Answers to reviewer RC2 Eline Le Breton

We thank reviewer Eline Le Breton for the review and her fruitful comments that in our opinion improve the manuscript.

We place the comments of RC2 in black and our answers and changes to the manuscript in green letters.

Referee comment on "Basin inversion: Reactivated rift structures in the Ligurian Sea revealed by OBS" by Martin Thorwart et al., Solid Earth Discuss.,

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This manuscript is a short paper presenting seismic activity in the Ligurian Sea, detected by the recently deployed AlpArray seismic network (offshore component LOBSTER), and therefore fits very well with this special edition of Solid Earth. The data and results are very interesting as it shows clusters of compressive earthquakes in the center of the Ligurian Basin, suggesting inversion of this part of the basin, and at intriguing high depths (10-16 km; lower crust - upper mantle). However, the authors need to better present/discuss the uncertainties of the method applied and their results, and improve the discussion of their results in terms of rift-related structures and strength of the lithosphere (see main comments below). Therefore, I suggest major revision.

Main comments:

- Section 3 - Data, methods & results: Section 3 lacks information on the uncertainties of the method applied and the results, especially regarding the depth of earthquakes and the orientation of the fault planes, which are essential to assess/support the interpretation in terms of rift-related structures and rheology that follows in section 4. Table 1 provides uncertainty range on the depth of each event but it is not explained how this was estimated?

We added the horizontal uncertainties in Table 1 and inserted a second table with strike directions and uncertainties. Programs that were used to estimate the uncertainties are named in the text. We added the sentence in section 3.2: "*Strike directions and their uncertainties are presented in figure 4c. The uncertainties result from a systematic grid search for polarity and amplitude ratios using FOCMEC. Afterwards, the 20 best possible solutions for each event were averaged and the standard deviation was calculated (Tab. 2).*". We added the section Appendices to provide more information on the data quality and results.

- Section 4.2 – Orientation pre-existing rift-related faults: the title of section 4.2 should be changed. This studies provides insight on the present-day seismic activity of the basin but not on the rifting history. The authors discuss here the orientation of the faults obtained from the focal mechanisms of the earthquakes and that they interpret to be inverted, pre-existing rift-related faults. I agree, a change of strike from c. SW-NE to more SSW-NNE may reflect (not 'mimic') the rotation of normal faults formed during rifting during the CCW rotation of Corsica-Sardinia towards the SE relative to Europe. But this paragraph needs rephrasing and more information should be given, e.g. the exact strike (and dip?) of the fault planes obtained from the focal mechanisms. The authors should also quote papers concerning the evolution of continental rifting that shows younging of rifting-related structures towards the center of the basin (e.g. Brune et al. 2014, Nature communications) to support their interpretation. Also, the rotation of Corsica-Sardinia, was not only between 21-16 Ma but started with continental rifting at about 35-30 Ma, as indicated by the age of syn-rift sediments (e.g. Séranne 1999,

J. Geol. Soc. London; Jolivet et al. 2015, Tectonics; note the total amount of rotation between 35-0 Ma is estimated to a minimum of c. 53°, Le Breton et al. 2017). The phase between 21-16 Ma is often interpreted as the phase of oceanic spreading in the Liguro-Provencal Basin (e.g. Speranza et al. 2002; Le Breton et al. 2017), as suggested by the age of post-rift sediments along the margin of Gulf of Lion (e.g. Séranne 1999; Jolivet et al. 2015) and Sardinia (e.g. Sowerbutts and Underhill, 1998, J. Geol. Soc. London).

We changed the title to "*Orientation of pre-existing rift-related faults*". We changed "mimic" to "*reflect*" in the abstract and conclusion. We added the reference to Brune et al. (2014) and added the sentence in the discussion to support our interpretation: "*Thermo-mechanical modelling suggests that rifting-related structures get younger oceanwards (Brune et al., 2014).*". We rephrased the section on the rotation angles and timing.

- Section 4.3 – Rheology of the lithosphere: This section is important as the depth and location of the earthquakes in the upper mantle, in the middle of the basin is indeed quite intriguing. First, the author should better present the uncertainty on the nature of the crust and depth of crystalline basement (CB on Figure 5) in this part of the basin. Then, they discuss the seismicity in terms of strength of the lithosphere. However, Handy & Brun (2004, EPSL) discussed that seismicity is an ambiguous indicator of strength and proposed that earthquakes are more reasonably interpreted as a manifestation of transient mechanical instability within shear zones and may be used to locate active weak zones within the continental lithosphere. This should be mentioned and discussed here, as shear zones commonly form through lower crust-upper mantle during continental rifting (see for example Naliboff et al. 2017, Nature communications). Finally, when discussing the strength of the lithosphere, temperature is indeed an important parameter but the discussion here is not clear. Why does stretching of the lithosphere would cause "lower" temperature at the crust-mantle boundary (l. 229)? Stretching involves thinning of the lithosphere thus increasing of the geotherm, which is reflected by higher heat flow, as mentioned later in the text (l.248-253). This is contradictory and should be clarified.

We added to the discussion the uncertainties of the model for the crystalline crustal thickness: "*The crustal structure in the vicinity of clusters C1 and C2 is well imaged by the LOBSTER seismic refraction profile p02 (Dannowski et al., 2020)**. Uncertainties remained for the depth of the crystalline basement and the thickness of the crystalline crust, while the depth of the crust-mantle boundary is well imaged. The study** provides no indication of a high amount of mantle serpentinisation at its southern end.*".

We added Handy and Brun (2004) to the discussion which indeed helps to make our argumentation clearer. The seismicity is not reflecting strong lithosphere but rather weak zones in a possibly strong lithosphere. The high mantle S-wave velocity (Vs=4.7) and the low Vp/Vs ratio (1.72) argue for a strong lithosphere. We also rephrased the conclusions and abstract according to the new discussion: "*~~The observed cluster events~~A high mantle S-wave velocities and a low Vp/Vs ratio support the hypothesis of strengthening of crust and uppermost mantle during rifting-related extension and thinning of continental crust.*".

We rephrased according to the reference to write clearer why crust can strengthen during extension: "*Stretching of the lithosphere will cause **cooling of rocks within the crust and result in a decrease of pressure** ~~lower temperatures~~ at the crust-mantle boundary, which in turn, will strengthen the entire crust **(Pérez-Gussinyé and Reston, 2001)**.*"

Specific comments:

Abstract (lines 20-22) and Conclusions (lines 259-263) need to be improved/rephrased (see main comments above). For example, I would not say 'away from the abandoned rift' but away from the center of the rift basin; 'mimic' -> 'may reflect'

Changed to "*rift-related*", "*rift basin*" and "*may reflect*"

Line 35: the entire basin might be under compressive stress but the inversion is mostly observed along the margins of the Tyrrhenian Basin

Rephrased: "*… of the ~~entire~~ basin* ***that is mainly observed along the margins*** *(Zitellini et al., 2020)*.".

Line 45: 8 months – precise 2017-2018

Added

Line 52: rollback of the Apennines, Calabrian and Gibraltar subduction zones

Added

Lines 53-54: south-eastward migrating (or retreating) Apennines-Calabrian arc (Frizon de Lamotte et al.)

Changed as proposed

Line 56: Alboran Basin: c. 25 – 8 Ma (see for example Comas et al. 1999, Proceedings of the Oceanic Drilling Program, Scientific Result, Vol. 161)

Changed and Reference added

Lines 62-63: I would call it Liguro-Provencal Basin (SW part), not Balearic Sea. Gailler et al. 2009; Afilhado et al. 2015; Moulin et al. 2015 are geophysical studies between Gulf of Lion – Sardinia, which is the southwest part of the Liguro-Provencal Basin. And they mentioned "atypical" oceanic crust, it should be mentioned.

Changed and added 'atypical'

Line 70: Gattacceca et al. (2007, EPSL) should be also mentioned here.

Added

Lines 73-75: please add time constraints here, since when the opening of the Tyrrhenian Sea ceased?

Added "***slowed down or*** *ceased*" to express that it is very recent if it ceased.

Lines 75-76: today

Added

Lines 180-181: The uncertainty on the depth of the crystalline basement (CB on Figure 5), especially for this part of the profile where the distinction between sediments and thinned continental crust cannot be done (Dannowski et al. 2020), should be mentioned and discussed (here and/or in section 4).

Added here: "***There remains uncertainty on the depth of the crystalline basement from the refraction seismic study (Fig. 5e) (Dannowski et al., 2020), however, the*** *~~The~~ C1 and C2 events …*"

Line 191: How does the counter-clockwise rotation of Adria would generate regional compression in the Ligurian Basin? Larroque et al. (2016) discuss the southward propagation of the deformation from the Alps-Ligurian basin junction to the southern margin of the basin, for me this goes in (1) Africa-Europe convergence.

We only summarise the different observations of motion and this includes the rotation of Adria as a possible source for the compression of the two clusters.

Lines 193-194: Le Breton et al. (2017) and van Hinsbergen et al. (2020) are not really relevant here. Our plate reconstructions do not indicate where the Europe-Adria convergence is accommodated today, but provide information on the long-term plate motion and kinematics. They would be more relevant in geological setting, when presenting the geodynamic evolution of the area over the last 35 Ma.

We agree and removed both works in this context.

Line 195-196: what about the inversion of the northern margin of the Ligurian Basin? (as mentioned in section 2, see also Billi et al. 2011, Bulletin de la Société Géologique de France 182).

We added: "*An analysis of two decades of dense GPS data presents a ~0.4 mm/y motion of Corsica representing a NNW-SSE shortening that is compatible with the tectonic and seismicity observations at the Ligurian margin (Masson et al., 2019).*"

Sentences lines 182-183, 200-201 and 203-204: This is not very clear, do the authors suggest that these earthquakes occur along one fault plane (as projected in their profile AB, l. 200-201) or along different fault planes (as mentioned l. 182-183; 203-204)? And why (based on what arguments/observations)? The rupture lengths/areas must be small, as indicated by the low magnitude of these earthquakes, and may explain why the postrift sediments are not affected. But how does it tell more information on the location of theses earthquakes along one or more fault plane(s)?

We added an explanation to section 4.1 based on the waveform families observed in the data (section 3): "*C1 consists of two waveform families indicating repeated activation of the same fault plane for events of the same family. Events of one family have very similar waveforms (Fig. 4a) because they originate from the same fault plane. Events of family 1 occur at greater depth than events of family 2. We observe two possible fault planes (Fig. 4c, Tab. 2). For the second fault plane the event locations and the direction of the fault plane coincide indicating that the same fault was activated at different depths. For the first fault plane the events occurred on two neighbouring faults. The same is true for the relationship between C1 and C2, where we observed a third waveform family. Based on the data we cannot conclude if the clusters C1 and C2 belong to one fault plane or to two separate nearby fault planes, therefore we use the term 'rupture area' in the further discussion.*".

Line 200-201: 'push' direction -> slip direction (?)

Changed SE to NW

Line 204: 'can be taken up by these remaining' -> could reactivate pre-existing ; 'rifting structures' -> rift-related structures (check throughout the text); 'enabling' -> suggesting ongoing

Changed (throughout the manuscript)

l. 216: 'turned' -> inverted

Changed

l. 224: water in the formation of ?

Rearranged

l. 234: interpreted to reflect inversion along pre-existing normal faults

Changed

Figures

Figure 2: I would remove Balearic Sea and keep only Liguro-Provencal Basin (the authors could add the North Balearic Transform Zone, e.g. van Hinsbergen et al. 2014, Tectonics, as a delimitation between the Liguro-Provencal Basin and the Algerian Basin). I suggest also to add on this map the (inferred) location of oceanic crust (or atypical crust) vs exhumed mantle, and zones of basin inversion described in previous work and mentioned in the text.

We added the NTBZ taken from Hinsbergen et al. (2014). We added the reference to the list. We removed "Balearic Sea". We do not add the suggested zones of inversion and proposed location of oceanic crust. We cited a number of studies that show the outline of the oceanic crust and describe the zones of inversion in the western Mediterranean. The zones of inversion are wide and of different ages and we want to keep the map as simple and understandable as possible showing the main geological features and location of the basins we describe and discuss.

Figure 5: It would be interesting to plot the clusters of earthquakes directly on the seismic velocity model (e). At about 30 km distance, the velocity contour 5.5 km/s deepens, does the location of cluster C1 coincides with this change in velocity?

The deepening of the 5.5-isoline at the profile end is most probably an artefact resulting from lower resolution of the model at the end of the profile. We keep plotting the clusters beside the profile to prevent misunderstanding of the location of the cluster still enabling an easy comparison.

References

Bethoux 1992: Quaternaire (not quate)

Changed

Maggi et al. 2000: Journal (Geology) is missing

Added