepano Smt, Loreto et al reported (Fig. 5) an interpretation of the CROP28A profile displaying fold structures associated to small reverse faults dipping to the south. In contrast, in Fig. 7 a large thrust fault dipping to the north (identical to that reported by Torelli et al., 1990) has been mapped, which is not coherent with the seismic data interpretation. **b)** The structural map (Fig. 7) features a pop-up structure bounded by thrust faults at the Sisifo volcano, located southwest of the Marsili volcano, but the associated seismic profile crossing the Cefalù basin (CROP M6B, Fig. 2 of Loreto et al.) is not shown. It is worth noting that previous investigations of this sector of the Tyrrhenian region (Pepe et al., 2005; Milia et al., 2018) reported the Sisifo volcano bounded by normal faults forming a set down throwing towards the Marsili basin. **c)** In addition, according to the authors, the Alcione volcano is displaced by a normal fault and a couple of reverse faults at the base of the western flank (CROP M27; Fig. 6 in Loreto et al.). However, in the structural map, the reverse faults appear localized in a particularly restricted area at the base of the volcano; this feature allow us to interpret it as a deposit on the sea floor associated to the distal part of a volcano lateral collapse, consistent with the occurrence of the normal fault below the central volcano edifice. **d)** Even if the structural map reports some transcurrent faults, their seismic documentation is sparse. Indeed, WSW-ESE strike-slip faults were mapped in the Ustica Ridge, but no vertical faults or flower structures are visible on the seismic profile located north of Sicily crossing these structures (CROPM28A, Fig. 5b in Loreto et al.). **e)** The new structural map (Fig. 7 of Loreto et al.) displays a complex fault pattern of normal faults with different ages in the entire basin and the occurrence of normal, reverse and strike-slip fault systems south of the 40° N latitude, offshore northern Sicily and Calabria,. In the "Conclusion" section, Loreto et al wrote: "According to the fault distribution that our new structural map highlights, the southern Tyrrhenian Basin is dominated by normal, inverse and, likely, transcurrent faults recalling a shear zone". However, the authors did not report the presumed shear zone on their structural map and fail to explain how normal, reverse and transcurrent faults of the southern Tyrrhenian Basin can be associated.

a) The southern Tyrrhenian tectonics has been long debated, several authors report thrusts others normal faults bounding the Drepano – Ustica Ridge (Torelli et al., 1990; Bigi et al., 1992; Lentini et al., 2006; Serpelloni et a., 2010, and several others). Our data displays north verging and south verging thrusts which is the conventional model for most works. Our multichannel seismic profiles (CROP, Medoc, CS and MS), across the Drepano-Ustica Ridge are limited, although we have the most extensive deep penetration grid available in the area. Thus, we extended the interpretation laterally, interpreting the features in the bathymetry and available seismological data (Presti et al., 2013). We did not include comparative minor structures in the map (although mapped on seismic profiles) as Torrente et al point out.

b) Sisifo volcano imaged on Crop M6A. Based does not contain kinematic markers to define a fault system bounding the volcano, most of the imaged structure appears to be volcanic products. Pepe et al. 2005, propose thrust faulting near Sisifo, whereas Milia et al., 2018 listric normal faults along the margin. The available Crop data have low penetration and poor resolution in this sector and the interpretation is disputable. However, this area affected by a significant number of thrust-mechanism earthquakes (Presti et al., 2013).

c) the data available are 2D lines, tens of km apart, which do not allow to accurately map the lateral extent major faults, unless supported by a morphological expression which is lacking in this case. The interpretation suggested by Torrente et al. does not accounts for the imaged basement structure.

d) Typically, transcurrent faults are geological features not easy to identify even if crossed by a seismic line. The detection along the seismic line of a compressive/extensional structure do not make a fault to be transcurrent. This is particularly true if the area affected transcurrent deformation contains little sediment, as this case. We used in other sector the continuous bathymetry coverage to propose a transcurrent component of the WNW-ESE faults cutting the Drepano-Ustica Ridge (Fig. 7 in Loreto et al.).

e) We did not map the shear zone because it is inferred and not imaged, but we correctly used the term "recalling" I HAVE NOT IDEA WHAT YOU MEAN WITH RECALLING, PERHAPS YOU MEAN "RESEMBLING"? shear zone. It is worth noting that the Drepano-Ustica Ridge is affected by a complex fault system with documented normal, inverse and transcurrent faults. The focus of our work was to synthesise the major fault systems and use them to infer the basin evolution. The presence complex fault system northward of Sicily is discussed also in Cuffaro et al. (2011) and we did not further extend the available interpretation.

2.2. Faults age **a)** The overall fault set was separated in subsets with different age. Nevertheless, it is not clear to which ages these structures should be associated. Indeed, the age of the faults in the main text and figure caption of the structural map (Fig. 7 of Loreto et al.) appears contradictory: in the text "black faults" are Upper Miocene (Tortonian-Messinian), "pink faults" are Middle Miocene (Langhian-Serravallian). In contrast, in the figure caption "black faults" are structures whose activity started during Langhian-Serravallian, while "purple faults" are structures, whose activity started during Tortonian Messinian and ended in the Early-Middle Pliocene. **b)** Furthermore, based on the seismic line interpretation of the northern sector (CROP 37, Fig. 1a), we can see planar faults active from Messinian to P-Q (see inset), in the adjacent depocenter (west of Etruschi seamount) a presumed fault bounds an irregular surface (top of the Messinian) affected by diapirism, whereas the red horizon at the base of MSC seems to be continuous eastwards across the fault. **c)** More important, the structural map displays Middle Miocene (pink) faults on the Tuscan margin (Fig. 7 of Loreto et al.). In contrast, the presumed normal fault reported at the eastern edge of the seismic profile (CROP 37) displaces a Cretaceous thrust sheet (see Matilda well stratigraphy) and is covered in onlap by the PQ unit, corresponding to a Pleistocene unit in the well stratigraphy. **d)** In addition, the interpretation of the eastern sector of this seismic profile is unclear and should be explained. **e)** Above all, in the study of Loreto et al., the stratigraphic data provided and analysis of the literature made on this topic are not sufficient to argue the age of the structures. **f)** Whereas, the timing of several tyrrhenian basins has been discussed in several uncited previous studies that analyzed and interpreted the structures of the Tyrrhenian and peri-Tyrrhenian sedimentary basins with calibrated seismic profiles from well and outcrop stratigraphies (Milia et al., 2014, 2017a, 2017b, 2017c; Milia and Torrente, 2015a, 2015b, 2022).

a) The thank Torrente et al for spotting that at page 11, in the first paragraph, we mistakingly stated that black faults are Upper Miocene in age and pink faults are Middle Miocene in age. Instead, the correct association is black fault are Upper Miocene (Langhian (?)—Serravallian) and pink fault are Upper Miocene (Tortonian-Messinian), as correctly appears in the figure caption of figure 7 in Loreto et al.

b) It cannot be excluded that below-seismic-resolution, I.e. a few-meters-thick evaporite deposits are present in the small narrow basin between the Etruschi and the continental margin of Corsica. However, the clear reflector geometry of the Plio-Quaternary and Messinian sediments showing strata tilting with thickening of the deposits towards the Etruschi basement wall is typical of normal faulting and not halokinetic processes.

c) as reported in the figure legend of Fig.7 the "purple" (not "pink" as reported by Torrente et al.) stands for fault activity of Tortonian/Messinian time ending in the Early/Middle Pliocene, not Middle-Miocene, then not in contrast with the Matilda well stratigraphy

d) we guess that Torrente et al. are referring to the fault traces at CDP 2500. Simply we mapped a main fault that displaces a pre messinian reflector and a subsidiary fault that merges against the main fault.

e) at this point Torrente et al state that "the stratigraphic data provided and analysis of the literature made on this topic are not sufficient to argue the age of the structures". First, it is worth underline that all the stratigraphic information available in the Tyrrhenian basin is derived by more than a decade of sampling by dredging and coring of the sea bottom carried out during the seventies by the Italian institutions and by DSDP leg 13, site 132, DSPD leg 42, site 373 carried out in the same years. Meanwhile, the Tyrrhenian was mapped with thousands of kilometers of seismic reflection lines, gravity and magnetic field measurements, heat flow measurements. Finally, on top of this huge amount of work, ODP leg 107, sites 650-656 (Kastens & Mascle, 1990) provided the key age calibration for the seismic reflectors identified in the seismic lines. This stratigraphic information is fully utilized (Hsü et al., 1977; Kastens et al., 1988; Selli, 1977; Marani & Trua, 2002; Mascle et al., 2004; Curzi et al., 1980; Argnani & Trincardi, 1993; Sartori et al., 2001, 2004; Sartori, 2005; Moeller et al., 2013, 2014; Prada et al., 2014, 2015, 2016) in our work and the seismic lines presented in our paper are of very high quality and published at high resolution and representative of key area (Northen Tyrrhenian Sea, Vavilov and Marsili sub-basins, Cornaglia and Campania terraces; Sardinia Valley, northern Sicily, Paola and Sant'Eufemia Gulf basins). We argue that the few clarifications asked by Torrente et al. on the seismic interpretations one of which a clear typo, another a forgetfulness while the others fall within the normal dialectic when two people interpret the same seismic line because no matter how much we try to give an objective interpretation, in reality it is always subjective, but this should not affect the validity of our entire work.

f) In addition to the stratigraphic information mentioned in the previous paragraph there are those derived from the wells located on the Italian continental platform (Matilde, Michela, Mimosa, Martina, etc.) which were performed by the Italian Oil company, AGIP (now ENI) in the seventies We underline the fact that this data set provide a very limited contribution to understand the stratigraphy of the deepest part of the Tyrrhenian Basin and its western and southern side. The whole eastern Tyrrhenian margin is made of several small, confined basins where is not possible to laterally propagate the stratigraphic calibration through the topographic highs. In addition, the whole eastern margin was affected by huge volcanism interfering with the normal sedimentation. Moreover, the whole eastern Tyrrhenian margin is characterized by the absence of clear evidence of messinian deposits which are the most useful stratigraphic marker of the Tyrrhenian Basin. Since most of the works of Milia et al and Milia and Torrente are based on the stratigraphic information given by those commercial, we wonder if they are overestimating the importance of their contribution for the understanding of the stratigraphy of the Tyrrhenian Basin

3. PLIO-QUATERNARY THICKNESS MAP

Loreto et al. merged and analysed several geophysical datasets. Regarding their data set they wrote: "Unfortunately, the low density of seismic data along the peri-continental margin do not allow to define the real lateral extension of basins. We modified PQ isopachs comparing the contour lines from bathymetric map with the isopachs trend to reduce edge effects and increase the resolution of map, defining accordingly the lateral extension of basins." We certainly agree that the Plio-Quaternary thickness map of Loreto et al. is not reliable in the peryTyrrhenian margins, due to the low density of seismic data, but we also point out that the bathymetric map fails to reveal the presence of any fault in the shelf area, where many basins are overfilled by sediments. Nevertheless, maps of PQ thickness, or maps from which this thickness can be derived, on the eastern Tyrrhenian margin (Latium, Campania, Calabria and Sicily) have been published in several uncited studies (Iannace et al. 2013, 2018; Milia et al. 2013, 2017a, 2017b; 2018, 2021; Milia & Torrente, 2015a). These studies display the result of the interpretation of high-density seismic data calibrated by borehole stratigraphies and released thickness maps reaching a resolution of hundreds of thousands of years.

We did not mapped the Plio-Quaternary thickness, as there are previous maps done with lower penetration data but a more extensive data grid. We focused in the fault structure of Tyrrhenian Basin taking advance of our deeper penetration data -mostly processed/reprocessed by us- and the available bathymetry.

4. FAULT TIMING AND EVOLUTIONARY STAGES

The early stage of rifting of the Tyrrhenian Sea is a high debated topic. In the "Previous Works" section, Loreto et al. wrote: "Based on chronological information provided by the ODP leg 107, Kastens et al. (1988) suggest that the Tyrrhenian Basin started to open offshore northern Sardinia in the Tortonian (Fig. 1b), or earlier (Lymer et al., 2018; Sartori et al., 2001), and offshore southern Sardinia in the Messinian (Fig. 1c)". Actually, Sartori et al. (2001) proposed that rifting processes started on the Sardinia margin during Tortonian, Lymer et al. (2018) before Messinian and Milia and Torrente (2014, 2017 2022) during Serravallian-Tortonian times. Mattei et al. (2002) dated an upper Serravallian clastic unit at Amantea (Tyrrhenian Calabria coast), covering the crystalline substrate. Milia et al. (2009) recognized in the Paola basin a seismo-stratigraphic unit, overlying in onlap the crystalline basement, correlated to SerravallianTortonian deposits, outcropping along the coast. Therefore, these previous studies documented the Serravallian onset of the Tyrrhenian extension.

Milia et al. (2009) propose that Serravallian deposits lie directly on metamorphic rocks. However it should be noted:

1. The correlation in Milia et al. (2009) between marine seismo-stratigraphic units with on-land outcrops is speculative, because they use drillholes Marta and Marisa, in which no Serravallian deposits were drilled. Instead, Messinian sediments lie in an erosional contact on pre-Triassic units.

2. Milia et al. (2009) interpret in line CROP M27 that the basement of the entire continental margin offshore central Calabria is made by metamorphic rocks; while other authors interpret Messinian deposits.

3. The first proposal of a Serravallian onset of the Tyrrhenian extension is from Mattei et al (2002) and given the uncertainty we simply refer to this first paper.

Even if the structural map of Loreto et al. displays Langhian-Serravallian normal faults (black faults in their Fig. 7) on the eastern Sardinia margin, it is not clear how this age was assigned, because the authors did not distinguish a Langhian-Serravallian seismo-stratigraphic unit and have not argued this point. The LanghianSerravallian tectonic activity has been documented for the first time by Milia et al. (2017c) in the Corsica, Cagliari and Cilento basins, which are not the subject of the study of Loreto et al. For the above *reasons, the authors have not presented an original contribution to the knowledge of the early stage of Tyrrhenian rifting.*

We supported in the paper the the Langhian-Serravallian onset of Tyrrhenian extension using the age of basaltic rocks sampled at the Cornacya Smt (12.5 Ma; Mascle et al., 2001; marked with an orange square in Figure 9a in Loreto et al), and the age of >13.8 Ma) of outcropping sediments in the Amantea Basin (Mattei et al., 2002). We propose that the pre-messinian, syn-tectonic deposits imaged in our data may have that age (e.g. Fig. 2 of this response letter).

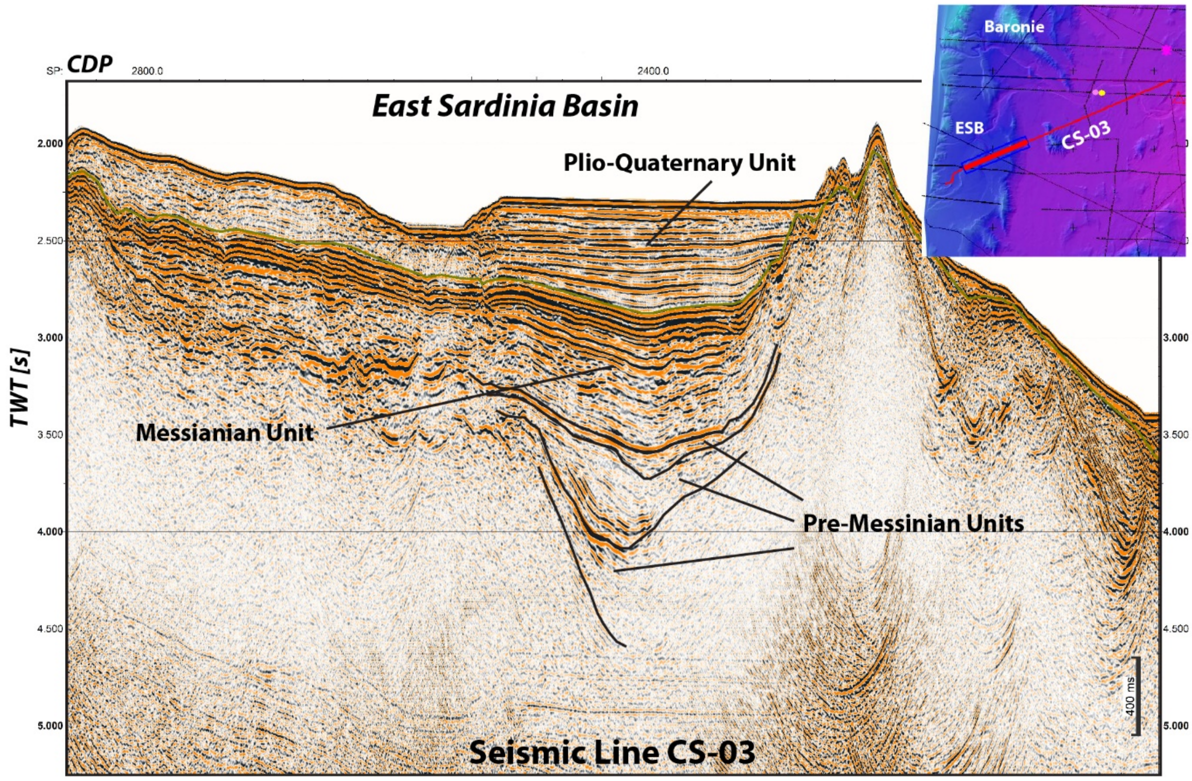

Figure 2 – Seismic image of the Eastern Sardinia Basin (ESB) showing the Plio-Quaternary unit, undeformed in the upper part, superimposed on the Messinian deposits. The latter lay above at least three units with variable thicknesses and growing structures. We have interpreted these units as pre-Messinian

Loreto et al. recognized the unit PQ as more recent seismo-stratigraphic units in some Tyrrhenian basins and units P and Q (separated by unconformity X) in other basins. However, considering that the isopach map presented refers to the Plio-Quaternary (Fig. 8 in Loreto et al.), how was it possible, on the basis of these data, to distinguish two evolutionary stages (one in Pliocene and the other in Quaternary) of the Tyrrhenian basin?

We did not differentiate Pliocene from Pleistocene sediments in the *isopach map* and thus the evolutionary stages use information from the literature, (e.g. ODP sites 650 or the 651, Kastens et al., 1988) and others in Figure 3 in Loreto et al. and other previous works (Sartori, 2005; Trua et al., 2004; De Astis, Ventura, & Vilardo, 2003; Bortoluzzi et al., 2010).

In conclusion, insufficient evidence (original data and literature data) is provided to support the kinematic model of the four (Langhian/Serravallian, Tortonian/Messinian, Pliocene, Pleistocene) Tyrrhenian Basin opening phases (Figure 9 of Loreto et al.). Given the scope of the work, it would be of paramount importance to include the features of Tyrrhenian basins developed during the different stages of the polyphase Tyrrhenian rifting.

We used almost all streamer data and wide-angle seismic data collected in the last 50 years in the Tyrrhenian and selected for the figures the most representative examples. The summary is the model what in figs. 4, 5, 6 and the map of figure 7. Our paper is the first basin-wide tectonic study of the Tyrrhenian.

Even if the paleogeographic reconstruction of the Paleo-Tyrrhenian basins during Miocene times is a challenging task, because the subsequent Pliocene-Quaternary backarc opening step away these older sedimentary basins, we suggest Loreto et al. to refer to previous uncited studies.

We cite all relevant literature, admittedly we may not always refer to papers that propose similar results to previous publication. The paper scope is not a review, but to provide a new integration of most existing observations that are relevant at basin scale.

5. DEFORMATION STYLES AND DETACHMENT MODEL

A) Loreto et al. wrote: "According to our reconstruction, the Tyrrhenian Basin started to open as pure shear, symmetric rifting, and evolved to a simply shear, asymmetric rifting hyperextended margin (sensu Mohn, Manatschal, Beltrando, Masini, & Kusznir, 2012)." However, the authors furnished an incomplete description of the Tyrrhenian detachment fault, traced only in a couple of points on a seismic profile (MEDOC 8; Fig. 1b, CDP 28000-30000 and CDP 42000-43000) and tectonic sketch (Fig. 10b of Loreto et al). For this reason, the fuzzy geometry of the detachment fault invalidates the authors' considerations on the extensional style in the central Tyrrhenian, as well as on a change from pure to simple shear style. **B)** Loreto et al. wrote: "The most efficient decollement layer in a continental margin that has undergone full rifting may be located at the Lower/Upper crust Transition (Figure 10b), often corresponding to Ductile/Brittle Transition (DBT; Condie, 2005)." The DBT locally coincide with the Moho, as well-imaged on our seismic profiles (CDP 5500–6500 in Figure 5a) and also observed in others rifting systems as the Galicia margin (Boillot et al., 1995; Reston & McDermott, 2011; Whitmarsh et al., 2001), the Alboran Basin (Watts, Platt, & Buhl, 1993; Gómez de la Peña et al., 2018) or Gascoyne Basin (Mutter & Larson, 1989)". The rheological stratification of the continental lithosphere, based on a combination of brittle friction and plastic flow law, derived experimentally for quartz, feldspar and olivine, shows that the Moho seismic discontinuity does not correspond to any brittle-ductile transition (Fossen, 2012). Indeed, the Moho discontinuity divides the crust from the upper mantle, while the BDT (it is more correct to refer to a brittle-ductile transition than in the opposite way to a ductile-brittle transition) leads to a change in the deformation behavior and is thus located within one or more specific lithospheric layers (e.g., within the upper and/or lower crust and/or upper mantle) and not at the base of the layers. If the authors identify a decollement in correspondence of the Moho depth this can be due to the ductile conditions of the lower crust (in this case the BDT would be above the Moho depth discontinuity). **C)** In the section "The Tyrrhenian back-arc basin opening model" Loreto et al. reported several basins worldwide controlled by detachment faults and wrote: "we can consider this model also suitable for the northern/central Tyrrhenian Basin…. this process may have occurred in the Tyrrhenian back-arc basin". It must be stressed that a model of detachment faulting and mantle exhumation in the Tyrrhenian Sea has already been published. A detachment fault was first recognized in the Vavilov area by Mascle and Rehault (1990) and then imaged on CROP seismic profiles by Milia et al. (2013), while later on, Milia et al. (2017a) proposed a first kinematic evolution. According to the latter authors the ultimate stage of extension in the distal region led to: (i) complete embrittlement of the crust; (ii) direct prolongation of crustal faults to upper mantle depth; (iii) serpentinization and mantle exhumation

A) The symmetry or asymmetry of a rift system does not depend on the presence of a detachment fault as in Wernicke 1981 model. This is a common misunderstanding and we recommend Torrente et al. to read Perez-Gussinye et al., (JGR 2003) and Ranero and Perez-Gussinye (Nature 2010) that discuss it in considerable detail the evolution from pure to simple shear in qualitative and quantitative manners.

B) Following the previous point, we also strongly recommend Torrente et al., to read Perez-Gussinye and Reston(JGR 2001) and recent modelling papers that account for the rheological evolution of rift systems. The Brittle Ductile Transition (BDT) is obviously not fixed at any particular geological marker, as it is depended on temperature. Thus, as extension progresses and the crust thins the BDT may indeed reach Moho levels for a particular amount of time, or may even be in the upper mantle and all the crust behave brittle.

C) A detachment fault model in the Tyrrhenian basin has been previously postulated by Mascle and Rehault (1990) and Milia et al 2017. Mantle exhumation, i.e. mantle tectonically brought to the seafloor, was first shown by Prada et al, 2014 and 2015, with high-resolution wide-angle seismic data, but not integrated by Milia et al 2017. We based our reconstruction for the entire Tyrrhenian basin evolution on those velocity models and all available seismic images (reprocessed Crop, Medoc, CS MS and also the ST-Sithere), and all ODP drill wells, and the bathymetry. Clearly Mascle and Rehault (1990) did not have those informations available, and Milia et al 2017 focus on the Campanian margin using hard-copies of vintage industry data, with a local coverage, low spatial and vertical resolution, and outdated processing so that the images (un-migrated in most cases) are of comparably poor quality.

6. CRUSTAL ARCHITECTURE AND OCEANIC ACCRETION

Loreto et al. (2021) wrote: "Although Sartori et al. (2004) considered the Cornaglia Terrace as thinned continental crust, the seismic velocity with the classical oceanic Layer 2/3 seismic structure (Prada et al., 2014, 2015; Grevemeyer et al., 2018), clear wide-angle PmP reflections and near-horizontal Moho reflections, which is associated with a continuous high-amplitude triplet (grey thick dashed line; Figure 4b), support that the basement of Cornaglia Terrace is made of oceanic-type rocks."… "In the central part of the Tyrrhenian Basin, based on tomographic models, Prada et al. (2014, 2015) proposed that extension evolved till to continental break-up and oceanic crust accretion in the Cornaglia and Campanian Terraces (green areas in Figure 9b). This event preceded the deposition of the Messinian evaporites (Figure 4b), which show deformation mainly related to salt tectonics (CDPs 13000– 18000). Based on this hypothesis, crustal thinning and oceanic crustal accretion occurred in less than 6 Ma, from Serravallian to end Tortonian (i.e. ranging from 12.5 to 7.2 My)"…. "According to Prada et al. (2016), in the centre of the Tyrrhenian Basin, the oceanic accretion phase, once the crustal thinning reaches a βv factor > 3, was soon followed by mantle exhumation contemporary with basaltic intrusions (7.2 My basaltic breccias and basalts drilled at DSDP 373; Hsü et a., 1978)." However, Prada et al. (2014), combining different geophysical data, proposed a peculiar model of the crustal architecture of the Tyrrhenian Sea featuring a central region of exhumed mantle (bathyal plain) flanked by two oceanic sectors (Cornaglia and Campania Terraces), surrounded by two continental sectors (Sardinia and Campania margins). On the basis of the modeled crustal architecture, Prada et al. (2014) suggested an unusual evolution of the Tyrrhenian region: from an extending continental crust to back-arc oceanic crust formation, to mantle exhumation. **a)** Loreto et al. do not provide geological data to support the crustal architecture suggested by Prada et al. (2014) **b)** and do not propose an evolutionary model. **c**) We would also like to point out to some problems with the crustal model of Prada et al. (2014) that was advocated- by Loreto et al. (their Fig. 10b). First, the crustal architecture, featuring oceanic crusts in the Cornaglia and Campania Terraces, was hypothesized only on geophysical grounds. In the case under study (Cornaglia and Campania Terraces), well stratigraphies and dredges did not sampled a Neogene oceanic crustal suite but continental crystalline basement, Tethyan ophiolites nappes and shallow-water coarse clastic and evaporites, Tortonian-Messinian in age, recovered in wells and dredges of the Cornaglia and Campania Terraces, support a stretched continental crust interpretation (e.g. Kastens and

Mascle, 1990; Sartori et al., 2001, 2004; Doglioni et al., 2004; Milia et al. 2017a). **d)** Second, better age constraints are needed to support the timing of the proposed Tyrrhenian evolution (continental rifting, oceanic crust formation and mantle exhumation). **e)** Third, the Tyrrhenian crustal model and evolution are in stark contrast to both the accepted detachment model of passive margin (e.g. Morley, 1995 and Fig. 10c; characterized by a central region of oceanic accretion) and conventional evolution of lithospheric extension, featuring a continuum process (from continental crust extension, formation of exhumed upper mantle, continental break-up and eventual oceanic crust formation; e.g. Whitmarsh et al., 2001; Lavier and Manatschal, 2006; Péron-Pinvidic and Manatscal, 2009). For all the above reasons, a new model of Tyrrhenian rifting should be supported by additional data / or argued and above all **f)** should be illustrated by a sketch in cross-section.

a) The results of Prada et al. (2014) are based on wide-angle seismic models and gravity modelling, they are not contested in our paper because we believe they are correct. The bulk of our analysed data, the seismic images and bathymetry, can neither prove not disproved those results. This is a common misunderstanding: some papers try to infer basement nature from streamer seismic image, which may be fair in some circumstances, but streamer data usually do not provide physical properties from within the basement and wide-angle seismic data do.

b) The kinematic model of figure 9 (in Loreto et al.) and the extensional model of figure 10 (in Loreto et al.) encapsulate the evolution.

c) All published dredge data from the Tyrrhenian was taken into account by Prada et al.. Also eee response to a).

d) Yes of course, and that is why we wrote the IODP proposal "TyrrhenIan Magmatism & Mantle Exhumation" (TIME) . The project was approved and the Tyrrhenian IODP Expedition 402, will take place in early 2024 (http://iodp.tamu.edu/publications/SP.html). Nevio Zitellini is one of the Chief Scientist.

e) There is no "accepted" detachment model in the international community. The modern wide-angle seismic data available in the Tyrrhenian, which is all from our group, is comparable or better than most wide-angle seismic data sets from any rifted margin around the world. Obviously this is a topic that goes beyond the expertise of Torrente et al., but the models of the nature of the basement in the Tyrrhenian are based on robust comparatively high-resolution wide-angle seismic results. All drilling and dredging published in the Tyrrhenian are compatible with the crustal model proposed in Prada et al., 2014, 2015, 2016 and 2018. The soon to happen Time IODP expedition will test some of the remaining open questions.

f) The kinematic model of figure 9 (in Loreto et al.) and the extensional model of figure 10 (in Loreto et al.) encapsulate the results from Prada et al., 2014, 2015, 2016 and 2018.

Conclusions

a) In conclusion, the Loreto et al. article presented structural maps and tectonic models not fully supported by their analysis and interpretation. Even if the conclusion of Loreto et al, about the fact that the Tyrrhenian Sea basin was affected by extensional tectonics, is correct, **b)** the new structural map proposed by the authors is questionable, since the proposed deformation style and detachment model do not match the observations. **c)** Furthermore, the final tectonic model of crustal architecture and oceanic accretion present some weakness and should be supported by a more detailed discussion and accurate analysis of the literature, **d)** suggesting a possible kinematics evolution.

A-d) Admittedly, all results in a paper can be improved with further data and work. For our contribution we have used the largest modern seismic, bathymetric and sample databases from the Tyrrhenian and have integrated those observations with modern concepts of rifting, partially arising from our work in basins around the world. Some of the proposals may be surprising when you focus your research in one single basin, but the unexpected finding in the Tyrrhenian will surely be further documented and augmented with coming scientific campaigns, some already planned in this region.

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