Received: 1 August 2023 | Accepted: 4 August 2023

DOI: 10.1111/bre.12816

REPLY TO COMMENT

Basin Research IAS EAGE WILEY

Reply to the comment of Torrente et al. on 'Extensional tectonics during the Tyrrhenian back-arc basin formation and a new morpho-tectonic map' by Loreto et al. (2021)

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 concern very specific aspects on the interpretation we presented in the paper figures rather than the general contribution and conclusions of our paper. The criticisms raised by Torrente et al. on the seismo-stratigraphic, tectonic and age interpretations of the faults, on the evolution of the Tyrrhenian Basin from the Serravallian to present and on our proposed detachment model are discussed in order to clarify our interpretation. Furthermore, Torrente et al. state that a series of articles published by them considered crucial for the understanding of the Tyrrhenian evolution were not cited in Loreto et al. (2021). Here we suggest that we quoted the most relevant literature used to support our models. In the following, we refer to the sections in the comment of Torrente et al. (2023), citing the statements in bold-italics, followed by our replies.

We address the criticism points raised sequentially, using the numbering as presented in the comment of Torrente et al. 2023.

2. FAULTS INTERPRETATION AND STRUCTURAL MAP

2.1

We mapped the fault based on the geometry of basement (fault) blocks and strata. Although no stratigraphy was defined and no finite offset values were given, that does not prevent locating the fault properly. There are numerous examples in literature showing a similar approach in many different extensional basin around the world, a number of them from our own work (Bjerkvik, 2012; Gabriela et al., 2014; Loreto et al., 2021; Lymer et al., 2018, Moeller et al., 2013, *just to cite some*).

2.1.1

We do not explicitly or implicitly contradict Lymer et al. (2018) in our work and our interpretation is not necessarily contradicted by that article. However, it is a fact that our interpretation does not neglect the lateral continuity of the PQ Unit towards the West.

It seems contradictory to us that Torrente et al. support the idea of seismostratigraphic continuity in Lymer et al. (2018) and other comments citing the paper of Lymer et al. (2018), which relies on low-depth 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 image the entire sediment package, the top of the basement and often the entire crust with a reflection from the Moho. Perhaps Torrente et al. are not aware of the significance of the difference between our data and those presented by Lymer et al. (2018). The latter were collected with 1 airgun and a 150 m long streamer. These data are single channel data with maximum depth penetration, that is, 6 s TWT, and low-lateral resolution, considered that each point in depth has been investigated one time. Our data, collected with a multi-airgun source (12 GI Gun) one order of magnitude larger in volume and with the signal recorded on streamers from 2400 to 4500 m long, provide a seismic image with high-depth penetration, recording up to 18 s TWT, and high lateral resolution being each point in depth sampled 35 times. The big quality difference in the images makes some of the claims, such as the lateral continuity of the PQ horizon, unsupported.

2.1.2

As far as we are aware, the west-dipping fault that affects the Orosei Cahnnel does not reach the seafloor in seismic line published from that area (Prada et al., 2014, 2015; Sartori et al., 2004; Zitellini et al., 1986).

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 observed in deep penetration seismic data between Sardinia and the Baronie Smt (Fabbri et al., 1981), for example MCS line MEDOC 8. Lymer et al.'s (2018) data imaged only the Upper Unit of the Messinian evaporites and not the Mobile Unit. While they mapped fault close to those we mapped, our data image the basement structure and theirs does not. Thus, we suggest this better resolution of basement supports our interpretation.

2.1.3

In the caption to figure 4b of Loreto et al. we stated 'Remarkable reflections are pointed out with black lines'. Only when the interpretation can be made with confidence the reflectors were coloured in green (base PQ) pink (× unconformity), and red (base of Messinian deposits). In our specific case, we identified one of these reflections on the fault hanging wall 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. The presence of a normal fault descending to the east modifies the geometry of the horizons making their lateral continuity, from hanging wall to footwall, difficult to follow.

We used coloured reflectors when the unit was clearly identifiable, while when unclear we mapped them in black but did not assign an age. So, in this specific case, we mapped some reflectors in black to show the general trend of the margin, but we were 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 here) and display gentler dips on the opposite side.

The lateral changes in 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 here); or it could be generated by the AGC used for display. The seafloor multiple (marked with a dotted blue line in figure 4, Loreto et al.)—is at about 6 s-TWT (light blue arrows in Figure 1 here), and thus much deeper than the multiple proposed by Torrente et al. The black reflector (pointed out with a green arrow in Figure 1 here) is thus primary and not a multiple.

2.1.4

The tectonics of the southern Tyrrhenian region have been long debated. Several authors report thrusts and others normal faults bounding the Drepano–Ustica Ridge (Bigi et al., 1992; Lentini et al., 2006; Serpelloni et al., 2010; Torelli et al., 1990, amongst others). Our data display north verging and south verging thrusts, which is the conventional model for most published works. While our multichannel seismic profiles (CROP, Medoc, CS and MS), across the Drepano-Ustica Ridge are limited, we have the greatest depth penetration seismic grid available in the area. Thus, we extended the interpretation laterally, interpreting the features in the bathymetry and those from available seismological data (Presti et al., 2013). We did not include comparatively minor structures in the map (although mapped on seismic profiles) as Torrente et al. point out, due to the lack of lateral continuity, but these are second order in our tectonic model.

The Sisifo volcano is imaged on Crop M6A. This profile 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. (2010), propose thrust faulting near Sisifo, whereas Milia et al. (2018)

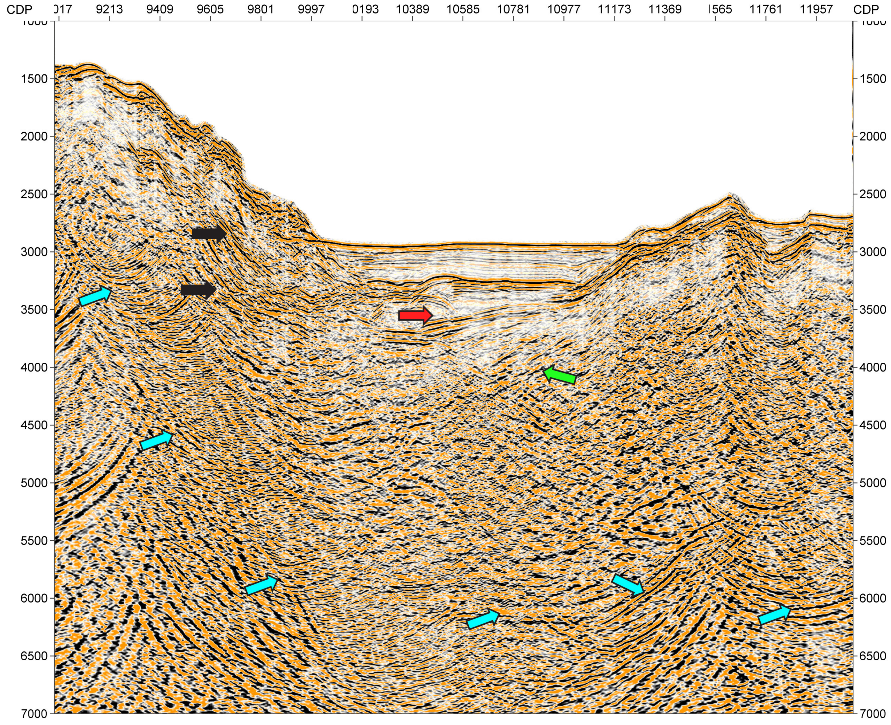

FIGURE 1 Detail of basin narrowed between Baronie and Marussi seamonts, MCS profile Medoc 8. Black arrows point out at very steep horizons; red arrows point out at transparent sediments likely associated with evaporites; green arrow point out to steeper deeper horizons related to pre-Messinian rocks; light blue arrows point out at multiple reflections.

suggest listric normal faults along the margin. The available Crop data have low depth penetration and poor resolution in this sector and their interpretation is open to debate. However, this area is affected by a significant number of thrust-mechanism earthquakes (Presti et al., 2013) giving support to our interpretation.

The data available are 2D lines, 10s of km apart, which do not allow accurate mapping the lateral extent of major faults, unless supported by a morphological expression which is lacking in this case. The interpretation suggested by Torrente et al. does not account for the imaged basement structure.

Typically, transcurrent faults are geological features that are not easy to identify even if crossed by a seismic line. The detection along the seismic line of a compressive/extensional structure does not make a fault transcurrent. This is particularly true if the area affected by transcurrent deformation contains little sediment, as in this case. In the other sector, we used the continuous bathymetry coverage to propose a transcurrent component of the WNW-ESE faults cutting the Drepano-Ustica Ridge (figure 7 in Loreto et al.). Anyway, we accept that this is open to debate and that more data are needed to better understand the real role of the Drepano-Ustica ridge.

We did not map the shear zone because it is inferred and not imaged, but we correctly used the term 'recalling' shear zone, considered that a clear seismic image of deformations associated with a transcurrent system is not detectable within the dataset available, but several clues allow to hypothesis the presence of a shear zone (see the above). 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 of complex fault systems north of Sicily is discussed also in Cuffaro et al. (2011) and we did not attempt to extend the available interpretation.

2.2

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

It cannot be excluded that below-seismic-resolution, that is, 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.

As reported in the figure legend of figure 7 the 'purple' (not 'pink' as stated by Torrente et al.) indicates fault activity of Tortonian/Messinian time ending in the Early/Middle Pliocene, not Middle-Miocene and so not in conflict with the Matilda well stratigraphy.

We guess that Torrente et al. are referring to the fault traces at CDP 2500. Here we simply mapped a main fault that displaces a pre-Messinian reflector and a subsidiary fault that merges against the main fault.

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 underlining 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 70s by the Italian institutions and by DSDP leg 13, site 132, DSPD leg 42, site 373 carried out in the same years. Additionally, the Tyrrhenian Basin was mapped with 1000s of km of seismic reflection lines, supplemented by gravity, magnetic and 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 reflectors identified in the seismic lines. We fully utilised this stratigraphic information (Argnani & Trincardi, 1993; Curzi et al., 1980; Hsü et al., 1977; Kastens et al., 1988; Marani & Trua, 2002; Mascle et al., 2004; Moeller et al., 2013, 2014; Prada et al., 2014, 2015; Sartori, 2005; Sartori et al., 2001, 2004; Selli et al., 1977) in our work. The seismic lines presented in our paper are of very high quality and published at high resolution and representative of key areas (Northern Tyrrhenian Sea, Vavilov and Marsili sub-basins, Cornaglia and Campania terraces; Sardinia Valley, northern Sicily, Paola and Sant'Eufemia Gulf basins). Regarding the clarifications suggested by Torrente et al. on the seismic interpretations; one is a clear typo, another is forgetfulness on our part, 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. This should not affect the validity of our entire work.

In addition to the stratigraphic information mentioned in the previous paragraph, there are additional stratigraphic constraints 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 70s. We underline the fact that this data set provides a very limited contribution to understanding 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 propagate laterally the stratigraphic calibration across the topographic highs. In addition, the whole eastern margin was affected by major volcanism disrupting somewhat the normal sedimentation history. Moreover, the whole eastern Tyrrhenian margin is characterised 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 et al., 2017 are based on stratigraphic information given by low resolution or unmigrated data, their interpretations on Tyrrhenian Basin evolution are perhaps open to question.

3. PLIO-QUATERNARY THICKNESS MAP

We did not map the Plio-Quaternary thickness, as there are previous maps made with lower depth penetration data and with an unexplained Tiff to SEGY conversion procedure, picking and gridding of target horizons. Instead, we produced a more extensive data grid and we focused on the fault structure of Tyrrhenian Basin, taking advantage of our deeper penetration data, mostly processed/reprocessed by us, and the available bathymetry.

4. FAULT TIMING AND EVOLUTIONARY STAGES

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

- The correlation in Milia et al. (2009) between marine seismo-stratigraphic units with onshore outcrops is speculative, because they use the drillholes Marta and Marisa, in which no Serravallian deposits were encountered. Instead, Messinian sediments lie on an erosional contact with pre-Triassic units.
- Milia et al. (2009) interpret in line CROP M27 the basement of the entire continental margin offshore central Calabria is comprised of metamorphic rocks; while other authors interpret Messinian deposits (Argnani & Trincardi, 1993; Loreto et al., 2019; Pepe et al., 2010).
- 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 rather than multiple subsequent works.

In our paper, we supported 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. Figure 2 of this response).

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 (Bortoluzzi et al., 2010; de Astis et al., 2003; Sartori, 2005; Trua et al., 2004). The four evolutionary phases are clearly discussed in our paper from page 13 to 14.

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 figures 4, 5, 6 and the map of figure 7. Our paper is the first basin-wide tectonic study of the Tyrrhenian Basin.

We cite all relevant literature. Admittedly, for space reasons, we may not always refer to papers that propose similar results to previous publications. The aim of our paper was not a review, but to provide a new integration of most existing observations that are relevant at the basin scale.

5. DEFORMATION STYLES AND DETACHMENT MODEL

The symmetry or asymmetry of a rift system does not depend on the presence of a detachment fault as the Wernicke (1981) model. This is a common misunderstanding and we recommend reading Pérez-Gussinyé et al. (2003) and Ranero and Pérez-Gussinyé (2010) that discuss in considerable detail the evolution from pure to simple shear behaviour, both qualitatively and quantitatively.

Following from the previous point, we also strongly recommend reading Pérez-Gussinyé and Reston (2001). The Brittle Ductile Transition (BDT) is obviously not fixed at any particular geological marker, as it is depends strongly on temperature. Thus, as extension progresses and the crust thins, the BDT may indeed reach Moho levels for a given amount of time, or may even be in the upper mantle, so then the entire crust behaves in a brittle fashion.

Further, decollements have been mapped in several seismic profiles shown in Loreto et al. (2021) that are Medoc 8 and CS04.

A detachment fault model in the Tyrrhenian Basin has been previously postulated by Mascle and Rehault (1990) and Milia et al. (2017). Mantle exhumation, that is, mantle tectonically brought to the seafloor, was first shown in the Tyrrhenian Basin by Prada et al. (2014, 2015), using high-resolution wide-angle seismic data, but this was not integrated by Milia et al. (2017). We based our reconstruction for the entire Tyrrhenian Basin evolution on velocity models published in Prada et al. (2014, 2015) and all available

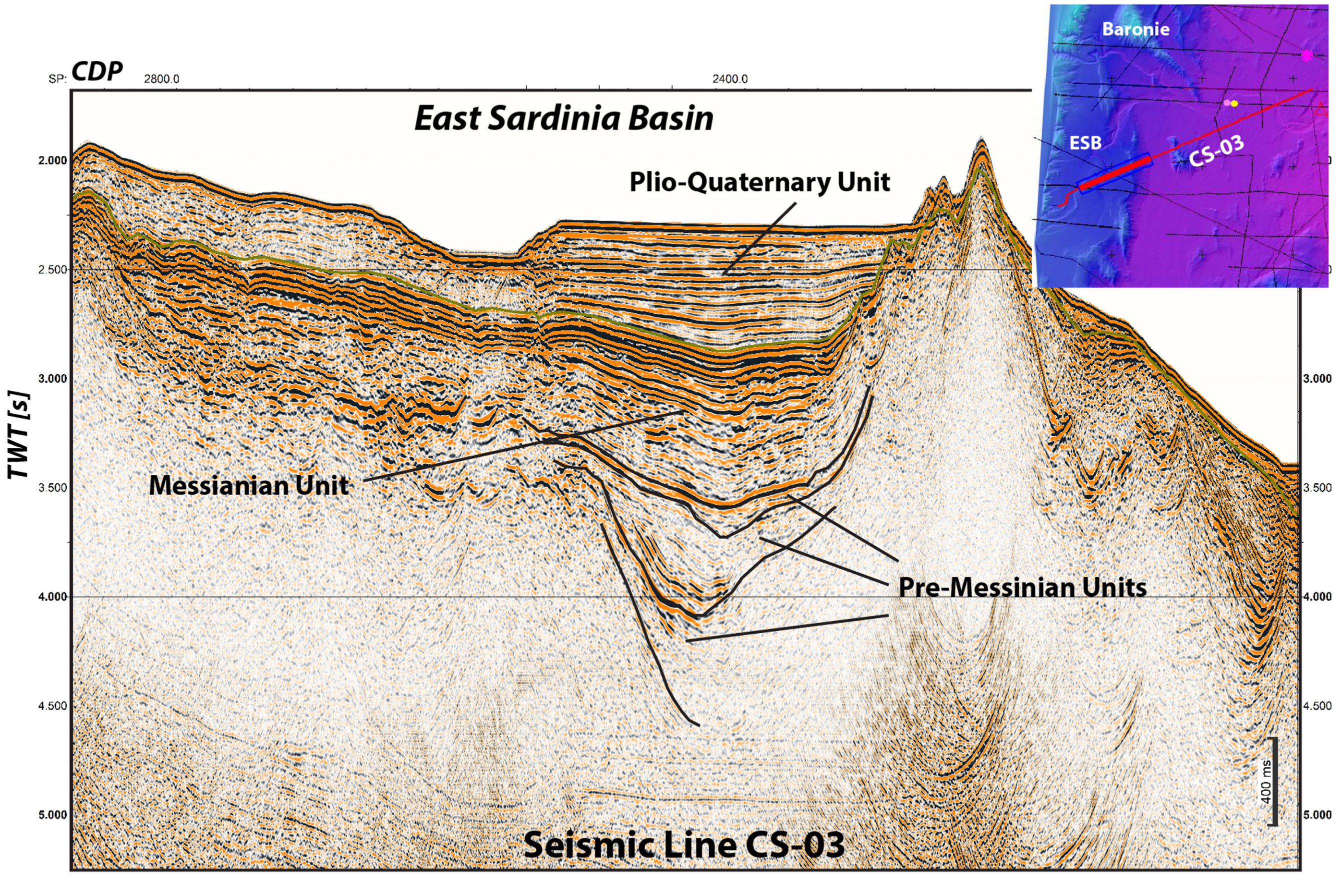

FIGURE 2 Seismic image of the Eastern Sardinia Basin (ESB) showing the Plio-Quaternary unit, undeformed in the upper part, superimposed on the Messinian deposits. The latter lies above at least three units with variable thicknesses and growth structures. We have interpreted these units as pre-Messinian.

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 that information available, while Milia et al. (2017) focussed 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 (unmigrated in most cases) are of relatively poor quality.

6. CRUSTAL ARCHITECTURE AND OCEANIC ACCRETION

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

The kinematic model of figure 9 (in Loreto et al.) and the extensional model of figure 10 (in Loreto et al.) encapsulate the evolution proposed from compiling what we consider available good quality/appropriate depth resolution seismic data and coupling these with available stratigraphic constraints.

The basement below the Messinian deposits in the Cornaglia and Campanian Terraces was never sampled and it is an unknown. The few samples of crystalline rocks collected outside the Vavilov Basin are from topographic highs like the Flavio Gioia Smt, the Baronie Smt, etc., (see sampling map of Colantoni, 1981), which not necessarily represent the crystalline basement below Cornaglia and Campanian terraces. Similarly, the ODP-well 654 that sample rocks from Miocene to Pleistocene is located at the western border of Cornaglia Terrace at the top of a high, and therefore cannot be considered representative of the deep crust below the Terrace. Anyway, all published dredge data from the Tyrrhenian was taken into account by Prada et al. (2014, 2015, 2016).

We agree with the statement that 'additional data / or argued should support the Tyrrhenian opening model'. For this purpose, 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). Four of the five authors of Loreto et al. are project leaders.

There is no 'accepted' detachment model for the Tyrrhenian Basin in the international community. The modern wide-angle seismic data available here, which is all from our group, is of comparable or better quality than most wide-angle seismic data sets from rifted margins around the world. 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, 2018). The coming Time IODP expedition will test some of the remaining open questions.

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, 2018).

1 | CONCLUSIONS

Clearly, results in a paper can generally be improved with further data and work. In our contribution we used the largest modern seismic, bathymetric and sample databases from the Tyrrhenian Basin and have integrated those observations with modern concepts of rifting, based on experience gained from our work in basins around the world. Some of our propositions may be surprising when taken in the context of a single basin, but we might expect unexpected findings in the Tyrrhenian Basin during future scientific campaigns, some of which are already planned in this region.

ACKNOWLEDGEMENTS

Seismic data interpretation was carried out through IHS Kingdom Suite software, freely available to us in the frame of IHS University Grant Program.

FUNDING INFORMATION

The work has been supported by the Italian National Research Council.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/bre.12816.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

M. F. Loreto[1]
N. Zitellini[1]
R. C. Ranero[2,3]
C. Palmiotto[1]
M. Prada[3]

[1]*CNR-ISMAR, Istituto di Scienze Marine, Bologna, Italy*
[2]*Institució Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain*
[3]*Barcelona Center for Subsurface Imaging, ICM, CSIC, Barcelona, Spain*

Correspondence
M. F. Loreto, CNR-ISMAR, Istituto di Scienze Marine, Bologna, Italy.
Email: filomena.loreto@bo.ismar.cnr.it

ORCID

M. F. Loreto https://orcid.org/0000-0003-1960-8684

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